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SUSTAINABILITY - ITS INCORPORATION INTO THE MECHANICAL ENGINEERING DESIGN PROCESS

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A thesis submitted in partial fulfilment of the requirements for
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In memory of my mother Mrs Elsie Johnson who passed away December 2012. She was always in the background supporting my endeavours

GENERAL CONTENTS

ABSTRACT

As an engineering design practitioner both as an educator as well as a practicing design consultant it became clear that there was a need for a sustainability measurement tool for the mechanical engineering product designer who actually designs products, that is, the engineer who drives the Computer Aided Design (CAD) station. This need was confirmed upon consulting several publications but in particular the codes of practice of the Institution of Mechanical Engineers, (I.Mech.E.) [A1.1], American Society of Mechanical Engineers (ASME) [A1.2], and The Royal Society of Engineers (RSoC) [A1.3], who prominently advocate sustainability practices to member engineers.

This research project aims were formulated to derive a sustainability measurement system for new products across the entire product life cycle. The process of design was used as the system driver with ISO Standards as the system regulator. The adopted technique was to use Embodied Energy as the measurement parameter and aggregate its application to the product throughout the entire product life cycle. Furthermore, saved or generated energy was accrued and used to offset the Embodied Energy input, resulting in an energy balance sheet. A computer algorithm was devised to collect, collate and disseminate the life cycle wide generated data. A control and guidance system was also required and evolved into a top down management system from CEO to the manual worker and governed by ISO Standards.

Key Findings and Achievements
Key achievements relate to a cohesive design-measurement-management system and are listed below

- Sustainability measurement across the entire product life cycle
- Complete system model integrates: management, process, measurement, data control
- Product life cycle improved with novel elements
- LCA and TBL closely linked – product influence to global influence
- Design process is the system driver
- ISO Environmental Standards are the system regulator
- Design for Sustainability (DfS) applied to the entire life cycle
- Algorithm: records, analyses, calculates, consolidates and disseminates data
- Integrated algorithm across the entire product life cycle
- Embodied Energy metric applied across the entire product life cycle
- Energy accounting system provides a net energy balance
- Detailed data obtained at a product level
- Integrated dataflow across the entire life cycle
- Field feedback information allows real time design iteration
- Cohesive management strategy linked to ISO standards
- System adaptable to specific manufacturing plants

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GENERAL GLOSSARY

Artificial Energy:	Notionally the energy derived from fossil fuels used in the creation of a product.
3BL:	Triple Bottom Line
Carbon footprint:	The value of carbon emissions released during the conversion of energy from fossil fuels
CAD:	Computer Aided Design
CDS:	Concept Design Specification
CEEV:	Certified Embodied Energy Value
Component:	Individual item contributing to a total product or simply
Depth of section:	In beam theory the depth of section is the distance between the upper surface of the beam and the lower surface of the beam. An increase in depth of section generally improves the load carrying capacity of the beam.
DfS:	Design for Sustainability
EE:	Embodied Energy: additive energy required to create a product.
EER:	Embodied Energy Reduction
EPA:	US Environmental Protection Agency
EPS:	Energy of Primary Source: Embodied Energy applied to a product to include all energy input to a product during its life cycle
FSA:	Final Sustainability Audit
Harvested Energy:	An entry in the energy balance sheet which accrues energy saved and energy generated from products during the Phase 2 Life Cycle
ISO:	International Organisation for Standardisation
KESB:	Kinetic Energy Storage Battery
LC:	Life Cycle
LCC:	Life Cycle Cost
LCI:	Life Cycle Inventory
Metric:	Measurement Device
Natural Energy:	Notionally the energy derived from natural means such as hydro-electric, wind, solar; used in the creation of a product.
NGO:	Non-governmental Organisation
Part:	See component
PCO:	Product Creation Organisation
PDS:	Product Design Specification
PH_1SLV :	Sustainable Life Value for Phase 1 Life-Cycle
PH_2SLV :	Sustainable Life Value for Phase 2 Life-Cycle
PPM:	Planned Preventative Maintenance
PM:	Proactive Maintenance
Product :	An assembly of parts e.g. vehicle, ship, printer, cycle (the main item of interest)
PS:	Product Specification
PTI:	Predictive Testing and Inspection
PV:	Photo-voltaic
QMS:	Quality Management System
R&D	Research and Development
RCM:	Reliability Centred Maintenance
RFID-codes:	Radio frequency identification codes
RM:	Reactive Maintenance
SCM:	Sustainability Centred Maintenance
SCMA:	Sustainability Centred Maintenance Algorithm
SDV:	Sustainable Disposal Value: Embodied Energy required to dispose of the product
SDeV:	Sustainable Design Value: Embodied Energy required in the product design process
SED:	Sustainable Engineering Design
SEP:	Sustainability Enhancement Program
SGBV:	Sustainable Giveback Value: Embodied Energy gleaned or saved
SLV:	Sustainable Life Value
SMaV:	Sustainable Maintenance Value: Embodied Energy required during

	maintenance processes
Smart Product:	A diverse meaning of a product that is equipped with, usually RFID technology for tracking, location and interconnecting communication between products and communication nodes
SMV:	Sustainable Manufacturing Value: Embodied Energy required to manufacture the product
SSV:	Sustainable Source Value: Embodied Energy required to source the material.
SUV:	Sustainable Use Value: Embodied Energy used by the product during its useful life
TDC:	Total Design Control
TDCMS:	Total Design Control Management Strategy

NOMENCLATURE PHASE 1 LIFE CYCLE

C_{e1}	Transport energy coefficient (Joules/kg.m)
D_{ENERGY} :	Energy used during the design process (joules)
E_{1m}	Quantity of excavated mass (kg)
$E_{1ecoeff}$	Extraction energy coefficient (joules/kg)
$E_{Factory}$	Total energy used by the manufactory (joules)
E_L	Extended life (years)
EPS	Energy of Primary Source (joules)
Kg	unit of mass (kilograms)
L_G	Standard guaranteed life of product (years)
LNo	Number of life extensions
m	metres
M_{man}	Mass of Manufactured Product (kg)
$M_{sourcing:}$	Mass of Useful Sourced Material (kg)
$M_{Transport:}$	Product mass transported to customer (kg)
N_1	Waste fraction from process 1
N_2	Waste fraction from process 2
N_3	Waste fraction from process 3
N_{DESIGN}	Proportion of SMV Energy used in the design process (joules)
N_P	Number of Products produced / annum
P_1	Primary Processing operation (joules/ kg)
P_2	Secondary processing operation (joules/ kg)
P_3	Tertiary processing operation (joules/kg)
$P_{1ecoeff}$	Primary process energy coefficient (joules/kg)
$P_{2ecoeff}$	Secondary process energy coefficient (joules/kg)
$P_{3ecoeff}$	Tertiary process energy coefficient (joules/kg)
P_{1m}	Mass exiting the first process (kg)
P_{2m}	Mass exiting the second process (kg)
P_{3m}	Tertiary processing operation (joules)
P_M	Individual Product mass (kg)
R_E	Energy saved by recycling (joules)
SDeV	Sustainable Design Value (joules)
SEE	Specific Embodied Energy (joules/kg)
$SEE_{Sourcing}$	Specific Embodied Energy (sourcing process) (joules/kg)
SLV_{PH1}	Sustainable Life Value Phase 1 life Cycle (joules/kg)
SLV_{PH2}	Sustainable Life Value Phase 2 life Cycle (joules/kg)
SMV	Sustainable Manufacturing Value (Joules/Kg)

SSV	Sustainable Source Value (Joules/Kg)
SSV_{Mass}	Total mass flow sourced and processed (kg)
STV	Sustainable Transport Value (joules/kg)
T_1	Transport to primary processing plant (joules/kg)
T_2	Transport to secondary processing plant (joules/kg)
T_3	Transport to tertiary processing plant (joules/kg)
T_4:	Transport to manufacturing plant (joules/kg)
T_{1e}	Energy needed to transport mass from point of excavation (joules/kg.m)
T_{2e}	Energy needed to transport mass from process 1 to process 2 (joules/kg.m)
T_{3e}	Energy needed to transport mass from process 2 to process 3 (joules/kg.m)
T_{4e}	Mass transported from third process (kg)
T_{1m}	Mass transported from point of excavation (kg)
T_{2m}	Mass transported from first process (kg)
T_{3m}	Mass transported from second process (kg)
T_{4m}	Mass transported from third process (kg)
W_{1e}	Primary process waste energy (joules)
W_{2e}	Secondary process waste energy (joules)
W_{3e}	Tertiary process waste energy (joules)
W_{1m}	Waste mass from Process 1 (kg)
W_{2m}	Waste mass from Process 2 (kg)
W_{3m}	Waste mass from Process 3 (kg)

NOMENCLATURE : PHASE 2 LIFE CYCLE

E_{AP}	energy applied during use (e.g. petrol, gasoline, diesel) (Mj)
E_{COAL}	Annual coal energy (Mj)
E_{ELEC}	Annual electrical energy (Mj)
E_{GB}	Annual bottled gas (Mj)
E_{GP}	Annual piped gas (Mj)
E_{OIL}	Annual oil energy (Mj)
EPS_R	Energy needed for recycling alternative materials per kg (j/kg)
EPS_S	Energy needed for recycling steel per kg (j/kg)
EE_T	Total Embodied Energy applied to the product
E_{UL}	Energy generated during product use (Mj)
F_{DAYS}	Factory, number of working days
F_{EP}	Factory overhead (manufacturing) (input energy proportion/product)
F_{TE}	Total annual energy (maintenance factory) (Mj)
H_{REC}	Cumulative negative residual energy lost to recycling (Mj)
H_{REU}	Cumulative positive energy harvested from reused parts (Mj)
LU	Life Usage (Life of product between maintenance periods)
M_S	Mass of steel (kg)
M_R	Mass of alternative materials (kg)
N_{IP}	Cumulative number of installed parts
$N_{IP}EE$	Installed parts total Embodied Energy (Mj)
N_{REC}	Cumulative recycled parts
N_{REU}	Cumulative reused parts (number of times a part has been reused)
N_{ULA}	Number of life usages accrued
REE	Residual Embodied Energy (Mj)

CHAPTER 1
INTRODUCTION

Since man began to trade goods there have always been two goals. The first goal was to make profit and the second goal was to enhance the human circumstance. The two goals are interminably linked since goods had to be “needed” by the market so that they could be sold. Furthermore goods needed to be affordable to create market demand and allow vendors to make a profit.

Modern society, though sophisticated, is still driven by these two goals, profit and human improvement, and it is hard to find a society where these two goals are not fundamentally tattooed into the psyche of every individual.

It is an accepted truth that commercial product creation is always cost driven and everything has a cost. This belief does not consider the environmental “cost” when materials are dragged out of the earth to feed our ever increasing need for products. Many commodities are diminishing, have become scarce, or have disappeared and, therefore, the environmental impact is also an important incumbent “cost” which has often been ignored but has now become necessary to consider. What can persuade business and product creators to include environmental impact in their perspectives?

Social pressures to turn “green” is a major consideration for many commercial enterprises but often these enterprises merely pay lip service

Natural cost rises due to shortages. When a commodity becomes scarce, its market value rises. When materials become expensive, the users of such materials will either look around for alternatives or conserve what materials are available.

The first oil shortages, witnessed in the early 1970’s, US Dept of State [1.37], were largely artificially imposed shortages that increased the cost of oil almost overnight. The crisis had the effect of galvanising vehicle designers to produce more economical cars that were lighter weight, smaller, more efficient, etc. The drive to produce alternative prime movers (engines) which did not rely so heavily on fossil fuels was also generated.

The mind set of business, the public and governments is money orientated. It is only when shortages of commodities become apparent and costs increase that a change in mind set will take place. A sustainability mind set is currently only shared amongst a minority of environmental hero’s but is growing amongst many protagonists. In some areas, legislation and standards [1.26, 1.27, 1.28] have been created to assist environmentalists and are excellent application guides. Standards often provide the basis for legislation and effectively standardise the approach to a particular service or system. In later chapters ISO standards for environmental management are applied as a platform on which to base the management strategies.

Perhaps some of the most active strategies are led by the engineering institutions such as the Institution of Mechanical Engineers (I.Mech.E), American Society of Mechanical Engineers (ASME) and the Royal Society of Engineers (RSE). These institutions amongst others have included new sustainability elements in their Codes of Practice [Appendix sections A1.1, A1.2, A1.3]. Furthermore their accredited undergraduate engineering courses currently have an inbuilt significant sustainability element derived and applied by the Engineering Council's UK Spec [1.38].

The not-so-subtle approach is to educate undergraduate student engineers in the ways of sustainability. This may take a generation to accomplish but the message delivery is arguably more powerful than merely creating standards, though these also have their part to play.

Traditionally engineering designers designed and manufacturing engineers manufactured the design. In the late 1950's Genichi Taguchi suggested that quality should be placed in the hands of the designer. This revolutionary approach prompted a design and manufacturing revolution and was the catalyst which drove production techniques into quality mass production although new production techniques had been pioneered by people such as Samuel Colt [1.38] and Henry Ford [1.39], quality of manufacture still largely remained the domain of craftsmen and artisans to produce and create quality goods.

There are a great number of demands placed on the modern design and production environment. Some of these are traditional demands such as that of reducing cost. Newer demands however are becoming prominent including those which require reduced environmental impact when a new design is created. This relatively new discipline is "Sustainable Engineering Design".

Taguchi was one of the first proponents of placing the emphasis on the designer who takes control and specifies quality. The greater demands and expectations placed on new products effectively requires that designers must take a greater role in specifying and controlling the new product from its inception right through manufacture to packaging and even marketing. This is effectively Sustainable Engineering Design. The design function can no longer be compartmentalised since it is the only function that can overview and control the whole process of product creation from “cradle to grave”.

It is within the designer's skill and ability to apply sustainable design techniques to create a long life product. It is the designer and ONLY the designer who has the overview of the whole design and manufacture process.

This whole life process involves the following elements:

- specify sustainable materials,
- design for sustainability
- design for sustainable manufacture,
- design for sustainable use,
- design for sustainable maintenance
- design for sustainable disposal

It is within the designer's remit to overview the entire life cycle of a product from sourcing materials through to end of life disposal. In order to perform this task properly there needs to be a sustainability measurement system and an overview sustainability management system in place.

This research project therefore is dedicated to:

- defining sustainability,
- providing a suitable measurement system
- enabling the design function to consider the whole life cycle of a product
- creating a credible management system which will engage all personnel from the chairman to the lowest worker.
- providing a tool for the measurement of sustainability in the new products

1.0 Sustainability and its Application within Engineering Design

1.1 What is Sustainability?

In 1983 the United Nations General Assembly first addressed the heavy deterioration of the human environment and the natural resources that the human race required to survive. Javier Perez de Cuellar, Secretary General of the United Nations created a commission to investigate aspects of sustainability for the entire world. The commission's task was to rally countries to work and pursue sustainable development together. The result of this initiative was that the Brundtland Commission was quickly established led by Gro Harlem Brundtland, the former Prime Minister of Norway.

In 1987 Gro Harlem Brundtland published the first part of the "Brundtland Commission report" entitled "Our Common Future" [1.5]. The report was wide ranging -- researching and interviewing politicians, industrialists, academics, Non-Governmental Organisations (NGO's), the general public and anyone who wished to contribute to the findings. The report’s findings extended through many diverse areas of sustainability and the impact of man on the ecosystem of the planet highlighting the result of a depleted ecosystem on mankind. The areas of interest can be summarized as the three main pillars of sustainable development: economic growth, environmental protection and social equality.

More importantly the Brundtland Commission defined sustainability as follows:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs".
>
> It contains two key concepts:
>
> - The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
> - The concept of limitations imposed by the state of technology and social organization and the environment's ability to meet present and future needs.
>   Brundtland [1.5]

The concept of needs is really a geo-political requirement and is very valid. From the engineering design discipline point of view the second concept is very relevant and should be in the back of the mind of every designer when creating new products. The statement highlights the fact that our planet has a limited capacity to support an ever expanding human race with all its technology and social systems.

1.2 Is Sustainability Achievable?

After considering the definition of sustainability and then realizing that the planet's ecosystem has limitations, the question should be asked: "Is sustainability achievable?"

In order to answer this question perhaps a slightly different definition should be considered:

True Sustainability…….

> …… is development and use of products and services where ZERO resources are taken from the earth Johnson et al [1.36]

A similar view was put forward by Pope [1.29] who submitted that physical and geo-scientific systems were a combination of sustainable and unsustainable elements, thus suggesting that in any system 100% sustainability cannot be achieved. Traverso et al [1.32] combines several indices for "more efficient sustainability assessment" but concluded by suggesting that even with the best models 100% sustainability is not achievable. To quote an anonymous industrialist "Everything costs money, everything has an environmental impact."

Any product development requires resources in terms of materials and the energy to manipulate those materials. It is certainly true that sustainability can be improved by recycling materials, reusing appliances, and repairing components to reduce material usage. These are known as the 4R's, listed as follows:

- Recycle
- Reuse
- Repair
- Reduce

It is true that many people and institutions feel that by accommodating the 4R approach they have done enough. Certainly adoption of the 4R's greatly improves sustainability but most efforts address the end of the life of a component or product, merely enabling materials to be reused in some way. The adoption of the 4R approach does not usually consider the environmental impact of a product prior to its end of life. It is important to note that the extraction of raw material from the earth, its manipulation and manufacture, and especially its usage may contribute more to environmental impact than any strategy which may be adopted at the end of that product's life.

The extraction of materials, their manipulation, usage and eventual disposal will always require energy. No matter what sustainable strategies are in place the one single requirement that will always be needed is energy to extract and create the product and it is energy which is required for a product to continue through Its Life Cycle.

Since a sustainability measurement device (metric) has to cater for almost any product, specific metrics such as carbon dioxide are unable to cover the whole life cycle of a product. Research revealed that one commodity was input (or eventually output) throughout the whole life cycle of a product. That commodity was energy (Joules) or more specifically Embodied Energy as originally set out by Ashby [1.24]. This is the metric therefore selected for the life-cycle sustainability measurement process. The use of Embodied energy has several benefits:

- Embodied Energy could be applied to any product or any service
- Embodied Energy is relatively easy to convert from any energy storage commodity, such as, coal, nuclear, petrol, diesel, wind, solar, etc.
- Embodied Energy can be used to measure to all six life-cycle elements
- Embodied Energy can be used as a currency to define the value of sustainability for a product
- Embodied Energy value can be used to offset the input of Embodied Energy thereby using the value as an accounting device

In man's ever-increasing quest for new products, there will always be a requirement for materials and there will always be a requirement for energy. Sustainable strategies may assist in reducing the environmental impact but the reality exists that it may NEVER be possible to achieve true sustainability where there are no new resources extracted from the earth. Appropriate strategies may, however, help us to come closer to attaining this "Holy Grail" in sustainability.

Richard Moles [1.23] in his publication suggested that there is a difference between sustainability which is an aspirational future situation and sustainable development which is the process by which we move from the present towards a future situation. The statement acknowledges that true sustainability may not be 100% achievable but by employing sustainable development of techniques, and aspirational future sustainable products might be used as a target.

Engineering institutions such as The Institution of Mechanical Engineers (I.Mech.E.) [1.29] or the American Society of Mechanical Engineers (ASME) [1.30] acknowledge the reality that sustainability cannot be 100% achievable, but seek to influence engineers globally by incorporating the principles of sustainability into their codes of practice.

1.3 Sustainability Past and Present

Recent decades have shown an increase in awareness of environmental impact and the need for sustainability. Development of techniques to measure impact has aided increasing development of awareness.

However until modern times the impact of human infestation on the planet was fairly minimal since no one used electricity or internal combustion engines. The use of tools that were manufactured from material extracted from the earth began the degradation of the environment since the material was irreplaceable.

During Tudor times (1485-1603) the motive power was from natural resources such as horses, sailing ships, windmills, and water wheels. Even this pre-industrial society was not truly sustainable because commodities were taken from the earth which could not be replaced. Iron ore was quarried and trees were cut at a rate that was difficult to sustain.

The advent of the industrial revolution in Europe and America began the need for more and more energy. In the beginning, mechanical power was generated from steam engines which were used to drive farming machines, diggers, engineering machine tools, and entire mills in the steel, textile and many other industries.

These powerhouse machines spawned other industries such as engineering, coal mining and ship building. The prosperity of towns and entire countries became dependant on steam power. All this power came at a price: pollution! Natural water courses became clogged with industrial slime and debris. The air around industrial centres became laden with soot and other unpleasant, unhealthy contaminants. The term "Dark Satanic Mills" used by William Blake in his poem “Jerusalem” (1804) came to represent this pollution though it seems he originally intended to draw attention to Britain's industrial might and its propensity for manufacturing weapons of war.

The pollution caused by steam power was tangible. Airborne smog and chemicals affected health and life expectancy of the population. A typical industrial landscape can be seen depicted in Figure 1.1.

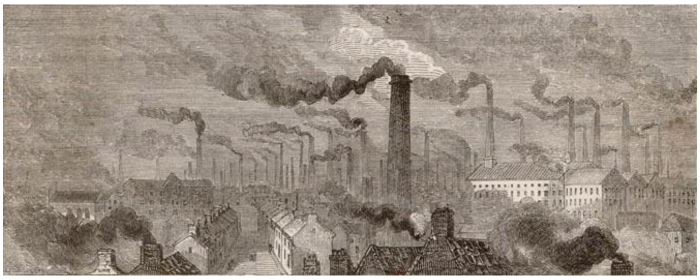


Figure 1.1; A Depiction of Pollution in Manchester UK (Circa 1850) [1.2]

Electric motors and the internal combustion engine gradually replaced the steam engine but it was the clean Air Act (1956) in the UK and in the US (1970) which reduced the air pollutants dramatically and forced steam power into near oblivion.

The generation of energy through coal and oil power stations and the use of the internal combustion engine created pollutants. These pollutants, such as carbon dioxide, carbon monoxide, nitrogen oxide and sulphur were more dangerous because these pollutants could not be seen. At the turn of the century millions of internal combustion engines burning fossil fuels (oil derivatives) were used daily worldwide. The emissions created enormous health problems in large urban areas but perhaps more concerning was the increase in global warming, largely attributed to the increase in carbon dioxide in the atmosphere. Furthermore polluting chemicals derived from the burning of fossil fuels were shown to deplete the protective ozone layer in the stratosphere.

Measurement of these pollutants and their effects on the earth’s ecosystem has shown a definite deterioration. As the evidence mounted, so did scientific, political and popular concern. Whilst pollution was the original focus of concern, the need to measure the environmental impact has evolved and broadened the concern.

The publication of “Our Common Future”, often called merely “The Bruntland Report” published in 1987 [1.5], established and defined a new approach to environmental protection, that of *Sustainable Development*.

Sustainable Development deals with the causes of environmental impact rather than merely the results. The broad view of sustainability takes in many disciplines including the built environment, geographic sciences, mechanical engineering, sociology, psychology, finance and business.

The discipline of mechanical engineering with allied disciplines such as electrical and chemical engineering are at the forefront of new product development. As a society, humans have become reliant on appliances and other products. Every item we purchase is used and eventually discarded in some way. Each product has been designed and manufactured by artisans and engineers and its production, use and disposal naturally impacts the environment. In order to achieve desired longer term sustainability, it is the design and manufacturing engineers who can deliver the sustainable products.

Individuals and companies often talk about sustainability with little idea of how this can be achieved within their organisation. There are, however, some individuals as well as organisations that have embraced sustainability for many years. The real key to achieving sustainability is to educate and empower more people and organisations into adopting a practical approach to sustainability in terms of mechanical engineering design.

Architects and builders have long since built sustainable structures. Even early man built dwellings that were self-sustaining. There are many modern examples of sustainability in the Built Environment. Perhaps some of the better examples can be found in the recycling of building materials. Figures 1.2 and 1.3 below show the reuse of building materials applied to newer buildings.

Figure 1.2: Ancient Stonework Used in "New Build" Walls [1.1]

Figure 1.3: Example Ancient Stonework Used in a Modern Wall [1.1]

The geophysical environment has also been actively enhanced by the application of sustainable projects. An excellent example of geophysical sustainability can be seen in figure 1.4 which shows beach groynes on a UK beach. These wooden structures are built like fingers out in to the sea perpendicular to the shore, thus preventing long shore drift and preserving the shore line.

Figure 1.4: Beach Groynes [1.1]

There are some excellent examples of sustainability in mechanical engineering, however it could be argued that not enough is being done since much of the sustainability focus is applied to the easier elements of sustainability such as recycling.

Recycling of steel and other metals is well practiced as is the recycling of some plastics. Steel recycling rather than newly hewn iron in the US is shown in figure 1.5. Although the average was between 70% and 80%, in 2009 a dizzying height of 103% was reached.

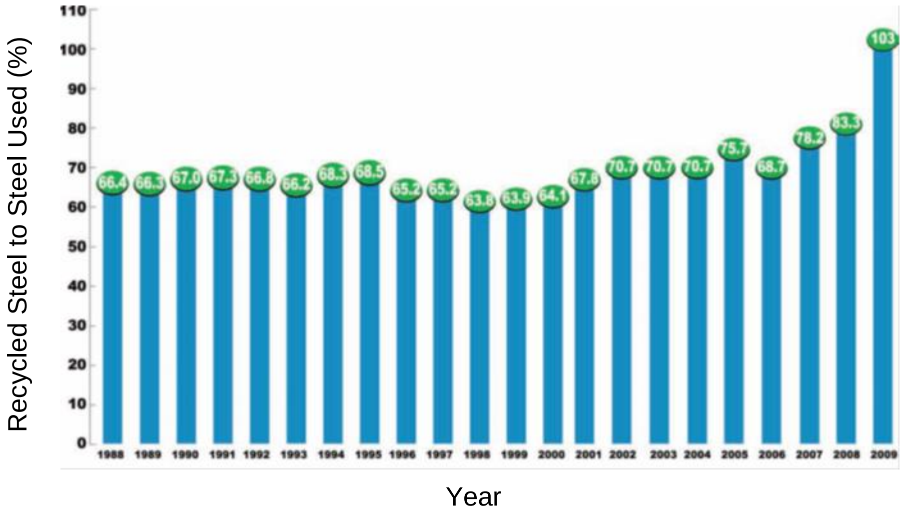


Figure 1.5: Overall Steel Recycling Rate [1.4]

Vehicle manufacturers normally aim for 90% recycling of materials in vehicles at the end of their life. This includes plastics and other components. In the US steel recycling from vehicles reached rates of 121% of the steel used in new vehicle output in 2009 with averages close to 100% [1.4].

Vehicle manufacturers have also been attempting to design and manufacture the sustainable use of vehicles by optimising reduction of mass in new designs. Design optimisation is a major weapon in the sustainable design armoury. For instance, a reduced mass vehicle requires a smaller engine and smaller brakes, tyres and so on. Merely by reducing the overall mass, parts become smaller and fuel use is reduced leading to fewer emissions and lower environmental impact.

Power plants have also been the target of Design Engineers' creativity in the development of leaner burning internal combustion engines and more specifically the development of hydrogen engines and electric vehicle drives.

Though there has been much forethought by individuals and institutions to develop sustainably engineered products the question has to be asked, "Is this enough?"

Resources are still being stripped from the earth at an alarming rate. Worldwide steel production was around 127.5 million tonnes in 2010 [1.4] with only around 70 million tonnes being recycled even though steel is the world's most recycled commodity. If design and manufacturing engineers are to demonstrate an environmental conscience the response must be "We can do more!"

Recycling is on, however, only one aspect of sustainability and generally pertains to the end of life of a product. In chapter 3, figure 3.3 shows the design and manufacturing sustainability model which considers the whole life of a product rather than just the final stage of the product's life.

Many global companies have sustainable policies in place but each has its own approach and its own agenda. This is easy to understand when there is such a diversity of products and industries. There is a great need for a cohesive and coherent approach so that all designers can work towards similar goals and create a significant effect.

1.4 Classic Design and Manufacture Model

The classic design and manufacture process shown in figure 1.6 has been used for centuries. The designer receives the brief, creates the concept design, and converts the concept design into manufacturing drawings which are then used by the manufacturing function to create the product.

This particular model is used by many companies with little thought about the source of the material, the energy used in manufacture, and energy used during the product's use. Furthermore no consideration is given to the disposal of the product. Often at the end of useful life, the product is simply thrown into a garbage bin.

In order to apply sustainable techniques the entire life of the product needs to be considered. This is within the sphere of the designer. It is the designer who can:

- specify the source of the raw material
- specify the method of manufacture,
- create a product system that is environmentally friendly in use
- design into the product a set of components which can be disposed of in a sustainable manner

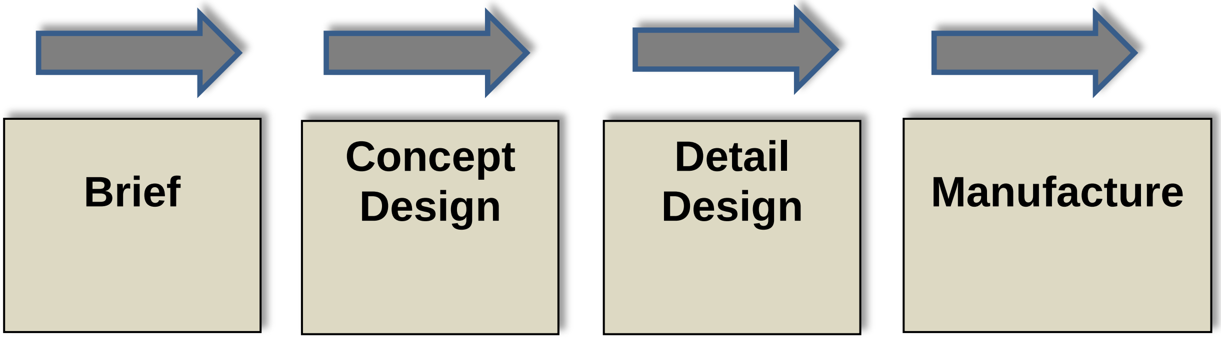


Figure 1.6: Classic Design and Manufacture Model [1.1]

It is the *designer*, therefore, who is the key to future sustainable products and to achieve this it is therefore essential to change the mental attitude of the designer as did Genichi Taguchi in the 1960s with his approach to quality manufacturing.

1.5 The Taguchi Approach to Quality Manufacturing, Rao et al [1.35]

Genichi Taguchi, a manufacturing and statistical engineer, promoted theories in the late 1950’s and early 1960’s concerning the quality of manufactured goods. He noticed that the quality of manufactured goods was usually left to the manufacturing craftsmen which meant that every craftsman was essentially building every product as a single item. This took time and was expensive. Taguchi suggested that quality could be specified at the design stage before components were manufactured. He also recognised that to achieve designed-in quality the mind-set of the designers had to be changed. The approach tasked designers to become more precise in the content of their technical drawings. Engineering designers created better components by introducing standards, tolerances, surface finish, precision machine tools, etc. which lead to large quantity, batch production methods. The Taguchi approach revolutionised batch production since it produced consistent quality during manufacture.

As designers were eventually made more aware of the “new” design method, manufactured goods were produced in huge quantities and became more available at a lower cost and higher quality.

1.6 The Taguchi Analogy Applied to Sustainable Engineering Design

Taguchi suggested that quality should start with the designer who should specify exactly how the product should be made and set quality specifications. The manufacturers would adhere to these specifications so that a product of the required quality would emerge.

The Taguchi analogy Rao [1.35] can be applied to Sustainable Engineering Design (SED). Sustainability cannot be confined to individual elements of the product life process. It has to be considered at the very beginning of the design stage and it is therefore within the scope of the design function to apply the Principles of Sustainability to the whole life of the product.

It is the designer who is the key and who must envisage and design components using sustainable techniques, equipment and methods.

It must be acknowledged that although some engineering designers have sustainability in the forefront of their design practice, the majority of engineering designers may only pay lip service to SED. In order to achieve true SED the designer’s mind set has to be modified.

The design and manufacture process outlined in figure 1.6 creates products which enhance the social benefits to mankind. It also creates value and therefore profit. These two benefits are known as the *double bottom line.*

The Engineering Design Process can no longer be related purely to cost and social benefits. The Engineering Design and manufacture process must now accommodate cost, social and sustainability benefits. This has become known as the *Triple Bottom Line*

A new design and manufacture model can now be formulated that combines the original design and manufacture model with sustainable elements and is shown in figure 1.7.

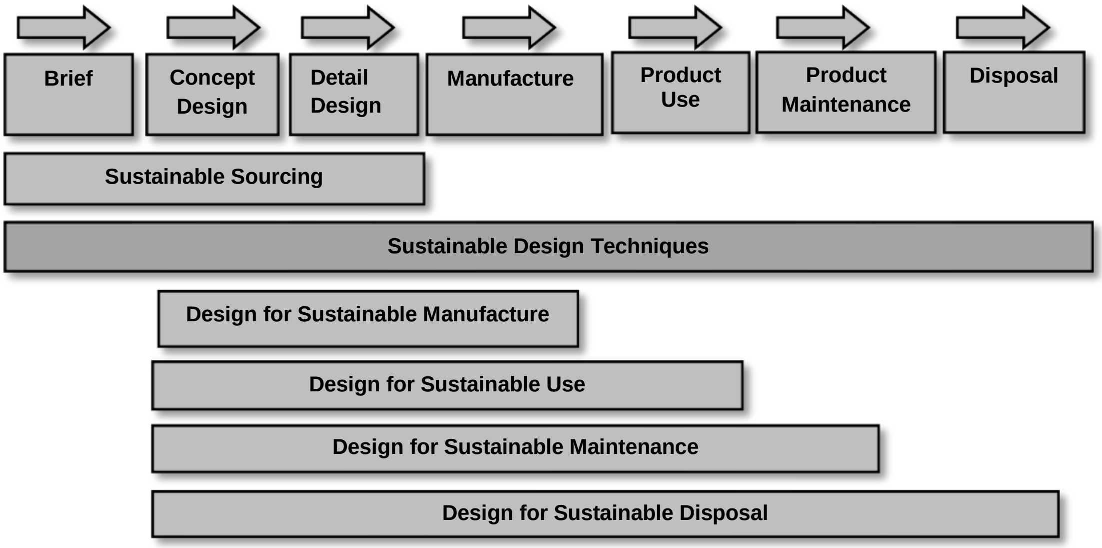


Figure 1.7: Sustainable Engineering Design Whole Life Model [1.1]

It was only a few years ago that reduction in pollution was the watchword for environmentalists. This was a crude yardstick for what has now developed into and has become "Sustainability". The term "Sustainability" encompasses many disciplines from farming to the creation of buildings and from protection of the natural environment to power generation. Within the engineering design discipline the methodology surrounding sustainability has evolved into a multi-faceted approach. The new model shown in figure 1.7 now encompasses the whole engineering process from sourcing of materials to disposal of the product at the end of its life. It is the "Whole-Life-Cycle" approach, often called “Life Cycle Analysis” (LCA).

1.7 Sustainable Sourcing (Eco Sourcing)

Sourcing material spans a vast area. It not only examines the extraction of raw material but also transport of those materials. Sustainable sourcing could be from a sustainably certified source as are some timbers, but may include sourcing recycled materials.

1.7.1 Transportation

Raw materials will always be hewn from the ground and then transported to the processing point using fossil fuels to provide the energy to propel the transporters. This practice is often over very long distances.

The current common practice is for western organisations to source products in the Western Pacific Rim; China, Japan, Korea. This is largely done on the basis of reduced cost since the cost of labour is relatively lower in the Pacific Rim countries than in the West. When large quantities can be produced and freight containers can be filled, it is cheaper to transport over long distances than extract from geographically closer resources.

It should be remembered that the environmental impact of these goods is roughly similar in the Pacific Rim as it would be in the West. The difference in impact on the planet’s resources is in the burning of fossil fuels to generate energy for transportation. Responsible sourcing would mean that designers would specify local suppliers, thus reducing the environmental impact of transporting goods long distances. An added benefit is that local industries would thrive. The argument is that of cost against energy reduction. It is cheaper to import into the West from Asia than to manufacture goods locally. Companies are almost always driven by the need to make profit and reducing costs by importing goods from Asia is likely to be the cheapest option. Here the energy reduction argument loses out to cost savings.

Some commodities have to be transported since they are available only in another part of the world. In such cases the question would be, “how can these goods be transported using sustainable methods?” Before the advent of steam propulsion for ships, only wind power was available to be used. This natural power is 100% sustainable. In the modern era perhaps sailing ships could be resurrected and employed or perhaps modern sailing versions could use the natural elements for propulsion. This is not wishful thinking but reality as can be seen in figure 1.8.

Examples such as the MV Beluga (see figure 1.8) have shown that the wind can be harnessed to provide part of the necessary propulsive power for large modern freighters. For example, Gerd Wessels of Wessels Reederei says “There is enormous free wind-energy potential on the high seas. With *Skysails* [1.7] we can reduce energy by 30% on a good day, giving at least 15% annual fuel savings.”

Figure 1.8: Skysails MV ”Beluga” [1.6]

Similarly, Eco Marine Power [1.8] have designed solar powered craft from small ferries to freighters. figure 1.8 shows Eco Marine Power solar ferry “Medaka”. Critics may scoff at using sail or solar power for freighters but the future may require use of non-fossil fuel energy sources. Vessels such as the "Medaka" shown in figure 1.9 may be powered purely from solar generated electricity. Some large freighters currently use hybrid solar power/diesel, the solar energy contributing approximately 20% to 30% of the total energy required to drive the ship. [1.8]

Figure 1.9: Solar Power Ferry “Medaka” [1.8]

1.7.2 Techniques

Techniques could be changed to accommodate processes that gave a sustainable benefit over current techniques. A recent emergent technology is rapid prototyping. This has grown alongside the development of 3-D computer models and has usually been associated with the 3-D printing of actual sized plastic models.

New techniques in this area create 3-D components using laser fused metal powders. This technique effectively reduces time to manufacture by printing a component at the assembly point thereby reducing transport costs and environmental impact since the component can be formed with no waste at the assembly plant.

1.7.3 Managed Source

All raw materials should be labelled with a "Sustainable Source Value" (SSV). The main feature of this would be to inform the designer of the environmental impact of the raw material. This may at first appear to be expensive and complicated but the system already exists with managed exotic timber which carries a certificate of authenticity of sustainable sourcing. In the design of street furniture (external seating) local UK governing authorities generally have a policy of specifying that the timber for the seating element (usually Iroko) is sourced sustainably. The certificate shows where the timber was grown and how it will be sustainably replaced. If such a system could be used for other materials such as steel, designers could select a material according to its sustainable impact.

1.7.4 Material Flow Systems – Open and Closed Loop

This concept, introduced in the 1990’s, is now being embraced by many countries including those in the European Union (EU). Joke Schauvlike, [1.9] President of the EU Environmental Council states, “We must deal with our materials, and with our energy, more efficiently. At the end of their life we must be able to reuse materials as new raw materials. This is called completing the cycle." This approach was discussed in economic and energy terms by Clift and Allwood under the title “Rethinking the Economy” [1.10].

It can be seen that the present linear design-manufacture systems model, figure 1.6 is not sustainable over the longer term as manufacturers do not consider the issues of raw material extraction and transport as discussed above nor the end-of-life issues once the product is no longer usable or is obsolete.

> In the closed-loop material flow system model, figure 1.10, materials and components would be recovered and reused reducing material inputs and outputs as close as possible to zero. This produces a hierarchy of sustainable end-of life disposal techniques which are commonly termed as the 4R's: Recycle, Reuse, Repair and Reduce

The 4R’s will be dealt with in more detail later pages, however, the use of recycled material in a new product can be considered as prudent sustainable sourcing of raw product.

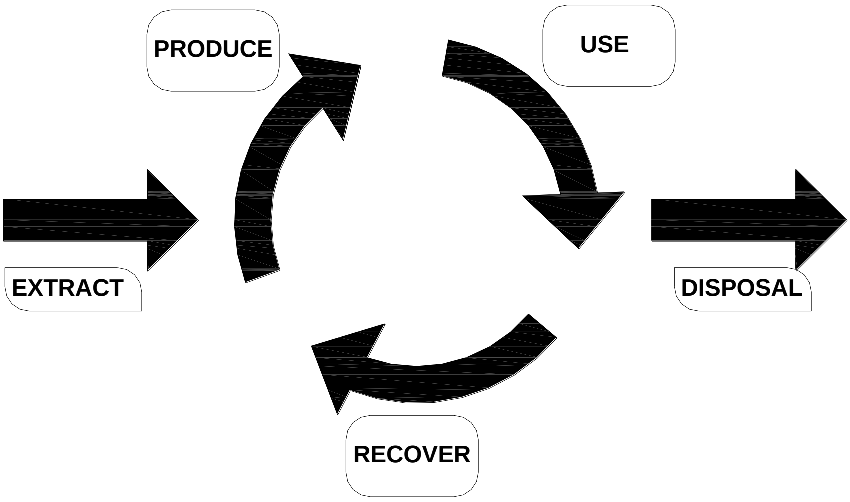


Figure 1.10: Closed Loop Material Flow Systems Model [1.1]

1.7.5 Recycle

Recycling of end of life components and materials has, in some quarters, been a way of life for thousands of years. Throughout the world peasants have built their houses with building materials appropriated from ruined castle walls. In the modern era many products are now recycled and whole industries are being built on the recycling of many products. Older vehicles at the end of their life are stripped of their useful components before being crushed and re-smelted. Various components taken off those vehicles are then resold. There is a thriving used parts business for breakers yards and more recently internet sales of appropriate parts.

The use of recycled tyres is a great success story. The tyres are retrieved from discarded vehicles and processed by stripping and granulating the remaining rubber. These granules can then be reused in a diverse range of items including speed humps (see figure 1.11), children's playground flooring, artificial tarmac for driveways, bullet absorbing walls for firing ranges and a seemingly endless list of items.

Figure 1.11: A Typical Speed Hump Manufactured from Recycled Rubber Tyres [1.11]

Other commodities which can be recycled include glass, cardboard, newspapers, plastic bottles, wood, rainwater, horse manure, etc. This list is not exhaustive and shows the diverse possibilities of recycled products and materials.

1.7.6 Designers Duty

It is the duty and responsibility of the designer to source materials from sustainable sources or at least from sources which have a reduced impact on the planet's resources. The actioning of this responsibility would reduce the Sustainable Source Value (SSV).

1.8 Design for Sustainable Manufacture (Sustainable Manufacture Value, SMV)

The designer or design team selects the manufacturing process including selection of techniques and materials. Industries differ in their manufacturing techniques and the materials they use. The fabrication industry normally uses material which is black finished (hot rolled) mild steel and standard sections. Attachment methods are normally electric arc welding and other welding variations. The machine tool industry on the other hand often combines cast-iron low carbon and medium carbon steel with high precision machining methods. Designers in each of these industries are specialists with intimate knowledge of what could be achieved and how to achieve a particular design shape through the available manufacturing methods.

For many centuries, the formation of components has mostly relied upon the removal of material to create a shape. This process results in a great deal of waste both in material and energy required to remove the material. Casting components creates the shape with much less waste, but still requires a great deal of energy to produce molten material and then machine to final size. Sometimes an energy-expensive process cannot be avoided but the designer should focus on ways to reduce energy and material waste. Attention should also be directed towards the selection of materials that can be processed easily and select manufacturing methods that are not highly energy hungry.

1.8.1 The Smart Factory

Sustainable manufacturing may be expanded beyond component manufacture. Factories can improve their energy usage. Larger organisations are beginning to realise that the old methods of manufacture in large factories can be costly in many ways. High energy use increases product cost and is also environmentally expensive in both in obtaining the energy and in dealing with the factory waste in an eco-friendly way.

It is difficult to change the practices of older factories and often this is not done because the task is so daunting; however, use of an appropriate program can produce small changes which make a large difference over time. New build factories, however, offer the opportunity of creating "smart factories".

1.8.1.1 Marks and Spencer

Marks and Spencer commissioned a clothing manufacturer in Sri Lanka to build and renovate a £7 million factory along environmentally friendly guidelines. [1.13]. Brandex, the largest Sri Lankan apparel exporter in 2007, converted a 30-year-old factory into an eco-friendly plant. The plant has reduced the company's carbon footprint by 77% from 2076 metric tons to 494 metric tons. The plant has achieved its green credentials by applying the following techniques and systems:

- Skylights in the roof reduced the need for overhead lighting.
- LED light systems (low-energy lights at each workstation) further reduced the need for overhead lighting.
- Water recycling made water available for toilet flushing and for external irrigation. Sewage treatment on-site using anaerobic digestion helped recycle water.
- Rainwater harvesting made up 15% of the recycled water.
- Harvesting of biogas from anaerobic digestion of sewage created enough gas to power the kitchen.
- Waste recycling. (Waste fabric, plastics, paper)
- New build used bricks made from stabilised Earth (better insulation)
- Low energy evaporative cooling system replaced air-conditioning reducing energy required.

It is estimated that the plant will be 40% more energy efficient than other factories and uses 50% less water through water recycling.

1.8.1.2 Renault Tangier Smart Factory [1.14]

Renault has built a factory at Tangiers in Morocco which will reduce its carbon dioxide emissions by 98%. Operational from 2012, this reduction has been achieved by all the electrical power being generated by renewable energy sources such as wind, solar power and hydroelectricity.

Figure 1.8: Renault Smart Factory [1.14]

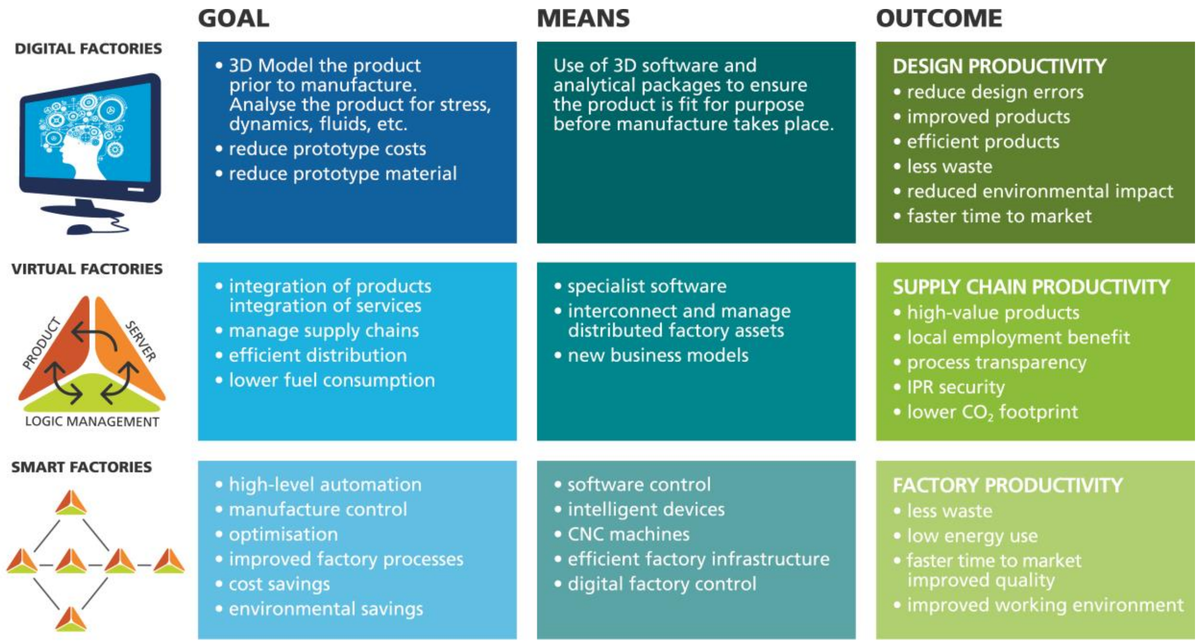
The main consideration thus far has been conservation of energy by preventing energy escape from buildings but smart factories do more than just reduce energy escape or use.

The term "smart factory" is a global term referring to many of the smart practices which contribute to sustainability in manufacturing. A smart factory actually encompasses three basic areas of the sustainable manufacturing.

- Virtual factory
- Digital factory
- Smart factory

The advent of computing technology has brought about more efficient and almost instantaneous communication. It was inevitable that computer technology would become the basis of management processes from inception of a design to the final distribution of a product. Computer technology provides the means to achieve high-level goals of high production, more efficient overall management, and improved energy efficiency which reduces the environmental impact.

Designs now conclude with near complete prototypes on-screen as a 3-D image. This eliminates building of prototypes thereby saving all the effort, cost and material that this process would normally require. More precise distribution control reduces fuel consumption and therefore reduces carbon emissions. Finally control of the factory environment reduces environmental impact with enhanced factory efficiency and improved manufacturing efficiency. The outline of the "Smart Factory" can be seen in figure 1.13.



	GOAL	MEANS	OUTCOME
DIGITAL FACTORIES	• 3D Model the product prior to manufacture. Analyse the product for stress, dynamics, fluids, etc. • reduce prototype costs • reduce prototype material	Use of 3D software and analytical packages to ensure the product is fit for purpose before manufacture takes place.	DESIGN PRODUCTIVITY • reduce design errors • improved products • efficient products • less waste • reduced environmental impact • faster time to market
VIRTUAL FACTORIES	• integration of products integration of services • manage supply chains • efficient distribution • lower fuel consumption	• specialist software • interconnect and manage distributed factory assets • new business models	SUPPLY CHAIN PRODUCTIVITY • high-value products • local employment benefit • process transparency • IPR security • lower CO$_2$ footprint
SMART FACTORIES	• high-level automation • manufacture control • optimisation • improved factory processes • cost savings • environmental savings	• software control • intelligent devices • CNC machines • efficient factory infrastructure • digital factory control	FACTORY PRODUCTIVITY • less waste • low energy use • faster time to market improved quality • improved working environment

Figure 1.13: Smart Factory Based on Information Process Technology [1.25]

1.8.1.3 Smart Factories

It can be seen from figure 1.13 that smart factories aim for reduced waste, reduced energy, faster time to market, and better quality. This can be achieved through automation, and control and optimisation of factory processes.

1.8.1.4 Virtual Factory

Factory efficiency can also be improved by good planning and good management. The main essence of the Virtual Factory is to manage supply chains and create value by integrating products and services. When this is achieved, much of the trial and error of logistics and planning will be removed. Efficiencies will be gained by precise application of energy for transport, combining products, etc.

1.8.1.5 Digital Factory

The advent of 2-D CAD, 3-D CAD and digital control has transformed manufacturing. It is now possible for a designer to create a 2-D image on specialist software, transform it into a 3-D model, perform stress and other analysis, and send it via wireless technology to a machine tool which will manufacture the component.

This is a far cry from the days before computers when draughtsman drew out the image on paper which was then sent through all the factory systems such as planning, purchasing and production before it even reached the machine tool where the operator would then use his personal skills to manufacture the component.

In real terms the advent of the digital factory has improved quality, improved usage of components, improved life of components, reduced cost, and made the time from conception to production very quick.

Before computers were utilised, the concept-to-product time for a normal family car was perhaps five or six years. In the digital factory using these specialised engineering software tools it is now possible for a car to be complete only 12 to 18 months after its conception. The dramatic reduction in time is a consequence of sharing digital information across a company or even between companies so that the design of, for example, an engine can be instantaneously shared with the designers of the vehicle body, thus keeping everyone informed and design work on the complicated engineering projects being completed in parallel. Computer Weekly [1.41]

Using the techniques described above for smart factories, engineers can now create new products with energy efficient manufactories, but it is also necessary for engineers to focus on not only creating energy from renewable sources but also conserving energy and storing energy. The use of natural light, intelligent building management systems, recycled waste disposal, LED lighting, rainwater harvesting, use of bio-waste for the generation of biogas are all ways in which manufacturing plants can better their Sustainable Manufacture Value (SMV)

Packaging reduction and the use of recycled materials is also a major method of improving the SMV. Mattel, the toy company, has for some time been instrumental in reducing the source fibre for its packaging and has reduced the amount of packaging thus not only saving on cost but improving the SMV. [1.22]

1.9 Design for Sustainable Use (Sustainable Use Value, SUV)

For certain classes of machinery and equipment, longevity as a working unit is arguably the element that has the most impact on the environment. It is therefore incumbent on users to maintain their equipment so that extended life avoids the procurement of new products and hence avoids the incumbent environmental impact.

There is however a conundrum that is highlighted 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 in its production. This is a case where 100% sustainability cannot be achieved but can only be reduced by appropriate design application. Large plant manufacturers, for example, have optimised the design of their machines over the years to use lean-burn diesels, minimising engine size and emissions by using flywheels to reduce peak demand. This is also the approach adopted by Caterpillar Industrial Power Systems under Gwynne Henricks, Chief Executive Officer Caterpillar Europe. At the CEA conference in 2011, Ms Hendricks clearly indicated to the audience that designing for sustainable usage and extended product life cycle was the key challenge facing the industry in the development of new products.

Similarly, emerging technologies have allowed radical improvements in electric car charging thereby reducing the need for low-efficiency internal combustion engines at least for short journeys. Future developments show great promise for electrically powered vehicles with some analysts suggesting that they will replace the internal combustion engine in a few years.

Designers have to take responsibility for the environmental impact of their equipment. Ending reliance on fossil fuel for power may not be achievable but it may be significantly reduced. This can be done in several ways which are discussed below.

1.9.1 Design Optimisation

Designers often choose just a few aspects to optimise. Vehicles designers can optimise for reduced weight; mechanical structures can be optimised for strength; buildings optimised to accommodate earthquake oscillations; ships optimised for speed through water; and so on.

Since the first fuel crisis in the 1970’s vehicle manufacturers have been optimising for reduced mass in their passenger vehicles. The reduction of mass in a passenger vehicle means that the engine can be small, the brakes can also be smaller, tyres can be reduced and many other features required to move the mass can also be diminished. The primary motivation is to reduce fuel consumption but the greater consequence is reducing the environmental impact in manufacture and also during the vehicle’s useful life.

There are many modes of optimisation. Again, taking a passenger vehicle as an example, town cars are optimised to carry passengers at low speeds and have low power engines but are manoeuvrable so that they can easily negotiate an urban environment. Conversely, a sports car is designed for speed with a powerful engine, low profile wheels and a streamlined body shape so that slips through the air. Both vehicles carry passengers but are optimised in different ways for a different goal.

The main thrust here is to use only materials and services that are necessary to complete the task. In a recent business trip from the United Kingdom (UK) to the USA the author’s attention was drawn to the difference between the size of engines in the airport shuttle bus. Both in the UK and in the USA the shuttle bus held 12 passengers. The engine capacity of the UK shuttle bus was 2 litre whilst the engine capacity of the Florida shuttle bus was 5.8 Litre. Why, was a 2 litre engine considered adequate in the UK but not considered adequate in the USA?

Sometimes this "over design" can be attributed to mind set where the designer does not evaluate a normal practice as possible over design. Over design could also be attributed to the design approach of "if it looks right, it is right". This is a very subjective approach and overdesign may be the result. Careful optimisation is therefore required using analytical tools to reduce the materials needed for a product. The great benefit of using these analytical tools is that it will reduce the environmental impact through reduced material usage and reduced energy needed for manufacture.

A reduction in engine size leads to a lighter vehicle with smaller brakes, reduced body structure and reduced fuel consumption and emissions. A great example of optimised vehicle design is racing cars. Here the emphasis is on acceleration and speed but in order to achieve those goals a reduction in weight is required. Some of the best engineers strive to shave grams from every component in the racing vehicle.

Optimisation can also be applied to achieve *Sustainable Use* in selecting appropriate power systems and methodology so that during use there is an improvement in the *Sustainable Use Value* (SUV). In this case a large item of construction plant would perhaps use a lean burn diesel engine which has been conditioned to reduce emissions. The engine may even burn biofuels which generally tend to further reduce emissions or at least create the fuel from the sustainable source. By employing such optimisation methods the environmental impact from usage can be reduced.

1.9.2 Incorporate Equipment that Gives Back

Emerging and young technologies such as solar power and wind power can easily be incorporated into many products. New build houses for instance could incorporate solar panels photovoltaic (PV) panels on the roof. Vehicles could also be fitted with PV panels and also extract energy from the air they disturb in travelling by incorporating micro wind generators within the wheel arches. The energy passively collected by such devices can be combined to offset energy used by the vehicle. This strategy means that the design team includes elements into equipment that collect energy effectively creating a “give back” value.

1.9.3 Reduce Energy Usage

There are many options to reduce energy use: design equipment which is lighter in weight thus allowing the application of smaller power units; specify lean-burn internal combustion power units; use electric drives when possible so that natural energy can be applied rather than fossil fuel energy. As renewable power availability grows it is widely assumed that electric drives will utilise this increasingly popular power source of the future.

So far, the above examples considered installing power plants which use less energy but it must not be forgotten that conserving energy is just as important. Insulation against heat loss or consolidation of waste heat utilising heat exchangers are excellent methods of improving efficiency.

1.9.4 Use of Natural Energy

Energy is applied to drive a product through its usage phase. For instance a vehicle will require petrol or diesel for it to function. It makes sense to use naturally generated power and low energy solutions where possible. It is the designer’s responsibility to select the lowest energy option and to design that option in new products thereby improving the Sustainable Usage Value (SUV). One of the many ways this could be done is by applying electrical drive units such as those in electrically powered vehicles and other transport vessels. Hydrogen engines, whilst still in their infancy, have a zero usage impact on the environment and could also become an alternative power source of the future.

1.9.5 Energy Storage

No matter how clever the application, it is inevitable that there will always be resource extraction from the environment. Devices have to be built which have the capacity to generate energy for those processes that demand it. Some of these devices which actually generate energy are dealt with elsewhere, however, energy storage must be considered. Large chemical batteries are useful and efficient to use, although their manufacture and eventual disposal can take a heavy toll on natural resources.

An alternative to chemical storage is the use of Kinetic Energy Storage Devices (KESB's). These devices are essentially flywheels which rotate at high speed storing kinetic energy which can then be converted back through generators into usable electricity. Flywheel batteries can be very high tech systems requiring a significant amount of manufacturing resources. Other systems can be low tech and made to normal engineering principles which demand fewer resources from the environment for manufacture.

Whichever method is adopted, the resources used in its manufacture are given back during the use of the device. These storage devices can be charged in the early morning when there is low demand and therefore when energy is available. When there is high demand within the electricity grid at early evening, the role of the flywheel can be reversed so that energy can be introduced back into the national electricity grid. This lowers the electricity demand peak thereby reducing the maximum generating capacity needed.

In a slightly different application a large bank of flywheel batteries could store the output from a several power stations when demand is low and return it to the grid during high demand periods. This would mean that a quantity of flywheel batteries could actually eliminate a power station.

Batteries also become useful when high energy demand is required by a single user. A typical example would be that of an aluminium smelting foundry which uses enormous quantities of energy during the smelting process. A bank of flywheel batteries could absorb energy at times of low demand and inject it into the smelting system when operationally required.

The emerging technology of electrically powered vehicles requires not only infrastructure but also a quick means of recharging. A bank of flywheel batteries in strategic locations would provide a quick recharge of an electric vehicle, perhaps domestically or whilst parked at the supermarket store.

Energy storage devices possess a very low Sustainable Use Value (SUV) simply because the resources needed to create them is more than compensated during the *Use* element during the life of the device.

1.10 Design for Sustainable Maintenance (Sustainable Maintenance SMaV)

1.10.1 The Need for Maintenance

The goals of any designer striving to build sustainability into his products must include extending the life of the products. Dixit, Culp et al [1.33] were concerned with maintenance in buildings and also put forward the necessity to maintain components and products to extend their life. This is a different perspective since our throw-away society, which developed during the 1960's, entreated designers to build a finite life (design life) into their products. For instance a washing machine will perhaps have a finite life of around three years. Manufacturers will argue that if products last for extended periods, eventually the market will be saturated and there will be no more sales. Though this may happen to a degree, it is inconceivable that humanity will no longer require new products. Instead the emphasis will move towards maintaining and refurbishing equipment.

This shift in emphasis is highlighted by the example of a West Yorkshire company HE&A Ltd who manufacture mechanical handling equipment such as brick and block Clamps. During the recent recession HE&A Ltd found difficulty in selling new products. The company switched its business model to that of maintenance and refurbishment and survived the recession. When the recession eased and customers were able to purchase new equipment, business in new products improved once again. HE&A Ltd benefited in that the maintenance and refurbishment side of the business continued to flourish when few new products were being sold. In this case financial restrictions had forced customers to maintain and reuse older equipment but they were eager to purchase new products when the financial restrictions eased. Managing Director, Phil Hazeltine said "Customers have learned that it is cheaper to maintain and refurbish than to buy new, but eventually equipment will wear out and the purchase of new products is inevitable".

It is normal practice for high-value products to be designed with maintenance in mind. It would be inconceivable that a passenger vehicle or an aircraft would be discarded simply because it needed a small part replaced. Anyone who has ever owned a passenger vehicle will understand that scheduled maintenance is necessary in order to keep it running efficiently.

Internal combustion engines are able to be maintained by changing oil filters, spark plugs, etc. Brakes are designed so that brake pads and shoes become sacrificial elements and can be replaced. It is quite common to see vehicles still running which are over 10 years old. Vehicles over 30 years old are maintained by enthusiasts supporting a thriving industry purely for the maintenance of elderly vehicles.

As the designer creates new products it is his/her responsibility to design sustainability into the product so that it is not just high-value products which can be maintained but also the smaller low value products such as toasters, food mixers and the plethora of small items which the consumer would normally discard after developing a problem.

Some excellent examples of small sustainable products are shown in figure 1.14, the Aldis Projector and the Dualit toaster shown in figure 1.15. Both these examples were originally subject to "accidental" sustainable engineering design, however they correctly embrace principles

The “Aldis” projector shown in figure 1.14 was built during the 1950’s prior to the "plastics revolution". The components are die-cast and are fastened by screws. Though the projector may not have been designed and manufactured with sustainability in mind, it can nevertheless be taken apart completely so that components can be replaced, cleaned and returned to service. This kind of construction can be extended to many other products so that maintenance is the first thing to consider when the device develops a fault. The mind-set of the consumer also needs to be changed since the current approach is to throw the product away when a part breaks.

Figure 1.14: Aldis Projector: Die-Cast Parts Allow Easy Maintenance [1.1]

Figure 1.15: Dualit Toaster: Designed for Easy Maintenance [1.15]

The Dualit toaster shown in figure 1.15 is part of a classic range of kitchen appliances which have been designed and built with ease of maintenance in mind.

In 1946 Max Gort-Barton launched the first flip-sided toaster. From the beginning the original toaster and the following range were designed to be easily maintained and to impart a long life. Perhaps sustainability was not Max Gort-Barton's original aim, but it has come to represent a long lived, maintainable household product.

It is certainly true that with the Dualit range, when components wear out they can easily be replaced by the customer. This is true sustainability through maintenance. The toaster and the other products in the Dualit range possess a very large Sustainable Maintenance Value (SMaV). . It is significant however that Dualit is a thriving company with a design approach that allows easy maintenance. This is very sustainable methodology.

Sustainable longevity derived from regular maintenance can be applied to many engineered components. The water well rock drilling machine shown in figure 1.16 uses a rotation gearbox which slides up and down the mast as the drill string buries itself in the ground. At the top of the hole very sharp abrasive debris is forced upwards hitting the underside of the rotation gearbox. The lower gearbox seal as indicated in figure 1.16, within the gearbox suffers accelerated wear due to the arduous conditions.

The gearbox needs to be maintained by changing seals and refurbishing the shaft by depositing chromium on the shaft at the contact point of the seal creating a hard contact face for the seal. The deposition, usually chromium, is then machined back to the correct size and the shaft replaced in the gearbox along with new seals and fresh oil.

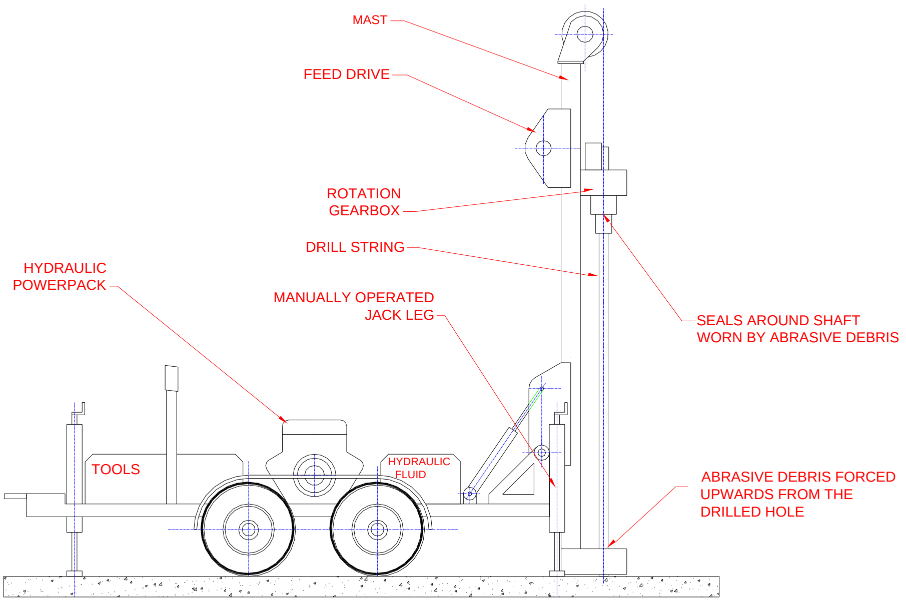


Figure 1.16: Trailer Mounted Water Well Rock Drill Used in Remote Areas [1.1]

Often drilling operations occur in very remote areas and for drill crews have been known to discard an entire leaky gearbox and replace it with a spare. The solution would be to design a gearbox so that it could be maintained in the field and to this end the gearbox designers use a specialist cassette seal comprising a lip seal and a sacrificial sleeve arrangement as shown in figure 1.17 and 1.18.

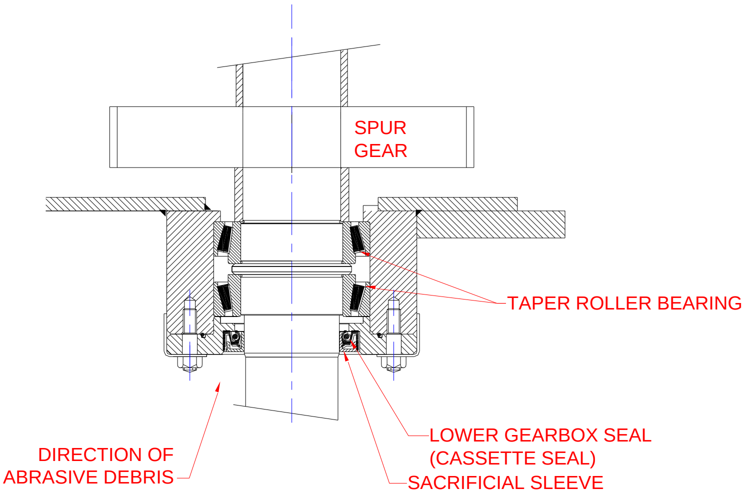


Figure 1.17: Portion of Gearbox Showing Lower Gearbox Seal [1.1]

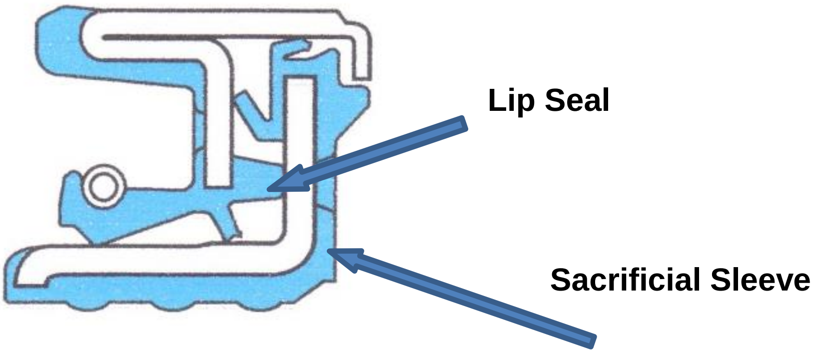


Figure 1.18: Example of Cassette Seal Showing Sacrificial Sleeve [1.16]

The application of this specialist seal ensures that the gearbox can be stripped to its basic parts in the field. The cassette seal is merely replaced there being no damage to the shaft. Carrying a small seal as a spare saves a great deal of time, effort and money and substantially increases longevity. The most important aspect of this is that the gearbox can be maintained, prolonging its life and reducing the energy required for its transport and later refurbishment by chromium the position on the shaft.

In this case a little thought by the designer reduced environmental impact dramatically prolonging the life of the gearbox, reduced downtime, and improved the serviceability of the whole drilling rig.

1.10.2 Lubrication

During the design of mechanical parts much emphasis is made on tolerances, surface finish, seal and bearing selection, but often lubrication of the moving parts is left until last, almost as an afterthought. Lubrication is really "liquid engineering" since without lubrication moving parts would quickly become hot and seize. The introduction of the correct lubricant and also the lubricant delivery system could prove to be one of the most important elements of a working machine since their correct application will increase the longevity of the components or product.

Wind generators are often situated on hilltops or perhaps out at sea in very arduous conditions. Designers aim for a 20 year life span but one of the acknowledged weak points in any wind generator is the bearing system of the turbine shaft.

A bearing failure may be catastrophic for the wind turbine since the heat generated could create a fire, endangering the whole machine sometimes with spectacular results as shown in figure 1.19.

Figure 1.19: Wind Turbine Fire [1.18]

Failure within the turbine nacelle may however be due to several problems from electrical failure to mechanical failure of moving parts but the lubrication system is equally important to preventing failure. Specialist lubricants have been developed so that the bearing will perform whatever the conditions. The consequences of a bearing or lubricant failure are that the whole nacelle has to be dismantled for repair. The obvious answer is to provide longevity in terms of design, easy maintenance and the correct selection of components, including appropriate system lubrication.

1.11 Design for Sustainable Disposal (Sustainable Disposal Value SDV)

The designer is the creator of the product and has the influence to create a sustainably friendly disposal technique. In the past the designer's primary goal has been to reduce cost but he should now widen his approach to include sustainable disposal. 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 should also consider the 4R’s: Recycle, Repair, Re-use and Reduce.

1.11.1 Recycling Considerations in Disposal

Thus far the material sourcing that has been considered has been from an original source; however, this need not be the case since materials can be garnered from several other sources, including recycled materials. Much of the procedure for recycling involves taking-in end of life products, extracting similar materials and reforming them into a raw material which can be used in place of the original materials in a re-manufacturing process. Vehicle tyres are an excellent example in that the rubber is granulated and used in forming various rubber products including soft flooring for playgrounds and road speed humps.

Some materials, such as building materials have been a recycled source for thousands of years. In more recent years steel has been successfully recycled and is now the world’s most recycled material. There has also been a surge in the variety and diversity of recycled materials. These include: shoes and clothes, electrical appliances, glass, non-ferrous metals, vehicle tyres. It is estimated [1.17] that up to 90% of discarded items and products can be recycled or reused.

Many processes in manufacturing require fewer raw materials. Unfortunately recycled materials are often a mixture of similar materials which present difficulties in remanufacturing since impurities of various material types may threaten product quality. For example, the recycling of glass is quite common and it is relatively easy to recycle however recycled glass arrives at the recycling plant but in many colours such as brown, blue, green and clear. This coloured glass must be seperated if the end product is to be a clear glass bottle.

The main problem with the recycling is that materials have a mixture of components rather than a single material. Separating the recycled mixture is often achieved by hand and is obviously labour-intensive. Some inventive companies have created products which can be produced from a mixture of similar materials. Excellent examples of such products are:

- plastic roof tiles from a variety of recycled plastic types, e.g. polypropylene, polyethylene, ABS, etc.
- simulated wooden planks made from a variety of recycled plastics and used as seating planks in street furniture.
- paving stones manufactured from multiple colours of granulated glass

Materials gleaned from recycling processes are less costly and use less energy than the original source material. The use of recycled material also means there is reduced energy consumed in extraction of original materials additionally cultivating sustainability. The practice of recycling also creates a local economy since recycling of materials can take place and be processed locally.

1.11.2 Repair / Refurbish Considerations in Disposal

Die cast components and products were the norm in the 1950's. Items were held together with screws and could be dismantled and repaired. During the early 1960's the advent of plastic and its use for toys, kitchen implements, garden tools, household devices and many other products created "snap-together" products that were almost impossible to dismantle without breaking the product and hence rendering them difficult to repair. It was the beginning of the "throw-away society." The mind set of "throw away and buy another" has started to change towards refurbishing and re-using but a large shift in the mind-set of both designers and consumers has yet to occur.

Refurbishment means that products are not thrown away but restored so that the product's life can be extended. Economic recessions are great events for focusing both consumers' and manufacturers' minds into reducing cost. Rather than buy new equipment after discarding old products, economic recessions tended to encourage companies into refurbishing components rather than buying new.

During a recent recession in the UK, the civil engineering industry suffered greatly. That the building of new houses and many large civil engineering projects were cancelled which led some equipment suppliers into financial difficulties. A West Yorkshire (UK) manufacturer of brick and block crane attachments (HE & A Limited) found a lucrative market in refurbishing equipment and supplying spares as the new-equipment market evaporated. Figure 1.20 shows a typical brick / block crane attachment.

This is a product which has been manufactured for several years with no real consideration for sustainability or refurbishment. The company created a new design of brick/block clamp which was designed specifically with refurbishment in mind. The clamp may be welded if it breaks and components replaced when worn. It can be restored to a working product with much less input and with a much smaller impact on environmental resources than the manufacture of a new product. This is an excellent example of refurbishment giving an extended life and providing a very low Sustainable Disposal Value (SDV)

Figure 1.20: Brick/Block Clamp [1.21]

An excellent example of an item with high SDV is the small motorcycle used in India and Pakistan. In these countries the favoured individual transport is the 70cc or 100cc motorcycle shown in figure 1.21.

Figure 1.21: 70cc Motorcycle [1.1]

Here the designers have taken the initiative and designed a vehicle with a low resource impact value. These motorcycles have simple parts, are low cost, and easy to repair. They have a relatively low impact on resources when manufactured and also have a low impact in use. They can be refurbished and repaired as long as parts are available. It is a simple task to remove the faulty parts since it has been designed for easy maintenance. This is an excellent example of cost-led sustainability or conversely an example of sustainability driving costs down. Since these motorcycles can be repaired, refurbished and maintained, the life of the vehicle is almost infinite and provides a very high Sustainable Use Value, SUV and a very high Sustainable Disposal Value, SDV.

1.11.3 Re-use and Refurbish Considerations in Disposal

Re-used and refurbished products and materials use less energy in restoration than using new material that had been extracted fresh from the Earth. Often this fundamental fact is overlooked by the requirement to manufacture items at a low-cost. In recent years purchasing products from overseas producers it has often been cheaper than it was to refurbish equipment at home. The design of machinery and equipment for repair and refurbishment gradually became less common and a throw-away culture developed. Indeed much of design thinking is set to give the product a finite life so that when the user deems that the product is at the end of its life, it is just discarded and a new item purchased. In this way manufacturers ensure that newer versions of their product are always in demand.

The solution is for individuals and institutions to generate an alternative mind set where sustainable techniques are employed when considering end of life strategies.

1.12 Give-back

No matter how products much are re-used, refurbished or recycled the plain fact is that the usage of resources is merely being slowed. There will always have to be some amount consumption of earth's resources.

Give-back is a technique where designers actually build devices which *give back* to the environment or perhaps create multiple-use components for different products. Solar power panels on car roofs and micro wind generators built into vehicles are just two ideas that could be explored. Most vehicles are left outside for much of their life. PV panels set into the roof and built-in micro wind generators could produce energy which could then be stored. Trading this stored energy in to a central repository could earn a discount to the fuel or the recharging of an electrically powered vehicle. This would improve the Sustainable Give Back Value (SGBV) of the product.

In another application solar panels could be incorporated on the roof of new buildings where the energy generation possibilities would be enormous from solar panels mounted on the millions of homes in the UK.

Consider a hypothetical application where all the 23.4 million dwellings in the UK and all the 28.7 million cars in the UK were fitted with a modest solar panel. The energy generated would amount to 0.26% of the total UK annual power consumption. This seems a small amount but the value is around $3 billion or £1.8 billion. See appendix A2.1 for more precise analysis. This exercise demonstrates what might be achieved when design thinking includes “give-back” methods.

Energy can now be generated from multiple renewable resources from wave energy to wind energy but the great challenge is how to integrate this into the electricity grid. Many renewable energy resources are intermittent since the wind can only generate energy on windy days and the sun only shines during the day. Therefore, the energy thus generated needs to be stored.

As part of collaboration between the University of Huddersfield, UK and ESP Ltd, a battery flywheel system has been developed, shown in figure 1.22. Kinetic Energy Storage Batteries (KESB) have the capacity to store large amounts of energy in a spinning flywheel. At peak times these devices can be tapped to provide the electricity grid with power. Several thousand of these in a single facility could provide enough storage capacity to eliminate a power station. This is an excellent example of high Sustainable Give Back Value (SGBV) since a flywheel does not take from the environment during its use and its presence creates efficiencies in the electricity supply system. Its presence also avoids other large systems, such as power stations, from being built with the inevitable enormous drain on the environment.

Figure 1.22: Idealised Flywheel Battery 20KWh Storage [1.19]

An excellent example of Sustainable Give Back Value (SGBV) is the World Trade Centre Building in Bahrain, figure 1.23. This building incorporates wind generators. The building rises 240m. The shape of the towers is designed to funnel the wind onto the wind turbines generating up to 675KW which can be 15% of the total power consumption of the building.

Figure 1.23: Bahrain World Trade Centre Showing Wind Turbines [1.20]

1.13 Sustainability Overview and Formulation of Aims

Sustainable development was introduced in 1987 by the Brundtland report [1.5]. The report was commissioned by the United Nations and was intended to encapsulate a global sense of sustainability. By its very nature it was a broad ranging document which left much of the detail to protagonists involved in varied subject areas. Many countries, institutions and individuals have taken the lead laid down in the report and introduced concepts and methodologies since the report’s inception but the subject is so diverse there is still a great deal of scope in introducing concepts and models in defining and accurately measuring sustainability. Furthermore the implementation of sustainability is an evolving field.

The aims of this research project were formulated by investigating sustainability in the field of mechanical engineering, concluding with the perception that there was a deficiency of a sustainability measurement and implementation tool which mechanical engineers could use when formulating new products. This perception was later confirmed and further defined through the publications review process. This revealed that were limited publications relating to certain areas of the product life cycle. In particular maintenance and material sourcing were ill served.

Many sustainability applicants use various measurement systems to suit the particular topic but it was clear that a measurement device would be necessary that could span products and services in a global sustainability measurement system. Embodied Energy was the metric adopted, being able to be applied to services as well as products in the creation usage and disposal processes. This metric has previously been successfully used by other researchers, notably Ashby [1.24].

The research project aims were eventually defined as the development of a sustainability measurement system for mechanical engineering designers when designing new products and services. The end result was a methodology that applied sustainability and gathered information which could be used to influence decisions from company level up to global level. In order to achieve the complex data acquisition and manipulation a computer algorithm was developed and for its coordination and control a complete top to bottom management system based on ISO standards.

It is intended that the complete package can be implemented into a company environment to enable sustainability assessment of its procedures and output.

CHAPTER 2
Review of Publications

2.1 Summary: Literature Review

Sustainability is an umbrella term related to environmental conservation and covers many subtopics in many different disciplines. Sustainability means many things to many people. To the economist, sustainability means continual improvement of money flow into the economy of a country, company or household. To the scientist, sustainability may mean continuation of a system of process. To the environmentalist, sustainability means sustaining the planet earth ecosystem. Environmental conservation with the inclusion of sustainability can be discussed in diverse as fields as life sciences, the built environment, geographic sciences, pollution, ozone depletion, and global warming to name just a few. The investigation and measurement of sustainability involves very broad issues and parameters and involves measurement parameters as varied as the research project. In this project the audit/measurement process has been narrowed by approaching the topic from the practical designer's point of view and is discussed below. Detailed elements of an environmental audit are presented so that contributions can be made to the bigger picture of sustainability in engineering design.

The first serious environmental compliance audits can be traced back to the 1970's where a few United States corporations adopted eco-methodology in response to a domestic liability laws, Welford [2.61].

The Brundtland Commission in 1987 launched the report "Our Common Future", [1.5] introducing the term "sustainable development". This was a significant milestone and triggered the expansion of environmental measurement and audit by many governments, institutions, companies and individuals worldwide. Some of the early schemes include "Eco-Management and Audit Scheme" (EMAS) in 1993 and the first publication of ISO14001 in 1996 Welford [2.61].

Environmental audit was defined by the United States Environmental Protection Agency (EPA) as "a systematic, documented, periodic, and objective review by regulated entities comprising facility operations and practices related to the meeting of environmental requirements." EPA cited in Anthony et al [2.87]

The term "Environmental Audit" was defined by the Confederation of British Industry as: "the systematic examination of the interactions between any business operation and its surroundings. This includes all emissions to air, land and water, legal constraints, the effects on the neighbouring community, landscape and ecology, the public's perception of the operating company in the local area. Environmental audit does not stop at compliance with legislation. Nor is it a 'green-washing' public relations exercise. Rather it is a total strategic approach to the organisation's activities." Paramasivan [2.88]

2.2 Approaches and Definitions

The word "sustainability" is a general term which means different things to different people and institutions. (To the ecologist, sustainability may mean the avoidance of adverse environmental impact on a river system or the preservation of an animal species from extinction. To the economist, sustainability would be the preservation and growth of a company or nation. To the scientist, sustainability is ensuring a mechanical, biological or chemical system continues to survive.) Sustainability can be considered as an umbrella framework within which individual projects might be run in a more sustainable fashion thereby improving sustainability of the larger whole.

The position of this research project within the sustainability spectrum needed to be verified so that direction and context of the project could be defined. With this in mind it was useful to first review and define the frameworks that are used to determine the influence of human activity on the environment. Research shows that various institutions, scientific bodies, researchers, etc., apply their work to one or a combination of the following approaches.

- Triple Bottom Line (TBL)
- Life Cycle Analysis (LCA)
- Cradle to Cradle (C2C)
- Environmental Standards

Each approach was reviewed to ascertain the most appropriate framework for this research project. The review follows.

2.2.1 Triple Bottom Line (TBL)

Triple bottom Line (TBL) is an accountability framework with three elements: social, environmental and financial. These three divisions are also sometimes known as the 3P's: people, planet and profit, or the "three pillars of sustainability". Interest in triple bottom line accounting has grown in for-profit, non-profit and government sectors. The term was coined by John Elkington in 1994. The Economist [2.136].

2.2.2 Life Cycle Analysis (LCA)

Life Cycle Analysis (LCA) is sometimes known as "cradle to grave analysis" and is an assessment technique relating to environmental influences from a product throughout its life-cycle. The analysis covers extraction of materials for production through manufacture, use and eventually disposal and offers a broad investigation with the possibility of a detailed analysis of environmental concerns. The data can then contribute to the umbrella framework. According to the US EPA [2.140] the following general elements should be applied.

- compile an inventory of energy and material inputs and environmental releases;
- evaluate the potential impacts associated with identified inputs and releases;
- interpret results to assist in making informed decisions.

2.2.3 Cradle to Cradle (C2C)

Cradle to Cradle (C2C) is an approach to the design of products and systems that views human industry in the same terms as cyclical natural processes. Materials are viewed as nutrients circulating in healthy, safe metabolic systems. The strategy suggests that industry must protect and enrich nature's biological metabolism while also maintaining a safe, productive technical metabolism. It is an overall economic, industrial and social framework that promotes the creation of systems that are efficient and waste free. The model can be applied to many aspects of human civilization such as urban environments, buildings, economics and social systems. Cradle to Cradle is a registered trademark of McDonough Braungart Design Chemistry consultants and the phrase "Cradle to Cradle" was originated by Walter R. Stahel in the 1970s.

2.2.4 Standards and Eco-Labels

There are many standards and eco-labels on which an environmental approach can be based depending on the industry and the environmental system. The most useful standards are often considered to be the ISO14000 series since their combination of broad management approach and detailed analysis is relevant for many sectors.

During the course of the literature review and during the development of the project, ISO standards were considered -- several that were particularly useful in setting out the LCA approach. These included: Eco-design Directive [2.4], ISO14040 - 2009 Environmental management [A2.5], ISO14044: 2006: Environmental Management LCA Requirements [2.6] and PAS2050: 2011: Specification for the Assessment of Life Cycle Greenhouse Gas Emissions of Goods and Services [2.7].

Many of the references dealt with very specific topics, such as PAS 2050: 2011 [2.7] which considered greenhouse gas emissions, but, nevertheless, they were helpful in showing different ways to approach sustainability analysis.

These standards cover many aspects of environmental attentiveness and are broad as well as deep in their coverage so that they can be used for many diverse environmental situations. The standards and others plus several prominent eco-labels are reviewed in-depth in Chapter 4.

2.2.5 Framework Overview

The assessment of sustainability is a particularly difficult conundrum, but the adage, ”measure it to manage it” becomes very relevant. Within an appropriate sustainability context, audit and measurement has become the focus of many researchers, institutions, and indeed nations. Measurements take many forms depending on the system. Detailed sustainability analysis may use precise measurements such as carbon emission or energy usage. A more global assessment may use trends and indices that incorporate a variety of measurements.

These sustainability assessment approaches are championed by several researchers. Gurav Ameta [2.25] presents recent trends in design for sustainability from a strategic point of view and uses LCA and TBL as a background framework. He suggests that when using these frameworks, clear system boundaries are critical for proper auditing and measurement and that the use of indices are only one measurement device. He suggests that there are several weaknesses with indices relating to weighting, aggregation and comparisons which dilute the quality of the data. Alternatively, he suggests direct measurement such as that of energy usage or sulphur emission.

Chapas [2.113] champions the use of LCA in the sustainability design process to allow the LCA to be segmented into individual life elements. Mayyas [2.29] also supports the use of the LCA as a framework and combines it with TBL, thus broadening the scope into environmental, social and economic realms. A product sustainability methodology is put forward by Mohannad [2.89] who extensively uses LCA, TBL and the range of environmental standards within the ISO 14000 series. The approach appropriately employs life cycle phases in order to obtain a detailed analysis. The model produces a sustainability index (Prod SI) which is then applied to the TBL and thus broadening the approach to influence economic, social and environmental features. This is certainly a step forward in applying a model but does not define measurement methods. He made an enormous contribution in introducing his PROD SI index but omits major elements such as sustainable design, maintenance practices and end of life disposal. Since there are gaps in the work offered by Mohannad, the research covered in this current project takes his work several stages further in measurement techniques and in approach.

Much of the information relating to environmental products and LCA has been developed by researchers and practitioners within the built environment. Patxi et al [2.141] suggested a life-cycle approach to new buildings. Embodied Energy was considered as a measurement parameter but this was quickly converted to kilowatt.hour (kWhr) and then to cost. The life cycle approach put forward has merits, but the entire the life cycle was not considered. The publication merely included procurement, building and usage, and omitted maintenance and end of life disposal.

Theo Hacking [2.142] provides a framework based on the triple bottom line for comparison of assessment techniques. This overview is very general and is intended for the global analysis rather than a detailed, and precise analysis, but nevertheless champions TBL has the most useful framework tool.

Cradle to Cradle is a relative newcomer to the framework analysis stable. Anders [2.26] explained the difference between C2C and LCA by saying that C2C attempts to increase the positive footprint whilst LCA attempts to decrease the negative environmental footprint. C2C calls for the elimination of the concept of waste and forms its methodology from nature’s nutrient recycling and suggests designing systems with waste that other processes can take up as nutrients. Anders criticises the C2C model explaining that the C2C concept is highly visionary, idealistic and impractical since it disregards waste disposal and energy needs. He goes on to suggest that though LCA is more practical, it does not contain any long-term vision strategy. C2C, however, defines a clear vision of a desirable sustainable future.

Life Cycle Assessment (LCA) has been used and applied by many other researchers when considering sustainability in their field. Researchers such as Landolfo [2.8], Ashby M [2.9], Granta Design [2.11], Heiskanen [2.32], Hauschild [2.33] and Wanyama [2.34] all put forward LCA as an appropriate framework to assess sustainability and covered use of sustainable materials all through sustainable manufacturing and management.

The LCA approach described within the previously mentioned publications offered four fundamentals relating to the life cycle of a product, listed below.

1. sustainable sourcing
2. sustainable manufacture
3. sustainable product usage
4. sustainable end of life disposal

2.2.6 Sustainability Assessment and Framework Selection

The general aim of this project is to create a means of measuring, managing and implementing the principles of sustainability that can be used at the detail level in the design of new products and to create an auditing tool that the designer can use to assess the sustainability value of his work. This is a practical approach and therefore requires a practical framework on which to build. The basic framework choice lies between LCA and C2C. The work presented by Chapas [1.13], Mayyas [2.29] and Mohannad [2.89] suggested that work at the detail level would be best served by a framework of LCA. These researchers and others also suggested that the combination of LCA with TBL and various standards would serve as a complete system using specific data at the detail level and combining it with a wider approach thereby expanding the data into a more global viewpoint incorporating sustainability, economy and society. In addition, the application of environmental standards such as ISO14001 and others in this series, would ensure appropriate management, recording and systemic application.

It was considered that C2C is useful but the criticisms by Anders indicated that it was not practical to use for the focus of this project, however some concepts such as zero waste are useful to keep in mind as a desirable goal.

2.3 Review of Auditing and Measurement Techniques

It is essential that measurement and auditing techniques are reviewed to ensure applicability for the precise nature of the data available and also to ensure the data is in a usable format for later dissemination. Auditing and measurement techniques are varied and complex. Some researchers use specific measurements of energy usage, carbon dioxide output, sulphur emission, etc., whilst others prefer to use indices and trends. The focus of these measurements and eventual use may be as varied as compliance with standards, environmental impact, ecological sustainability, systemic preservation or global sustainability.

Ness [2.91] provides a sustainability assessment framework loosely based on the TBL and incorporating detailed product analysis from LCA which is then expanded into cost pressures on one side of the model to global indicators on the opposite side of the model. His three main columns are shown below in figure 2.1 and shown alongside the TBL for comparison.

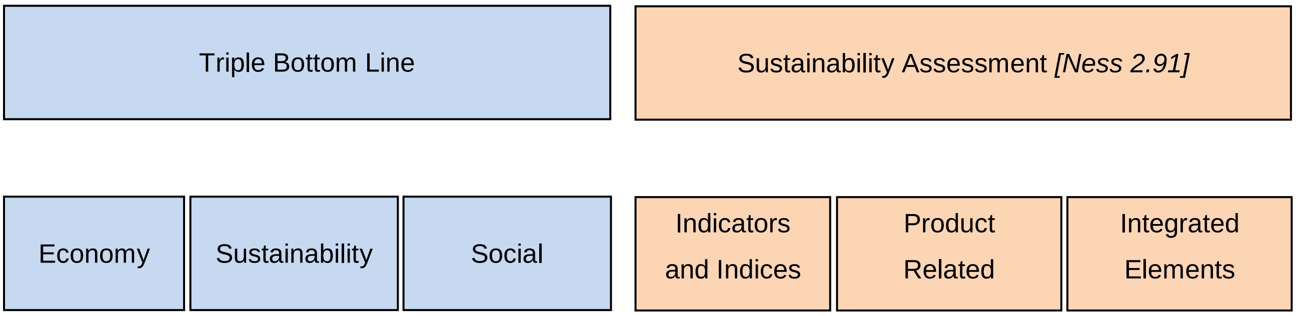


Figure 2.1: The Basic Sustainability Assessment Model Suggested by Ness [2.91]

Ness' model eventually evolved into seven indicators which are listed as follows:

1. sustainable national income
2. genuine progress indicator
3. adjusted net saving
4. ecological footprint
5. well-being index
6. environmental sustainability index
7. human development

This noble effort by Ness attempts to categorise the varied elements which contribute towards the sustainability appreciation. Whilst some of the features comply with and contribute to the thinking of other researchers in the use of LCA and TBL, the model can be seen to be a tool that combines indices which would be useful for urban, national, continental and global assessments. Some of the elements are extremely useful such as the use of LCA, system dynamics applications and use of standards.

A major contribution to simplifying the complex measurement process was made by Choida [2.90], who was primarily concerned with sustainable audit practice. He succinctly described five audit categories: compliance, systems, environment, ecological and sustainability.
Choida [2.90] also suggested three steps for the audit practice:

- develop a framework for environmental auditing
- test environmental audit guidelines against the framework
- employ practical measures to improve the performance of auditing

Though Choida's model is concerned with auditing, the suggested system and practice suggests some fundamental building blocks which can contribute to the focus of this research project. Several of these suggestions have been adopted as shown in later chapters and integrated into the overall research approach.

In his work on urban environments, Moles [2.28] suggested that sustainable development was a process by which a current system was moved from the present towards an aspirational future sustainable situation. He used numerous parameters to judge the urban pulse of several townships and his measurements included energy usage, carbon dioxide emission, food tonnage, cost of living, waste, water, transport costs, and many more. In all, 174 indicators were identified, combined into several classes of indices, and eventually translated to an ecological index.

It was significant that Moles realised that the measurement of sustainability in a complex urban environment requires complex data acquisition which requires manipulation into an understandable index. He further suggested that during the manipulation of the data, there was a danger that the resulting index could become diluted and may be influenced by subjective weightings.

The complicated nature and complexity of sustainability auditing and measurement leads many researchers to use indices and trends. Much of the primary information used in indices was at some point a quantified value, however, the aggregation and combination of the data into an index tends to dilute the information. Concerns were voiced by Moles and several other researchers including Gurav Ameta [2.25], Singh [2.31], Moran [2.97] and Babcicky [2.95].

The complex nature of sustainability audit and measurement grows as the focus expands from individual products to a more global view. As the complexity grows, there are few other means of judging the value of sustainability other than using an index. There are many notable organisations that use indices successfully. These include the United Nations, national governments, urban centres (cities and towns), companies and other institutions such as universities. Neumayer [2.30] was concerned with human development and sustainability and attempted to link the Ecological Footprint (EF) Rees [2.27] to the United Nations Human Development Index (HDI). This was a classic application of indices used at national, continental and global levels.

Pope [2.92] also proposed that indices are created to assist in assessment strategies and lists several indices such as "Strategic Environmental Assessment" (SEA), "Environmental Impact Assessment" (EIA) and advocates the use of the TBL. Pope was also eloquent in agreeing that as assessment focus shifted from detail issues to more global issues, indices grew broader and inherently less accurate. He concluded that "nevertheless a carefully formulated index can be invaluable for considering multiple and complex variants." Pope [2.92]

Pope also suggested that a sustainability assessment should consider whether or not an investigation is sustainable, rather than simply assessing "direction to target". In short, Pope proposed that a sustainability assessment should be evaluated for its accuracy and outcome before committing resources to a complete sustainability assessment. Further assessment for sustainability requires a clear concept of sustainability as a goal defined by criteria against which the assessment is conducted.

The view echoed by many researchers is that the complex nature of sustainability assessment requires ever more complex indices in the expansion from detailed assessment through urban, national to global assessment. Even though there are complications and problems, indices are considered to be a viable assessment method. Figure 2.2 below indicates the nature of the measurement/assessment conundrum and the effect on the influence levels.

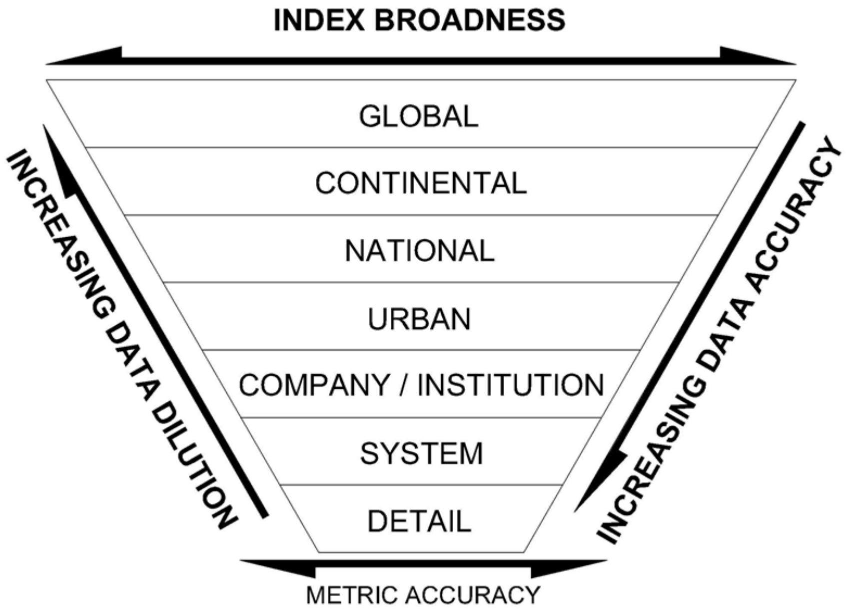
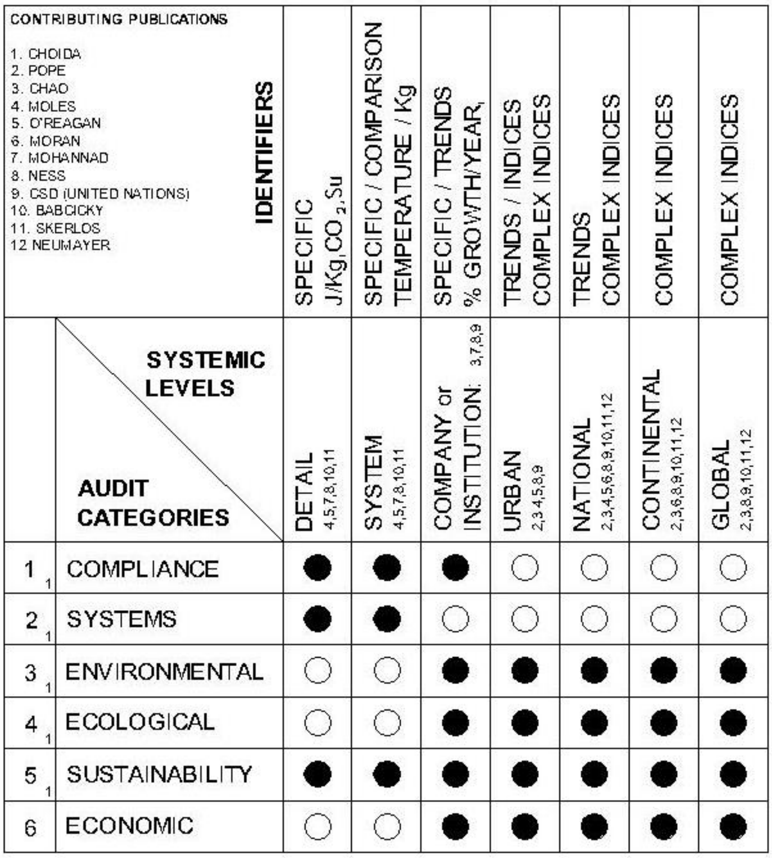


Figure 2.2: The Nature of the Sustainability Measurement/Assessment Profile Related to Influence Levels

Figure 2.2 is a synthesized review of several publications. It reveals that at the detail level directly measured metrics are used such as renewable energy, Embodied Energy, carbon footprint, watt.hr and cost, to name a few. There are as many metrics as there are systems being measured, and measurement is complicated further when considering the end use of the data and its inevitable manipulation into an index format. As the intended use of the data becomes more global, more conditions and manipulation is required to give a broader picture but this very action dilutes the data. The complexity of many sustainability measurement systems require computing algorithms in order to produce viable data that can be used and directed for a particular decision-making process. Several of these are reviewed below.

Antiohos [2.16] related his work in designing a new cement building material with low Embodied Energy where the metric was Embodied Energy, measured in joules. Kim [2.93] was primarily concerned with economic outcomes but used watthr/kg as a base measurement which was then converted to a cost. The cost metric is often used especially when an economic study is being conducted. The work of Martin and Gatzen [2.94] endeavoured to decrease the operational cost of high-performance oil field services and the most useful metric was the cost of components, systems and facilities.

Audit levels and measurement parameters vary between researchers. Five audit levels were put forward by Choida and it is helpful to combine Choida's audit levels with measurement parameters used by other researchers. The chart in figure 2.3 combines Choida's audit levels with data gleaned from the numerous researchers and adds a sixth level, "Economic". This is appropriate since many researchers used cost as the basis for index measurement data. The identifiers listed are those taken from the various publications (listed in the diagram) and are a stylistic example of the measurement parameters found at the various systemic levels.



CONTRIBUTING PUBLICATIONS

1. CHOIDA
2. POPE
3. CHAO
4. MOLES
5. O'REAGAN
6. MORAN
7. MOHANNAD
8. NESS
9. CSD (UNITED NATIONS)
10. BABCICKY
11. SKERLOS
12 NEUMAYER

	IDENTIFIERS	SPECIFIC J/Kg,CO_2,Su	SPECIFIC / COMPARISON TEMPERATURE / Kg	SPECIFIC / TRENDS % GROWTH/YEAR,	TRENDS / INDICES COMPLEX INDICES	TRENDS COMPLEX INDICES	COMPLEX INDICES	COMPLEX INDICES
	SYSTEMIC LEVELS AUDIT CATEGORIES	DETAIL 4,5,7,8,10,11	SYSTEM 4,5,7,8,10,11	COMPANY or INSTITUTION: 3,7,8,9	URBAN 2,3 4,5,8,9	NATIONAL 2,3,4,5,6,8,9,10,11,12	CONTINENTAL 2,3,6,8,9,10,11,12	GLOBAL 2,3,8,9,10,11,12
1_1	COMPLIANCE	●	●	●	○	○	○	○
2_1	SYSTEMS	●	●	○	○	○	○	○
3_1	ENVIRONMENTAL	○	○	●	●	●	●	●
4_1	ECOLOGICAL	○	○	●	●	●	●	●
5_1	SUSTAINABILITY	●	●	●	●	●	●	●
6	ECONOMIC	○	○	●	●	●	●	●

Figure 2.3: Combination of Audit Levels to Metric Types

The chart shows that the lower order systems and compliance with regulation requires specific analysis at both detail and system levels. Specific analysis is also used at the company and institutional level, but, indices become more useful as the focus becomes wider and a broader range of data measurements are incorporated.

It was found that there is a great body of work relating to sustainability in the field of the built environment but by comparison a relatively small number of articles have been published relating to sustainability for mechanical engineers. At a detail level Ashby [2.9] and Granta Design [2.11] have made significant contributions.

2.4 Sustainability Tools and Algorithms

There are several tools available to the sustainability engineer. The review of the most popular in order reveals variability in depth, coverage, end-use and usefulness.

2.4.1 Green Delta

Green Delta is a specialist sustainability consultancy service that offers tailored software using life cycle assessment. Their expertise specifically covers carbon foot printing in particular and promotes the use of ISO14040 and ISO14044 as standards on which to base frameworks. They will supply software tailored to a particular manufacturer but the primary focus is manufacturing with a second focus on usage and end of life disposal. The strengths of the software lie in data management, life-cycle costing and quality assurance. The data supplied by the company does not specify what measurements they use. Green Delta [2.146].

2.4.2 Open LCA

Open LCA was developed by *Green Delta* and is a free, professional life cycle assessment and footprint software package with a broad range of features and many available databases. The software accesses data from measurement data which is free on the web and is intended for use at the business level and at a global level. Since it is free access and could use unvalidated data, the data generated may not be as reliable as from other systems. Open LCA [2.147].

2.4.3 Gabi

Gabi is a general LCA tool that considers environmental optimisation and strategic risks by identifying information relating to environmental impacts and is targeted at an organisation’s processes and products. Though the system and software uses some measurements, those measurements are unspecified but nevertheless are quickly converted to indices which are then used for communication lines and political decision-making. Gabi [2.148].

2.4.4 Eco-Rucksack

The instigation of Eco-Rucksack occurred at the world Summit on Sustainable Development (WSSD) in 2002. The tool is based on the concept of natural resource efficiency which decouples energy and material consumption from economic performance. This tool applies product life cycle as a framework and uses material flow analysis where the main metric is mass (kg). The main focus is on sourcing materials and manufacture with some attention to disposal but the index generated does not consider the importance of the product, the use of the product or its value to human sustenance. Eco-Rucksack [2.149].

2.4.5 Granta Design LTD

CES Edupac is the software package marketed by Granta Design Ltd and is a comprehensive and interactive materials intelligence database. It offers detailed analysis of materials but in its eco-package LCA is offered as a framework. Its great advantage is that it possesses manufacturing information as well as substantial materials database and is useful as a first estimation of a product’s

Embodied Energy. Whilst comprehensive, its drawback is that it is too general and cannot be tuned to detailed design work. Furthermore, its life cycle analysis does not recognise design energy, energy spent in maintenance and cannot accrue any energy that is being harvested. Granta Design [2.11].

2.4.6 SimaPro LCA Software

SimaPro uses life cycle analysis as a framework for collecting, analysing and monitoring the sustainability performance of products and services. The literature shows the SimaPro package to be comprehensive but measurements are unspecified and there is reluctance to offer the elements that constitute product life cycle. SimaPro [2.143].

2.4.6.1 Eco-IT is the software tool marketed by SimaPro and is comprehensive in allowing the modelling of complex products in the life-cycle environment. The software uses several metrics including carbon dioxide and is intended to be used by the designer to guide the design of products. The end result is aimed at higher level decision-makers and so converts much of the data to indices. Significantly the life cycle assessment does not include design or maintenance and does not account for any accrued, harvested energy. Eco-IT [2.145].

2.4.7 Sustainability Tools Overview

There are several attributes to those sustainability tools that were reviewed. Without exception they use life cycle analysis but collect the data from many different sources and, after compiling and manipulation, use data at a business or more global level. Some sustainability tools such as Open LCA [2.147], use data from many different sources and after manipulation applies it to a business or even global level. Gabi [2.148] uses life cycle costing as its end result. The generated data creates indices, environmental impact assessments and is used at a strategic level. Green Delta [2.146] applies data management, life-cycle costing and quality assurance and is the only sustainability tool that practices the use of environmental standards, such as ISO14040 and ISO14044. Green Delta targets its information at a more strategic level.

The diverse nature of sustainability measurement is reflected in the tools reviewed, but some sustainability tools use particular metrics. Eco-Rucksack [2.149] decouples energy and material consumption from the economics of manufacture by using mass (kg) as a metric. Granta Design Limited [2.11] with their EduPack software package is probably the most useful since it uses an LCA framework and offers an Embodied Energy value for each life cycle element. The focus is aimed at the manufacturing engineer and offers an Embodied Energy value at each life cycle phase. It even offers a form of end of life value if items are recycled. The main drawback is that the global nature of the approach renders the sustainability analysis light on details and vague in several areas. It does not include energy used in design or that used in maintenance and only includes energy saved through recycling goods for the end of life value. Nevertheless it is a comprehensive package that is useful for the designer. All the tools without exception used life cycle assessment as the main framework. Several tools used specific metric values to obtain their data.

Eco-IT [2.145] used carbon foot printing, Eco-Rucksack [2.149] used mass (kg), EduPack Granta[2.11] used Embodied Energy. It is significant that those sustainability tools that used specific metrics also use the data for specific and results. Several other sustainability tools, Gabi [2.148], Open LCA [2.147], Green Delta [2.146], used indices which were directed at a more business or global level.

2.4.8 Sustainability Tools Embedded into CAD Software

Some software packages embed sustainability measurement devices within the software package to give access to a sustainability measurement tool during the design process. The magazine Graphic Speak [2.152] suggested that Autodesk Inventor was one of the most popular CAD packages with 12 million users over 30 years. World Access Magazine [2.151] rated Solid Solutions, Solid Works CAD package as the fastest-growing general-purpose package in the world but Apollo [2.153] suggested AutoCAD Inventor was most popular. It is arguable which company produces the most popular general-purpose package.

A review was conducted of both companies to assess their embedded sustainability approaches. Autodesk [2.154] provides sustainability consultancy advice but surprisingly does not embed sustainability tools within their CAD products. In contrast Solid Solutions [2.155], the vendors of Solid Works CAD software, offer embedded sustainability programs within their CAD suites. This inclusion is based on Gabi [2.148] sustainability software which is a general life cycle assessment tool that in general creates indices used in high-level decisions.

In general, software tools tend to be vague on data acquisition and produce end results that are aimed at decision-makers above the detail level of product creation. This view is voiced by Curran MA [2.144], who suggests that "professional life cycle analysis software has reached a certain maturity and is most likely not to focus on application of LCA but rather on usability aspects." Curran also states “early LCA software originally had more detailed measurement data input for quality and clarity”. There are notable exceptions that take specific measurements and apply them as a detailed level such as Eco-Rucksack [2.149] and EduPack [2.11].

2.5 Literature Survey Topic Synopsis

The literature survey showed that much of the research on sustainability is at a highly idealistic level and focused on systems rather than practical applications: Weenrn [2.36] generalised on sustainable product development. Bakshi et al [2.37] overviewed challenges for process engineering. Roy [2.38] clarified product service systems. Johansson [2.40] investigated success factors for eco-design integration. Kobayashi et al [2.43], Kobayashi et al [2.44] analysed strategic evolution of eco products, Lindahl et al [2.45] expounded on Environmental effect analysis.

Many institutions, such as the Institution of Mechanical Engineers (IMechE) [2.16], American Society of Mechanical Engineers (ASME) [2.17], The Engineering Council [2.18] and The Royal Society of Engineers [2.24], however, are bound to a global level. The codes of practice have been modified in recent years to substantially include sustainability. The word “sustainability” and influence of sustainability actually appears in 6 of the 10 basic codes of practice for the IMechE and ASME. Through their codes of practice, these institutions influence budding engineers as well as those of experience and, by their very nature as global institutions, have to take a global stance. It should be said, however, that these institutions also organise definitive publications and lectures which deal with detail, often with a sustainability bias and are targeted towards various industries. Much of the literature attempts to address sustainability across many disciplines. Though this information is correct and very useful, its impact is somewhat diminished purely by the broadness of the approach.

Much of the writing on sustainability relates to geographic sciences or the built environment where sustainability has been a major priority for centuries and is very prominent in the modern setting. More specific titles relating to the project goals formed the basis of the literature survey.

Research work that is available for the practical engineering designer who wishes to apply principles of sustainability to his designs is limited to just a small number of publications. Some of the major works are Periera [2.14], Ashby [2.9], Granta Design [2.11], Byggeth et al [2.100], Rose [2.101], Zwolinski et al [2.102 Ueda et al [2.103], Spicer et al [2.104], Yu SY [2.105].

The literature review considered publications and from 1997 through 2014 the bulk of which were during the latter five years of that period. The review uncovered many key publications along with a great breadth of topics relating to sustainability. Such diversity required an accounting and categorising method. General sifting of the publications led to the topic subheadings outlined in the literature survey statistics in figure 2.4

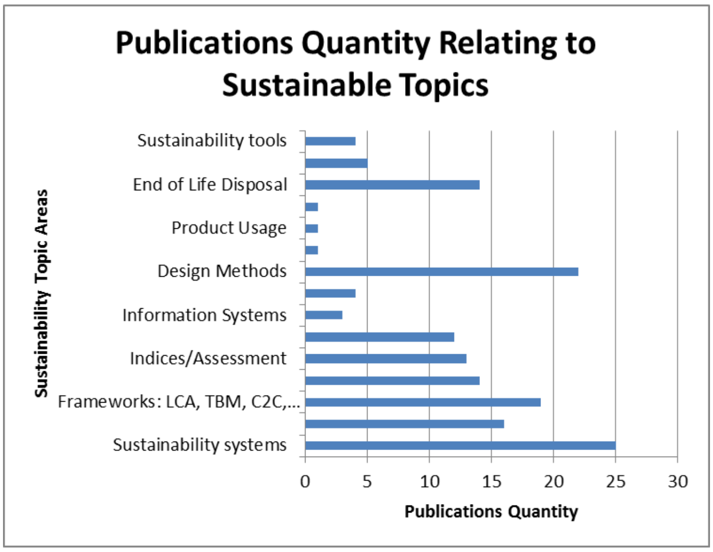


Figure 2.4: Statistics for the Literature Survey Relating to Sustainability in the Field of Mechanical Engineering

The graph in figure 2.4 shows various applications of the principles of sustainability which are listed on the vertical axis of the bar chart which cover the six elements that comprise the entire life cycle of the product. The publications were reviewed so as to place them into a particular subheading.

The statistics show that there are more publications dealing with the overview of sustainability systems than those dealing with precise detail of sustainability measurement applications. Sustainability related to design methods is also a popular subject. It is generally recognised, Ashby [2.9], Wimmer [2.20], Neilsen [2.21], and others that, in any new product, sustainability has to be generated by the design function. Luttrop et al [2.114] shows with detailed graphics the considerations of a designer when creating a product and strongly suggests that sustainability requirements should be included in the basic design criteria. He put forward ten "golden rules" for sustainable design which complement the approach taken by the author of this thesis and are discussed further in Chapter 4.

Sustainability assessment frameworks is the next frequent publication topic, closely followed by publications relating to end of life disposal. End of life disposal is an important part of the sustainability process, but it is an element which is often considered at the expense of other life cycle elements. In papers that consider end of life disposal it is significant that many of these papers consider recycling of material. Refurbishing and re-use, which can be considered as an equally important aspects of sustainable disposal, are less well served. Re-manufacturing, which can be termed as refurbishment, is a subject of several papers by Mont [2.19], Kerr [2.123], Williams et al [2.125], Sundin [2.130] and Seitz [2.131]

It is noteworthy that there are only a small number of publications tackling the subjects of sustainable sourcing, sustainable manufacture, product usage and product maintenance.

Sustainable sourcing was considered by Ashby [2.9] and Ashby et al [2.99]. Ashby's approach to materials is to apply Embodied Energy as a measure of sustainability, a metric which has been adopted in this research project and which is used by several other researchers, mainly those who are working on detailed analysis of products and systems, Mayyas [2.29], Pope [2.92], and Patxi [2.141]. Sustainable manufacture was considered by Ranky [2.115] and Wenzel et al [2.35]. Both these publications followed similar lines and considered the process of best practice, manufacture, reducing energy input and waste output.

Within the sample a relatively small number of publications, Ashby [2.9] and Ashby et al [2.99] hinted at sustainable use, applying Embodied Energy as the means of measuring this element of the life cycle. In these publications, maintenance was treated as a minor element in the life cycle of products and was not recognised as being an important element in relation to sustainability.

Recognition of the importance of maintenance in life cycles was highlighted by two publications. The first was by Kerley [2.117] who reported that Rolls-Royce Aero Engines Division now leased their engines to the airlines, taking responsibility for maintenance and redesigning the engines to effect easier and quicker maintenance. This position, however, was for not for an altruistic reason such as sustainability but rather for safety, efficiency and cost saving. It did highlight, however, that design for maintenance can be a major consideration since efficient maintenance applies only a small value of Embodied Energy while still preserving the longevity of the unit. Savings of Embodied Energy by extending the life of a product quickly outweigh the Embodied Energy applied during the maintenance process. An easy and speedy designed-in maintenance process reduces maintenance effort and hence maintenance energy.

The second publication pertinent to maintenance was a keynote presentation by Takata [2.118] who put forward a theory of "Circular Manufacturing" which included maintenance and refurbishment whilst performing feedback on newly maintained products within the usage cycle. Feed forward was also applied on those products that needed maintenance, refurbishment or recycling.

Though management was a reasonably well represented in publications, it is useful to explore the processes utilised by those researchers. Sarkis [2.51] reported on a decision framework to assist with the green supply chain management whilst Beamon [2.52] also considered the logistical management of the green supply chain. Westka [2.49] appeared to take the most practical management route by discussing assembly and disassembly processes and their logistics within the product life-cycle, White et al [2.56], whilst Karlsson [2.55] considered an overview which was broad rather than specific. These papers were useful in that they offered some elements of appropriate management practice which proved useful in formulating a management strategy for this research as discussed in Chapters 6 and 7. Interestingly none of the papers reported using ISO Standards relating to environmental management which indicated their management processes were unique to their institution rather than set in a global context.

The researchers quoted above dealt with systems rather than data, but research by Framling [2.62] suggested the use of Product Life-Cycle Management (PLM). This system proposed the use of computer aided technology enabling communication between products and other information systems with the aim of improving efficiency, reducing energy and reducing environmental impact. The use of computing systems creates a controlled environment which eventually can retrieve and assimilate information, component by component. Framling suggests that this is the future of sustainability control and measurement.

End of life strategies were adequately covered in the literature with many researchers considering specific products. For instance Mont [2.119] considered remanufacturing baby prams whilst Kerr [2.123] put forward a process for remanufacturing photo-copiers. It is significant in that seven of the thirteen references in this section related to recycling of materials; four were related to remanufacturing and three papers discussed design for disassembly. Harjula et al [2.128] was the most useful in suggesting that material separation techniques should be designed-in at the design stage in order to make recycling more efficient.

Sustainable product development featured highly in work using standard concept generation techniques and applying them to the sustainability argument. Several researchers used Quality Function Deployment (QFD) including Akayo [2.71, 2.72 and 2.74], Bakker [2.73] whilst others Chang et al [2.76] applied TRIZ. These papers covered the methodology of applying idea generation techniques whilst designing with a raised sustainability profile. The case studies were informative in that they provided insight into idea generation of design parameters within inclusion of a sustainability element.

It is clear that design for sustainability is prominent in the approach of a large number of researchers. In particular Luttrop et al [2.114] is a champion promoting the design function as the primary driver for the inclusion of sustainability within new products. He also put forward practical methodologies that are guides for the practical designer.

2.6 Future Developments

The complex nature of sustainability assessment is discussed in many publications. Data is often aggregated, modified, weighted and combined to give an index which is then the basis for decisions. Indices are useful for high levels of sustainability assessment but at the product design and manufacture level, precise measurement is more appropriate. Some forms of data are difficult to measure, but once achieved, the data should be ready for use in a productive fashion. In other words, acquiring data requires a purpose. Measured data from the product level can be used to control the life cycle and assist in management processes to create increasing efficiencies, including financial, social and sustainable efficiencies as proposed by the triple bottom line framework.

Data acquisition and control are therefore becoming the new sustainable frontier and systems such as that proposed by Matsokis et al [2.63] are destined to become more useful as product life-cycle control becomes more desirable. The earlier mentioned adage “measure it to manage it” now becomes a very real necessity. Measurement may take place, but there is so much data from such complex products and systems that a comprehensive data management system is necessary. Matsokis and Kiritsis [2.63] put forward a data management process called Product Life-Cycle Management (PLM) which proposed that product information can be collected and used in a multi-organisational context. They proposed that such information could be shared across products and information systems so that products can be modified and efficiencies created thus reducing the energy used. Framling [2.62] extended the PLM methodology to include sharing information through smart products and networks.

Taiichi Ohno [2.65], general manager for Toyota, introduced the “Just in Time” (JIT) management strategy which required a precise level of control over individual products similar to that put forward in PLM management strategies. Data was originally stored on Kanban cards attached to each product. This has progressed to embedded memory chips and systems modernised using bar codes, RFID-codes, satellite location techniques and internet communication systems. These methods were discussed by Vernyi [2.66] and Kochan [2.67] and are complemented by the work of Kiritsis, Matsokis and Framling. Technologies such as these allows feedback data to be communicated from products in-the-field to the central communication node thus enabling logistical efficiencies to be made and energy usage to be improved.

The PLM proposals build on valuable work such as JIT accomplished within the manufacturing industry and apply it to sustainability and data management using modern computing and communication techniques.

2.7 Application of the Literature Review to the Current Research Project

The initial general aim of this research was to develop a sustainability tool for the engineer involved in the product creation process. The literature review confirmed the need for a detailed sustainability measurement system at the product level and showed that most practical researchers used LCA as an applied framework. The information thus generated was used to create indices which fed into the broader umbrella framework of the Triple Bottom Line. There are other approaches such as Cradle to Cradle but these are deemed idealistic by Anders [2.26] and others. The work afforded by Chapas [1.13], Mayyas [2.29] and Mohannad [2.89] suggested that work at the detail level would be best served by a framework of LCA. These researchers and others also suggested that the combination of LCA with TBL and various standards would serve as a complete system using specific data at the detail level and eventually combining it with a wider approach. This research project proposed such a system combining frameworks and standards.

2.7.1 Standards

A review of standards, later reviewed in detail in Chapter 4, revealed that the ISO14000 series [2.1], [2.2], and [2.5], were comprehensive and dealt with several aspects of application, measurement and management of sustainability. Furthermore within this set of standards, methodologies are specified which allow seamless meshing within the set but also with other management software such as ISO9001 Quality Standard. ISO 14000 series standards are therefore used in this project.

2.7.2 Measurement Complexities

The complex nature of auditing sustainability systems has led many researchers to use combined data in creating indices and trends. Figure 2.2 synthesises the data and shows that that at the detail or product level there needs to be a precise measurement system rather than an overview system. Indices are generally used for decision making in more global programs. Depending on the process, device or situation that was measured, researchers used appropriate measurement systems. For instance Antiohos [2.16] applied Embodied Energy (Joules) to building materials whilst Kim [2.93] was concerned with economic outcomes but used watthr/kg (Joules/kg) as a base measurement. The cost metric is often used especially when an economic study is being conducted. The work of Martin and Gatzen [2.94] reviewed operational costs of oilfield services where the metric was dollars.

Several researchers who work at a practical level have applied Embodied Energy as a measure of sustainability. The approach by Ashby [2.9] and Ashby et al [2.99] was to apply Embodied Energy as a measure of sustainability across the product life-cycle. This is a metric which has been adopted by researchers who work on detailed analysis of products and systems and include, Mayyas [2.29], Pope [2.92], and Patxi [2.141]. The use of Embodied Energy as a metric efficiently lends itself to measure activity within all the elements of the life cycle analysis and has been adopted.

A major requirement of the measurement metric was that it needed to span industries and have the ability to measure services as well as products. The metric also needed to generate a value for each of the life cycle elements. Several metrics were considered including carbon footprint, but the only measurement device that would fulfil the requirement was that of Embodied Energy.

Almost all reviewed articles were concerned with the measurement of the effects and the drains on the environment. Datschefski [2.157] was the only researcher in the review who suggested that the sustainability of a product may also be gauged by considering renewable energy and though this metric relates to the *use* of generated energy, it seems reasonable that the energy generated by a product, such as wind generator, solar panel, etc., is considered within the Embodied Energy tally.

2.7.3 Frameworks

The LCA framework allows the generated data to be fed back to the design function, but also to other elements of the product life cycle including the management team. In this way products can be modified and enhanced in their function and sustainable efficiency. Management processes may be installed to control this data and product material flow based on guidelines within available standards, with ISO standards being the most apparent choice, Green Delta [2.146]. Such systems deal with the product and its cycles but contribute to a wider brief. Here TBL is considered the most useful overview framework choice, engendering a practical approach whilst considering social, economic, and sustainability features. Gurav Ameta [2.25], Ness [2.91], Choida [2.90] and Mohannad [2.89] are all proponents of TBL especially when linked to measurement systems and the life cycle analysis.

2.7.4 Vision: Sustainability Measurement and Management System

The vision of the whole sustainability management and measurement system comes into sharp focus when four major features are combined into a cohesive structure. The envisioned system shown in figure 2.5 can be used to measure sustainability at a product level and can also influence higher-level decisions. Linked to figure 2.2, influence levels, it can be seen how measurement parameters of the envisioned system can be applied.

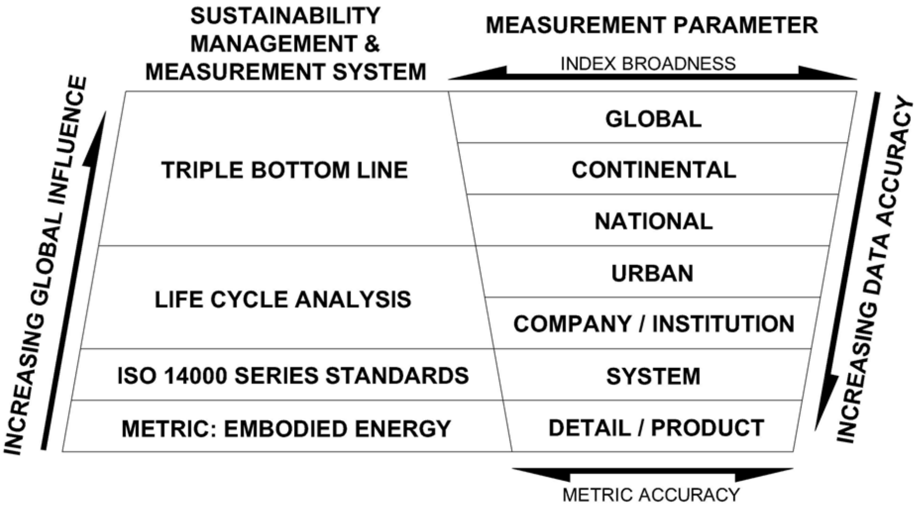


Figure 2.5: Sustainability System Vision Linked to the Sustainability Measurement Profile

The new amalgamated vision for this project consists of:

- Triple Bottom Line (contextual overview)
- Life Cycle Analysis (detailed analysis and measurement)
- ISO Standards (guidelines for managing sustainability data and systems)
- metric of Embodied Energy

The combination of these features creates a broad audit system that can be used for single components and/or multiple component products. Guidance derived from the management strategy can influence departments, components, regions and more global applications. Detail data can be derived by applying LCA and feeding the generated data upwards to the TBL level where influences can cover economic as well as social aspects. Environmental data systems are prescribed by the application of ISO standards which can then in to other management standards and provide a global network to other individual institutions.

2.7.5 Inclusion of Maintenance

It is evident that the life cycle analysis used by most researchers incorporates sourcing, manufacture, usage and disposal, yet there are other requirements for energy input during the product life cycle. Many products are maintained and in so doing the product is kept serviceable, thus avoiding the procurement of a new product. The logic suggests that the effort and materials of procurement can therefore be used to help offset the energy input in creating the original product. Although Mohannad [2.89] used LCA with Embodied Energy, he omitted to use maintenance and end of life strategies. The influence of maintenance on sustainability is included in this project.

2.7.6 Inclusion of Design

Once developed, sustainability strategies, models and methodologies can be applied to practical design problems. In the light of the overview of literature survey topics shown by the bar chart in figure 2.4, research efforts for this project were directed at one or more of those areas which were least serviced by the publications. These topics are:

- Sustainable Sourcing
- Sustainable Manufacture
- Product Usage
- Product Maintenance

It is generally recognised, Ashby [2.9], Wimmer [2.20], Neilsen [2.21], and others that, in any new product, sustainability has to be generated by the design function. Luttrop et al [2.114] put forward a case where sustainability should be combined with the product as the design process takes place. Luttrop [2.114] champions the use of design across all aspects of the life cycle analysis suggesting that the designer is in a unique position in that he can influence elements of the life cycle analysis. Chapas [2.113] advocates a multidisciplinary management team at the design stage so that all life cycle elements can be considered. He also suggests that certification should be applied through appropriate standards. Spangenberg [2.156] also advocates design for sustainability (DfS) and makes two major points: “Without the contribution of design, the full potential of sustainable production and consumption, and thus sustainability, cannot be realised.” “Similarly, only in a sustainability perspective, can the full potential of design can be released.” Clearly, researchers consider design to be the cradle for sustainability in new products. It follows that if design is considered to be such an important activity then it should be included in the life cycle analysis model.

2.7.7 Inclusion of Giveback

Giveback is a novel addition to the LCA and is an accounting device that accrues all saved energy and all harvested energy during the product life cycle. It is used in the energy balance sheet to offset the input energies.

2.7.8 New System Proposal

The life cycle analysis discussed in section 2.2.5 above can now be modified with the additions of elements of *Design* and that of *Maintenance*. This updated life cycle analysis also includes *Sustainable Giveback Value,* a novel energy accounting element. The whole model vision is shown in figure 2.6.

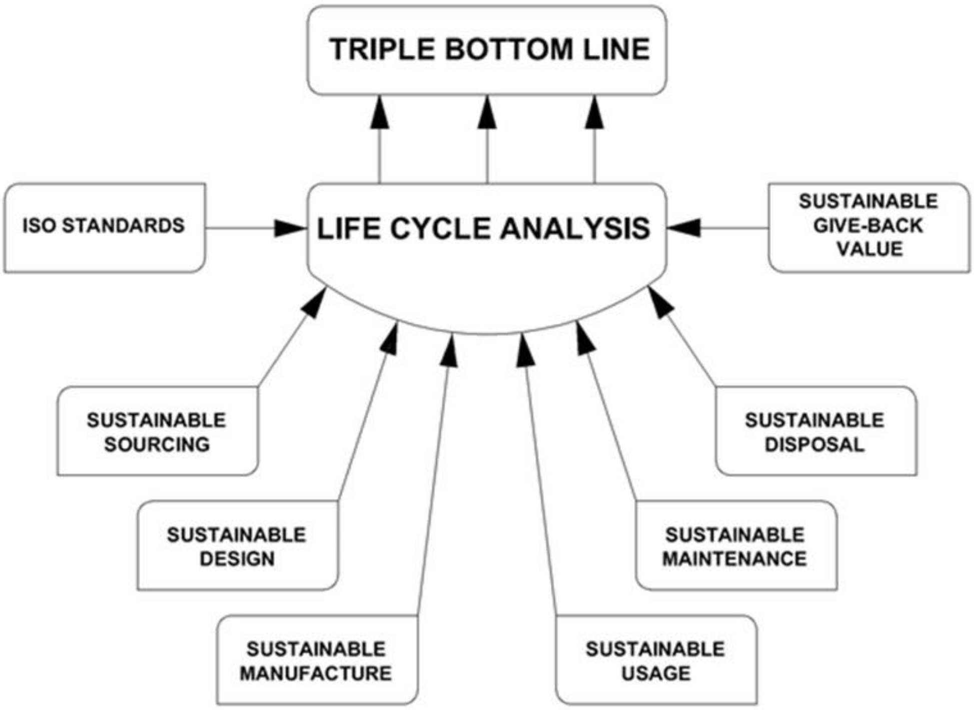


Figure 2.6: Novel System Vision: Life Cycle Analysis with Life Elements

1. sustainable sourcing
2. **sustainable design**
3. sustainable manufacture
4. sustainable usage
5. **sustainable maintenance**
6. sustainable disposal

   plus

7. **sustainable give back**

These have been combined into a single graphic, figure 2.6, showing the six life cycle elements contributing to the life cycle analysis. Also included in figure 2.6 are two other major influences, ISO Standards which provide the management and administration format and Sustainable Giveback Value (SGBV) which provides the accountancy value that accrues harvested energy. SGBV can also be added to the life cycle elements making seven in all.

2.8 Observations and Specific Area of Research (Research Aims)

Many measurement systems including online sustainability management/measurement packages are focused on providing data to enable higher level decision making. In this way much of the precise data is converted to indices or broadened and modified to suit the data purpose. This is useful for decisions at company level and above but is unusable at the detail/product level where precise data needs to be returned and fed back to appropriate personnel working within the six elements of the LCA.

After reviewing the literature several major conclusions were drawn:

- Many publications deal with measurements and direct the data to higher-level decision-makers
- Some elements of sustainability and LCA are not well reported or receive only cursory consideration in most current models. These neglected aspects include:
    a. Maintenance has been included in several models but has rarely been quantified.
    b. Maintenance must be included in sustainability systems since it can prolong the life of a product thereby avoiding the new procurement.
    c. The requirement for a reliable sustainability assessment system at the detail level so product data can be fed back to those personnel who are creating products.
    d. The requirement for a cohesive management system which receives and coordinates product information during the product life cycle and can feed detailed data to appropriate personnel or can modify the data for use at company, district, national and global levels.
    e. The requirement for a more precise the Embodied Energy accounting system that includes the novel additional elements to the LCA.
    f. The requirement for a feature in the Embodied Energy accounting system which includes energy harvesting.
    g. The requirement for a second feature in the Embodied Energy accounting system that includes energy generation

Additional observations requiring additional emphasis include:

h. The concept that the design function is the only element in the life-cycle process that can overview the entire life cycle is put forward by several researchers. This puts the design of the whole product from sourcing to disposal in the hands of the design function.

i. Data is often generated and manipulated so that it can be used at levels above product level. Few researchers report on feedback of data to the product creators. Kerley [2.117] and Takata [2.118] are two exceptions**.** A system is required which returns precise data to the personnel who are creating products and who can use this precise data to improve those products.

2.8.1 Conclusions and Research Goals

The original general aim of the research was to provide a sustainability measurement tool with which the product creators could measure the value of sustainability within the products they were creating. The review of current research publications indicated that some of this work was in progress but there were some notable gaps covered. These gaps have been discussed above and have been expanded for further discussion in the following chapters as outlined below.

Chapter 3: Review of Environmental Certification and Environmental Standards

During the literature review it became clear that the environmental standards and environmental certificates were a necessary part of any sustainability measurement structure. Chapter 3 reviews the certificates and standards that relate directly to the sustainability of products.

Chapter 4 Design for Sustainability

Although design for sustainability is reasonable well covered by numerous papers, this chapter describes the enhancement of the life cycle analysis and the description of the design methodologies which can be used in Design for Sustainability. The chapter describes:

1. Enhancements to the original life cycle with novel elements
2. the proposal of a methodology for measuring sustainability
3. the proposal for sustainability audit based on the normal design route
4. proposals for maintenance as a key area which can increase the longevity of products
5. practical methodologies to achieve Design for Sustainability

Chapter 5 The Measurement of Sustainability

Part One (The Measurement of Phase 1 Life Cycle Embodied Energy)

1. applies Embodied Energy as a measurement device
2. applies the enhanced life cycle model
3. subdivides the life cycle model into Phase 1 and Phase 2
4. introduces a management approach “Total Design Control Management Strategy” TDCMS
5. defines a detailed measurement method for Phase 1 Life-Cycle Embodied Energy
6. creates a detailed algorithm that accrues and defines Embodied Energy applied during Phase 1 Life-Cycle.

Part Two (Phase 2 Life-Cycle: Measurement of Embodied Energy and Harvested Energy)
(introduces management systems, measurement techniques and case study applications)

1. defines sustainability centred maintenance (SCM), a detailed system based on maintenance and refurbishment that allows measurements of energy which incorporates feedback and feed forward of materials and components and feedback of information to the design team and the TDCMS
2. creates an algorithm which accrues all the energy in Phase 2 Life-Cycle both input and harvested and adds it to the Embodied Energy applied during Phase 1 Life-Cycle.

3. introduces the new term of Sustainable Giveback Value (SGBV) which is an accounting value that enables harvested energy to be used in an energy balance sheet.
4. formulates an energy balance sheet accruing all energies input and output, resulting in a net energy balance. This is a combination of Sustainable Life Value Phase 1 and Sustainable Life Value Phase 2 (SLV Ph1 & Ph2)
5. projects how the information generated during the entire life cycle process can be used and applied at a detailed level by being fed back to the TDCMS and on a more global level by its application to the triple bottom line.

Chapter 6 Total Design Control (describes Total Design Control Management Strategy)

1. creates a management system which puts design in control and to influence the six elements of the entire product life cycle
2. proposes that design for sustainability has to be a team approach
3. defines the novel management strategy of Total Design Control
4. identifies that the design process is key to guiding the management and control of the entire life cycle.
5. builds management strategies around the classic design approach.
6. applies sustainability audits at appropriate points during the design process.
7. defines the TDCMS within a management structure
8. outlines the TDCMS design team composition
9. integrates TDCMS with environmental standards (ISO14001)

Chapter 7: Sustainability Enhancement Program (SEP) (an executive level sustainability management programme)

1. introduces an executive management strategy, Sustainability Enhancement Program (SEP)
2. operates as a top tier management strategy integrating with TDCMS and SCM
3. integrates SEP with ISO14044, Environmental Management and ISO 60300, Dependability Management and RCM.
4. defines the whole management system from SEP through TDCMS to SCM and links the whole strategy to Phase 1 and Phase 2 Life-Cycle

The general aim of this research is to create a means of measuring sustainability within new products. Current thinking has been considered and revised to include new elements to the life cycle analysis model. It was also observed that much of the data currently collected, even at a detail/product level, is aimed at higher levels for decision-making purposes.

The focus of this research is to provide precise data in the form of Embodied Energy which can be used as a precise indicator of the value of sustainability within a product. The data can be used by the product creation team or for higher level decision making

The creation of a sustainability assessment tool has been attempted previously, but in this research there are several aspects which are novel introductions. The literature review created an overview picture of the practical realities and difficulties of sustainability with imprecise attempts to quantify or value the level of sustainability in a product. This research is therefore initially focused on creating an engineering design based sustainability model which leads to the proposal of a measurement system capable of creating a value for the "amount" of sustainability embodied in a product.

Research emphasis is also focused on creating a practical approach by which engineering designers can apply the principles of sustainability. This resulted in the concept of "Total Design Control" which takes its lead from the fact that the design function is the only element in the entire product creation process that can overview the six elements of a product lifespan.

The generalised framework upon which project will be based is shown in figure 2.6 and listed as follows:

- Measurement Device (Embodied Energy, joules)
- Life Cycle Analysis (detailed analysis and measurement)
- ISO Standards (guidelines for managing sustainability data and systems)
- Triple Bottom Line (contextual overview)

The literature review revealed that there is a great deal of work being undertaken in the many fields of sustainability. The review also revealed that there are some areas and topics where there is scope for further detailed work and it is precisely these topics which are addressed by this research project.

CHAPTER 3
REVIEW OF ENVIRONMENTAL CERTIFICATION AND ENVIRONMENTAL STANDARDS

3.0 Environmental Certification and Environmental Standards

In order to commercially benefit from a shift to sustainability in engineered products, designers and manufacturers need to be able to show the market that their products incorporate principles of sustainability and to demonstrate those benefits. Though the design/manufacture operation may wish to apply sustainability for altruistic reasons, they still have to survive in the hard commercial world where money is the operational currency.

Companies often wish to advertise their environmental performance, but there is staggering number of methods, standards and labels promoted by governments, private consultancies and lobby groups. This multiplicity leads to extra costs for the company and a great deal of customer confusion.

Much of the early research and sustainability labelling involved the food industry with labels such as *Fair Trade, Rainforest Alliance*, and *Organic*. An early leader in the sustainability movement in Europe was Der *Grune Punkt* . Although this group focused on recycling but, as pointed out in earlier chapters, recycling is only part of the story. There is still value in these labels which consider discrete elements of the product life cycle, but this kind of isolated approach does not allow itself to be applied to a broad spectrum of products. Furthermore, the design engineer is tasked to encapsulate the whole life cycle.

It is also true that the application of sustainability to a product is met by the market with some scepticism, disinterest and ignorance. Research carried out by The Hartman Group [3.4] indicates that consumers do not place a high value on sustainability when selecting products; indeed it seems that many in the sample populations did not have a clear concept of sustainability.

Delmas *et al* [3.5] suggested that the increasing number of eco-labels could lead to information overload, consumer confusion, and scepticism. To give credence to this claim they related that there were more than six coffee eco-labels, presenting confusing choices to the public.

Their conclusion was that an effective labelling/guidance system must fulfil a number of basic criteria:

- increasing consumer awareness
- increasing consumer confidence in the eco-pedigree of a product
- increasing consumer willingness to pay a higher price

These three elements along with their underlying detail can be seen in figure 3.1. Producers tend to align themselves with one or more of the recognised labels but there is a risk in that the label chosen may not be accepted or desired by the market.

Most developed countries possess various standards and labels, some of which are quite specific relating to a particular industry. Some have been devised by lobbyists while others are provided by governments. For instance some labels deal with energy whilst others deal with product performance whilst others may deal with carbon impact. Most are useful, but being specific they only cover a small element of the environmental argument. There follows a short review of some of the major eco-labels.

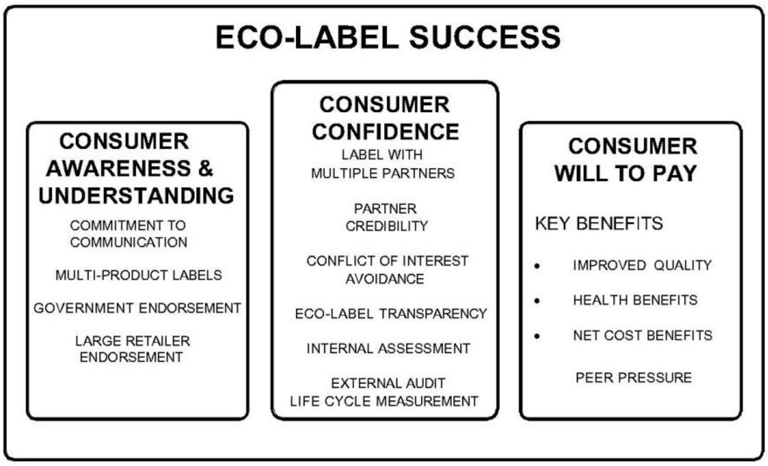


Figure 3.1: The Basic Requirements for Eco-Labelling

3.1 Standards and Labels Review

Eco-labelling can be viewed as an attempt by commercial organisations and lobbyists to create some sort of sustainability standard. These parameters equally apply to government organisations and standards institutes whose influence not only affects to the engineering community but many organizations worldwide.

The management of sustainability and its implementation cannot stand alone. There needs to be some form of platform on which to base the sustainability focus. If products are to be created by the design team using the entire life cycle and the Triple Bottom Line (3BL) as criteria, they need to have a framework within which to work. Such a framework needs to provide efficient application and be recognisable to consumers. Several leading eco-labels and standards have reviewed so that one or more may be combined to form a platform for the proposed management of sustainability.

3.1.1 Carbon Neutral

This label was developed by the Carbon Neutral Company [3.7] in 1998 aimed at measuring the carbon output of various organisations. Greenhouse gas emissions were monitored along with certification on the basis of verifiable evidence of reducing carbon emissions.

3.1.2 The Energy Star Label

The Energy Star Program was set up by the US Department of Energy in conjunction with the US Environmental Protection Agency in 2000. The scheme partners the European Union with the European Commission administering the program. Bateman [3.8].

The system examines energy levels across thousands of products for home and office including domestic appliances, computer monitors and printers. Being backed by both the US and European administrations, many companies have chosen to use this label. Unfortunately a large proportion of the buying public tend to look at the cost of appliances rather than energy efficiencies. Ward *et al* [3.9]

3.1.3 The Blue Angel (Blauer Engel)

Blue Angel is a German certification and is a well-known eco-label worldwide. RAL [3.10]. It promotes environmental and consumer protection and, since it is owned and run by the Deutsch Federal Ministry, possesses a great deal of consumer confidence. The labelling agency concentrates its efforts on ensuring the environmental quality in goods or services in the following for areas

- health
- climate
- water
- resources

The label has been very successful in the home market of Germany where they claim 76% brand awareness and that 39% of buyers are influenced by the label.

3.1.4 The EU Eco-Label

This is a European wide standard and is administered by "competent bodies" in each European country. EU Ecolabel [3.11]. It boasts that its products are less damaging to the environment and must meet a set of published environmental criteria. Perhaps the most distinguishing characteristic of this label is that it covers the whole life of a product including:

- extraction
- manufacturing, packaging and distribution
- use by the consumer
- end of life disposal

Although this is a European wide standard, owned by the European Community, Delmas [3.5] suggests that the label does not have depth in the market.

3.1.5 The Carbon Reduction Label

This label is owned and was set up by the Carbon Trust in 2007 which later became The Carbon Trust Foot printing Company to reflect its broadened aspect. A product or service branding this label indicates to the consumer that carbon footprint has been measured and that there is a commitment to reduce the carbon footprint further with newer product iterations. Analysis is based on a whole life cycle and uses British Standards PAS 2050 [3.12] as its base model.

3.1.6 The Energy Saving Trust Recommended

This is based in the UK market and is a "best in class" product certification and labelling scheme and is run "not for profit" by the Energy Saving Trust [3.13]. It is intended that manufacturers, suppliers and retailers can participate to help their customers identify the lowest energy products. The product categories range across several sectors including:

1. appliances
2. consumer electronics
3. IT goods
4. lighting
5. heating
6. installation
7. glazing

Under the trust's recommendations, only products that meet strict criteria can gain products certification. For instance only A+ refrigerator specifications will receive the label. The certification process is very searching and detailed. Certification criteria cover planning, consultation and peer reviewing before implementation.

3.1.7 British and ISO Standards 14000 Series

The British and ISO Standards are discussed in more detail below but essentially build on the very successful ISO9000 system that quantifies and audits procedures in quality management. ISO14000 series [3.1, 3.2, 3.3, 3.15] were derived principally to apply and manage environmental protection. They cover the whole life cycle of products and services and use energy as the metric. Of all the standards and eco-labels reviewed the ISO14000 series of standards offer the industrial designer the best opportunity of applying and managing sustainable products throughout their life cycle.

3.2 Greenwashing

Greenwashing is a term coined by several watchdog groups where they point out that, although some companies are "genuinely committed to making the world a better place", other some are cynically using the environmental slogan "green" to dupe the consumer into thinking their product is eco-friendly. This is a particular hobbyhorse of Greenpeace [3.14] on their greenwashing website.

Terrachoice [3.15] is another prominent watchdog in the United States. In their report in 2010 they noted that even though many companies practised reviewing their own products or perhaps use external agencies, an alarming 95% of companies committed one or more sins of greenwashing. Terrachoice listed the most flagrant types of greenwashing as:

- *hidden trade-off*-using a narrow set of criteria to claim sustainability
- *no proof*-claims which cannot be easily substantiated
- *vagueness*-generic claims are made with no real basis or substantiation
- *irrelevance*-where the claim is true but is not relevant
- *lesser of two evils*-claims that product is less polluting than another in a similar class such as using petrol rather than diesel.

- *fibbing*-claims are made in the full knowledge that they are untrue
- *false label worship*-claims of third-party endorsement which are untrue

Though a little simplistic in definition, it seems that a company with poor sustainability performance but promotes itself with positive media communication is actually greenwashing. “Consumer Beware” seems to be applicable to sustainability labelling and public relations.

3.3 Eco-Label Reviews and Conclusions

On reviewing eco-labels there seems to be a stated goal of reducing energy or carbon but efforts only target a minor element of the product’s life. There is a multiplicity of labels and standards which tend to overload the consumer with choices to an extent where many consumers will ignore the eco-label and purchase the lowest-cost product. Adding to the confusion are the, sometimes outrageous false claims leading to greenwashing. Most of the reviewed labels are limited in their approach and do not address the three basics of the Triple Bottom Line (3BL)

- profit,
- improvement of the human condition and
- reduction of environmental impact.

Without adherence to and having the perspective of the 3BL there is little opportunity to promote sustainable improvements through technological change. Only the design function can achieve sustainability through this avenue. .

The most far-reaching standard that covers the elements of the 3BL are the British and ISO14000 Standards. These are comprehensive and detailed and cover not only overview management but also discreet application management. The Standards suggest methodology for auditing systems and recording data. Their aim is to provide a substantial platform on which to base management overview systems and application systems within a sustainability programme. In doing so they take into consideration that in order to implement such a sustainability programme, the company needs to make a profit and create products that will entice the consumer to purchase. The need for flexibility in this regard nurtures the company into naturally considering and enhancing the 3BL. The standards are discussed in detail below in the next section.

3.4 ISO14000 Series Standards

As of 2003, 146 countries belonged to The International Standards Organisation (ISO), which was founded in 1946 to develop international industrial standards. The American National Standards Institute (http://www.ansi.org/) represents the United States in ISO. In the UK, representation is from The British Standards Institute and in Germany representation is by DIN or Deutsches Institut für Normung.

Many companies may be familiar with ISO through its 9000 series, which offers quality management standards for manufacturing processes, customer relations, and employee relations. ISO14000 series was introduced in the late 1990s, with modifications in 2004, 2006, 2009 and 2014 and specifies environmental management for an organization.

Some of the ISO14000 series programs, such as ISO14001, allow certified companies to carry the ISO label for their products and services. ISO14001 can be divided into three management stages:
1) Planning requirements
2) Implementation and operation requirements
3) Checking and corrective action requirements
Some standards cover the organization and some cover the product. In order to gain ISO certification, your company, product or service has to be accredited by an ISO-certified auditor.

The standards in this range provide a platform for environmental management systems but also for implementation of practical environmental applications. There are 4 standards ISO14001-2004 [3.1], ISO14001-2014 [3.2], ISO14040-2006 [3.3], and ISO14044-2009 [3.15]. ISO14001-2004 is still valid but is due to be superseded by ISO14001-2014 in October 2014

3.4.1 ISO14001: 2004 Environmental Management Systems Requirements

This standard sets out requirements for managing environmental systems and implementing a sustainability management program. The scope of the standard provides an organisation with the structure to establish, implement, maintain and improve an environmental management system. Furthermore, the adherence to the standard gives conformity to the environmental management approach by clarifying the organisation's self-determination and in turn achieving credibility from consumers and external bodies alike. Eventually the standard suggests the organisation should seek certification and registration of its environmental management system.

The use of ISO14000 series standards as a framework was advocated by several researchers. Mohannad [3.18], created a Product Sustainability Index (PRODSI). The index used various metrics and was used to influence higher level decisions being broad in its approach but nevertheless was useful in use of standards. Pope [3.19] investigated strategic tools such as the “Strategic Environmental Assessment" and "Environmental Impact Assessment" but suggested that the use of ISO standards as a framework would be useful and logistically efficient. Skerlos et al [3.20] also advocated the use of standards as he developed six points for the implementation of a sustainability assessment system and suggested standards would provide a suitable framework.

3.4.2 An Environmental Management System Requirements

Much of the responsibility for implementing an environmental management policy is given to the management team of the organisation which is responsible for applying, maintaining and auditing such a policy.

The standard sets out elements which must be installed in such an environmental management policy. Some of the major items are listed as follows:

- planning
- implementation and operation
- communication
- documentation
- operational control
- monitoring and measurement
- internal audit

These are merely a few of the complexities explained within the standard, but matches the objectives and requirements of the sustainable development management system as discussed in Chapter 6.

The requirements follow a fairly logical procedure where *planning* is the first element to take place before *implementation and operation* of the system can begin. There needs to be *communication* between entities and of course the usual *documentation* of performance parameters.

Elements which are just as important relate to the control of the management system: *control of documents*, *operational control* and *being in control of emergencies* which includes some form of preparedness and planned response.

There is also required a detailed level of monitoring and measurement where evaluation of compliance takes place and, in the case of nonconformity, corrective action can be implemented. The control of records is necessary for an internal audit system which can then be monitored by the management team.

Annex A of the standard goes into great detail explaining how and why the suggested elements can be achieved.

The authors of the Standard ISO14001 have linked many aspects to ISO9001 which is a standard related to quality assurance and management techniques. In Annex B of ISO14001 there is a table of comparative elements elegantly showing that companies that have adopted ISO9001 have already achieved quality management structures which are synonymous with ISO14001. Annex B clearly shows that there is a great deal of equivalence in terms of process approach, scope and quality management systems, quality policies, management commitment, responsibility, authority and many, many more.

3.4.3 ISO14001: 2014 Environmental Management Systems Requirements

This new standard released in October 2014 replaces the previous ISO14001-2004.

As environmental awareness evolves and new challenges become established then standards need to evolve to meet those new challenges. This new ISO14001 Standard has been modified to meet new environmental challenges and it also includes revisions which conform to new ISO management standards requirements. These revisions now include a high-level management structure even though the core text is very close to the 2004 version. The new Standard suggests that these changes have been made to benefit users implementing multiple ISO management standards.

One major change is that there is now a feedback loop from performance and evaluation back to the planning stage. This means that planning is not static but dynamic and can be improved. See figure 3.2. This has an iteration effect throughout all the management elements and mirrors very closely the Total Design Control Management Strategy (TDCMS)

In Chapter 6 the TDCMS is put forward as a relevant operational management scheme to assist in the sustainable creation of products. In the TDCMS methodology, in order for products to be improved there has to be feedback from throughout the life cycle of the product. The new ISO reflects this need in its management systems which, it suggests; require upgrading when new inputs emerge and when new output requirements are necessary.

Feedback to the design function has always been necessary so that new design iterations could take place. The TDCMS incorporated information feedback and could not operate without such data.

Previous standards have omitted the information feedback loop, but the new ISO14001-2014 with its incorporation of feedback information shows itself to be a suitable platform on which to base the TDCMS.

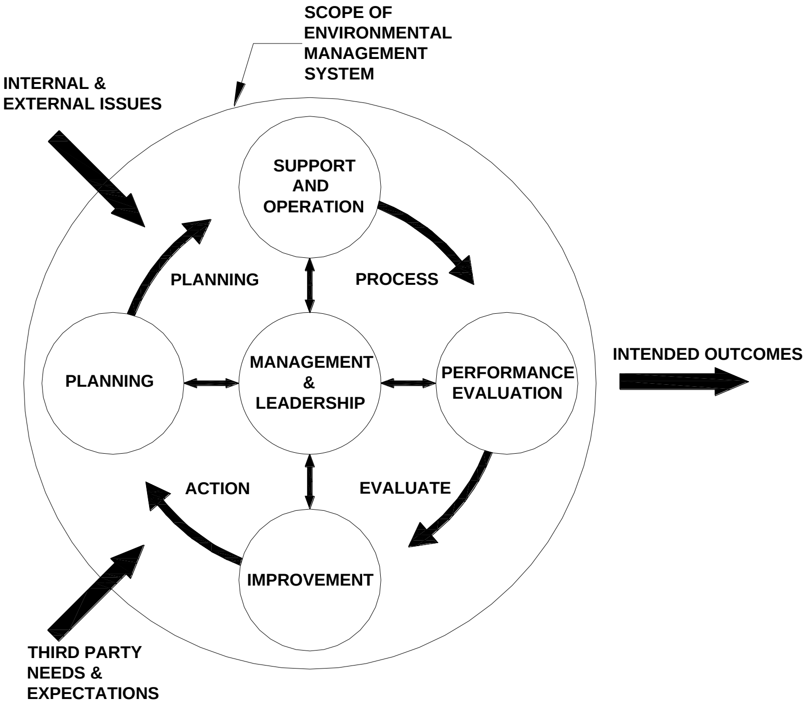


Figure 3.2: Environmental Management System Model for ISO14001-2014 [reproduced from 3.2]

3.4.4 ISO14040: 2006 Environmental Management — Life cycle assessment — Principles and framework [3.3]

This Standard provides an overview and a framework to cover the aims and scope of an environmental management policy. With the increased awareness of the importance of environmental protection, the Standard relates a management policy to possible impacts associated with products. Within such an environmental management policy the Standard considers the use and technique of a Life Cycle Assessment (LCA).

The Standard suggests that by using LCA several advantages can be gained:

- identification of opportunities to improve environmental performance of products at various points in their life cycle
- informing decision makers in industry, government or non-governmental organisations (NGO's). This can help with strategic planning, priorities, product design and process design, etc.
- selecting relevant indicators for environmental performance
- marketing including implementing an eco-labelling scheme, making claims, etc.

The management policy should have 4 components:

- the goal and scope definition,
- inventory analysis,
- impact assessment
- interpretation.

These 4 elements are very useful as a management overview to ensure that the environmental protection is properly targeted. They can, of course, be subdivided into detailed elements which effectively cover the scope of the Standard.

The Standard suggests that its scope covers Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI). The Standard also quite specifically states that it does not deal with specific methodologies nor describe the aid technique in detail. This is covered in other standards.

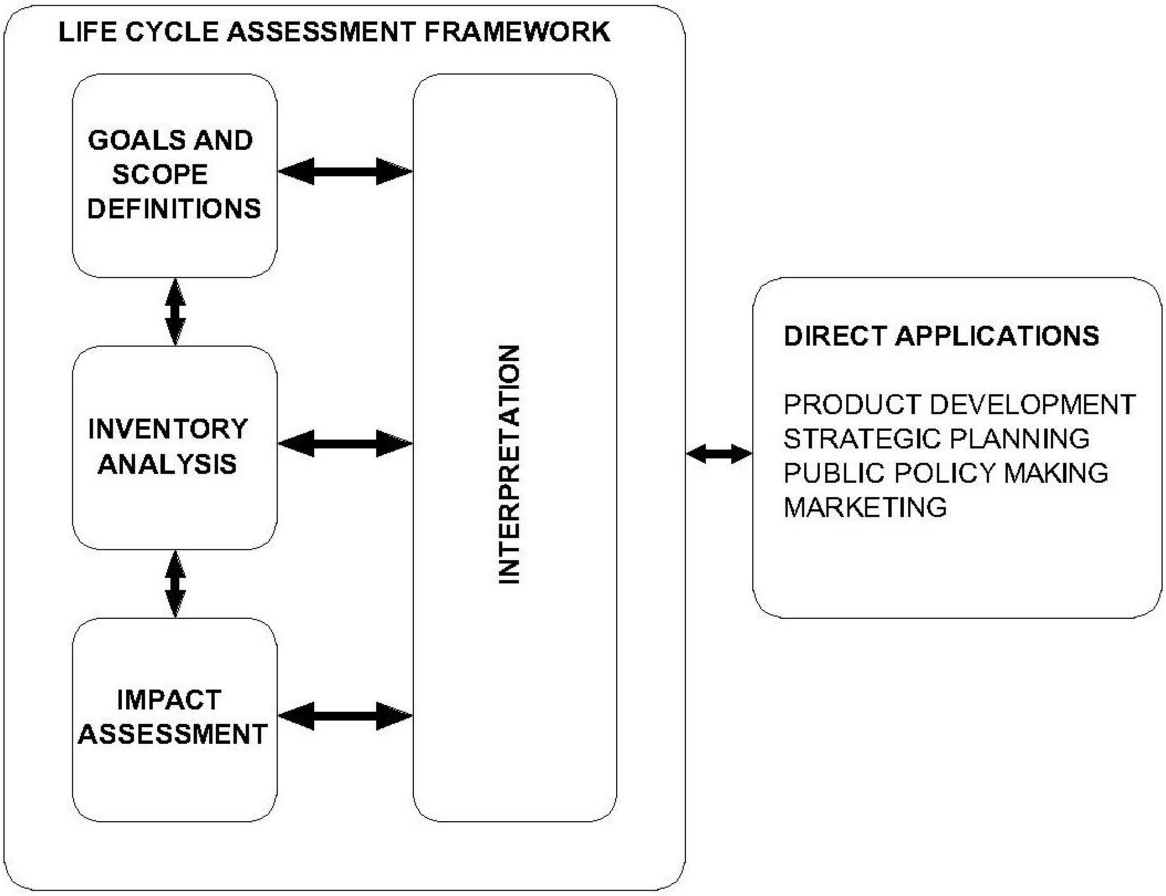


Figure 3.3: key Features of an LCA, Extracted from ISO14040-2006 [3.3]

3.4.5 ISO14044: 2009 Environmental Management — Life Cycle Assessment—Requirements and Guidelines [3.15]

It can be seen from the review of ISO14040 diagrammed above that it provides a framework to manage the environmental aspects of the life cycle of a product. The essence of the Standard is that it informs the implementing agency of what actions needs to be taken.

ISO14044 should be used in conjunction with ISO14040. ISO14044 compliments ISO14040 by providing detail on "how" LCA environmental policy can be achieved. Early paragraphs provide the same overview and approach as ISO14040 but this Standard goes on to specify further detail such as applying a system boundary.

The system boundary determines which unit processes should be included within the LCA and explains that consistency with the goal is necessary and the criteria used should be identified and explained.

The elements included within the boundary may comprise mass, energy, and some form of environmental significance. The standard is quite flexible allowing institutions to select their own measurement criteria such as carbon dioxide, sulphur oxides, etc. Significantly the standard also suggests that energy input (Embodied Energy) may also be a major measurement device. The standard also defines data quality and data presentation methods.

3.4.5.1 Life Cycle Inventory Analysis (LCI) [3.16]

The initial plan for conducting the life cycle inventory of an LCA is defined within the goals and scope of the study. The inventory however should be performed using specified operational steps as explained in figure 3.4.

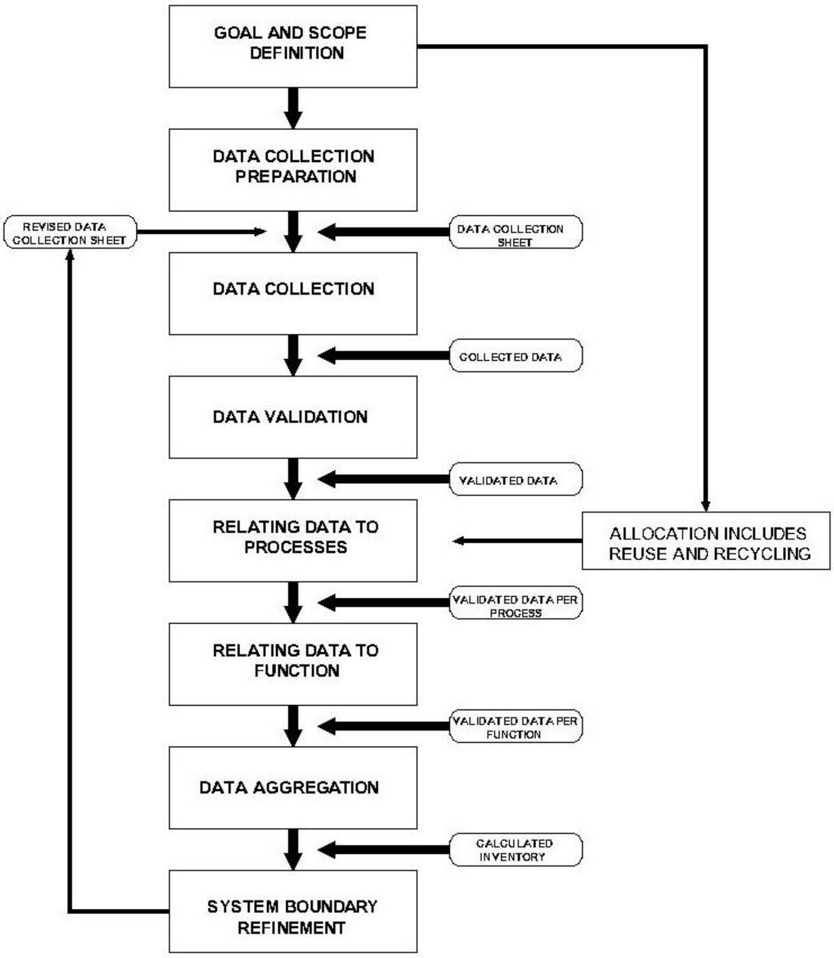


Figure 3.4: Operational Steps of a Life Cycle Inventory Analysis

Both qualitative and quantitative data may be used but must be specific to quantify but must be usable in quantifying the inputs and outputs of the selected measurement devices. The data collection, manipulation, and presentation could follow the following guidelines:

- draw process flow diagrams that outline the various processes to be modelled including their interrelationships
- describe each process in detail especially with reference to factors which might influence input and output of data
- require a list of the data flows into and out of the boundary for each process.
- describe the data collection and calculation techniques for any data received
- provide instructions to document clearly irregularities to expected data

Major headings are specified within the Standard to aid classification of data inputs. These may include:

- energy inputs, raw material, ancillary inputs and various physical
- products, co-products and waste
- releases to the air, water and soil
- various sundry environmental aspects
- validation of data
- relating data to unit processes and functional units
- refining the system boundary

After the raw data has been collected it requires manipulating and presenting in a meaningful fashion. The standard applies mandatory processes such as:

- selection of impact categories
- categorization of indicators
- characterisation models
- assignment of LCI results to the selected impact categories (classification)
- calculation of category indicator results (characterisation)

For each impact category the necessary components for the LCI analysis include:

- identification of the category boundary
- definition of the category indicators
- identification of appropriate LCI results that can be assigned to an impact category
- identification of characterisation models and appropriate characterisation factors

The standard suggests the refinement of data after collection. Refinement may include several standard processes which are normally applied to data manipulation which may include:

- statistical analysis
- normalising
- grouping
- weighting
- data quality analysis

There may be other background analyses performed such as:

- gravity analysis
- uncertainty analysis
- sensitivity analysis

These elements consider how the data has been collected, its relevance and its correctness.

3.4.5.2 Life Cycle Interpretation

Perhaps one of the most important issues emanating from an LCI study is that of identification of significant issues. Once identified, these issues can be evaluated and be submitted to sensitivity and consistency checks. Of course no study or analysis of data would be complete without conclusions and recommendations.

The results of the Life Cycle Interpretation element will then allow various certificates and labels to be applied. Labels such as "Energy Saving Trust Recommended" may be applied to a product to cover much of its life cycle whilst a "Sustainability Certificate Value" may actually be an Embodied Energy value issued with a product as it leaves the factory. There may also be a Sustainable Life Value (SLV) as proposed with this research where the actual Embodied Energy value is applied as the component leaves the manufactory but should include projected values for usage, maintenance and end of life disposal.

3.5 BS EN ISO60300 3 11: 2009 Dependability Management: An application guide to Reliability Centred Maintenance (RCM)

3.5.1 Scope

The Standard provides guidelines for the development of failure management policies using Reliability Centred Maintenance (RCM) techniques.

The RCM method can be generally extended to systems which are comprised of equipment and structure such as vehicles, ships, etc., but can also be extended to service systems. Each system is treated as a "living entity" which can then be broken down into its relative sub-systems, sub-sub-systems, etc.

3.5.2 The RCM Process

The whole RCM process can be subdivided into five major elements as follows:

1. RCM initiation and planning
2. functional failure analysis
3. task selection
4. implementation
5. iteration and improvement

Figure 3.5 shows the overall RCM process and the comprehensive program that RCM provides in terms of analysis process and also preliminary and follow-on activities. These are necessary to ensure that the RCM efforts achieve desired results.

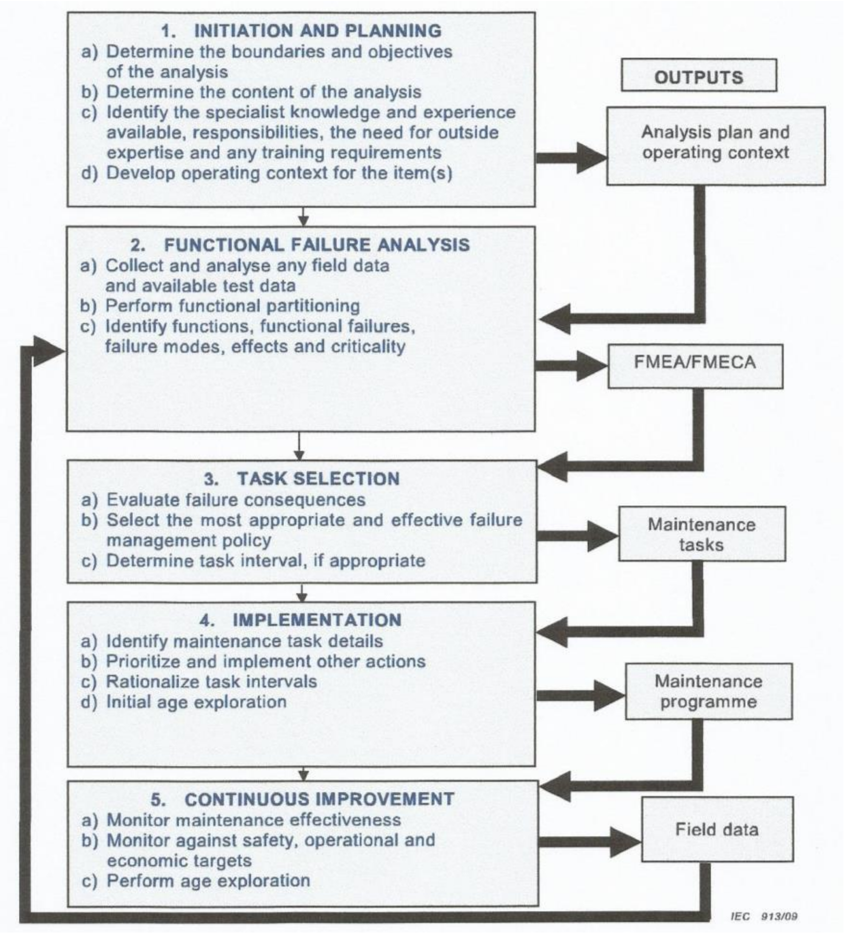


Figure 3.5: Overview of the RCM Process [3.17]

3.5.3 Objectives of the RCM Process

An efficient maintenance program requires the setting objectives. The objectives of an effective RCM program are listed as follows:

- to maintain the function of an item at the required dependability and performance level within its operating parameters

- to obtain the information necessary for design improvement or to isolate those items whose reliability proved to be inadequate.
- To accomplish these goals at a minimum Life Cycle Cost (LCC) to include maintenance costs and residual failure costs.
- To obtain information necessary for on-going maintenance programs which, through revisions improves on the initial program

The Standard recognises that service programs cannot correct design deficiencies and can only minimise deterioration from its original design levels. This recognition is quite meaningful as it shows that the RCM method concentrates on maintenance rather than design improvement, even though improvement is clearly one of the objectives listed above.

The Standard suggests that the implementation of RCM improves maintenance effectiveness and provides a mechanism for managing maintenance with a high degree of control. Potential benefits are summarised as follows:

1. system dependability can be increased
2. overall costs can be reduced
3. a fully documented audit trail is produced
4. processes are put in place to review and revise failure management policies
5. a management tool is provided which gives control and direction to the managers

The general RCM is aimed at improving dependability and reliability. A further goal is that of reducing maintenance costs. The priority here is to improve maintenance procedures, efficiency of maintenance, improve safety, and improve reliability. These are standard business objectives but when incorporated within the TDCMS program these extra benefits are added:

6. increased longevity improves the Sustainability Life Value (SLV)
7. increased longevity reduces overall Embodied Energy
8. adherence to an Embodied Energy Reduction program encompasses energy expenditure hitherto not considered e.g. the use of smart factories, local sourcing, etc.
9. monetary costs can lowered by avoiding the purchase of new equipment

The Standard gives a great deal of detail in what is required to achieve an efficient maintenance program as well as how this should be applied and documented. The Standard explains how general maintenance can be split into preventative maintenance and corrective maintenance as shown in figure 3.6. These elements, how they may be applied and how they may be documented are then explained in detail.

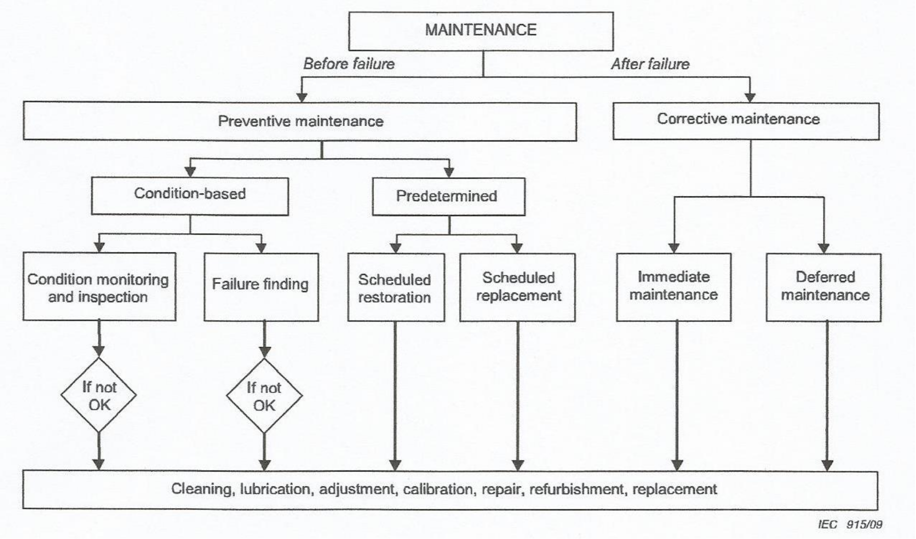


Figure 3.6: Types of Maintenance Task [3.17]

3.5.4 RCM Initiation and Planning

The Standard considers many aspects of the management of a maintenance programme and details planning methods including establishing maintenance tasks, identifying opportunities for design improvement, evaluating ineffective maintenance tasks and identifying dependability improvements. These elements will create a great deal of data and there is provision for data manipulation and recording.

3.5.5 Justification and Prioritisation

It is significant in section 3.2 The Standard suggests that RCM should only be implemented when there is confidence that it can be cost effective or when commercial considerations are overridden by other critical objectives such as safety requirements. Nevertheless the consideration of any commercial or critical objectives should cover the entire life cycle of the item product or system.

In order to maintain business goals, a list of priorities should be made and could include elements such as:

- maintenance efficiency
- dependability improvement
- design/operational change

These priorities will depend on the organisation's business objectives.

3.6 Sustainability Centred Maintenance (SCM)

RCM is a formal maintenance of the news by institutions on large projects such as ships, aircraft and vehicles, discussed by Allen [3.21], Steven [3.22] and Kerley [3.23] in their publications. Maintenance is often planned using an internal company system or using a maintenance programme attached to a particular product. The maintenance profile of a passenger vehicle is an excellent example of an individual maintenance programme. Sustainability centred maintenance is proposed in chapter 5 as a complementary programme that runs alongside normal maintenance and refurbishment programs. The normal maintenance programme will continue as planned but the information that can be gained during the process of maintenance/refurbishment is valuable for feedback to the TDCMS and also to log the status of used, reuse and recycle components.

3.7 Conclusions

3.7.1 Conclusions Relating to ISO14000 Series

Several prominent labels and standards have been examined to evaluate their potential for platforming the management strategies proposed such as TDCMS In Chapter 6 and later the "Sustainability Enhancement Program" (SEP) in Chapter 7.

In analysing the aims and requirements of these labelling and standards systems it became clear that no single eco-label was broad enough to overview the whole Embodied Energy Reduction (EER) process. Furthermore it became clear that since the EER process was aimed generally at *all* created manufactured products, many single eco-labels were too tightly defined even though some eco-labels possessed a fundamental management and coordination tool. It was further discovered that although rules within eco-labels specify certain behaviour one of their main uses in the sustainability argument is education of third parties, such as consumers, governments and NGO's.

When implementing a Sustainability Enhancement Programme or an EER program the structure is largely internal so that systems and procedures can be set-up, monitored, audited, etc. within the company structure. The end result is that various eco-labels can then be applied to the product to highlight specific elements.

In order to provide the platform for an internal corporate structure, the incorporation of ISO14000 series Standards is very suitable, thereby providing the structure, management and auditing methodology required of such a management system. In particular the ISO14001 Standards are particularly useful for implementing management systems in detail at an applications level. Within these Standards there is the strategic explanation, details and suggested methods to implement a detailed environmental management system which is practical and "hands-on".

ISO14040 and ISO14044 provide the backdrop for a higher level management system based on Life Cycle Analysis (LCA). ISO14040 outlines "what" should be done and ISO14044 explains in detail "how" implementation should be accomplished with a complete set of relevant data analysis and reporting techniques.

The approach taken by ISO14040 and ISO14044 applies an overview approach which controls the detailed management using an LCA technique. In Chapter 7 the concept of a "Sustainability Enhancement Program" (SEP) has been introduced which effectively provides an umbrella management system using LCA techniques and which governs the TDCMS which is concerned with implementation and the detail of creating sustainable products.

Both ISO14040 , ISO14044 along with SEP strive for the same goals using similar techniques. It is therefore appropriate to use the ISO14044 Standard as a platform for SEP. It can be seen from figure 3.7 that elements included in the SEP program are very close to those elements required by the ISO standards in general.

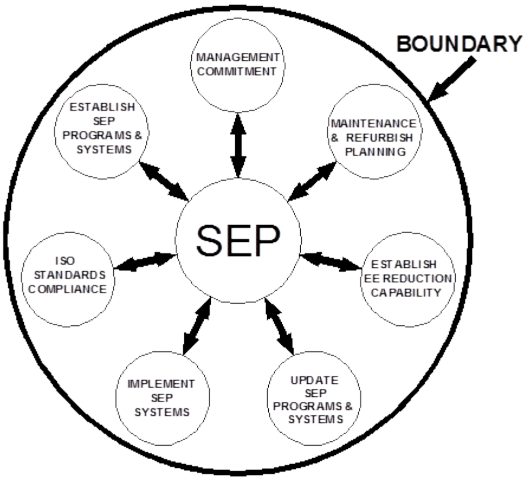


Figure 3.7: Sustainability Enhancement Program Main Elements (SEP)

3.7.2 Conclusions Relating to BS EN 60300 (RCM)

The RCM process is useful in that it is a well-established maintenance programme would be very suitable to run alongside the TDCMS model. The general aim of the Standard is to apply a management and practical application system that minimises deterioration of equipment. The thrust of this is to maintain reliability but actually includes the sustainable goal of prolonging the life of the equipment. Previous chapters suggest that increased longevity of components and products means that production of new components is avoided which means that expenditure of Energy of Primary Source (EPS) is also avoided. Chapter 5 and Chapter 7 proposes Sustainability Centred Maintenance (SCM) programme which complements RCM by providing a means of extracting sustainability data and feeding that data back to the TDCMS.

Within the Standard there are several references to feedback to the design function and whilst there is a great deal of detail relating to *what* to maintain, *how* to maintain and *how* to document maintenance there is very little instruction in relating to methods of feedback to the design function. The SCM program will therefore provide this extra function. In this way the Standard, through its various references, and the complementary inclusion of SCM will provide information so that the design function can reiterate and improve on current designs after receiving feedback information.

The general RCM is aimed at improving dependability and reliability. A further goal is that of reducing maintenance costs. When combined with SCM and related to the TDCMS program several extra benefits can be added, as listed in section 3.5.3, such as: increased longevity, improved SLV, reduction of Embodied Energy, reduction of costs, etc.

CHAPTER 4
DESIGN FOR SUSTAINABILITY

4.0 Total Design Control Overview

The role of the engineering designer becomes more and more complex with every passing year. The designer or design function has to be creative, produce a conceptual product which has to fulfil the market needs, design it in such detail that it can be manufactured and whilst all this is taking place the designer has to consider how to keep the cost of the product low. Now it is necessary to add design for sustainability (DfS) to the portfolio. This is a view put forward by Spangenburg [4.17] who expounds that "design for sustainability should play an important role in the sustainable production and consumption of products" and further opines that "thus far DfS has made few inroads into the design profession". Spangenburg [4.17] also made two major points, "without the contribution of design, the full potential of sustainable production and consumption, and the sustainability cannot be realised". The second point was that "only with a sustainability perspective can the full potential of design be released".

Environmental demands mean it is no longer possible to design and manufacture in the traditional sense. Design now has to become the lead function and take *Total Control* of the entire life of a product from sourcing materials to prescribing methods of how to dispose of the product at the end of its life. The design function is the only function that overviews the entire life of the product. Luttrop et al [2.18] promotes Ten Golden rules of sustainable design which in essence cover the entire life cycle of a product. These are general guidelines and a useful for enabling explicit eco-design implementation and the product creation stage. Chapas [4.19] takes a broader view. He suggests that research and development (R&D) is intimately involved in ensuring environmental societal and economic performance and suggests that a formalised design procedure is not only necessary for creating functionally and sustainably efficient products but also is required for certification bodies such as Energy Star.

4.1 Traditional Approaches

There has always been a drive to reduce the creation costs of products and is a primary objective for designers and manufacturers alike. A quote from an anonymous industrialist defines the problem:

"Everything costs money"

Recent years have seen a growing emphasis on providing products which are environmentally friendly (sustainable). It is a fact that many businessmen, designers and manufacturers consider this an expensive enterprise but in reality the design and manufacture to sustainable values and requirements often leads to lower cost production.

4.2 The Sustainability Umbrella Model

The traditional goal of designing to cost has now been joined by the need to design and manufacture for sustainability. The above quote can be expanded into:

"Everything costs money and everything has an environmental impact"

All new products therefore need to be developed for *low cost* and *high sustainability* which often go hand-in-hand. It can be argued that products designed with sustainability as a primary objective are designed under an umbrella of sustainability which covers **all** other facets of the design process. Consider the sustainable whole-life model proposed in figure 4.1

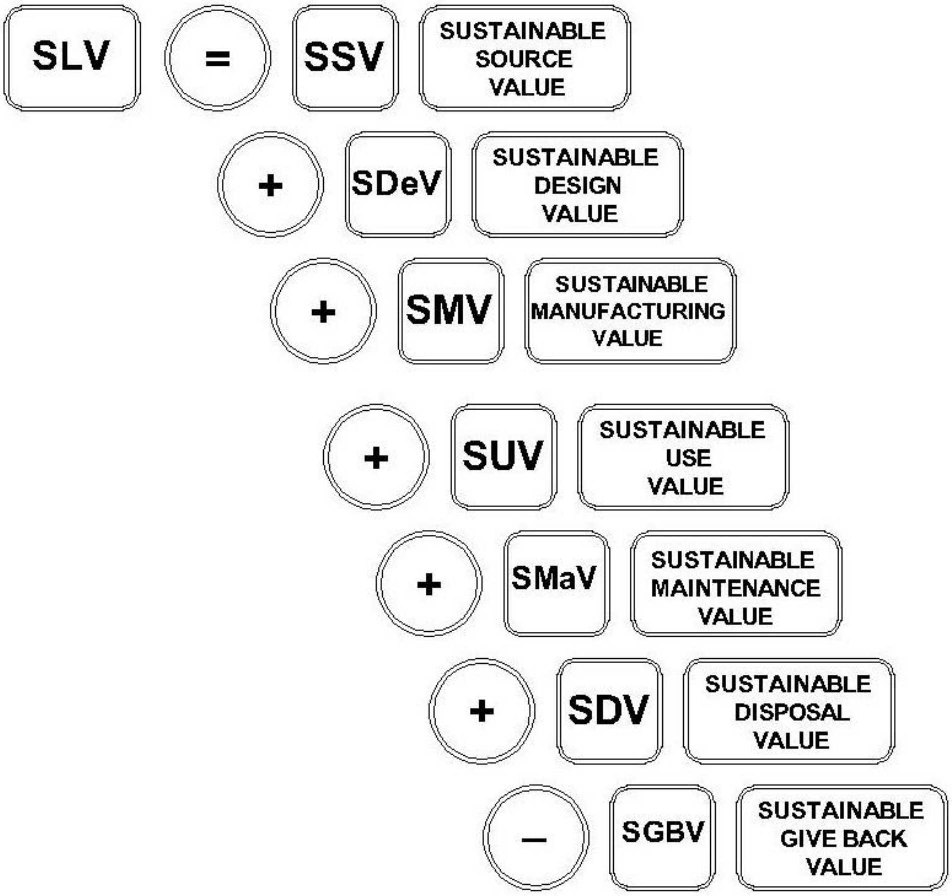


Figure 4.1: Sustainable Life Cycle Model [4.5]

4.3 Total Design Control

The entire life model shown in figure 4.1 takes the standard LCA model and adds some novel elements. SDeV is the sustainable design value and is derived by assessing the energy used by the design team during the creation of the product. SMaV is the energy required during maintenance and refurbishment and accounts for the energy input to the product to bring it to a serviceable condition. This element not only accounts for energy input but also for harvested energy. When a product is maintained and returned to service the act of maintenance avoids the procurement of a new product and therefore avoids the incumbent "Energy of Primary Source" (EPS). Since this energy is saved it can be considered as bonus energy and be used to help offset the applied energy of the original product. End of life potential (EoL) has been used by Ashby [4.11] and accrues the energy saved by recycling materials. For instance: recycling aluminium takes only 5% of the original EPS. EoL considers this as an energy saving. Sustainable Giveback Value (SGBV) is an enhancement of this process and accrues any energy that is harvested or generated by the product. For instance, energy can be harvested from the maintenance process after which the product is returned to service thus avoiding the procurement of new products and saving the new product energy. Energy can be generated by products such as a photovoltaic panel. This also can be added to the SGBV in order to offset the positive energy values against the input or negative energy values. SGBV therefore is an energy accounting device.

Any manufactured product will consume a certain amount of energy in its manufacture and this could be derived from several sources. The energy could have been derived from fossil fuels which can be considered as "synthetic energy" and will possess a "carbon footprint". Increasingly the energy used in the creation of a product will be derived from a renewable source such as hydroelectric or perhaps wind or solar energy. This then can be considered as "natural energy".

Energy is required whenever a process is applied to a material. A finished product has had expended on it certain amount of energy which is normally considered to be "Embodied Energy" Ashby [4.14]. This value of energy is a combination of synthetic energy and natural energy. The Embodied Energy Diagram in figure 4.2 indicates the likely proportions of synthetic versus natural energy within the Embodied Energy of a product. Eurostat [4.1], AEG[4.2].

Conservative estimates from Eurostat [4.1] put natural energy generation in 2012 at 22% worldwide which will grow to 40% in 2050 according to AEG [4.2]. Desmog [4.6] suggests the possibility of an ambitious 95% worldwide natural energy generation by 2050 and suggests that the technology exists but the current will is lacking. Some countries are more focused than others with grants and tax incentives for renewable power installations. These installations will gradually reduce in cost Eurostat [4.1] making renewable power installations much more attractive.

EMBODIED ENERGY	Year 2012	Year 2050	Year 2050
Synthetic	78%	60%	5%
Natural	22%	40%	95%
	Eurostat [4.1]	AEG [4.2]	Desmog [4.6]

Figure 4.2: Alternative Energy Proportions

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 seems that a value of energy per process is an appropriate measurement value. This complicated process has been much simplified by Granta

Design Ltd of Cambridge, UK who has created a sophisticated design tool which calculates the Embodied Energy at various stages of a products development. Granta [4.3]

It can be seen from the sustainable life cycle model in figure 4.1 that the overall design of a product requires whole life consideration. Furthermore the designer must not design in isolation. The designer or design team has to be in control of all aspects of the design from sourcing, design instigation through to manufacture, eventual disposal and, in some cases, marketing. This is TOTAL DESIGN CONTROL and is a view that was put forward by Chapas [4.19] where he suggested a multidisciplinary team to ensure compliance with regulatory and environmental systems. He went on further to suggest that this influence by the design team should encompass the entire life cycle. Though Luttrop et al [4.18] does not state the requirement for total design control specifically the “ten Golden rules” put forward imply that the design function should influence the entire product life cycle.

4.4 A New Design Approach (The Umbrella of Sustainable Design)

Any product which is brought to market has had energy applied to it in the form manufacturing and other processing activities. This then gives the product a value of "Embodied Energy". If the value of Embodied Energy could be reduced then so would the cost of processing. A reduction in Embodied Energy is also 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:

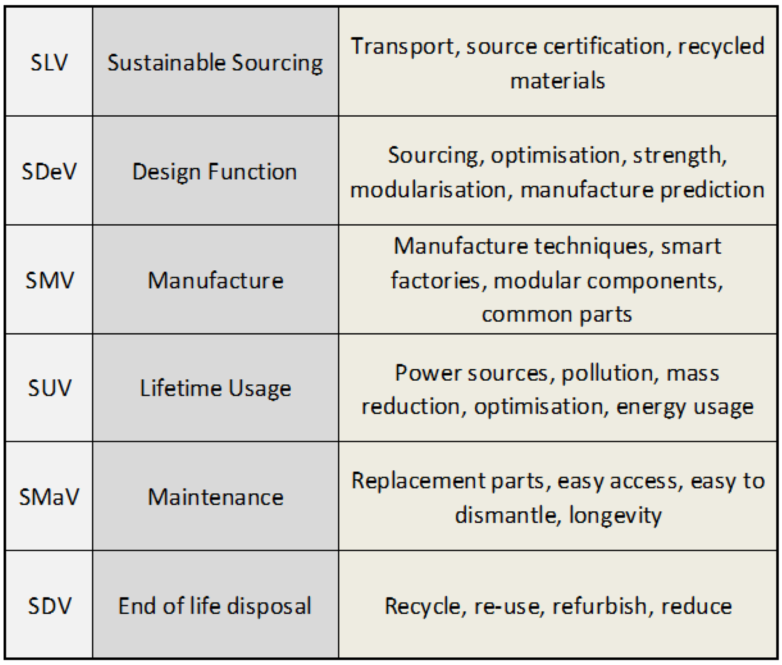
- design for low-cost product creation, and
- design for sustainable product creation

Products designed and created with sustainability as the primary objective can be generated under the umbrella model of sustainability which encompasses all the facets of design and manufacture. Design Objectives Model below in figure 4.3. The elements shown in figure 4.3 are endorsed to some extent by Skerlos [4.20] who put forward six points which relate the benefits of design influence on the sustainability value of a product. Skerlos expanded the design function into market values and developing market conscious policies. Luttrop et al [4.18] expounded the values of design on the entire life cycle. His work supports the elements of the design objectives model.

4.4.1 Design Implementation

Applied sustainable design techniques can create an efficient sustainable product. It is put forward that the use of Embodied Energy is an appropriate metric for assessing the sustainability value throughout the life cycle of a product and has previously been championed by several researchers including Ashby [4.11] , Skerlos [4.20]and Granta [4.3]. Logic suggests that if energy is being saved then costs are also being reduced. Since cost reduction is a major goal of any design work many of the Embodied Energy reduction techniques are already in place. It is suggested that the mind-set of the designer is modified from that of cost saving to that of Embodied Energy reduction so that new techniques and new approaches can be embedded in the design process. For instance rather than select materials that need to be transported long distances, the designer may choose to select local suppliers thus reducing the expended energy potential. Furthermore this designer considers energy harvesting and he may endeavour to include energy generation devices within the design. For instance a modest solar panel incorporated into every vehicle would generate energy during the lifetime of use. The following sections review design methodologies that can help to reduce the Embodied Energy input.

Consider the sustainable life cycle Model shown in figure 4.1. 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 extent by



SLV	Sustainable Sourcing	Transport, source certification, recycled materials
SDeV	Design Function	Sourcing, optimisation, strength, modularisation, manufacture prediction
SMV	Manufacture	Manufacture techniques, smart factories, modular components, common parts
SUV	Lifetime Usage	Power sources, pollution, mass reduction, optimisation, energy usage
SMaV	Maintenance	Replacement parts, easy access, easy to dismantle, longevity
SDV	End of life disposal	Recycle, re-use, refurbish, reduce

Figure 4.3: Sustainable Design Objectives Model [4.5]

The application of the Sustainable life cycle model in conjunction with the Sustainable Design Objectives Model, shown in figure 4.3, ensures that the design function controls the whole design process and in doing so includes all the design objectives, old and new, that is required of a new product. The great advantage of adopting this model is that the designer can oversee the whole process, integrating appropriate procedures and techniques throughout the life of the product.

4.4.1 Design Implementation

Raw materials need to have their source identified and in order for the designer to quantify the value of sustainability (Embodied Energy) this source identifier requires the Embodied Energy value applied to the raw material. This may seem a tall order but the process is already in place in several industries.

For example, in the aircraft manufacturing industry requires certificates of origin of materials which are sourced for consistency in strength leading to safer components. Materials from a non-certificated source may at first be suitable but may prove to be unreliable since it may not comply with material purity requirements, chemical composition requirements or strength requirements.

An excellent example of source certification is the sourcing of timber used in street furniture such as external wooden walkways, bollards, street benches and decorative elements. The best material for this purpose is iroko which will only be specified by UK local councils when there is a certificate declaring the timber is from a sustainable source. Johnson [4.5]. See also appendix A 4.1 for FSC Controlled Wood Certification policy. This approach clearly focuses retailers, importers and growers in ensuring the product is sustainable and to offer a certification of authentic sustainability.

Such an established system for other materials such as steel, rubber, plastics, etc., would help the designer to specify materials confident that they would be from sustainable source. Selecting a certificated material source would then be part of the control by the designer in selecting eco-friendly raw materials.

4.4.3 Recycled Materials

Recycled materials are gleaned from products which have come to the end of their first life and are ready to embark on their 2nd life as a new material. Energy is required to convert the recycled material into a usable raw product but this energy use is often a fraction of the energy used in obtaining the commodity from an original source.

As an example, the recycling of aluminium requires only 5% of the energy input of the original source. Ashby [4.11]. The most recycled material globally is steel which requires only 26% of the energy of primary source AISI [4.12]. Recycling creates a source of energy savings of 95% for aluminium and 74% for steel. Recycling for many materials is already the norm. Some of the more common recycled materials include; steel, rubber, glass, plastics, building materials, wood

Many products combine different materials creating difficulties in separating those materials for recycling. Knight [4.21]. It would be helpful to the end-of-life disposal engineer if material separation was a feature built-in at the design stage. This is already a feature in the passenger vehicle industry where designers aim for a recycled value of 90-95% of the materials in the vehicle. USEPA [4.22].

Such materials must be made available in a pure form with a certificate of authenticity showing the Embodied Energy value thus allowing the designer to control the sourcing of recycled raw materials thus quantifying the Sustainable Source Value (SSV)

4.4.4 Reduction of Haulage Dependence

Transportation of goods can never be eliminated but certain measures can be taken which will reduce the Embodied Energy required in that transportation. It is useful to roughly categorise materials and the reason for the transport as follows:

(a) Materials which are created near their extraction point, such as: aluminium, timber, certain foods such as coffee, tea, wine.

(b) Materials and products which are manufactured overseas and imported and could include such items as: passenger vehicles, golf bags, barbecues.

(c) Those items manufactured and then exported.

The energy used in transport will always be required whether it is generated from an artificial source or a natural source. In many cases the appropriate application of sustainable methods will reduce the dependence on artificial energy in favour of naturally generated energy.

Consider those materials in category (a) where there is no alternative but to transport the materials. The appropriate application of sustainable methods would apply natural power such as that used by sailing ships, which were a completely sustainable energy source, relying on natural wind power.

In the modern era where the convenience of diesel power overshadows many other options, natural energy usage such as that used in sailing ships, may seem implausible. There are enterprising companies which are offering systems which supplement diesel power for ships with sails and solar collectors Skysails [4.13]. Some short over-water voyages are powered completely using solar collected power. Such is the case with Eco-Marine Power who operates a ferry service across Hong Kong harbour. [4.14].

These innovative applications reduce the emphasis on carbon fuelled transport but require quantifying and certification so that Embodied Energy values are available to the designer. This system would put the designer in control by offering him the means of selecting materials with the lowest environmental impact.

Consider the imports and exports of categories (b) and (c) above. Many consumer items are manufactured overseas often because the cost is very low. Typically many consumer items are manufactured in the Far East countries such as China, Japan, South Korea, then shipped to destinations such as Europe and America. Unfortunately, this enterprise does not usually consider the environmental cost of transporting the goods. The amount of Embodied Energy used in manufacturing is about the same regardless of whether the product was manufactured in the Pacific Rim or in the West, but, Pacific Rim commodities require global transport which increases the Embodied Energy of those products.

As the tendency to use recycled commodities become more the norm, materials may be gleaned from local sources, thereby reducing transport costs and the Embodied Energy. Appropriate certification quantifies the sustainability value of a product allowing the designer to select appropriate materials and thus manage the environmental impact within his particular design project.

This method gives the designer control over material selection and creates other benefits such as the use of local materials and local labour leads to an improved local economy. Whilst it is inevitable that the goods will have to be transported, certification enables the designer to take control of the material selection element of the design thus improving the Sustainable Source Value (SSV).

4.5 The Sustainable Design Function

The design function is the only function in the entire product creation process that has a total overview of the life cycle and has the power to influence the whole process. In the past, the manufacturing function has often dominated the whole product creation process which led to inefficiencies in cost and sustainability. Corbett and Dooner [4.4] suggest that 70% to 80% of manufacturing costs are determined at the design stage. Manufacturing is only one aspect of the product creation process and should be incorporated as one of the elements in a life cycle model as indicated in figure 4.3.

4.5.1 Design Team Composition

The design function is in a unique overview position and can design-in features that actively reduce Embodied Energy and encourage energy harvesting and in doing so combine disciplines normally considered to belong to separate phases of the life cycle. Luttrop et al [4.18] hinted that there needs to be a design team of several disciplines in order to fulfil design objectives across the entire life cycle. This conclusion was echoed by Chapas [4.19] who suggested the instigation of a multidisciplinary team who could contribute to the design across the entire life cycle but also to comply with regulations, environmental systems, certification and other general management duties. Dixit and Culp et al [4.23] were mainly concerned with the built environment but recognised that facility managers routinely dealt with maintenance and replacement processes and that they should have an input to the design of the buildings at the design stage, therefore becoming part of the design team.

The design team should therefore comprise expertise from design, management, sourcing, manufacture, maintenance and material recovery to name but a few. Johnson, Gibson [4.24]The composition of a typical Total Design Control development team can be seen in figure 4.4. Such a core design team would influence the design and coordinate the six phases by applying Sustainability Principles enabling analysis of the Embodied Energy and its eventual reduction.

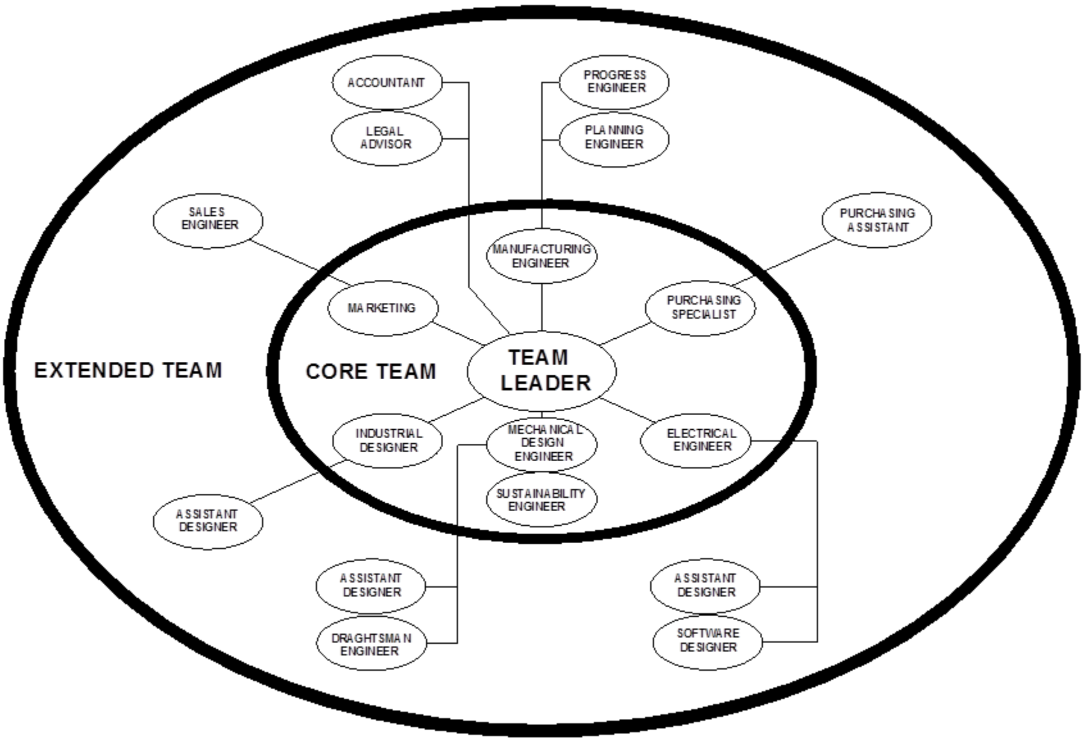


Figure 4.4: The Composition of the Product Development Team [4.24]

The composition of the product development team, shown in figure 4.4 highlights the need for multidisciplined personnel. Typically there needs to be someone to manage the project which in this case is the team leader. It should also be pointed out that even in the simplest of projects there needs to be a "Project Champion" who will provide momentum for the project and take responsibility for keeping it on schedule.

Though the model in figure 4.4 refers to personalities it is equally valid to createa design team relating to skill sets. Indeed this approach lends itself to multi-disciplinary personnel within the team. It should also be noted that the range of skills required to design products across the entire life cycle is unlikely to be possessed by a single person. Indeed, during the construction of the design team the team leader should avoid requiring team members to take on duties in which they are only partially skilled.

4.5.2 Design Constraints and Total Design Team Formation

The designer must always perform tasks under several constraints. Costs may be considered the severest of the constraints and may consist of:

- manufacturing costs
- development costs
- product support costs
- warranty costs

Other constraints may be listed as follows:

- timing and entry into the market
- product technology
- materials availability
- manufacturing technology
- volume: this dictates the method and rate of production. Small batches would be treated very differently from mass production.
- ability to develop the product
- projected life cycle
- sustainability and environmental impact

This list is driven entirely by the type of product and has to be treated as a template from which elements may be added or subtracted to suit the design.

Traditional design methods complete the design process before manufacture has begun. However, it can be seen from the above list of considerations that an essential part of the design process is manufacturing method (amongst many other elements) which has to be considered at the design stage.

The design function can be polarised as a single designer working alone so his skills and knowledge would need to span design techniques, the product, the industry and manufacturing techniques as well as design for sustainability techniques.

A multidisciplinary design team could proffer many specialist skills offering an integrated and balanced approach, considering many concepts simultaneously. The Product Development Team shown in figure 4.4 could therefore be expanded and specialized to suit a particular design and particular product. Specialists could include manufacturing staff along with marketing staff, purchasing staff, etc., but this group should also include sustainability engineers. The team can then assure product success by addressing that the following needs:

- Does the product work?
- can it be manufactured?
- it is saleable?
- it is profitable?
- it sustainable?

Since 70 to 80% of the cost is also prescribed at the design stage it can be seen that the designer has a huge responsibility and requires *Total Control* in order to fully respond to this responsibility. Some of the skills required within this multidisciplinary design team can be described by the particular tasks which are required and can be seen below.

4.5.2.1 The Value Engineer

The value engineer considers the manufacturing process, associated costs and material costs and traditionally sees the new design after it has left the design office. He may suggest modifications and improvements that would prove too costly after manufacture has already been implemented.

4.5.2.2 Manufacturing Engineer

The skills of a manufacturing engineer are very wide and varied. His role is to develop and create physical artefacts but his knowledge has to span production processes and the technology required to manipulate materials into a product. The manufacturing engineer will possess manufacturing, organisational and communication skills along with statistical and other mathematical skills and will seek out the processes that offer efficient cost and Embodied Energy savings.

4.5.2.3 Engineering Purchaser

The engineering purchaser requires a fundamental knowledge of engineering but his skills lie in negotiating prices for commodities as well sourcing components and materials with the smallest value of Embodied Energy.

4.5.2.4 Product Designer

The Product Designer's role is to combine art, science, and technology to create new products. It is the function of the product designer within the Total Design Team to create a product that is aesthetically appealing and which improves marketing potential.

4.5.2.5 Marketing

The marketing function will use surveys and analysis, establishing the requirements for the design of a product. It is not commercially viable to design and develop a product when there is no market and no perceived need. The sales function is often allied to the marketing function and is sometimes combined. Marketing personnel require some technical insight but their primary function within the design team is to advise on elements such as; market requirements, packaging, quantities and time to market.

4.5.2.6 Sustainability Engineer

This addition to the team is arguably one of the most important since the sustainability engineer will focus on the reduction of Embodied Energy as the product is being formulated and created. The task of calculating Embodied Energy will fall to this specialist and it will be his task to certificate the Embodied Energy of incoming components as well as the applying a sustainability certificate to the product as it leaves the factory. Within this role the sustainability engineer will need to network and communicate with several other members of the Total Design Control team.

4.5.3 Design Considerations

The Sustainable Design Objectives Model is shown in figure 4.3 outlines the general elements included in the design function but there are aspects of design which influence many other elements throughout the life cycle model and must be considered at the design stage. The design considerations are listed as follows:

- sourcing
- optimisation
- strength
- modularisation
- manufacture
- maintenance
- usage
- disposal

Such elements as optimisation, strength, modularisation and maintenance should be considered at during the design since they influence processes, additional uses, and expedience of disposal in later stages of the product's life.

4.5.3.1 Optimisation

In many cases design optimisation is an exercise in selecting the best compromise. For instance, there is always a compromise between adding mass and adding strength. An aircraft requires strength but it also requires low mass so aircraft designers always have to deal with compromise. Optimisation is a technique where the designer creates a product tuned for one particular purpose which ensures that Embodied Energy application is targeted for specific designs, reducing unnecessary energy application.

Optimisation tunes a product for a particular use and in so doing filters out many irrelevancies. For instance a vehicle optimised for urban use would tend to have a smaller engine than one developed for high-speed. The smaller engine would therefore suit the environment in which it was meant to function and would have minimal irrelevancies that would cost extra resources.

In tuning a product for a particular function, savings can be made throughout the life of the product and could involve savings in sourcing, manufacture, usage, maintenance and disposal. Such components would comprise bearings, lubricant, and tyres specifically to increase the longevity of the product. Optimisation therefore minimises Embodied Energy over the life cycle and contributes to the sustainable life cycle model shown in figure 4.1.

4.5.3.2 Strength

Many products require a minimum strength in order to perform their designed duty. Some devices require interior strength to avoid failure, the consequences of which could be fatal. An excellent example is an aircraft wing which requires internal strength when in use. Failure in flight would lead to fatalities.

During the design of such devices structural analysis can be performed to ensure appropriate strength is built into the structure. Modern analytical tools allow design engineers to calculate the performance of devices with high accuracy to enable reduction of material without compromising strength. Furthermore the flexibility of such analytical tools gives the designer the ability to devise more complex and stronger structural shapes, further reducing material content.

Though this section predominantly deals with strength and structures it should be remembered that there are other areas of engineering benefiting from digital analytical prediction. These include:

- dynamic analysis
- mechanisms analysis
- fluid flow analysis
- thermal analysis

A human tendency is to increase structural size "just to be on the safe side". This approach is commonly known as "rule of thumb" and increases factors of safety above those which are necessary. Mass is added which increases the strength but relieves the designer of performing precise prediction analysis. Applied correctly digital analysis allows precise prediction of performance, leading to more confidence with smaller safety factors, reduction of mass and reducing the Embodied Energy required to process the material. The design of a new vehicle may have a low mass body requiring a smaller engine and smaller brakes resulting in lower fuel consumption during its usable life; a suitably sustainable approach ably assisted by performance prediction analysis.

Reduction in mass can also be achieved by using a uniform stress technique where material (deepest cross-section) is applied where the stresses are highest.

The bridge shown in figure 4.5 is a beam supported at each end. The bending moment for this type of loading can be seen in figure 4.6. The greatest stresses are applied towards the centre of the beam so this is a non-uniformly stressed beam where stresses are higher at the centre.

Figure 4.5: Typical Fabricated Foot Bridge [4.5]

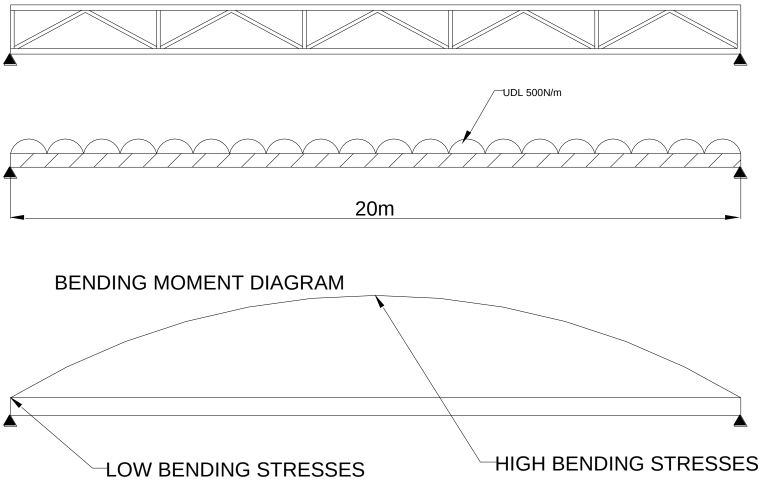


Figure 4.6: Typical Bending Moment for a Beam with a Uniformly Distributed Load [4.5]

In a uniformly stressed design the material and hence depth of section is applied according to the value of the stresses in the beam and the shape of the beam would be close to that shown in the bending moment diagram having a greater depth of section in the middle and a lower depth of section towards the support points.

This kind of technique can reduce material usage though it may marginally increase the Embodied Energy required to manufacture. Here there needs to be a trade-off between the energy saved in sourcing a lower mass of material and the increased Embodied Energy required during manufacture

Uniformly stressed beams however can be used to great effect when large quantities of items can be produced. A classic example here is that of a digger bucket arm, figure 4.7, which possesses a near uniformly stressed sectional design.

Figure 4.7: Classic Digger Bucket Arm [4.5]

The great advantage of structural analysis to define the strength needed in the structure without overdesign or including excessive material "just in case". The whole process is based on a scientific process rather than a "rule of thumb" approach which wastes material and often leads to excessive energy use in the building of the product. The analytical approach therefore offers a safe product while minimizing Embodied Energy value. This therefore contributes to the Sustainable Manufacturing Value (SMV).

4.5.3.3 Modularisation

A modular design approach subdivides the product into smaller components (modules) that can be independently created and applied so that the end result can be a variety of uses. A modular system can be characterised by the following:

- Partitioning of a product into discrete scalable, reusable modules. Each module consists of isolated, self-contained, independently functioning elements.
- Rigorous use of well-defined modular interfaces, which could include mechanical, electrical or software interfaces.

Modularisation enables a much lower level of customisation in design. Modules are often mass produced offering low cost production and a great deal of flexibility in design. It is also possible to easily add new solutions in the form of a new module. For example, a vehicle body may be produced for a luxury vehicle type but by using a different modularised engine, upgraded brake modules, paint, badges and modular interior, the vehicle can be converted into a sports version. This flexibility can be achieved without returning to the beginning of the design process.

Modular-build systems effectively standardise larger systems rather than just smaller components thus reaping cost advantages of large volume production. In a similar fashion modularisation also reduces the embodied energy in each package. If modules are mass produced, then they are more efficiently produced and therefore demand less Embodied Energy input and consequently have a lower environmental impact.

The use of modules reduces cost and allows easy maintenance due to quick replacement of modules. Refurbishment of modules is therefore possible which also prolongs the life of the main product. The use of modular construction fits well within the model of sustainability in reducing Embodied Energy and improving the Sustainable Manufacturing Value (SMV).

4.6 Design for Sustainable Manufacture

Manufacturing is often the most expensive part of the product development process. It involves the procurement of materials their manipulation and their finish to various degrees. This process usually takes place in a factory, using machine tools, labour and energy. It is the designer's role to design components and products which the factory can manufacture efficiently and must decide whether to fabricate or cast or whether to mill or turn. Corbett and Dooner [4.4] suggested that 70 to 80% of the production costs are defined at the design stage. With this in mind it is useful to list the elements which contribute to efficient manufacture and which are often automatically built into designs:

- minimise total number of parts
- develop modular design
- use standard components
- design parts to be multifunctional
- design parts for multi-use
- design parts for ease of fabrication
- avoid different fasteners
- minimise assembly directions
- maximise compliance
- minimise handling
- minimise energy input

4.6.1 Minimising the Number of Parts

A reduction in the number of parts normally leads to a reduction in handling, inventory, background paperwork, number of drawings, simpler product; etc.

Generally, a reduction in the number of parts in a product leads to a reduction in cost, a reduction of Embodied Energy, and an increase in sustainability manufacturing value (SMV) for the product.

4.6.2 Develop Modular Designs

It is useful to list some of the major energy saving elements that modular design can offer, as follows:

- design flexibility
- efficiencies of quantity production
- easier maintenance
- refurbishment possibilities
- reduction in Embodied Energy
- easy customisation using combinations of standard components
- resists obsolescence
- shortens the redesign cycle
- offers new generation products often using old modules
- changes provided with a minimum of design input
- simplifies final assembly
- reduces the number of parts to assemble

4.6.3 Multifunctional Parts

Parts which can perform several functions can often reduce the number of components. For instance, a structural member may also act as a conductor or perhaps a heat sink. Multifultional parts achieve the same benefits as reduction in the number of parts and usually leads to a valuable reduction to Embodied Energy improving the Sustainable Manufacturing Value (SMV) of the product.

4.6.4 Design Parts for Multi-use

A multiuse part is a component which can perform several functions depending on the end use of the product. A mounting plate may have several location holes, accommodating several sizes of electric motor flanges. The plate can be made in larger quantities thus reducing costs, improving manufacturing efficiency and reducing the embodied energy by avoiding large numbers of parts. The worm-wheel drive casing shown in figure 4.8. The casing is a multi-use device which can fit a range of sizes of electric motors and internal combustion engines. On the one housing is required for a multiplicity of uses and components.

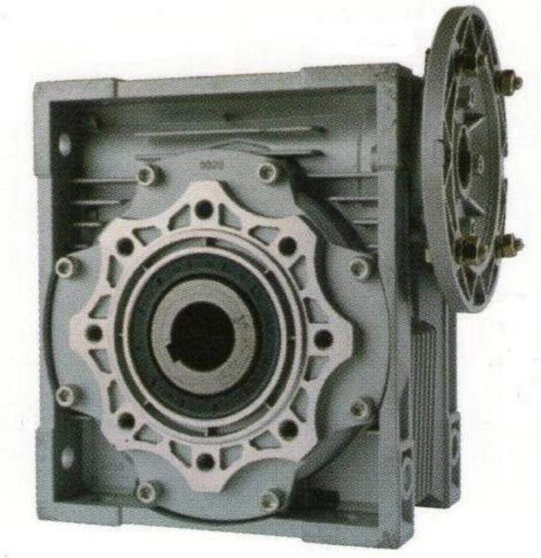


Figure 4.8: Worm-Wheel Housing Multi-Use Component [4.9]

Multi-use components offer the opportunity of reducing Embodied Energy, infrastructure costs and large numbers of varied components. This process greatly improves the Sustainable Source Value (SSV) and the Sustainable Manufacturing Value (SMV)

4.6.5 Design parts for ease of Fabrication and Assembly

A shorter time spent in fabrication and assembly will mean greater efficiencies and reduced energy input. The designer has ultimate control over the process since he selects the components and fastening methods. Consideration of the following points during the design process leads to these efficiencies:

- Reduce the number of parts
- Keep parts simple
- Apply modular components where possible
- Consider options of simpler assembly procedures
- Improve parts access (one direction assembly, space for access by hands, etc.
- Consider ergonomics for assembly personnel (fit components at reasonable heights, reasonable arms reach, etc. Will reduce worker tiredness)
- Reduce lengthy fastening processes (e.g. screws, welding, etc.)

Assembly is often a manual process and any reduction in time spent in this process will reduce energy input and costs. It will also reduce the energy spent on infrastructure (Workspace temperature), lighting, and all the other aspects required of a manufacturing plant. A reduction in such energy will improve the Sustainable Manufacturing Value (SMV).

4.6.6 Minimise Assembly Directions

Normally smaller components are attached to a base component and access by workers or automatic machines is essential for easy assembly. Minimising the steps in assembly and orienting the assembly for efficient access will lead to speeding assembly and the reduction in energy input. It is the designer's role to ensure that assembly can be completed in the most efficient way which usually involves minimising the number of parts and directions from which parts can be fitted.

This approach minimises assembly time decreasing costs reduces Embodied Energy thus improving the Sustainable Manufacturing Value (SMV)

4.6.7 Minimise Handling

Handling and moving components and assemblies to different positions or from one station to another is effectively dead time when work cannot be carried out on the product It is the designer's role to minimize this movement as much as possible by selecting procedures and methods to achieve this goal. The minimising of transport and handling has great benefits:

- reducing time moving components from one operation to another
- reducing energy
- reducing staff time on the job
- improving the speed of assembly or manufacture

With careful thought by the designer in applying the above suggestions will benefit the product by reducing its cost and reducing Embodied Energy thereby improving the Sustainable Manufacturing Value (SMV).

4.6.8 Minimise Energy Input

To minimize energy input parts should be designed that use the least costly material with the lowest Embodied Energy that "just satisfies" functional requirements. If the material more than satisfies the requirements of the duty then material and Embodied Energy is wasted. Formula One racing car engines are designed for a single race. If the engines could be used for two races then the engine is over designed and material and processing has been wasted. A Formula One engine is an extreme example of designing so that the function "just satisfies" requirements. Often designers need to build in some form of safety margin or "Factor of Safety" to compensate for various factors ranging from different operating environments to misuse by operators.

4.6.9 Example: Welding Methods

Some products are welded using spot welds but large fabrications are often continuously welded by some form of electric arc process. This process is expensive in both welder's time and electrical power. The designer should always review the welding regime and perhaps apply intermittent welds rather than continuous welds, thus reducing welding time and power input to the weld.

In many applications, however, a continuous weld is required in such places where the joint needs to be watertight or gas-tight. It is the designer's prerogative to select appropriate welds for appropriate conditions but should be mindful of the energy input and related costs.

In order to simplify fabrication time, effort and complexity, it is useful to break down the costs and energy input associated with a normal welding process. Barckhoff, Kerluke and Lynn [4.8] suggested that labour was 85% of the total cost of welding. The pie chart below, figure 4.9, shows the percentage cost of the major elements of a welding application.

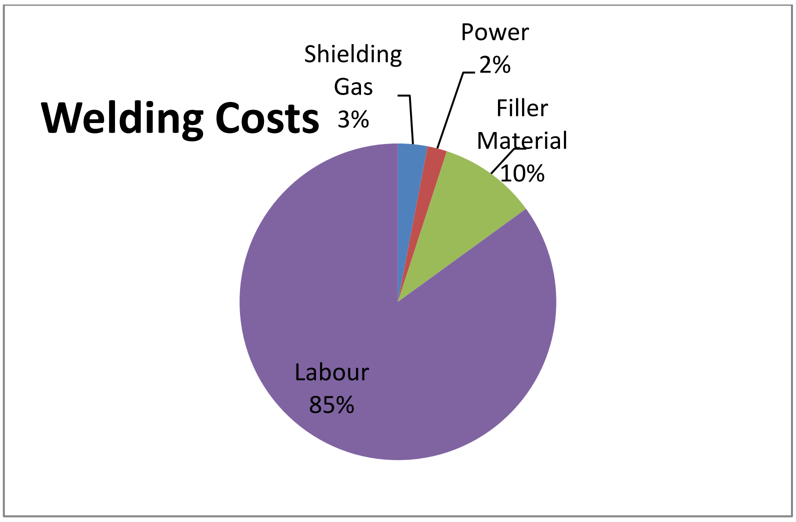


Figure 4.9: Percentage Costs of the Major Elements of a Welding Application [4.5]

Although power consumption is only 2% of the cost, power equates to Embodied Energy which should be kept to a minimum. Labour contributes 85% of the cost of the welding process a reduction in labour time would give a large cost saving, especially in factory overhead costs, and by implication a saving in applied factory energy consumption.

4.7 Design for Sustainable Product Usage

In some cases the energy required to bring a product to the market is insignificant to the environmental impact of the device in use. This is true of most vehicles and items of construction equipment. During its working life any digger similar to that in figure 4.7 will use much more energy than the energy required to create it. These devices are usually powered by diesel engines which burn fossil fuel, an "artificial energy". This artificial energy cannot be regenerated by the planet and therefore is not sustainable. If the digger could be powered by electric motors whose energy is captured from natural sources then the unsustainable energy use would be changed into a sustainable energy use thus improving the Sustainable Use Value (SUV). Wherever artificial energy is used (diesel, petrol, kerosene) there will be a large unsustainable element to the whole life view of the product.

Conversely a large flywheel system which stores energy will probably run for 10 years without stopping. The only impact on energy resources is in its inefficiencies relating to friction in the bearings. When comparing the flywheel to the digger, the digger possesses a very low Sustainable Use Value (SUV) whilst the flywheel possesses a very high SUV.

It is within the designer’s remit to select devices with the lowest environmental impact wherever possible. Of the current available technologies for providing power for the digger, the best drives are likely to be lean-burn diesel engines that use bio-fuels, which can be grown and are therefore sustainable. Biofuels still impact the environment since they emit carbon dioxide when burned in the engine.

4.7.1 Lifetime Usage or Life Cycle

Lifetime usage relates to the environmental impact and hence the energy used and pollution created during the life of the product. For some products the usage element of the life-cycle is the dominant feature of the whole Embodied Energy of the product. The case study below investigates the Embodied Energy within a rock drill, an item of construction equipment.

4.7.2 Case Study: Item of Construction Equipment; Water Well Rock Drill

Figure 4.10: Water Well Rock Drill [4.5]

The water well rock drill shown in figure 4.10 comprises many different and diverse components from steel fabrications such as chassis, fuel tanks, mast and gearboxes to bought-in components such as diesel engines, compressor, wheels, bearings, etc. Clearly the calculation of Embodied Energy within this product is complex but using "CES EduPack" [4.3] software the major components can be analysed and an overview can be formulated of the Embodied Energy applied at each stage of the whole life of the product.

It has been assumed that the rock drill has been manufactured through a fabrication process using low carbon steel. The rock drill was destined to be used in remote villages in the Himalayas and was transported via rail over 5000 miles. The engine powering the rig was 800 horsepower and the rig life was assumed to be five years. It has been assumed that most of the components can be re-used, refurbished or recycled. The full breakdown of details can be seen in the "Eco-Audit Report" in appendix A4.3.

The eco-summary for Embodied Energy is shown in figure 4.11a and 4.11b with the eco-summary for carbon footprint in figure 4.12.

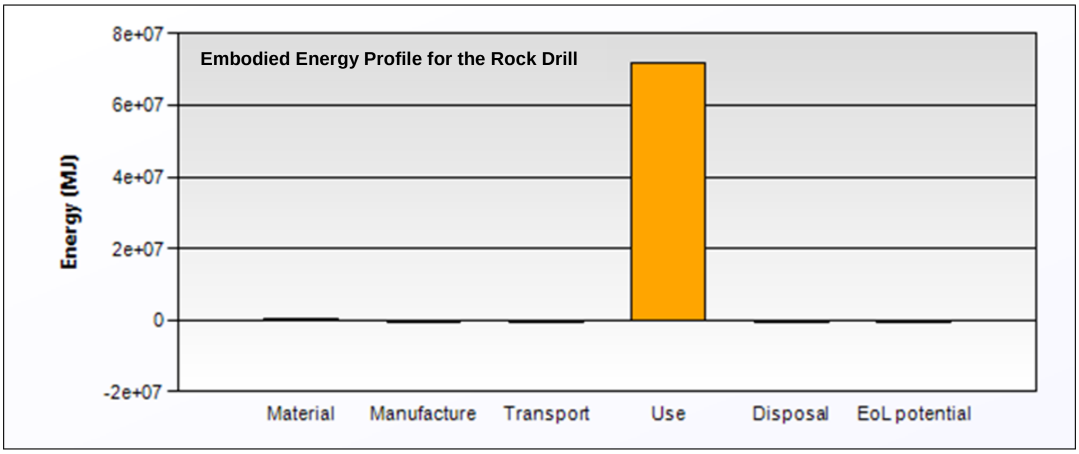


Figure 4.11a: Graphical Embodied Energy Profile for the Rock Drill

Phase	**Energy (MJ)**	**Energy (%)**	**CO2 (kg)**	**CO2 (%)**
Material	5.26e+05	0.7	3.62e+04	0.7
Manufacture	5.4e+04	0.1	4.06e+03	0.1
Transport	3.1e+04	0.0	2.2e+03	0.0
Use	7.18e+07	99.2	5.1e+06	99.2
Disposal	4e+03	0.0	280	0.0
Total (for first life)	**7.24e+07**	**100**	**5.14e+06**	**100**
End of life potential	-4.66e+05		-3.2e+04	

Figure 4.11b: Eco-Summary for Embodied Energy: Rock Drill Life-Cycle [4.3, 4.5]

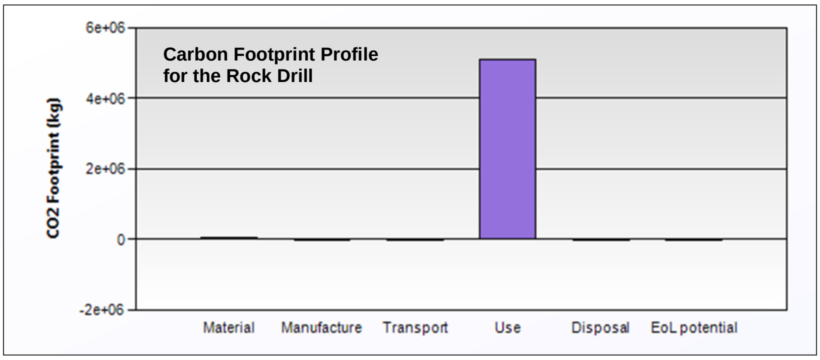


Figure 4.12: Eco-Summary for Carbon Footprint: Rock Drill Life Cycle [4.3, 4.5]

The carbon footprint and the Embodied Energy are very closely related. This close relationship is created because it is assumed that all the energy applied to the rig in extracting materials, through manufacture use and disposal is also applied by fossil fuels which can perhaps be termed artificial energy. The use of natural energy such as solar or wind power will inevitably reduce the carbon footprint but is unlikely to reduce the Embodied Energy value. If the drill rig is to function as normally used, it will still have the same value of Embodied Energy regardless of the energy source. If natural energy is used the rig function will become more sustainable and the carbon footprint will be reduced.

Both figures 4.11 and 4.12 indicate that the energy required in sourcing the materials, manufacture and transport is overshadowed by the energy used during the normal operation of the rig. If the designer is to reduce Embodied Energy he has to carefully consider the energy needed to power it and how that energy is derived.

4.7.3 Case Study: Steel Fabricated Footbridge

Figure 4.13: Steel Fabricated Footbridge [4.5]

The fabricated footbridge shown in figure 4.13 requires a large element of energy during material sourcing and manufacture. After installation, however, the footbridge is passive and requires no energy for it to function apart from occasional maintenance. The life span was expected to be approximately 50 years. An eco-audit using "CES EduPack” [4.3], software was used to determine the Embodied Energy. The results can be seen in figures 4.14 and 4.15 with a full detailed analysis in appendix A4.4. For the purpose of this exercise the material was assumed to be virgin material which could only be reused or recycled at the end of its life. Furthermore the deck was assumed to be timber from a certified source. This was also to be reused at the end of the life of the bridge.

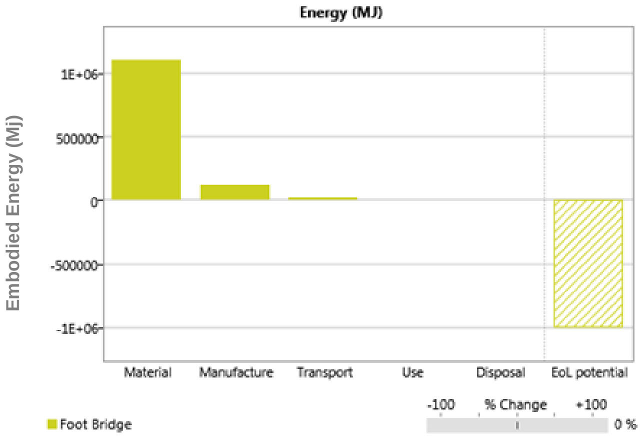


Figure 4.14: Eco-Summary for Embodied Energy: Foot Bridge Life Cycle [4.3, 4.5]

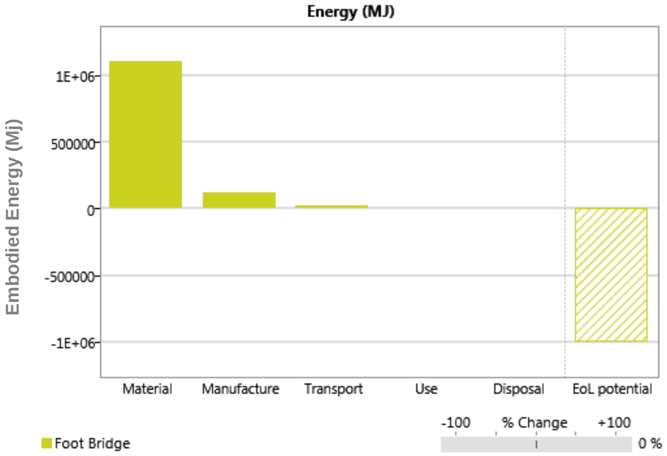


Figure 4.15: Eco-Summary for Carbon Footprint: Foot Bridge Life Cycle [4.3, 4.5]

The foot bridge requires no energy for it to function properly and therefore the Embodied Energy in its life-of-use is zero in contrast to the rock drill in figure 4.10. It is clear that the bigger part of the Embodied Energy over 1 MJ is used in obtaining the raw material with approximately 100 kJ used in manufacture. At the end of its life it was assumed that the steel and wooden components of the bridge would be reused or recycled, thus giving an enormous End of Life Potential of 1 Mj. This almost completely recaptures the energy used in sourcing material. It had previously been stated that true sustainability is almost impossible to achieve. The data displayed in Appendix A4.4 suggests that there will be a 94% end of life potential re-use of the steel components. The End of Life (EOL) component of the timber is only 6.5% but this seemingly low figure is misleading since the timber originated from a sustainable source so the EOL potential will naturally be much less. There will always be losses in a system but the bridge shown above offers a glimpse of the sustainable efficiency that could be achieved.

The "CES EduPack" [4.3] software gives the designer the opportunity to quantify the environmental impact in terms of energy expended and carbon footprint and is a useful design tool that puts the value of Embodied Energy on the product, but this is only an indicator since the software is very broad and does not cover all elements of the life cycle.

4.8 Design for Sustainable Maintenance

The designer should consider maintenance refurbishment as an essential element to improving the longevity of a product thus avoiding the procurement of new products with their incumbent embodied energy. Dixit and Culp et al [4.23] were concerned with buildings and replacement parts such as furnaces, motors, elevators, etc. and made the point that some components possess a shorter working life than the main product and that maintenance and refurbishment are an essential part of prolonging the life of the main product by removing these shorter lived components. There are excellent examples of products which have been maintained beyond what would be considered a normal lifespan.

Figure 4.16: 70cc Motorcycle [4.5]

The motorcycle shown in figure 4.16 is typical of the personal transport found in countries such as India and Pakistan. It is unknown whether these motorcycles were intentionally designed and built to sustainability values, nevertheless, they are an excellent example of a product which can be maintained almost indefinitely and therefore has excellent sustainable credibility. Maintainability of the motorcycle is achieved by having parts that can be accessed, removed and replaced with a fairly simple toolkit.

4.8.1 Maintenance: Designers Considerations: Johnson and Gibson [4.24]

When designing a product such as a motorcycle the designer needs to consider the following points:

- Life of product
- Life prediction of components and design for scheduled component replacement
- Sacrificial components, e.g. bearings, seals, etc.
- Simplicity of components and standardisation
- Accessibility for ease of removal of components
- Minimizing downtime by having dual components (redundancy) for continuous working whilst maintenance is being carried out
- Detail design for easy removal and component replacement; easy access, easy removal of fasteners e.g. cap Head screw, M12 hexagon heads external use: easy fitting, bearings, seals,
- Maintenance location: in the field or at the factory
- Modular build
- Lubrication and lubricant delivery

The sustainable approach to maintenance presupposes that there will inevitably be components which wear and which will need to be replaced. Highly used parts, such as bearings and seals will wear faster than others, and can be replaced at regular intervals. These are typical sacrificial components which protect the main product and are sacrificed in order to increase the lifespan of the main product.

4.8.2 Life of the Product

The design life refers to the period of time the product is expected by the designers to function normally. The life of the product depends on the product itself and its intended use. A short design life is illustrated by a disposable camera which has fulfilled its useful life once the roll of film has been exposed. Once the film has been extracted and converted into photographs, the casing is often re-used, re-packaged. This is an excellent example of environmental impact being reduced by recycling.

A digital camera illustrates a longer design life measured in years or decades. Design life is often related to obsolescence but many products are still working perfectly to their original design parameters long after their intended service life has expired. The user may consider these devices obsolete because it does not possess the latest technological advances.

4.8.3 Component Life Prediction

The designer must consider the lifespan of the product or at least the life expectancy of some of the components and must also appreciate that the early failure of some components when in use may lead to fatal consequences. The bearings carrying the rotors for a jet engine need a high level of reliability since their failure in flight with fatal consequences. This example shows that there has to be a compromise between frugal energy usage and that of ensuring reliability, perhaps through what may be considered as over design.

It is a useful concept to design components into a product so that their life can be predicted. This is often achieved by calculating the number of cycles, and replacing the component when its end of life is predictably close. One such component is the rolling element bearing normally rated with an L10 life. The life of rolling element bearings is defined as: "the number of revolutions at a given constant speed and load which the bearing is capable of enduring before the first sign of fatigue occurs in one of its rolling elements". SKF KC [4.25]. It should be noted that fatigue is not the only mode of failure of a bearing. The L10 life value relates to the expected survival of 90% (10% failure) of the bearings under prescribed loads and speeds cycling for 1 million revolutions. Statistically bearing companies expect a median life approximately 5 times the calculated basic L10 life.

The designer can relate the load and speed applied to a bearing enabling the calculation of the expected life through a number of cycles, thus predicting the life expectancy of a particular bearing and suggesting a maintenance/removal regime. Johnson & Gibson [4.24]. Life prediction is an essential part of the designer's remit since this guidance maintenance processes and removal of sacrificial parts that protect the main product. The fundamental view is that some parts may have a shorter life than others, especially high-use parts that can be sacrificed to ensure longevity of the main product. Kerley et al [4.28] was concerned with the reliability of aircraft jet engines and proposed the early removal of sacrificial components. Reliability centred maintenance (RCM) and the life prediction of components was put forward by Steven [4.27]. Rahimi [4.29] proposed removal of sacrificial components on routine maintenance missions to sub-sea equipment. Both Kerley and Rahimi were dealing with difficult to access products and their main concern was reliability, but this approach can be taken with most products. If a maintenance programme is applied then it can be kept in service, thus avoiding the use of procuring new equipment and hence avoiding the need to expend unnecessary Embodied Energy.

4.8.4 Simplicity of Components and Standardisation

Simple components are normally low-cost and require low energy to manufacture since component simplicity generally requires lower energy manufacturing techniques. They should also be easy to fit with a hole to locate component and fixing by a snap fitting. A replacement vehicle headlight bulb simply plugs into the headlamp socket which normally then fits into the headlamp receiving hole from behind the headlight housing, requiring only a quarter turn to fix it in place. The unit is located and fixed in one simple movement.

There are many standard components which can be purchased from most engineering stockists and include, bearings, seals, screws, rivets, nuts, pins, bearings, seals, etc. It is normally good practice to replace these low-cost, low energy items whenever maintenance is carried out.

4.8.5 Accessibility for Ease of Removal of Components

During the design process, the designer must consider the assembly procedure as well as the disassembly procedure for both production and future maintenance. The design of the device should provide adequate physical access to accommodate tools, extraction devices, and space to rotate spanners, sockets and screwdrivers. Components requiring regular replacement should be located to the outside of the product allowing easier access. Measures such as those indicated would reduce maintenance time and hence reduce energy overhead as well as cost.

4.8.6 Detail Design for Quick and Easy Maintenance

Component design requires the easy access for tools and extractors. For instance a shoulder may be provided for a bearing to locate against but the design requires that there is access for a drift to be inserted to knock out the bearing as shown in figure 4.17 which shows that there is access for the drift to knock the bearing out of the housing. The same method can be applied to other replaceable components such as seals.

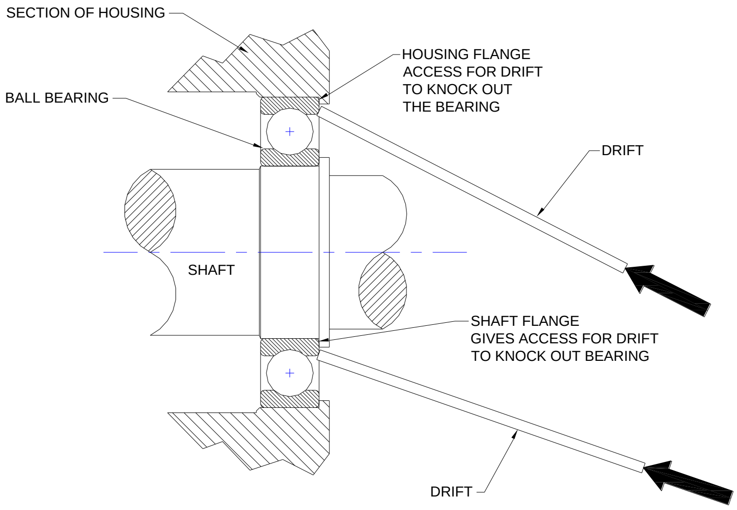


Figure 4.17: Provision for Removal of Bearings from a Bearing Housing and Shaft [4.24]

In considering easy and quick maintenance the designer should consider procedures such as that shown in figure 4.17. Such practices leads to shorter maintenance periods leading to lower energy usage in terms of factory overhead and power applied through powered tools.

4.8.7 Maintenance Location

The location of the normal maintenance practice has an enormous effect on the design and selection of components. If the maintenance can be done in comfortable surroundings of a workshop where there are available tools and a temperature controlled and clean work environment, then maintenance is fairly straightforward. Maintenance in the field is quite a different matter and the design approach needs to reflect that the maintenance engineer is likely to have just a set of hand tools and be without the facilities of a workshop.

Maintenance in the field could be in a quarry or in a mountainous region hundreds of miles from the nearest workshop. In such situations access to power tools may be limited and, depending on the process, might prove to be dirty and uncomfortable. A dirty environment is also the enemy of clean assembly and may cause premature wear. It is particularly important for hydraulic assembly to take place in a clean environment since small dirt particles could create premature wear insensitive components. Design practice should create products that promote quick, easy and clean maintenance thus reducing downtime, and reducing energy input.

4.8.8 Case Study of a Water Well Rock Drill

A water well rock drill was designed to operate independently in the bush in Africa and was designed for maintenance in the field. One particular component on the rig which had the most arduous use was the rotation gearbox which is highlighted in the schematic of the drill rig in figure 4.18.

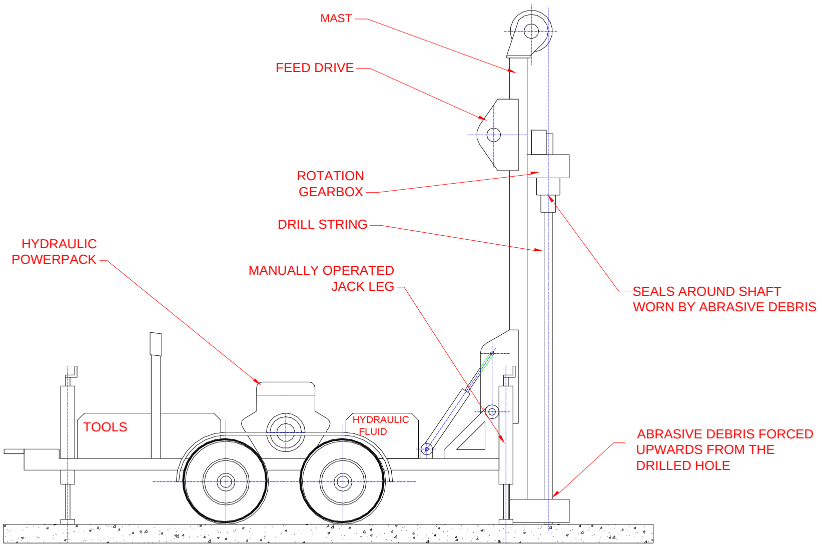


Figure 4.18: Trailer Mounted Water Well Rock Drill Used in Remote Areas [4.5]

The drilling operation forces highly abrasive dust to the surface hitting the underside of the gearbox. Seals in this location operate under extreme wear conditions. Inevitably oil escapes through the seal and forms a paste with the abrasive debris which tends to wear a substantial groove in the shaft under the seal. Under normal circumstances the shaft would be removed from the gearbox and the seal/shaft contact surface would be renewed by a deposition process. The shaft could then be replaced in the gearbox. Maintenance in the field is impossible under the circumstances and so during the design process a solution was found by the introduction of a "cassette seal", a cross-section of which can be seen in figure 4.19.

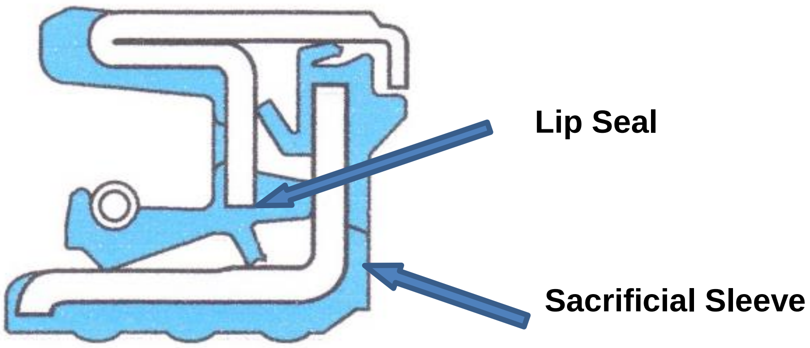


Figure 4.19: Example of Cassette Seal Showing Sacrificial Sleeve [4.10]

The seal provides a sacrificial sleeve on which the lip seal rides which means that the sacrificial sleeve wears rather than the shaft. Maintenance is now possible in the field since a new cassette seal can be fitted. Downtime in the field is now measured in hours rather than weeks and input energy is reduced as are maintenance costs.

4.8.9 Modular Build

For maintenance purposes the replacement of a module is quick and easy, the biggest advantage being that downtime is minimised and energy input is reduced.

4.8.10 Lubrication and Lubricant Delivery

Lubrication is often the last thing considered in any design but it should be a treated like any other major component. This addition to the list of parts, extends the life of the component many times thus improving the longevity and the value of sustainability.

4.8.11 Engineering Plastics

Engineering plastics are group of plastic materials that exhibit superior mechanical and thermal properties in a wide range of environmental conditions. These materials can be manufactured to suit a particular application and are excellent when encountering conditions in which rolling element bearings or other stationery bearings are unsuitable. Such conditions are listed below:

- low speed
- high load
- wet or submerged conditions
- dry conditions
- impossible to lubricate conditions
- oscillating shafts
- linear bearings
- high wear situations
- self-lubricating situations

The use of plastic bearings can sometimes be considered as “fit and forget” since properties allow them to function sometimes with little wear even in very arduous conditions. In many instances they are self-lubricating avoiding the use of lubricants and lubricant delivery systems. In this way plastic bearings offer extended product life and in some cases extended periods between maintenance processes thus reducing energy input

4.9 Design for Sustainable End of Life Disposal

Every product will eventually come to the end of its life. This may be due to a number of factors:

- Overtaken by technology
- Reduced popularity in the market
- Worn but failure imminent
- Worn beyond usefulness
- Functioning at less than full capacity
- Broken, beyond repair

It is the role of the designer to recognise these modes of failure and design into the product easy, low-cost and low energy methods of disposal. Sustainable thinking at the design stage will greatly reduce the Embodied Energy and cost in the disposal process.

The general approach to end of life disposal is by using the 4R approach:

- Reduce
- Re-Use
- Refurbish
- Recycle

These are almost universally accepted methods of disposal at the end of life of a product but when cross referenced to the end of life failure modes the designer may see some clarity in design approach methods. A chart cross-referencing failure modes to end of life disposal methods can be seen in figure 4.20.

	Reduce	Re-use	Refurbish	Recycle
Overtaken by technology		#	#	#
Reduced popularity		#	#	#
Worn but still functions		#	#	
Worn beyond usefulness		#		#
Low function capacity			#	#
Broken beyond repair				#

Figure 4.20: Failure Modes and Disposal Methods [4.5]

4.9.1 Reduce

In the context of end of life solutions "reduce" merely means consign as little as possible to land-fill. It also means that the remaining three options of re-use, refurbish and recycle should be applied as much as possible so that in theory 100% of a product is re-applied in some way with nothing being just "thrown away". The application of "reduce" can be more usefully employed during the design stage. An example of reduction, previously discussed, was the decrease in vehicle body metal thickness which reduced the mass of a vehicle. Such a reduction in mass would reduce consumption of earth’s resources and also improve the Sustainable Use Value (SUV) since less mass equates to less energy used to move the vehicle.

Reduction at the design stage also means "do not over design". Over design generally means more weight, more parts and more energy required to process the material into a component. Careful analytical work can be employed here so that the only material applied to a product is that which is needed.

4.9.2 Re-use/Refurbish

The re-use of articles applies to those products which are still functioning retain some useful life, which can be considered as residual Embodied Energy. Computer manufacturers have managed to reuse many computer base parts through modular construction. When new functions are required the computer is merely fitted with new modules but the base parts are reused.

Design for dismantling should become a feature of the design process enabling not only maintenance but also end of life disposal. Dismantled parts may be reused, refurbished or as a last resort, eventually recycled. This process avoids the procurement of new components saving incumbent Embodied Energy and also ensuring that any residual Embodied Energy is exhausted.

Industry relies on equipment functioning efficiently but as the equipment becomes worn and less efficient, refurbishment is often preferred rather than more expensive replacement. A piece of refurbished industrial equipment can be returned to full use and near 100% efficiency for a fraction of the cost of a new device and an enormous reduction in energy incumbent in a new product.

In line with the thinking of Stahel [4.7] of the Product Life Institute in Geneva,

"It is our contention that legislation, lobby pressure and tax-based initiatives will drive resurgence in equipment designed for ease of refurbishment and re-use, and that forward thinking producers will use a positive marketing message similar to campaigns such as “Fair Trade” will begin to place a premium on sustainably designed products."

Stahel [4.7] explores how moving from disposable products to service, refurbishment and repair delivery could lead to restructuring of a post-industrial economy into a performance economy. Stahel goes on to project a scenario where energy use would be partly substituted by skilled labour, as repaired products and recycled materials would create substitutes for primary material. Activities which are labour- rather than capital-intensive are less subject to the economies of scale which characterise the chemical and material industries. Thus Stahel's concept of the performance economy also embraces enhancement of a local economy and introduces a chain of end-of-life actions which the designer should now consider when designing a new product. The flow diagram, figure 4.21, indicates each level of the hierarchy.

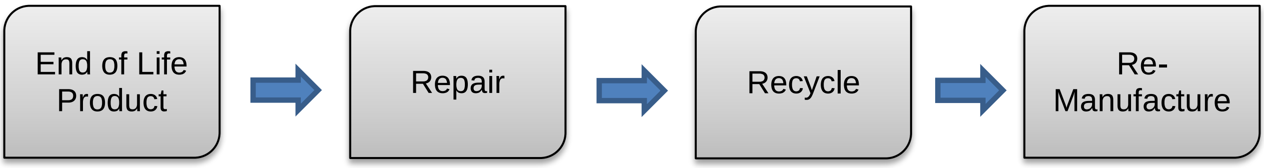


Figure 4.21: Flow Diagram of End-of-Life Actions [4.5]

The Stahel [4.7] concept, though excellent, is not detailed enough to be applied practically. Consideration needs to be made as to the type of product, material and its value. Though sustainability has to be in the forefront of the designer's mind, cost and refurbishment of low value items may be commercially unviable.

Some components such as bearings and seals are sacrificial. They are in place to protect the high value components such as shafts, and upon maintenance or refurbishment these particular components should be removed and replaced with new versions. The fate of the old components should be recycling where the material and component type need to be considered before disposal decisions are made. An enhancement of the flow of end of life actions in figure 4.21 can now be revised into the hierarchy shown in figure 4.22.

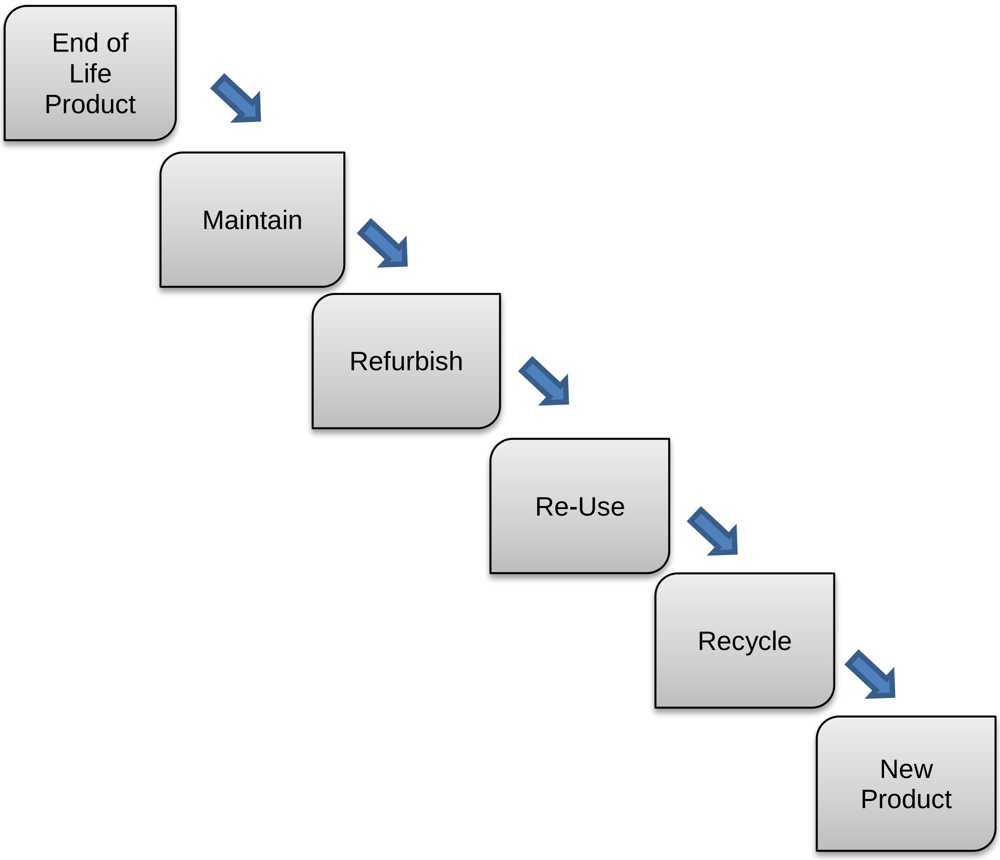


Figure 4.22: Model for End of Life Hierarchy of Decision Actions [4.5]

The responsible designer should therefore consider each component in the design and each level of the hierarchy. In order to plan the correct route of disposal the designer has to make decisions relating to the components included in the design. This is complicated since each component is individual and may function well even partly worn. It is therefore necessary to consider the component, the material, the function of the component, and its value.

As an example, a decision chart has therefore been devised for major components of the brick and block clamp shown in figure 4.23 and a schematic of the clamp figure 4.24, illustrating the location of the major components.

Figure 4.23: Brick and Block Clamp (Typical) [4.15]

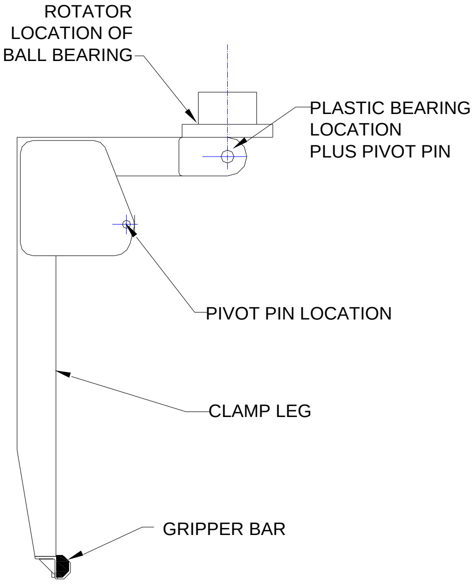
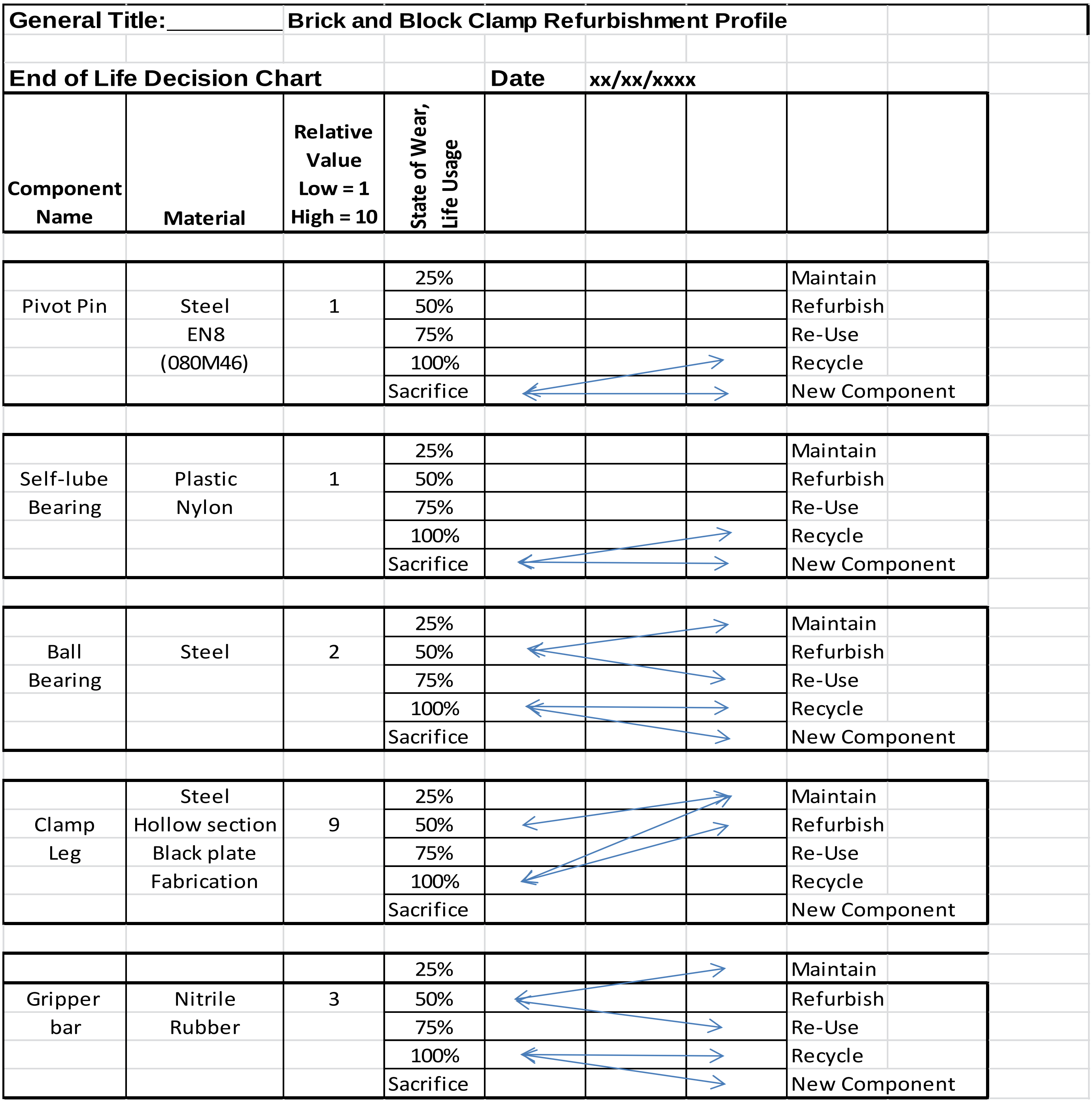


Figure 4.24 Schematic of the Brick and Block Clamp [4.5]



General Title:__________ Brick and Block Clamp Refurbishment Profile

End of Life Decision Chart **Date** **xx/xx/xxxx**

Component Name	Material	Relative Value Low = 1 High = 10	State of Wear, Life Usage				
Pivot Pin	Steel EN8 (080M46)	1	25%				Maintain
			50%				Refurbish
			75%				Re-Use
			100%				Recycle
			Sacrifice				New Component
Self-lube Bearing	Plastic Nylon	1	25%				Maintain
			50%				Refurbish
			75%				Re-Use
			100%				Recycle
			Sacrifice				New Component
Ball Bearing	Steel	2	25%				Maintain
			50%				Refurbish
			75%				Re-Use
			100%				Recycle
			Sacrifice				New Component
Clamp Leg	Steel Hollow section Black plate Fabrication	9	25%				Maintain
			50%				Refurbish
			75%				Re-Use
			100%				Recycle
			Sacrifice				New Component
Gripper bar	Nitrile Rubber	3	25%				Maintain
			50%				Refurbish
			75%				Re-Use
			100%				Recycle
			Sacrifice				New Component

Figure 4.25: End of Life Decision Chart [4.24]

The chart shown in figure 4.25 has several functions. It shows the design decisions and indicates to the designer how various components may be disposed of at the end of their life. A design when complete should have a technical specification file where all relevant documentation, analysis, parts, etc., are kept. This is required throughout Europe in order to verify a CE mark. The decision chart should also be kept in this file to provide information to the refurbishment team to help with disposal of each component.

By way of example, the end of life strategy is discussed below for several components.

4.9.2.1 Pivot Pin

Pivot pins provide hinge points but they are also a high load item and upon refurbishment the designer has selected to sacrifice the pin and replace it with a new component. The pin should be recycled.

4.9.2.2 *Self-Lube Plastic Bearing*

Engineering plastics are a major sacrificial element and are designed to be easily removed and replaced whilst the old bearings are recycled.

4.9.2.3 Ball Bearing

This is a major component which is housed in the rotator. Whilst more expensive than the plastic bearing, consequences of its failure is that the clamp cannot be operated. The designer has decided in this case that with 50% of its life still remaining, it will be maintained and reused. If it is deemed that the bearing has served its life, then it should be removed and replaced and the original bearing should be recycled.

4.9.2.4 Clamp Leg

This is a high-value item which should not be discarded. At 50% of its design life the designer has suggested that it should be maintained and at 100% of its supposed life, he has specified refurbishment and reuse. At some point the clamp may be bent out of shape through misuse. In this case refurbishment may not be possible and new parts may need to be manufactured. The old component will then be recycled.

4.9.2.5 Gripper Bar

The gripper bar is made from rubber and is the contact between the clamp and the brick product. It is a sacrificial part of the clamp but on refurbishment the designer has suggested that if it is only 50% worn, then it may be reused. At 100% worn, the sacrificial rubber gripper should be removed and replaced with a new component. The old component will then be recycled.

4.9.3 Recycle

When a piece of equipment or system is worn beyond usefulness or repair then the only option is to recycle the individual components. Eventually all components and products will end their useful life. The designers aim is to provide the wherewithal to separate and recycle all the different components and materials.

Inevitably components which are to be reused or recycled will need to be separated into their unique materials which is often the most difficult part of the recycling process. Glass cullet is often made up of multiple colours such as green, brown, blue and clear glass. Glass recycling agencies find difficulty in the separation of colours.

There are multiple different types of plastic such as; polypropylene, polyethylene acrylic, polycarbonate, polyurethane, etc. There is great difficulty in identifying and separating the different plastics when they all look very similar and there is no efficient detection method.

It is the role of the designer to solve these dilemmas. This can be done on several levels.

- Parts separation can be made simple
- Identification code may be stamped, cast or moulded into the component
- An Inventory of materials may be compiled for a particular product

If the end of life disposal is conducted efficiently, very little of any product should be discarded in land fill. The re-use of materials is not only cheaper than obtaining newly hewn raw materials but also requires much less energy and is therefore a very sustainable practice. The designer has the opportunity to plan for end of life disposal and doing so improves the Sustainable Life Value (SLV) of the product.

4.10 Conclusions to the Sustainable Design Function

The designer is in a unique position. It is he alone who can influence the whole life of a product simply by designing elements into the product which enhance certain outcomes. Luttrop [4.18], Chapas [4.19], Skerlos [4.20, Knight [4.21]. Sustainable design requires that the product is steered and focused towards low Embodied Energy input during its life cycle. Granta [4.3], Ashby 4.11]. The design function can also design-in elements to aid maintenance, increasing the longevity of the product and avoiding the procurement of new products. Kerley [4.28], Rahimi[4.29]. Design for end of life of a product is also within the responsibility spectrum of the design function where careful design aids individual material separation and material diagnosis. Knight [4.21]

Since products were first traded there has always been two major goals of design:
1. Low cost product creation
2. Human condition improvement

The third goal is now:
3. Reduce environmental impact (design for sustainably)

This is the embodiment of the Triple Bottom Line approach championed amongst others by Hacking [4.31] and Ness [4.30].

This Chapter reviews the design and manufacture process and puts it in to context when compared to the Current view of Life Cycle Analysis. Novel additional elements are proposed which include: Sustainable Design Value, Sustainable Maintenance Value and Sustainable Give-back Value, the latter being an accounting value that helps to offset Embodied Energy (energy input). These additional elements are the first steps in developing a sustainability measurement model that can assist in realising the third goal of the Triple Bottom Line “ Reduced Environmental Impact”

The designer needs to approach the design of new products with the focus of applying sustainable engineering design techniques. Many of these techniques are already in use in order to reduce cost but their use as a sustainability tool is a new approach where careful application can reduce Embodied Energy by extracting the residual life from part used components or by directing them towards recycling when economic concerns render a component unviable to reuse. The application of maintenance is expanded so that substantial energy savings through product/component reuse can be made. Much use is made of the proposals of Stahel [4.7]. These insights into maintenance have been expanded to form a much more detailed strategy.

The sustainable life cycle model presented in figure 4.1, shows that the design function can influence and thereby improve the Sustainable Life Value (SLV) of all the elements of this model since this is the total additive element of the entire life cycle and can be used to define the sustainability value of a product. This information and data, gathered from the SLV process can be fed into the elements of the Triple Bottom Line to influence decisions made at company, regional, national and global levels.

CHAPTER 5
THE MEASUREMENT OF SUSTAINABILITY

5.0 The Measurement of Sustainability

5.1 Measurement Overview

Many researchers use different parameters to measure “sustainability” or what might be termed “environmental impact”. It is true, however, that engineers and researchers will use the most convenient parameter to determine or measure the impact of the products they design. For instance the refurbishment of catalytic converters may use carbon monoxide output as a measure of the efficiency of remanufacture. A climate change specialist may use ozone depletion as an appropriate measure for their work.

Pollution is an environmental spectre that has been a concern for many decades, yet it is only in recent decades that specific information relating to the effect of pollutants has been available. Much of the emphasis has been towards greenhouse gases which often are the focus and measurement parameter for environmental work often relating to atmospheric and biospheric conditions.

5.2 Greenhouse Gases

Greenhouse gases are those gaseous constituents of the atmosphere both natural and anthropogenic that absorb and emit radiation of specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere and by clouds. This property causes the "greenhouse effect" which allows sunlight to pass through but absorbs heat radiated back from the Earth's surface, thus increasing global atmospheric temperatures. Water vapour, carbon dioxide, nitrous oxide, methane and ozone are the primary greenhouse gases in the Earth's atmosphere. There are also a number of entirely human-made greenhouse gases such as the halocarbons and other substances such as sulphur hexafluoride (SF), hydrofluorocarbons (HFC) and perfluorocarbons (PFC). Baede 5.15]

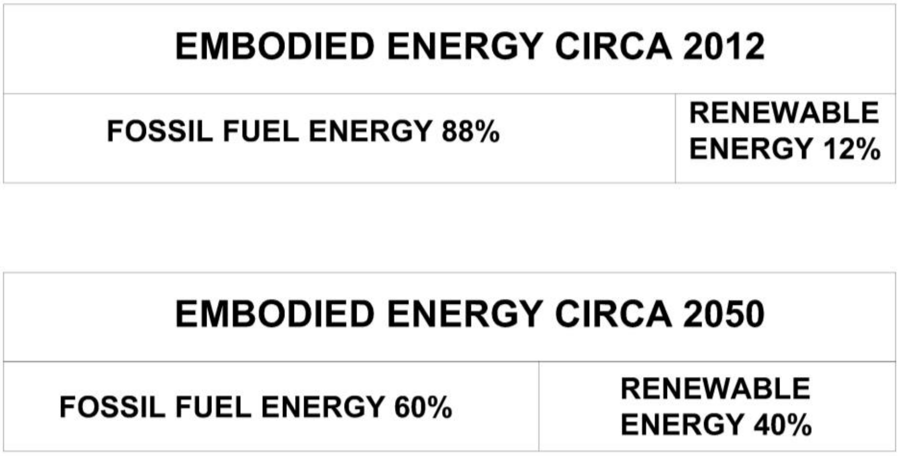
Carbon dioxide is often painted as the ogre of greenhouse gases, but it is not the largest constituent. According to Science Daily [5.8], proportions of the main greenhouse gases are as follows:

Water vapour	36-70%
Carbon Dioxide	9-26%
Methane	4-9%
Ozone	3-7%

It can be seen that water vapour is the biggest greenhouse gas yet the common assumption is that it is harmless. As a liquid, water is life-giving but as moisture in the atmosphere it prevents sunlight from reaching the earth and also acts as a blanket, keeping heat within the envelope of clouds.

Though carbon dioxide certainly contributes a large proportion of greenhouse gases, Science Daily [5.8], it is necessary to question why it has become an environmental yardstick. The focus on carbon dioxide cannot be considered wrong since it is a useful tool, but it does not really cover the whole picture. The use of carbon dioxide as a means of measurement assumes that most of the energy expended is derived from fossil fuels. In reality the growth of renewable energy and its increasing use is incrementally replacing the use of fossil fuels as figure 5.1 shows.

This view is further enhanced by the introduction of mobile power plants such as those used in electric vehicles and hydrogen powered vehicles. It is predicted, Eurostat [5.13] that the use of fossil fuels will slowly diminish until eventually the favoured energy source for prime movers will probably be electric. The idealistic view is that the power for such motion generators will be eventually derived from natural sources though, as indicated by figure 5.1, the reality may lie in the future. Eurostat [5.13], AEG [5.10].



EMBODIED ENERGY CIRCA 2012	
FOSSIL FUEL ENERGY 88%	RENEWABLE ENERGY 12%

EMBODIED ENERGY CIRCA 2050	
FOSSIL FUEL ENERGY 60%	RENEWABLE ENERGY 40%

Figure 5.1: Embodied Energy Proportion [5.13, 5.10]

Several approaches to the measurement of sustainability have emerged. Ameta [5.29] suggested that a framework of Triple Bottom Line (TBL) linked with Life Cycle Analysis was an appropriate platform on which to base measurements. He concluded that indices are useful for complex systems especially of a more global perspective but warns that indices can become diluted through aggregation and various modifications. Datschefski [5.31] proposed product sustainability should be measured using recyclability, safety, efficiency use of renewable energy and social effects, though this was for a very specific case study. Ameta [5.29] suggested that the use of indices was complex and would give a confused picture if applied at the product level. Energy Star [5.30] is a US Environmental Protection Agency (EPA) program which uses energy efficiency as it's metric and suggests that energy as an environmental measurement device can be used across all sectors including service industries and manufacturing and production industries though Energy Star focuses on promoting energy efficient products and services in use.

Mayyas [5.32] relates the LCA approach to the automotive industry and includes design and materials selection as important parameters in the product creation process. He goes on to suggest that an "environmental impact energy efficiency" rating should be applied to the life cycle including manufacture, packaging recycling and operational durability. Mayyas treats operational durability as a minor element it is significant that this is linked to longer life components. Mayyas does not refer to maintenance as an element but this research project uses maintenance as a key element to increase the longevity of products.

Yohanis [5.33] deals with civil engineering design and suggests that designers need practical measurement parameters which should be applied to early design models. In this study the measurement parameter is quickly converted to cost, from detailed measurements of operational energy and Embodied Energy. His publication goes some way to building an Embodied Energy profile through an LCA approach, but does not consider maintenance of the building or end of life disposal.

The review of measurement techniques and the literature survey examines several publications that propose various measurements methods. The view echoed by many researchers is that the complex nature of sustainability assessment requires ever more complex measurement methods in the expansion from detailed product measurement through urban, national to global assessment. This view is supported by Choida [5.34] and supported by Pope [5.35] and Ness [5.36] who both advocate using Embodied Energy at the product level and Moles [5.37] and Mohannad [5.38] who both champion the use of indices as the measurement requirement expands into a more global application. Even though there are complications and problems, indices are considered to be a viable assessment method. Figure 5.2 below indicates the nature of the measurement/assessment and indicates how the measurement of sustainability requires broader measurement devices in terms of indices as the sustainability focus expands towards a more global view. Figure 5.2 also indicates that detailed measurements at product level require more precise measurement systems.

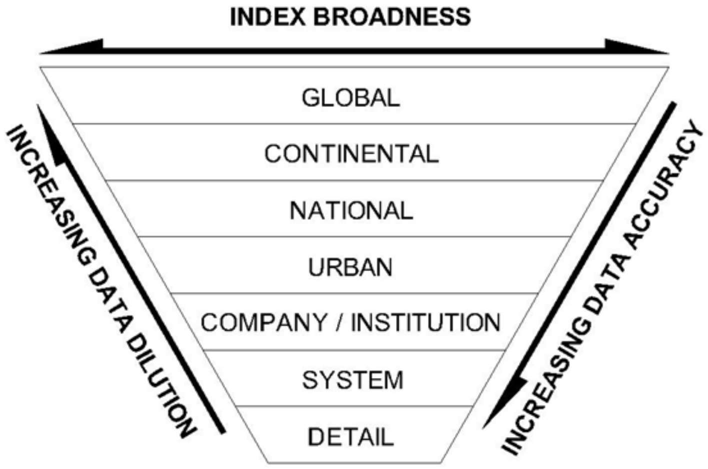


Figure 5.2: The Nature of the Sustainability Measurement/Assessment Profile

5.3 Energy as a Measurement Parameter

When reviewing sustainable design measurement options it is clear that measurement at the product level requires a precise measurement device. The conversion of materials into products uses energy in every element of the life cycle. Paxti and Hernandez [5.39] support this view in their use of an Embedded Energy accounting strategy in the procurement of building materials. One of the by-products of the energy usage is carbon dioxide, which is used as a metric by some researchers; however energy usage itself is a much clearer and convenient indicator of resource usage, Pope [5.35] and is an accurate indicator of the environmental impact, Yohanis [5.33]. Furthermore energy as a measurement device can be used across most sectors and most industries, Energy Star [5.30].

During a product’s life cycle energy is required to extract raw materials, convert them in to products, power them during their useful life, and dispose of them at the end of their life. It is therefore proposed that each step of the sourcing-conversion-use-disposal process is given a *Sustainability Value* measured in terms of energy (Mj). These values can now be assembled into a tool with which designers and environmentalists can judge the sustainable impact of a product. The definitions are listed below:

SDV: Sustainable Disposal Value: represents the energy used in the eventual disposal of the product.

SDeV: Sustainable Design Value: represents the energy used during the design process

SGBV: Sustainable Giveback Value: is a measure of how much resource is returned. This accounts for energy harvested during the product’s life cycle and is a novel addition to the energy accountancy aspects of LCA.

SLV: Sustainable Life Value: derived from the addition of SSV, SMV, SUV, SMaV and SDV and is a measure of the environmental resource impact during the life of a product.

SMV: Sustainable Manufacturing Value: represents the energy required to manufacture the product

SMaV: Sustainable maintenance value: represents the energy required to maintain the product. This value is likely to be very low relative to other values such as the SUV and can be deducted from the resource impact (Sustainable Life Value: SLV) as the model shows in figure 5.3. This is a novel introduction into the common composition of LCA

SSV: Sustainable Source Value: represents the embodied energy required in creating the raw material for manufacture.

SUV: Sustainable Usage Value: represents the energy required during the useful life of the product.

The approach of Mohannad [5.38] goes some way to support the Sustainable Life Value tool since he proposes an index (PROD SI) which uses LCA and information from detailed metrics. The index is intended to operate on an environmental, social and economic level but proposes the use of energy at the product level as a measurement device. The net Embodied Energy provided by the SLV model is intended to be a product level detailed measurement and would provide appropriate information to feed into Mohannad's (PRODSI) index.

Case studies in section 5.8 show how these SLV values can be collated into a single Sustainable Life Value (SLV). These indicator values should be kept as low as possible since the lower the value, the lower the impact on the earth's resources. Maintenance is a novel introduction into sustainability discussions even though it is normal practice to maintain products to extend their life so the increased longevity avoids the procurement of new product. Dixit and Culp [5.40] are part of a rare group of researchers who apply LCA to buildings and include maintenance and replacement components, acknowledging that some components will have a shorter useful life than the main product. They advocate the use of Embodied Energy as a measurement device and suggest that maintenance may be used to increase the longevity of the building. This view entirely supports the approach by this research project which is advocating maintenance and refurbishment in mechanical engineering products as a means to increasing longevity and improving product sustainability.

Sustainable Giveback Value (SGBV) is a novel introduction and is a value of energy that can be harvested from a product during its life. SGBV is an energy accounting value and can therefore be used to offset the Embodied Energy values which are applied to the product especially during the product creation phase.

The SLV model has been formulated with several metric requirements in place as put forward by Subhas and Sikhdar [5.41] and are listed below.

1. select sustainability parameters with system boundary
2. indicators or metrics selection; must be quantifiable
3. prioritise indicators and metrics for precision and quality
4. conduct an analysis that provides quantified data
5. use methodologies that combine and collate information suitable for appropriate decision-making

The SLV model selects a product as a boundary and uses Embodied Energy as the metric thus meeting the requirements of elements 1, 2 and 3. By using the metric of Embodied Energy item 4 is satisfied. As the SLV measurement process is outlined in later pages, it will be seen that item 5 is combined with the SLV model by providing control and feedback to the design team and the management function.

The sustainable accounting values shown above (SDeV, SMV, etc.) are combined below to give the overall sustainable impact tool or "Sustainable Life Value" or SLV. The *Sustainable Life Value* model can be seen in figure 5.3.

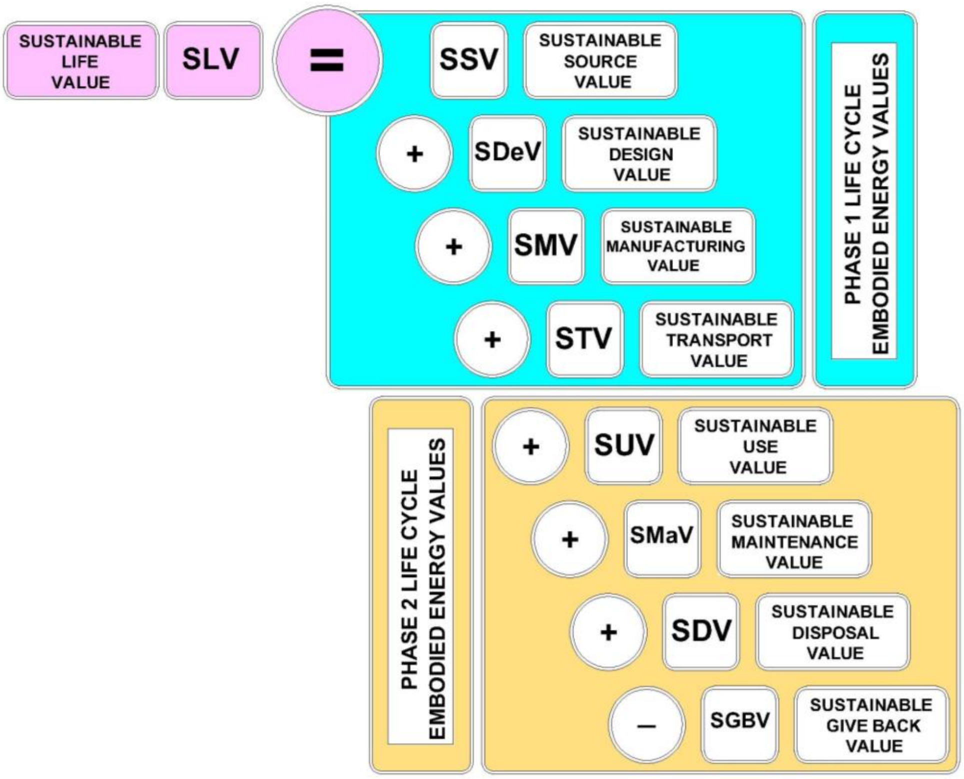


Figure 5.3: Sustainable Life Value Model Modified to Include Phase 1 and Phase 2 Embodied Energy

5.4 Sustainability Auditing

5.4.1 Scope of Auditing Phase 1 Life Cycle

Previous chapters have introduced the concept of *Embodied Energy* as a means of measuring the impact on the environment or more precisely the *Sustainability Life Value (SLV)*. The *Embodied Energy* (EE) approach needs to be redefined to reflect aspects of the life of a product. This has been labelled *Phase 1 Life Cycle Embodied Energy* and *Phase 2 Life Cycle Embodied Energy*. Phase 1 Life Cycle covers all the elements of sourcing, design, manufacturing, transport up to the point when the product leaves the factory. Phase 2 Life Cycle covers elements such as usage, maintenance and disposal plus the energy accounting device of Sustainable Give Back Value (SGBV).

Phase 1 Embodied Energy tends to increase in value due to energy input from the product creation process. Phase 2 Embodied Energy though, relatively unpredictable, has the potential of “saving” energy and perhaps creating energy depending on the product, thus creating Sustainable Give-back. The model thus developed splits Phase 1 and Phase 2 into smaller elements which can be individually evaluated for both energy creation and energy usage. Examples can be seen in the case studies in section 5.8.3 and 5.8.4.

Figure 5.4 illustrates the Embodied Energy usage and give-back for a typical product profile. The diagram shows that energy is applied to the product throughout every stage of the life cycle. During Phase 1 Life Cycle energy is applied during sourcing, design, manufacturing, and various transport operations. The usage element has a large value for energy input. This typically would be for a vehicle where fuel energy (petrol, diesel, etc.) would be put into the vehicle. If the product were a photovoltaic panel the usage phase would register zero energy input but a large value of energy generation.

Maintenance and disposal phases require energy to be implemented but taking a broader view, these two novel elements either save energy by avoiding the new procurement or harvest energy by extracting residual energy in the product.

Give back refers to all the energy saved or gleaned in order to offset the Embodied Energy which has been expended on the product during its life.

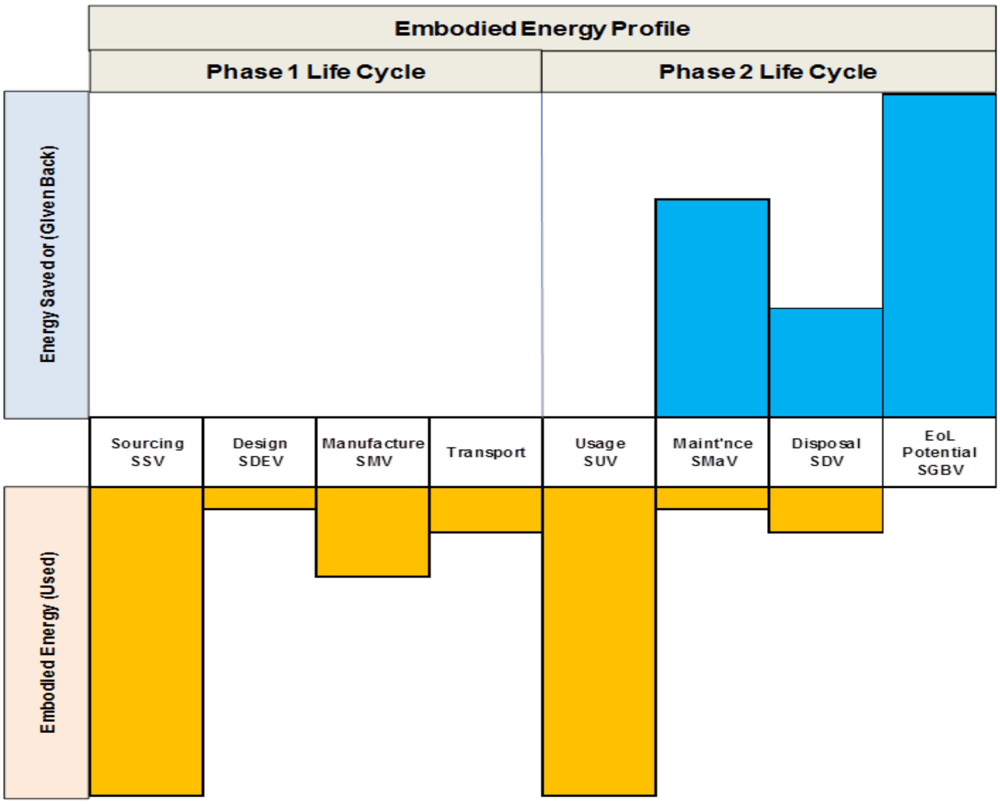


Figure 5.4: Embodied Energy Usage and Give Back Profile for a Typical Product

Phase 1 Embodied Energy is largely measurable since it deals with elements of the product creation process that are relatively tangible and can therefore be defined in terms of energy usage. Some of the major elements are listed below:

- Sourcing
    - Extraction of material and initial processing
    - Transport
    - Secondary material processing
- Transport to manufacture facility
- Design
    - Design function energy usage (electricity, heating, etc.)
    - Prototyping (incumbent manufacture, transport, scrapping of previous prototypes)
- Manufacture
    - Tooling
    - Manufacturing process
    - Factory efficiency (overheads, etc.)
- Transport to customer access facility

5.4.2 Marketing Sustainability

In order for the consumer to understand sustainability and the proposed measurement strategy, it is suggested that there needs to be a shift in marketing strategy combined with a shift in how the market purchases products. For example, when a vehicle is purchased, the purchaser is interested in future running costs such as fuel consumption, vehicle excise duty, insurance, which are also linked to how the vehicle might be used. The purchaser rarely considers the environmental impact of fabricating the vehicle to reach the saleable stage. With an enlightened approach to sustainability, the consumer can look for an SLV rating as well as a fuel efficiency rating.

Marketing and sales approaches should be modified to reflect the environmental impact of a product, which, in turn, will educate the purchasing public to the environmental cost as well as the running cost. In some part this is already being implemented with the marketing of hybrid electric cars. Word Press [5.14] examined some of the benefits of hybrid cars used in marketing campaigns. In such an eco-friendly product it would be expected that features of sustainability are prominent as marketing features. Some of the major marketing ploys are listed below:

- built with lightweight materials
- small and compact
- fuel efficient gasoline engines
- regenerative braking used to recharge batteries
- fewer emissions
- fuel efficient
- aerodynamic
- special tyres reduce rolling resistance
- driving a hybrid car allows you to wear your green badge credentials with pride

Several of these features such as “aerodynamic” and “fuel efficient” are already built into modern vehicles however many of the other points support the proposal that the design function influences the entire life cycle since these points will have been designed instigated.

5.4.1 Scope of Auditing Phase 2 Life Cycle

Phase 2 Embodied Energy is more difficult to define since it is dependent on the user, how the product is used, and the end of life strategy which often relies on the final user to instigate.

When the product begins its useful life, it will probably use, and therefore accumulate, more Embodied Energy thus beginning the accumulation of Phase 2 Embodied Energy.

The typical product profile shown in figure 5.4 illustrates the energy applied to the product in use. From a sustainability point of view it also indicates that:

- maintenance can ”save” energy
- appropriate sustainably applied disposal can “save” energy
- Components that can no longer be used can still have energy saving properties

Maintenance can increase the life of the product so that several standard lifetimes of the product can be gained thereby avoiding a number of new purchases. Increasing product longevity reduces the energy used in creating products by simply reducing the demand for new products.

End of life disposal techniques can be designed-in, making the end of life disposal simpler and more obvious to the consumer. This then becomes one of the responsibilities of the design function. Disposal incorporates recycling, refurbishing, reusing and reducing. All four of these actions save energy by avoiding the necessity for new products or by providing raw or recycled materials that are ready to commence their second life.

Recycling is the most obvious and arguably the most popular disposal method. The recycling operation requires a fraction of the energy required to extract primary material. For instance the energy required to recycle aluminium is only 5% of the energy required to extract raw material from the earth and process it into a useful material, Ashby [5.2]. This energy “saving” can be considered as “give-back”, or harvested energy and forms part of the SGBV value.

Refurbishing replaces worn parts and builds up worn elements to a state where they can be used once again. Refurbishing may be as simple as applying new paint to make an old product look new or as complete as re-welding a fabricated structure. The process of refurbishment also uses energy but effectively provides a working product with a much lower Embodied Energy input thus avoiding the purchase of a new device with its much higher incumbent Energy of Primary Source (EPS). The difference in Embodied Energy between the refurbished product and the new product can then be considered as “saved” energy or “Give-Back” energy.

Re-use also saves energy and is much used especially in the vehicle industry where end of life vehicles are stripped of useful parts and sold to replace damaged components on vehicles still in use. The process effectively saves energy by avoiding the purchase of new components and ensuring that the “residual life” in each component is used. This can also be considered as “give-back” since the process also avoids the procurement of new components.

5.5 Phase 1 Life Cycle: Computing the Embodied Energy Value

Having redefined the elements of the Whole Life Value model by considering the Phase 1 and Phase 2 of Embodied Energy, it is now possible to quantify the values. Each component of figure 5.3, the summative model for the sustainability value, requires defined inputs which are then combined for a final value.

Phase 2 Life Cycle Embodied Energy is difficult to measure in practice but can be predicted at the design stage or at least before the product leaves the factory. In order to more accurately define and measure the Embodied Energy and the giveback energy within Phase 2 Life Cycle it is necessary to understand the detail within each life phase element of Phase 2 Life Cycle. These include usage, maintenance and end of life disposal. Giveback energy (SGBV) should also be computed to offset the input of energy, so that an accurate value of Embodied Energy can be assessed for the entire life of the product. Measurement techniques for Phase 2 Life-Cycle are discussed below in section 5.9

Though the design function should be able to estimate the energy in the “best case scenario” for Phase 2 Life Cycle, an accurate figure can only be deduced after practical feedback from the Phase 2 Life Cycle elements. Methods which can determine this value by applying various management techniques are discussed in Chapters 6 and Chapter 7.

5.6 Phase 1 Life Cycle Embodied Energy Measurement

Phase 1 Embodied Energy can be measured by quantifying the energy used in the various initial creation phases and can be initially defined by determining the mass flow.

5.6.1 Phase 1 Embodied Energy and Sustainable Life Value (SLV_{PH1})

Phase 1 Embodied Energy can be defined by combining the energies applied in sourcing, design, manufacturing and transport. It is the Embodied Energy Value that would be certified on a product to compare to similar products.

The “Sustainable Life Value” for Phase 1 (SLV_{PH1}) per product (in joules) can be derived by multiplying the SSV by the product’s mass ‘M’ and adding the Design Energy Value (SDeV) + Manufacturing Energy Value (SMV x M) and the Transport Value STV x M. The general equation follows:

SLV_{PH1} = (SSV x M) + SDeV + (SMV x M) + (STV x M) (joules) ……….5.1

The design phase measurement SDeV is a pure energy value derived from a proportion N_{DESIGN} of the manufacturing energy used within the control volume of the manufactory. This is discussed below in detail.

Each SLV_{PH1} element can now be defined as follows:

Sustainable Source Value (SSV) (joules/kg)
Sustainable Design Value (SDeV) (joules)
Sustainable Manufacturing Value (SMV) (joules/kg)
Phase 1 Transport Value (STV) (joules/kg)

Thus Total Phase 1 Embodied Energy can be generally defined as shown in figure 5.5:

Phase 1 Embodied Energy								
SLV Phase1	=	SSV	+	SDeV	+	SMV	+	STV

Figure 5.5: Measurement Values of Phase 1 Embodied Energy

It should be noted that the units of SSV, SMV and STV are in joules/kg which can be considered as Specific Embodied Energy (SEE). SDeV energy units are joules and require adding to the SLV_{PH1} equation after the SEE values have been converted to pure energy by multiplying the SSV, SMV and STV values by the appropriate masses. The SLV_{PH1} equation therefore becomes

SLV_{PH1} = (SSV x $M_{sourcing}$) + (SDeV) + (SMV x $M_{manufacture}$) + (STV x $M_{Transport}$)
………..5.2

5.6.2 Measurement of Phase 1 Embodied Energy (SLV_{PH1})

Identified above in figure 5.5 are four elements which demand energy during the period from material sourcing to completion of manufacture. The parameters are repeated as follows:

SLV_{PH1} = SSV + SDeV + SMV + STV ………..5.3

The above processes can be readily measured in terms of energy requirement but variations will certainly exist in terms of process efficiency. Often the most energy consumptive part of any creation process is that of material sourcing.

5.6.3 Sustainable Source Value (SSV)

When a material such as iron ore is hewn from the ground, energy is applied to extract the mass and can be quantified as energy per unit of mass or joules/kg. The same energy/mass unit can be used throughout the various derivation processes including transportation between processes. The summation of all the sourcing processes is termed Sustainable Source Value (SSV) with units of joules/kg.

The sourcing of a material such as steel requires several processes listed below:

Iron ore is mined.
Iron ore is processed into pig iron..
Pig iron is processed into various forms of steel .
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 follows:
E_1: Extraction (j / kg)

T_1: Transport to primary processing plant
(Power x time / kg) (Watt.s / kg) = (j / kg)

P_1: Primary Processing (j / kg)

T_2: Transport to secondary processing plant
(Power x time / kg) (Watt.s/ kg) = (j / kg)

P_2: Secondary processing (j / kg)

T_3: Transport to tertiary processing plant
(Power x time / kg) (Watt.s/ kg) = (j / kg)

P_3: Tertiary processing (j/kg)

T_4: Transport to manufacturing plant
(Power x time / kg) (Watt.s/ kg) = (j / kg)

The following nominal expression can be developed which sums the energy values during the sourcing process.

$$SEE_{Sourcing} = E_1 + T_1 + P_1 + T_2 + P_2 + T_3 + P_3 + T_4 \text{ (joules/kg)} \qquad \text{……….5.4}$$

Further transport elements and processes can be added where necessary.

In order to analyse the sourcing process accurately, it should be realised that mass is the common commodity that is being processed. In order for the mass to be extracted, processed and transported through its various phases, energy must be applied. Before the Embodied Energy of each phase can be attributed, the mass flow has to be calculated.

A similar equation to (5.4) can be used to describe the mass flow as follows:

$$SSV_{Mass} = E_{1m} + T_{1m} + P_{1m} + T_{2m} + P_{2m} + T_{3m} + P_{3m} + T_{4m} \text{ (kg)} \qquad \text{……….5.5}$$

Equation 5.5 can therefore be represented in a basic mass flow block diagram as shown in figure 5.6.

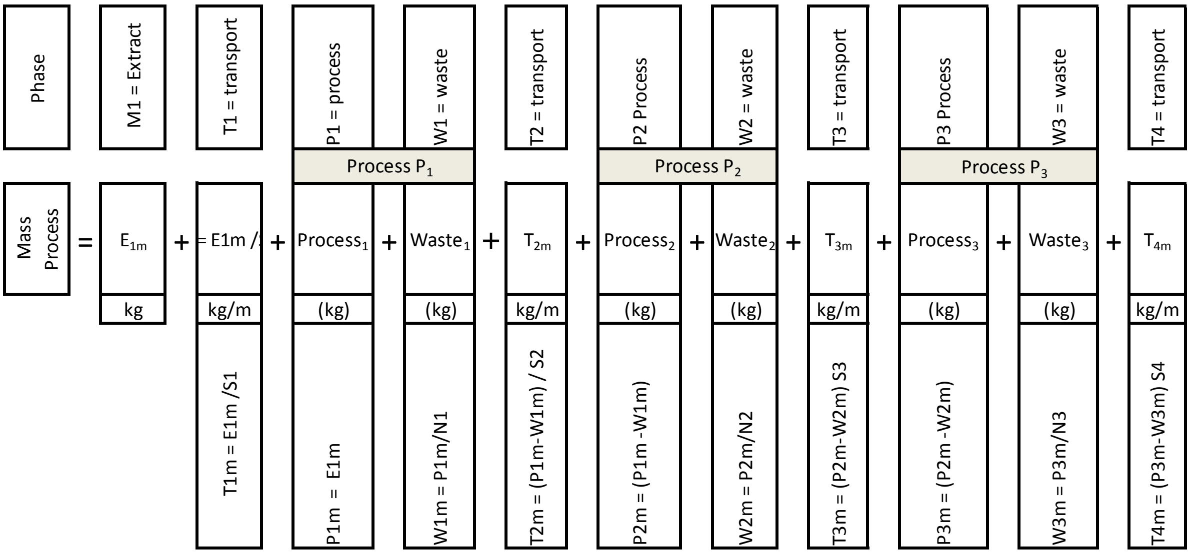


Figure 5.6: Mass Flow Block Diagram

Key

E1m =	Extraction mass
P1m =	Primary process
P2m =	Secondary Process
P3m =	Tertiary Process
T1m =	Mass Transport E1 to P1
T2m =	Mass Transport P1 to P2
T3m =	Mass Transport P2 to P3
W_{1m}=	Waste mass from process 1
W_{2m}=	Waste mass from process 2
W_{2m}=	Waste mass from process 3
N1	Waste Fraction from process 1
N2	Waste Fraction from process 2
N3	Waste Fraction from process 3

As the material progresses towards the end product, the additive Embodied Energy will continue to increase. Each subsequent process will be dependent on the previous process since there will be some waste ($N_{1,2,3,etc}$) which will inevitably reduce the useful mass to be processed at the next process. The process of converting iron ore to pig iron, for example, creates up to 45% waste according to US Dept. Energy [5.1]. Though this is waste product, it is useful to isolate it since energy is still expended on its creation which must be included in the total Embodied Energy for the useful product.

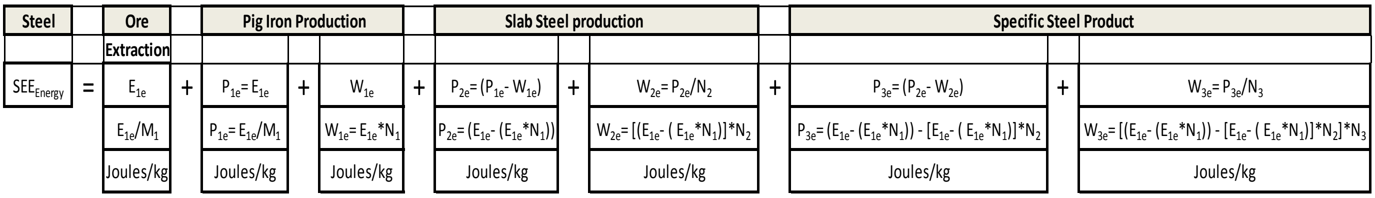
It is possible that a waste product will be usefully applied to another (second) product. Then it can be debated as to whether or not to include the waste's Embodied Energy within the original or second product. Ashby [5.2] argues that Embodied Energy should not be counted twice and that the Embodied Energy relating to waste product that can be usefully applied should not be included in the original product if the Embodied Energy has been considered in the second product. The current SLV model assumes that Embodied Energy used in creating the waste product is attributed to the first life since it falls within the first life cycle.

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 5.7.

A value of energy can now be attributed to each of the variables in figure 5.8. Each process can now have a *Specific* value of energy of joules/kg assigned to it so that the total Embodied Energy per unit mass (SEE) can be related to the mass of material used in creating the product as shown in equation 5.6.

$SEE_{Sourcing}$ = ΣEnergy/Unit Mass = Source Material Embodied Energy (j/kg) ……….5.6

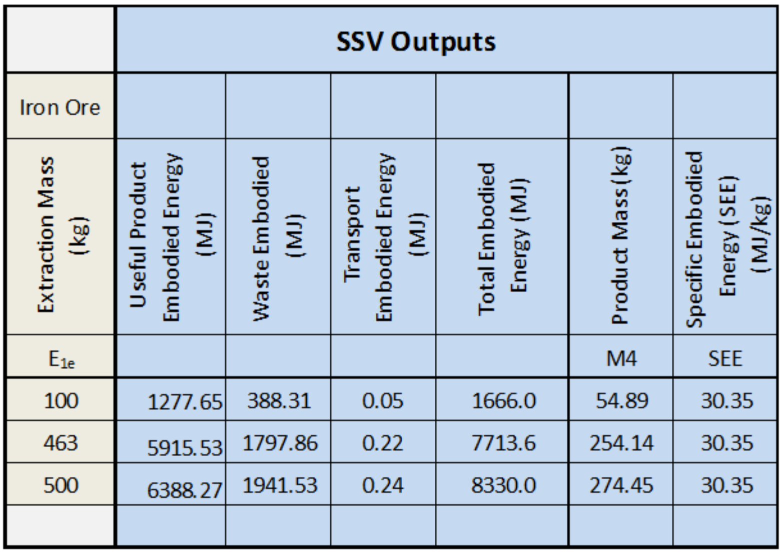
The process and transport elements of the sourcing process can now be formulated as an extended equation noting that the energy needed at each step is dependent on the mass fed into that process from the prior process. See figure 5.10



Steel		Ore		Pig Iron Production				Slab Steel production				Specific Steel Product		
		Extraction												
SEE_{Energy}	=	E_{1e}	+	$P_{1e}= E_{1e}$	+	W_{1e}	+	$P_{2e}= (P_{1e}- W_{1e})$	+	$W_{2e}= P_{2e}/N_2$	+	$P_{3e}= (P_{2e}- W_{2e})$	+	$W_{3e}= P_{3e}/N_3$
		E_{1e}/M_1		$P_{1e}= E_{1e}/M_1$		$W_{1e}= E_{1e}*N_1$		$P_{2e}= (E_{1e}- (E_{1e}*N_1))$		$W_{2e}= [(E_{1e}- (E_{1e}*N_1)]*N_2$		$P_{3e}= (E_{1e}- (E_{1e}*N_1)) - [E_{1e}- (E_{1e}*N_1)]*N_2$		$W_{3e}= [(E_{1e}- (E_{1e}*N_1)) - [E_{1e}- (E_{1e}*N_1)]*N_2]*N_3$
		Joules/kg		Joules/kg		Joules/kg		Joules/kg		Joules/kg		Joules/kg		Joules/kg

Figure 5.7: Example: Equation Relating to the Energy Required in the Sourcing of Steel

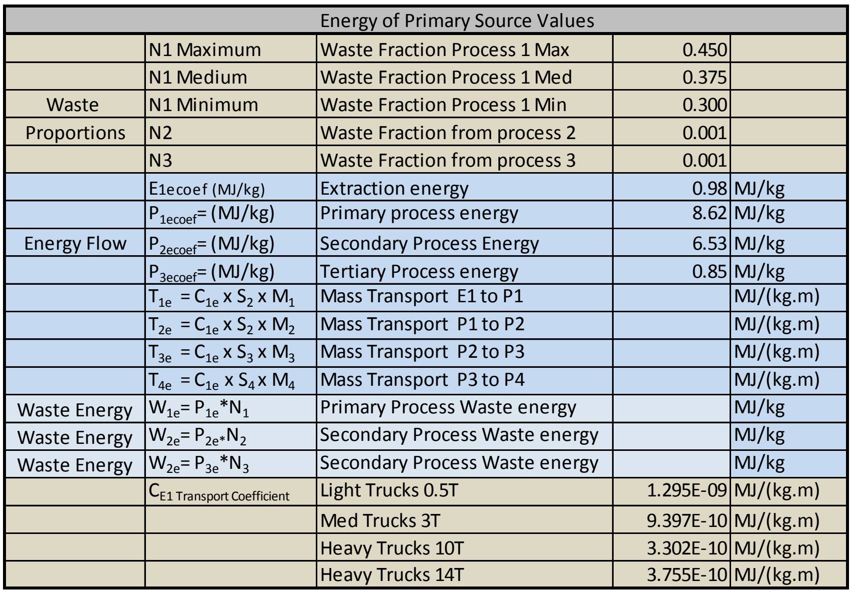
Data for the equation in figure 5.7 can be seen in figure 5.8.



	SSV Outputs					
Iron Ore						
Extraction Mass (kg)	Useful Product Embodied Energy (MJ)	Waste Embodied (MJ)	Transport Embodied Energy (MJ)	Total Embodied Energy (MJ)	Product Mass (kg)	Specific Embodied Energy (SEE) (MJ/kg)
E_{1e}					M4	SEE
100	1277.65	388.31	0.05	1666.0	54.89	30.35
463	5915.53	1797.86	0.22	7713.6	254.14	30.35
500	6388.27	1941.53	0.24	8330.0	274.45	30.35

Figure 5.8: Portion of Algorithm Showing Outputs for SSV

It should be noted that the waste fraction (N_1) has a maximum, medium and minimum value which reflects the variations in efficiency of steel manufacture from country to country and also process to process. Furthermore, the transport elements are based on road type transport of various carrying capacities e.g. 3 tonnes, 10 tonnes and 14 tonnes. Each capacity has been factored into the transport coefficient C_{e1} to give a homogenous value, and when multiplied by transported mass and distance, that can be included in the total Embodied Energy value. The transport coefficient can be refined by adding rail, truck shipping, and air transport values where necessary.



Energy of Primary Source Values				
Waste Proportions	N1 Maximum	Waste Fraction Process 1 Max	0.450	
	N1 Medium	Waste Fraction Process 1 Med	0.375	
	N1 Minimum	Waste Fraction Process 1 Min	0.300	
	N2	Waste Fraction from process 2	0.001	
	N3	Waste Fraction from process 3	0.001	
Energy Flow	E1ecoef (MJ/kg)	Extraction energy	0.98	MJ/kg
	P_{1ecoef}= (MJ/kg)	Primary process energy	8.62	MJ/kg
	P_{2ecoef}= (MJ/kg)	Secondary Process Energy	6.53	MJ/kg
	P_{3ecoef}= (MJ/kg)	Tertiary Process energy	0.85	MJ/kg
	$T_{1e} = C_{1e} \times S_2 \times M_1$	Mass Transport E1 to P1		MJ/(kg.m)
	$T_{2e} = C_{1e} \times S_2 \times M_2$	Mass Transport P1 to P2		MJ/(kg.m)
	$T_{3e} = C_{1e} \times S_3 \times M_3$	Mass Transport P2 to P3		MJ/(kg.m)
	$T_{4e} = C_{1e} \times S_4 \times M_4$	Mass Transport P3 to P4		MJ/(kg.m)
Waste Energy	$W_{1e}= P_{1e}*N_1$	Primary Process Waste energy		MJ/kg
Waste Energy	$W_{2e}= P_{2e*}N_2$	Secondary Process Waste energy		MJ/kg
Waste Energy	$W_{2e}= P_{3e}*N_3$	Secondary Process Waste energy		MJ/kg
	$C_{E1 \text{ Transport Coefficient}}$	Light Trucks 0.5T	1.295E-09	MJ/(kg.m)
		Med Trucks 3T	9.397E-10	MJ/(kg.m)
		Heavy Trucks 10T	3.302E-10	MJ/(kg.m)
		Heavy Trucks 14T	3.755E-10	MJ/(kg.m)

Figure 5.9: Key to Variables in Figure 5.7 equation

Although the example has been to complete the Embodied Energy value for the steel *sourcing* process; however other commodities such as aluminium and copper, for instance, could also be treated in a similar fashion.

5.6.4 Sustainable Design Value (SDeV)

SDeV is derived from the factory energy usage that is from the SMV which can be derived on a detailed basis by considering every process individually within the company. This may give a detailed breakdown of where energy is being used but such a detailed strategy is likely to have a minor effect on the overall energy usage value though it would be useful to determine which processes consume the most energy. This approach has been applied successfully by a number of high profile organisations including JCB to reduce their overall energy consumption. Focusing on energy usage within individual processes highlights areas where savings can easily be made.

A simpler methodology would be to draw a control boundary around the manufactory and determine the total energy overhead from utility measurements. Such measurements as electricity usage, gas usage, oil, coal, etc. would contribute towards this energy profile. Determination of the power usage profile used by the manufactory can use consumption of gas (bottled), gas (piped), electricity (artificially and naturally derived), oil and coal.

The values of these energy sources can be summed for the whole year and proportioned according to time used per product and amount used in design. In this way the energy requirement for the factory can be consolidated into one value: $E_{Factory}$.

$E_{Factory}$ = total energy used by the manufactory per annum (joules)
D_{ENERGY} = energy used by the design/office function (joules)
N_{Design} = proportion of total manufactory energy applied to design

Design Energy can be derived as shown in equations 5.7 & 5.8

D_{ENERGY} = SMV x N_{DESIGN} (joules/kg) ……...5.7

SDeV = D_{ENERGY} (joules) ………5.8

The SDeV relates to the design element only; there are many other elements which consume energy. A value of energy for the design element can be extrapolated by determining what portion or percentage of the entire factory energy use was consumed during the design phase. This is precisely the way the SDeV was estimated in the case study below in section 5.8.

The general office function for the factory with all its support systems contributes towards the manufacture of the product and should be considered as part of the manufactory overhead and proportioned for the design element perhaps based on relative size of design space to office space to entire factory.

The design of the product happens only once. The SDeV value of applied Embodied Energy should not be charged to the product continually. The SDeV should be written off over a short period rather like the monetary value of, a new machine tool is written off over a five-year period.

It is suggested that the SDeV value is written off against the number of products manufactured during the first year of production, after which time the value of Embodied Energy incurred by the new product should be discounted from the total Embodied Energy value for the product.

The SDeV can be derived as follows:

SDeV = D_{ENERGY} / Number of Products (N_P)

but $D_{ENERGY} = E_{Factory} \times N_{Design}$

giving

$$\text{SDeV} = \frac{E_{Factory} \times N_{Design}}{N_P} \quad \text{joules} \qquad \text{……..5.9}$$

5.6.5 Sustainable Manufacturing Value (SMV) (joules/kg)

Sustainable Manufacturing Value (SMV) can be used as a measure of the manufacturing process. SMV can be calculated by proportioning the energy overhead of a facility in comparison with the mass output of goods. The value would therefore be joules/kg. Another possible effective method would be to consider the factory as a control volume using the factory energy overhead and dividing it by the product mass output. The result would be an SMV in joules/kg described by equation 5.10.

The energy used in the manufacturing process "SMV" is the total value of factory control volume energy, less the energy used in design, as follows:

$$\text{SMV} = E_{Factory} - D_{ENERGY}$$

But $D_{ENERGY} = E_{Factory} \times N_{Design}$

$$\text{SMV} = E_{Factory} - (E_{Factory} \times N_{Design}) \qquad \text{……..…..5.10}$$

SMV therefore in terms of Specific Embodied Energy (SEE) can be derived as follows

SMV = $E_{Factory}$ / {Number of Products (N_P) x Product Mass (P_M)}

or

$$\text{SMV} = \frac{E_{Factory}}{N_P \times P_M} \quad \text{joules/kg} \qquad \text{…………..5.11}$$

5.6.6 Sustainable Transport Value (STV)

Though energy is expended on transport between each sourcing element it is expedient to create a separate transport energy value (STV) to the process energy value. The transport value carries the useful mass to the next process phase and is therefore dependent on the mass which exits the previous process. The modular equation diagram shown in figure 5.10 explains the concept.

	Transport				
Process	E_{1m} to P_{1m}		P_{1m} to P_{2m}		P_{2m} to P_{3m} and onwards
Energy	$T_{1e}= C_{1e}* S_2*M_1$	+	$T_{2e}= C_{1e}* S_2 * M_2$	+	$T_{3e}= C_{1e}* S_3* M_3$
			$T_{2e}= C_{1e}x\ S_2 * (M_1- (M_1*N_1))$		$T_{3e}= C_{1e}* S_3 * (M_2- (M_2*N_2))$
Unit	Joules		Joules		Joules

Figure 5.10: Energy Used in Transport between Sourcing Processes

The values for the Transport Coefficient, C_{1e}, can be found in figure 5.9. The units of the Transport Coefficient are: C_{1e} = Mj/kg.m

When multiplied by the mass and distance transported an energy value in joules is derived.

The coefficient (C_{1e}) values are based on truck transport of various carrying capacities which have been factored into the coefficient value. When multiplied by mass and distance transported, the emergent value becomes Mjoules and can be directly added to the total Embodied Energy for sourcing (SSV).

In the example using iron Embodied Energy has been derived for raw iron ore extraction with incumbent processing and transport to the stage where it is used in manufacturing as raw material for components. Figure 5.10 shows a portion of the algorithm depicting the Embodied Energy for steel as a raw material. The Sustainable Design (SDeV) and Manufacturing (SMV) values now require incorporating into the general equation.

5.6.7 Consolidation of Embodied Energy Values (SLV_{PH1})

The SLV_{PH1} can now be calculated by incorporating the derived values of SSV, SDeV, SMV and STV into the general equation (5.3).

It should be noted that SSV, SMV and STV are Specific Embodied Energy values with units of joules/kg. SDeV possesses a unit solely of energy in joules.

The aim is to derive an energy value per product as it leaves the factory and to this end the SSV, SMV and STV need to be treated differently from the SDeV.

Since SSV, SMV and STV are Specific Embodied Energy Values in joules/kg each value should be multiplied by the mass of each product times the number of products/annum, as follows:

Energy per product $= SSV \times P_M \times N_P$
$= SMV \times P_M \times N_P$
$= STV \times P_M \times N_P$

SDeV merely requires dividing by the number of products per annum as follows:

Energy per product $= SDeV / N_P$

Equation (5.3) can now be modified as follows:

$$SLV_{PH1} = (SEE \times P_M \times N_P) + (SDeV/N_P) + (SMV \times P_M \times N_P) + (STV \times P_M \times N_P) \quad \text{………..5.12}$$

Where:
P_M = mass of each product (kg)
N_P = Number of products per annum

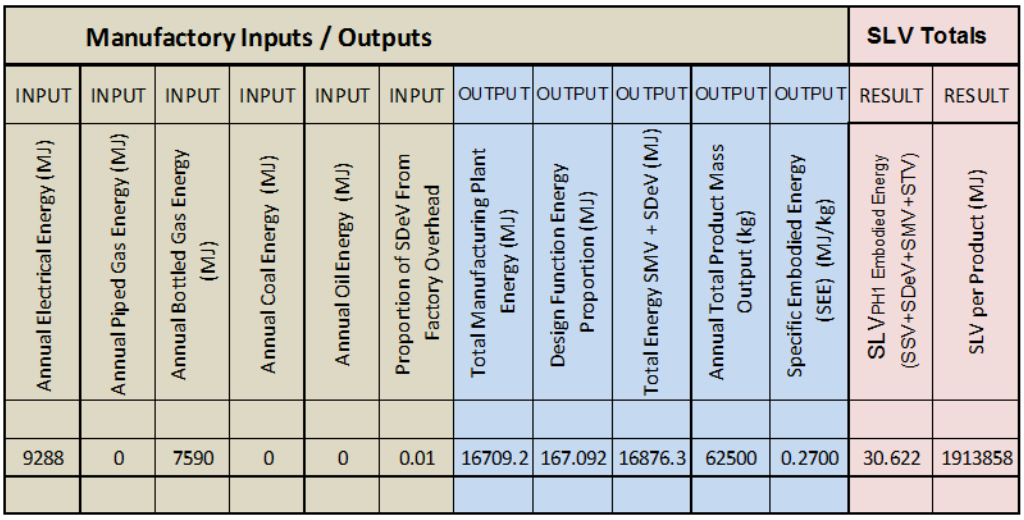
Such a simple equation belies the extremely complex nature of its additive sections. An algorithm was therefore devised that embodied all the various parameters mentioned above. The algorithm consists of:

SSV Input Values
basic coefficients
transport coefficients
transport distances
original extraction mass

Analysis Values
mass flow through
process energy
waste energy
transport energy

Output Values
embodied energy (useful product)
embodied energy (waste product)
embodied energy (transport)
total embodied energy (SSV)
useful product mass
specific embodied energy (SEE)

Equation 5.12, gives the true SLV_{PH1} energy value (joules) per product. This is also required for insertion in to the products' product specification. A portion of the algorithm which calculates the SLV_{PH1} can be seen in figure 5.11.



Manufactory Inputs / Outputs											SLV Totals	
INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	RESULT	RESULT
Annual Electrical Energy (MJ)	Annual Piped Gas Energy (MJ)	Annual Bottled Gas Energy (MJ)	Annual Coal Energy (MJ)	Annual Oil Energy (MJ)	Proportion of SDeV From Factory Overhead	Total Manufacturing Plant Energy (MJ)	Design Function Energy Proportion (MJ)	Total Energy SMV + SDeV (MJ)	Annual Total Product Mass Output (kg)	Specific Embodied Energy (SEE) (MJ/kg)	SLV_{PH1} Embodied Energy (SSV+SDeV+SMV+STV)	SLV per Product (MJ)
9288	0	7590	0	0	0.01	16709.2	167.092	16876.3	62500	0.2700	30.622	1913858

Figure 5.11: Portion of Algorithm Showing Contributions to SLV_{PH1}
(See Case Study Below in Section 5.8)

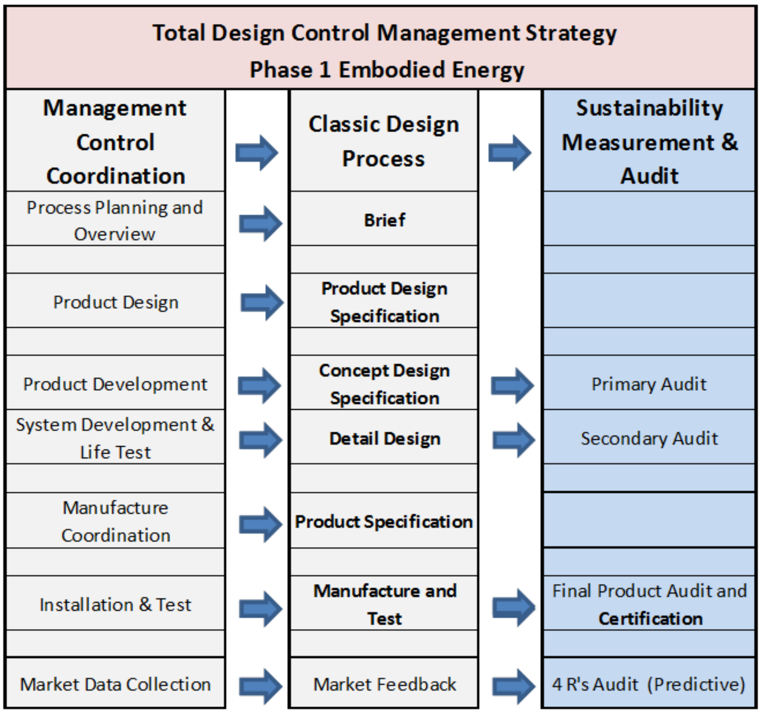
5.6.8 Multi-material Products

The theory and analysis outlined above assumes that a product is manufactured from a single material. In reality, even the simplest products are assembled from a multiplicity of various materials using a wide range of manufacturing processes. It may be the case that a component within a product has a mass of only a few grams but it may have required a huge value of energy to produce. In such a case a weighting factor should be introduced. In the case of a multi-component product, an SMV value of the Embodied Energy for each major component should be derived; this can be totalled and the summed value of the SMV submitted to equation 5.12.

5.7 Measurement of Sustainability within the Total Design Control Strategy

The Total Design Control Strategy, as applied to the design of new products using the Principles of Sustainability, is an important tool which uses a classic design process as a guide to sustainable development. This strategy would merely be theory if there were not some form of metric and feedback method to the management team and to the design function.

The measurement of sustainability is therefore paramount for management control and future product iterations if sustainability is to be considered. Figure 5.12 shows the TDC management strategy model and in particular several audit elements.



Total Design Control Management Strategy
Phase 1 Embodied Energy

Management Control Coordination		Classic Design Process		Sustainability Measurement & Audit
Process Planning and Overview	➡	Brief		
Product Design	➡	Product Design Specification		
Product Development	➡	Concept Design Specification	➡	Primary Audit
System Development & Life Test	➡	Detail Design	➡	Secondary Audit
Manufacture Coordination	➡	Product Specification		
Installation & Test	➡	Manufacture and Test	➡	Final Product Audit and Certification
Market Data Collection	➡	Market Feedback	➡	4 R's Audit (Predictive)

Figure 5.12: Total Design Control Management Strategy

The Total Design Control Management Strategy (TDCMS), figure 5.12. This strategy links management control elements to the *Classic Design Process*, Detailed in chapter 6, figure 6.5) which forms a route through the product creation process allowing the TDCMS to be implemented, triggered by each stage of the design process. As the design process progresses management control and coordination elements are prompted for each new stage. Implementation and application methods are fundamental to the design process and should be applied by the design team at an appropriate point. Sustainability measurement, *Primary Audit,* first takes place when the concept design has been formulated. Since this is the first time in the creation process that a product has taken shape, be it merely sketches and specifications.

The *Primary Audit* takes place after the concept design has been formulated and prior to any build work. This is a fairly crude energy value but will give the design team a projection of the Embodied Energy (SLV_{PH1}) of the new product. An example is given in the case study in section 5.8.3.

The *Secondary Audit* takes place as the technical details (drawings, parts list, models) are issued to the manufactory. This audit should be reasonably accurate since the product's specification has now been set. It also allows the use of an iterative approach to evaluate alternative materials, manufacturing methods and sourcing to optimise the detailed design.

The *Final Product Audit* takes place as the product leaves the factory and should be fairly accurate, while allowing for small deviations. At this point the SLV_{PH1} will have been measured and can be used as a *Certification Value* indicating the Embodied Energy applied to the product. See the case study in section 5.8.4.

In a competitive world, this certification value will prove to be a useful marketing tool where companies manufacturing similar products will strive to reduce their SLV_{PH1} certification value. In time, this competition will improve the "Available Sustainability Value" for new products as products with lower SLVph1 achieve greater success in the market.

5.7.1 Phase 2 Embodied Energy: Measurement and Estimates

Phase 2 Embodied Energy relates to the product after it reaches the customer who can drastically vary the use of the product. Phase 2 therefore has to be considered in two approaches.

5.7.1.1 The Design Phase

When a product is first formulated there is often no Phase 2 Life Cycle feedback information. The designer may be able to accurately measure the Embodied Energy in Phase 1 Life Cycle but Phase 2 Life Cycle Embodied Energy has to be estimated. When the product leaves the factory it possesses a measured SLV_{PHASE1} and an estimated SLV_{PHASE2} which are combined to create an overall SLV.

There are several generic measurement tools which are excellent for estimating the Embodied Energy throughout the whole life cycle but often they are too general for a particular product type. These generic tools also usually offer a conversion to carbon footprint by assuming that all the energy expended is through the derived energy from fossil fuels. However, since 22% of current energy generation is from renewable energy sources, AEG [5.10], Eurostat [5.13], generic life cycle energy additive tools have certain drawbacks. Nevertheless they can be useful in providing an estimation of Embodied Energy over the whole life cycle even when there is a lack of real feedback data. These can be supplemented by the design team's own analysis.

CES EduPack [5.11] was evaluated to be one of the more useful generic tools and has been used in the case studies below.

5.7.1.2 Post Design Phase

Phase 2 Life Cycle Embodied Energy can only be accurately measured using feedback from the field. Chapters 6 and 7 propose management methods which manage, control, instigate, and receive information which can be fed back to the design function. Once received, this information can be used to more accurately define Phase 2 Life Cycle Embodied Energy for a particular product. Furthermore this information can be used to look for ways to decrease the Embodied Energy of new products. In other words, the experience gained from current products can be transferred to the new products.

5.8 Case Studies

The objective of both case studies in section 5.8.3 and 5.8.4 is to provide examples of Embodied Energy measurement within the Total Design Control Management Strategy (TDCMS). The management diagram shown in figure 5.12 indicates that there should be a *Primary Audit, Secondary Audit* and the *Final Audit* applied to any new product. Two case studies are presented; one represents the *Primary Audit* and the second of represents the *Final Audit*.

5.8.1 Case 1 introduction: Kinetic Energy Storage Battery (KESB)

The Primary Audit is conducted when the concept design has been formulated. At this point the product is not a tangible item, merely drawings, models and a technical specification. *The Primary Audit* cannot be completely accurate since data is based on past experience and estimates, but the audit offers a target Embodied Energy value that the design team should endeavour to improve as the product progresses through manufacture. The Kinetic Energy Storage Battery (KESB) was designed as a concept and is now presented as an ideal case study to illustrate the *Primary Audit.*

The *Secondary Audit* represents an energy estimate as this technical specification is been formulated at the end of the detailed design period and just prior to manufacture. At this point the components are specified with accompanying manufacturing processes. The *Secondary Audit* is more accurate than the *Primary Audit* since the data is based on better specification of components and hence more accurate prediction of energy required during the manufacturing process.

5.8.2 Case 2 introduction: Brick and Block Clamp

The second case study represents a *Final Audit* when the product has been manufactured and is ready to leave the manufactory. This audit is the most accurate of the three audits. Actual design time and energy use can be directly computed from the company overhead. Ideally, the final value of the *Final Audit* should be an improvement on inaccuracy of the Primary Audit. The design team and the wider TDCMS team should be able to analyse the data to determine the parts in the Phase 1 Life Cycle that have absorbed the most Embodied Energy. The data used in this case study has been derived from a manufacturer of brick and block clamps of Halifax in the UK. This example features a real product which has been manufactured and matched with actual energy figures from the company overhead.

5.8.3 Case Study 1: Primary Audit: The concept design of a Design of a Kinetic Energy Storage Device (flywheel-based battery system)

This case study demonstrates the *Primary Audit* which is applied to a concept design with the purpose of defining a target, or indicator value for Phase 1 Life Cycle Embodied Energy. Once compiled in the form of an energy balance sheet the value which can be improved upon for the actual product design and manufacture.

A kinetic energy storage device was to be designed for use with the UK National Electricity Grid. A conceptual design can be seen in figure 5.13

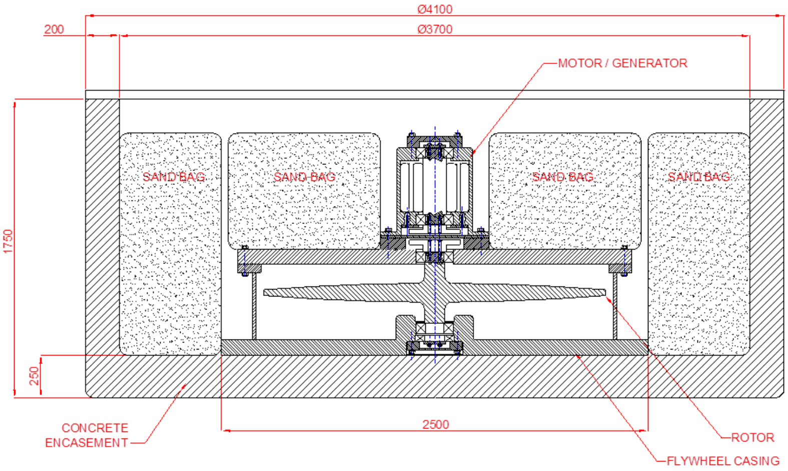


Figure 5.13: Concept Design for a Kinetic Energy Storage Device

The system was to be designed and built with sustainability and low Embodied Energy as primary design objectives; this particular analysis considers only the energy audit of the rotor.

Specification

maximum rotational speed	4000 rev/min
rotor style	tapered disc
maximum diameter	2 m
mass	1.7 tonnes
energy capacity	20 kWh
life expectancy	10 years

5.8.3.1 Case Study 1: Approach to the Energy Audit

The approach to sustainable design embraces the concept that the *Designer* or the *Design Function* is responsible for the product from material sourcing to disposal. Within this Whole Life Analysis there are seven elements which are defined below as the Sustainable Life Value (SLV) model, figure 5.14.

The model shows the measurement elements within the life cycle of a product and acknowledges that all products extract resources from the environment during their whole life but categorises the environmental impact as follows:

SLV: Sustainable Life Value: Overall environmental impact value and is a summation of the following six elements.

1. SSV: Sustainable Source Value: energy required when sourcing materials
2. SDeV: Sustainable Design Value: energy required for design work
3. SMV: Sustainable Manufacturing Value: energy required to manufacture
4. SUV: Sustainable Use Value: energy required during the products useful life
5. SMaV: Sustainable Maintenance Value: energy required to maintain the product
6. SDV: Sustainable Disposal Value: energy required to dispose of the product
7. SGBV: Sustainable Giveback Value: energy gleaned or saved

$$\boxed{\mathrm{SLV}} = \boxed{\mathrm{SSV}} + \boxed{\mathrm{SDeV}} + \boxed{\mathrm{SMV}} + \boxed{\mathrm{SUV}} + \boxed{\mathrm{SMaV}} + \boxed{\mathrm{SDV}} - \boxed{\mathrm{SGBV}}$$

Figure 5.14: Block Diagram Showing Sustainable Life Value Elements

5.8.3.2 *Case Study 1: Energy Accounting*

Energy accounting involves creating an energy balance sheet that totals all the energy input (negative energy) throughout the product life cycle. Energy harvested (positive energy) is also totalled giving SGBV and combined with the energy balance sheet. The end result gives a net figure of either negative energy or positive energy.

Since this was a concept design rather than a tangible product the bottom line of the energy balance sheet could only be compiled from non-measured information and other historical data, thus creating an indicator value of Phase 1 Life Cycle Embodied Energy. This would give the design team a target and suggest where large values of energy would be expended. To this end CES EduPack [5.11] was used to assemble some of the energy information required such as SSV, SMV, Transport and SDV. This data can be seen in the shaded boxes in the extract from CES Edupac in figure 5.15. See appendix 5A1 for precise information.

Material Sourcing, SSV

rotor	High carbon steel	Typical %	1.6e+03	2	3.2e+03	5.9e+04Mj	35.4

Manufacture, SMV

rotor	Extrusion, foil rolling	3.2e+03 kg	2.1e+04 Mj	64.5

Transport

rotor	32 tonne truck	5e+02	7.6e+03 Mj	33.3

Disposal, SDV

rotor	Recycle	2.2e+03 Mj	27.3

Figure 5.15: Extract from CES Edupack Data

Other parameters were divined using data supplied from a local company, JAS Ltd.

5.8.3.2.1 Case Study 1: Sustainable Design Value

SDeV was determined to be 1% of the SMV at **12** Mj

This value was calculated by taking the company electricity readings from JAS Ltd., a company based in the Wirral, UK, when, on several occasions, the manufacturing element was closed for maintenance, but whilst the design function was still working. The results from several different measurements were averaged and compared to the overall factory overhead. The resulting SDeV value of 1% of factory overhead was calculated and is unique for JAS Ltd.

5.8.3.2.2 Case Study 1: Sustainable Use Value (SUV) (Energy Harvested)

The energy applied to the flywheel during use is all converted into stored energy. Even though losses are inevitable they were considered to be negligible.

SUV was based on a single annual cycle

4 cycles per day
365 days per year
cycling at half power to full power (10 kwh = 36 Mj)

SUV = 4 x 365 x 36 = **52,560 Mj energy saved during one year** ……………5.13

This is positive harvested energy and can be added to the SGBV

5.8.3.2.3 Case Study 1: Sustainable Maintenance Value (SMaV)

SMaV was quoted at **320 Mj** as the energy used in ten days of factory overhead from JAS Ltd. This is energy expended on the rotor and is entered as negative energy on the energy balance sheet

The process of maintaining the rotor and returning it to service avoids the rotor being recycled and has further avoided the procurement of a new rotor with all its incumbent Energy of Primary Source (EPS). This positive energy can be harvested and added to the SGBV.

EPS = SSV + SDeV + SMV + Transport

EPS = 59,000 + 12 + 21,000 + 7,600 = **87,612 Mj** ………….5.14

5.8.3.2.4 Case Study 1: Sustainable Disposal Value (SDV)

The value of energy 2200Mj, quoted in figure 5.15 shows the energy required to convert the end of life components into reusable raw material through recycling. This value is applied to the material and is entered as negative energy on the energy balance sheet.

Recycled material avoids extracting new raw material from the Earth. The process of recycling requires energy, which in the case of steel is 26% of Energy of Primary Source (EPS), Ashby [5.2].

This means that 74% of EPS is saved and can be harvested as End of Life (EoL), a positive energy entry on the energy balance sheet.

EoL Energy = EPS x 0.76

From equation 5.14

EoL Energy = 87,612 x 0.76 = **66,585 Mj** ..………..5.15

This is positive harvested energy can be added to the SGBV.

5.8.3.2.5 Case Study 1: Sustainable Giveback Value (SGBV)

SGBV is an addition of all the energy harvested and appears as positive energy on the energy balance sheet.

SGBV = SUV + SMaV + SDV …………5.16

SGBV = 52,560 + 87,612 + 66,585 = **206,757 Mj**

The data was plotted in the bar chart shown in figure 5.16, the data for which is presented as the energy balance sheet in figure 5.17.

It can be seen that although sourcing and manufacturing required significant inputs of energy, the application of the rotor ensured that there was minimal energy required during its Phase 2 Life Cycle. Because the flywheel system stored energy with negligible losses, there is zero negative SUV. The energy gleaned during its usage phase is simply the energy that would have been saved by the battery system which would otherwise have been lost due to the vagaries of the energy generation system.

Positive maintenance energy harvested was included at 87,612 Mj and was derived by assuming that this first maintenance period would extend the life by one service life further. The first life will always cost the value of Phase 1 Life Cycle Embodied Energy.

The energy audit therefore concluded that when the energy savings were compared to the energy input there was 116,625 Mj net saving as shown in the energy balance sheet in figure 5.17. This is a *Primary Audit* applied to the concept design. The net energy value should now represent a target to be improved further by the design team by applying appropriate design techniques, manufacturing methods, local sourcing, etc., thus reducing energy expenditure.

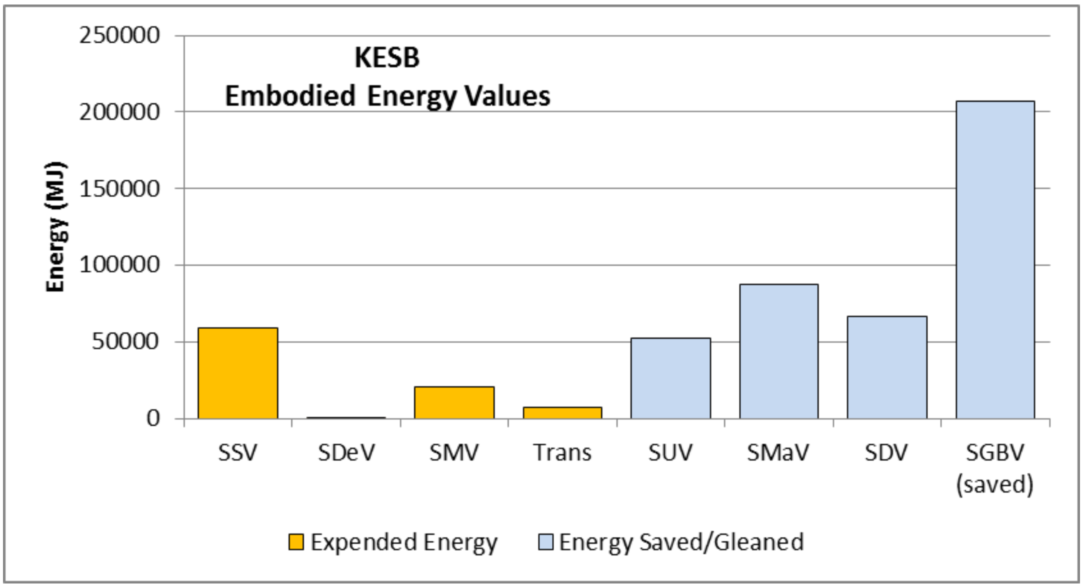
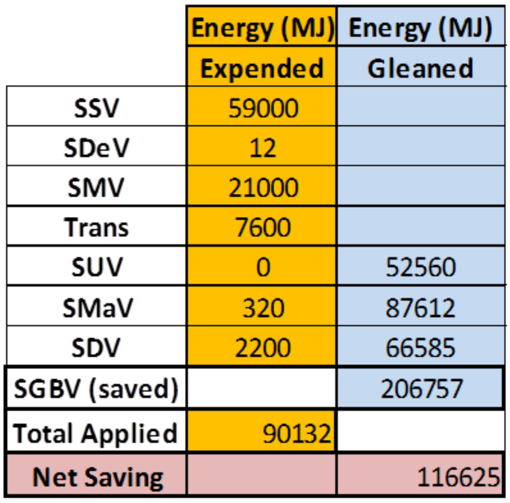


Figure 5.16: Whole Life Embodied Energy Values for a Flywheel Rotor



	Energy (MJ)	Energy (MJ)
	Expended	Gleaned
SSV	59000	
SDeV	12	
SMV	21000	
Trans	7600	
SUV	0	52560
SMaV	320	87612
SDV	2200	66585
SGBV (saved)		206757
Total Applied	90132	
Net Saving		116625

Figure 5.17: Data Represented in the Graph in Figure 5.16

The case study showed that a concept design can be analysed to create a sustainability measurement value based on Embodied Energy. The value thus derived may be based on historical data and projections and gives the design team an incentive to improve the product in the next design iteration.

In this case study the KESB does not require any energy input in its usage phase (SUV). In fact the KESB stores energy that would otherwise be lost. This can be applied to the positive column of the energy balance sheet as energy harvested.

The *Primary Audit* is intended to determine the possibilities with a new concept and can be used as a comparator with other similar products both within the same company and with those of competitors. The concept stage is a statement of functions and benefits of a product with a design that is often less than 50% specified. In this case the CES EduPack package was useful in giving an overview of the Embodied Energy the design team could expect. For more accurate estimates a more refined system is required. In a later stage of design the case study for the brick and block clamp, paragraph 5.8.4, CES EduPack was replaced by more accurate data provided by the TDCMS programme.

5.8.4 Case Study: Brick and Block Clamp: Final Energy Audit

A West Yorkshire company manufactures brick and block clamps similar to that shown in figure 5.18

Figure 5.18: Typical Brick and Block Clamp As Manufactured by HE&ALtd

(picture courtesy HE&A LTD, Sowerby Bridge, West Yorkshire)

The clamp is fabricated using a welding process from rectangular hollow section steel, black mild steel angle, and black mild steel plate. The manufacturing parameters are listed as follows:

Total mass =	250 kg.
Quantity/year	250
factory electrical energy/year	9.288 Gj
factory piped gas/year	Zero Mj
factory bottled gas/year	7590 Mj
design function energy proportion	(D_1) 1%

Note: The value of D_1 = 1% was derived by considering the energy used in the design office (heating, electricity, etc) and comparing the value against the factory overhead.

These values were inserted into the algorithm, a portion of which can be seen in figure 5.11. Though the algorithm was used, it was effectively applying the SSV equation 5.12 as follows:

$$SLV_{PH1} = (SEE \times P_M \times N_P) + (SDeV/N_P) + (SMV \times P_M \times N_P) + (STV \times P_M \times N_P) \qquad \ldots\ldots\ldots 5.12$$

The result for SDeV, SMV and STV was derived by the algorithm which was effectively the total manufacturing element of Embodied Energy per year the value of which was **1,913.9 Gj/year.**

The value of manufacturing element Embodied Energy per product is as follows:

$$EE/clamp = \frac{1{,}914 \times 10^9}{250} = \underline{\mathbf{7{,}656\ Gj/clamp}}$$

Figure 5.11 shows a portion of the algorithm which gives the Specific Embodied Energy (SEE) (joules/kg) for the sourcing of the material. This value was calculated to be 30.35 Mj/kg and requires adjustment so that mass of products and quantity of products per year could be considered. The value of SSV was therefore calculated using the first bracket in equation 5.12 as follows:

$$SSV = (SEE \times P_M \times N_P)$$

Where:
P_M = mass of each product (kg)
N_P = Number of products per annum
$SSV = (30.5 \times 10^6 \times 250 \times 250)$ = **1,906.3 Gj / year**

The Embodied Energy derived from manufacturing can now be combined with the Embodied Energy derived from material sourcing as described in equation 5.3, as follows

$$SLV_{PH1} = (SSV) + (SDeV + SMV + STV) \qquad \ldots\ldots\ldots..5.3$$

$SLV_{PH1} = (1,906 \times 10^9) + (1,914 \times 10^9)$ = **3,820 Gj / year**

Production Quantity = 250 clamps/year

SLV_{PH1} /clamp $= \frac{3,820 \times 10^9}{250}$ = **15.28 Gj/clamp**

This is the SLV_{PH1} and can be considered as a value to certify the Embodied Energy within each clamp.

5.8.4.1 Case Study 2: Energy Analysis Resulting in Modifications to the Manufacturing Process

The energy analysis encouraged the company's management to look at the usage of their energy. The initial breakdown was as follows:

Bottled Gas: Total usage		=	7,590	Mj/year
Heating	93%	=	7,058.7	Mj/Year
Manufacture	5%	=	379.5	Mj/Year
Shroud Gas Welding 2%		=	151.8	Mj/year

Heating was large space heaters heating the whole factory space.
Gas used in manufacture was directly applied to heat-shrink-fit components

Electricity: Total usage = 9288 Mj/year
Machine tools 30% = 2786 Mj/year
Welding 69% = 6409 Mj/year
Design 1% of O/all = 167 Mj/year

An analysis was conducted on the two highest energy uses: electricity used in welding and gas used in heating.

5.8.4.2 Case Study 2: Reducing Electrical Energy Used in Welding

The analysis discovered that continuous welds were being laid with a 6mm throat width which was far more than required for the strength of the component. Welding specifications were changed to intermittent welds (25mm weld and 25mm gap) with 3mm throat thickness. This reduced the length of weld by half and reduced the volume of weld by more than 50% resulting in an enormous savings in energy. In addition to a reduction in welding time of 85%, there was consequent reduction of electrical energy of 85%.

The energy saving was as follows:

Weld Energy = 6409 x 0.85 = **5,448 Mj**

Or an actual energy use of 6409 – 5448 = **961 Mj**

5.8.4.3 Case Study 2: Reducing Energy Usage for Heating

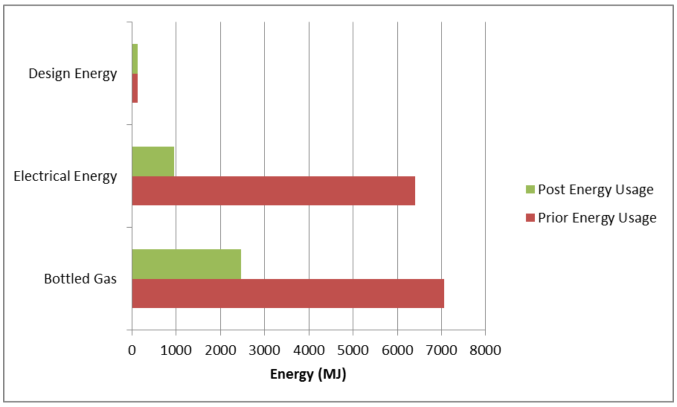
When analysing energy used in heating, it became fairly obvious that much of the generated heat rose to the roof of the factory where, due to the almost zero insulation, it was lost to the atmosphere. The management decided that a series of discrete rooms should be built around each operation. Each room could therefore be separately heated.

In practice this resulted is a 65% saving in gas used for heating.
The energy saving is as follows:
Heating Gas Total usage = 7,058.7 Mj/Year

Heating Energy saved = 7,058.7 x 0.65 = **4,588 Mj**

Or an actual energy use of 7058.7 – 4588 = **2,471 Mj**

The bar chart in figure 5.19 shows the original energy versus the energy required after modifications had been implemented. Design energy has been included to present a complete picture.



Key:

	Bottled Gas	Electrical Energy	Design Energy	Selected Energy Total
	(MJ)	(MJ)	(MJ)	(MJ)
Prior Energy Usage	7058	6409	167	13639
Post Energy Usage	2470.3	961.35	160	3591.65

Figure 5.19: Previous Selected Energy Parameters vs Selected Energy Parameters Post Modifications

5.8.4.4 Case Study 2: Energy / Cost Saving

The figures are proposed in figure 5.19 are analysed below with the aim of defining the refined $SLV_{Phase\ 1}$ for the clamp as it leaves the factory

Prior Energy Usage = 13,639 Mj/year

Post Energy Usage = 3,592 Mj/year

Energy Saving = 13,639 - 3,592 = **10,047 Mj/year**

Cost Saving = $\frac{10{,}047 \times 0.2}{3.6}$ = **£ 558 / year**

Based on a UK Energy Cost of £0.2 / KWh …………..from Compare my solar [5.7]

5.8.4.5 Case Study 2: Manufacturing Embodied Energy Value (Recalculated)

Prior manufacturing = 15.28 Gj/clamp

Saving per product = $\frac{10{,}047}{250}$ = 40 Mj/clamp

New $SLV_{Phase\ 1}$ = 15,280 – 40 = **15,240 Mj/clamp**

Although the saving with electrical welding energy was direct and effectively cost nothing to apply, the implementation of the heating policy was rather different in that it required an investment to create the discrete rooms where the payback period would be approximately 18 years. Savings with the welding practice were used to help offset the investment cost and bring the overall payback period from the analysis and implementation of recommended changes down to 8 years.

5.8.4.6 Case Study 2: Benefits

The following benefits are potentially realized by:

- reduction in applied energy
- reduced embodied energy per unit
- reduced welding time leading to greater throughput
- reduced costs per unit
- reduced factory energy requirement
- reduced factory costs
- increased profitability (lower costs and quicker throughput)

Normally the saving of energy is symbiotic with reducing cost, but sometimes saving energy requires capital investment as shown in the case study. Since companies have to survive in the commercial world, even with realization that saving energy is important the dilemma is how much money to invest in saving that energy. In the case of HE&A Ltd, some of the capital cost was offset against the energy savings by improving welding technique. Payback of around eight years was deemed to be acceptable. Perhaps more importantly, the exercise focused the management on energy saving and had the effect of influencing future policy towards the reduction of energy in new designs.

5.8.4.7 Case Study 2: Whole Life SLV Calculation (SLV $_{Phase\ 1}$ + SLV $_{Phase\ 2}$)

The case study so far has been to define a value for SLV $_{\text{Phase 1}}$ but it is also possible to make a projection to define the Embodied Energy relating to SLV $_{\text{Phase 2}}$

5.8.4.8 Case Study 2: SLV Phase 2 Profile Analysis

Define Expected Input Energies

It has been assumed that the entire clamp is steel and that it will be recycled in its entirety. The elements within Phase 2 Life Cycle include usage, maintenance and recycling.

1. Usage
2. Maintenance
3. Recycling

Energy Analysis (Input Energy)

1. Usage

The brick and block clamp is passive during usage requiring zero energy input.

2. Maintenance (Energy Applied by the Factory Overhead)

The following parameters apply to maintenance:

maintenance period	10 days/year
maintenance frequency	once per year
length of maintenance period	10 years

The energy applied to maintenance can be taken from the factory energy overhead.

Factory overhead per year 1,914 Gj/year factory overhead

$$\text{Maintenance Energy} = \frac{\text{factory o/head}}{\text{No. Clamps}} \times \frac{\text{No.days}}{365} \times \text{frequency} \times \text{Maintenance period}$$

$$M_E = \frac{1{,}914 \times 10^9}{250} \times \frac{10}{365} \times 1 \times 10 = \underline{\mathbf{2.1\ Gj}}$$

3. Recycling Energy (Energy Required to Convert Components into Recycled Raw Material)

Recycling parameters are as follows assuming materials are steel:

Unit Mass	$m = 250kg$	
Energy of Primary Source	EPS = 30.5Mj/kg	
Recycled energy proportion	E_P 26%	AISA [5.14]

Recycling Energy/product $R_E = m \times EPS \times E_P$

$$RE = 250 \times 30.5 \times 10^6 \times 0.26 = \underline{\mathbf{1.98Gj}}$$

5.8.4.9 Case Study 2: Define Expected Energy Savings

The elements During the Phase 2 Life Cycle energies might be saved or harvested are as follows:

4. Maintenance (Energy Harvested Through Maintenance and Improved Longevity)

Parameters

Standard guaranteed life	L_G	= 2 years
Extended Life	E_L	= 10 years
Original SLV_{PH1}	SLV_{PH1}	= 1,913.8 Mj/clamp
Life extensions	LN<u>o</u>	= (10/2) – 1 = 4

If the standard guaranteed life is two years and the extended life is ten years then savings have been made for 4 standard clamp lifetimes.

Embodied Energy saved by extending clamp life = EES

EES = LNo x SLV_{PH1} = 4 x 15240 x 10^6 = **60.96 GJ**

5. Recycling Energy R_E (energy saved by recycling to gain new raw material)

Parameters

Energy of Primary Source	EPS = 30.5 Mj/kg	
Mass of clamp	m = 250kg	
energy % saved by recycling	Es = 74%	AISA [5.14]

R_E = EPS x M x Es = 30.5 x 10^6 x 250 x 0.74 = **5.64 Gj**

5.8.4.10 Case Study 2: Energy Accounting

The energy input and output values across the life cycle for the brick and block clamp can be seen in figure 5.20. It shows that energy is input across the four elements of Phase 1 Life Cycle and totalled 15,668 Mj. Actual values can be seen in the Energy accounting tally in figure 5.21.

Energy was also expended in terms of maintenance and disposal elements to a value of 4,080 Mj. From the above analysis and from figure 5.21, it can be seen that due to sustainable maintenance and disposal 66,600 MJ were saved. This was a net energy saving within those two elements of **62,520 Mj**.

When all the energy expenditure and savings were tallied across the whole life cycle of the brick and block clamp, it can be seen in figure 5.21 that there was a net saving of **46,852 Mj**.

Efforts to reduce the Embodied Energy can continue by treating the net savings first realized as a goal to be surpassed. One opportunity to improve the savings still further is to increase longevity through shorter maintenance intervals, more robust bearings, etc.

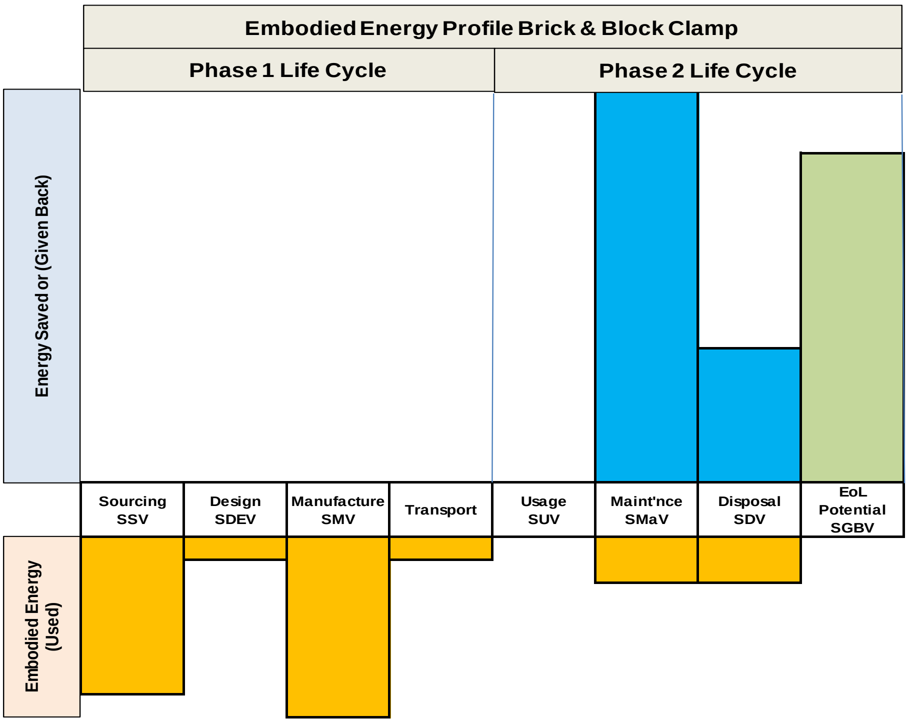


Figure 5.20: Total SLV for Brick and Block Clamp (SLV $_{\text{Phase 1}}$ + SLV $_{\text{Phase 2}}$)

Condition	Energy (MJ) Expended	Energy (MJ) Gleaned
SSV	7625	
SDeV	167	
SMV	7656	
STV	220	
SUV	0	0
SMaV	2100	60960
SDV	1980	5640
SGBV		66600
Totals	19748	66600
Net Total		46852

Figure 5.21: Energy Accountancy Values for Total SLV for Brick and Block Clamp

The case study showed that an energy value can be accurately derived as the product leaves the factory. This is an accurate measurement of the Embodied Energy possessed by the brick and block clamp as it passed through all the elements of Phase 1 Life Cycle. The value thus derived is based on accurate, measured data from the company overhead and accurate data from the materials and components used in the product. The net Embodied Energy value can be used by the design team to improve the next design iteration. The value can also be compared to and should be an improvement on the *Primary Audit* value. Furthermore, the final Embodied Energy value can be used by the marketing team as an indicator of efficient energy usage. In this case study the brick and block clamp is a passive device requiring no energy input in its usage phase (SUV). Neither does the brick and block clamp generate energy during the SUV period. There are zero energy entries on both positive and negative columns of the energy balance sheet.

5.9 Phase 2 Life Cycle: Determination of Input Energy and Harvested Energy

5.9.1 Objective of Phase 2 Life Cycle Energy Measurement

The objective of Phase 2 Life Cycle Energy Measurement is to produce an energy audit model based on Embodied Energy. The resulting energy balance sheet will add the measurement of Phase 2 Life Cycle Embodied Energy to the Embodied Energy input into the product during Phase 1 Life Cycle.

Phase 1 Life Cycle energy has been defined in previous sections of this chapter. Accurate energy measurements were taken to cover the energy input during Phase 1 (sourcing, design, transport and manufacture). The Phase 2 energy data was estimated and extrapolated using historical data and future, idealistic product usage. It is necessary to define a specific measurement process that considers energy input and energy which can be harvested in Phase 2 of the product life cycle. The complex and unpredictable nature of the Phase 2 Life Cycle creates a complex situation where the vagaries of product use, maintenance and disposal need to be considered.

When the product leaves the factory and is used by the consumer, it is recognised that the consumer may not use or maintain or disposal of product precisely as the designers intended. However energy measurements and a great deal of other product life usage data are required during all the elements of the Phase 2 Life Cycle so that it can be fed back to the design function to influence further product iterations. The total design control management can also use the data for further life cycle.

Relatively high value products such as vehicles, trucks, machine tools, etc., are programmed with a maintenance schedule. Dixit and Culp [5.40] suggest that maintenance is a major part of buildings and acknowledge that some components will end their useful life before the main products which, in this case are buildings. They also put forward the suggestion that maintenance personnel need to feed back to the architect information relating to the function and life expectancy of the components used in the buildings. They suggest that a maintenance schedule should be applied if this has not already been implemented.

This research project follows the approach taken by Dixit and Culp [5.40] Periodically the product is taken out of service and restored to full serviceability through the maintenance process. These periodic maintenance and occasionally refurbishment periods present an ideal point in the life cycle to replace worn components, reuse components, recycled old components, but it is also an ideal point to collect vital management and energy information that can be used for Embodied Energy measurement.

The Phase 2 Life Cycle Embodied Energy measurement process is therefore applied when maintenance and refurbishment processes occur. The normal product life cycle has therefore been modified to include maintenance with a value of SMaV as shown in figure 5.3. Also shown in figure 5.3 is the Sustainable Giveback Value (SGBV), which is an energy accounting value comprising energy saved, harvested or generated during Phase 2 Life Cycle. This is positive energy and can be used to offset energy input During Phase 1 and Phase 2 Life Cycle.

After a product is maintained, it is returned to service which avoids procuring a new product which is imbued with its own Energy of Primary Source (EPS) (SLV_{PH1}). EPS is the value of Embodied Energy which is applied to a product during the creation process from sourcing through manufacture. The maintenance process avoids engendering more EPS, the value of which can be harvested to be included as positive energy in the energy balance sheet. Some products such as photovoltaic panels may generate their own energy, which can also be applied to the energy balance sheet as positive energy. The maintenance process requires energy to be injected into the product, and will appear as negative energy on the balance sheet. The value of this energy is likely to be minimal when compared to the EPS. The phase 2 energy balance accounting model generates information and calculates several energy parameters to enable positive and negative energies to be compiled with the result of a net energy figure. The positive energy harvested is SGBV and the negative energy is Phase 2 Life Cycle Embodied Energy. The combination of the two values into the net energy figure gives SLV_{PH2}.

5.9.2 Introduction to Sustainability Centred Maintenance (SCM)

Maintenance and refurbishment are usually well established procedures within the life cycle of most products and stimulate reliability as the main focus. This saves costly failures, unserviceable products and above all ensures safety.

A maintenance and refurbishment programme is an excellent vehicle to convey a sustainability viewpoint and refocuses the emphasis on reducing Embodied Energy. The process can be termed “Sustainability Centred Maintenance” SCM. SCM introduces an energy accounting and information feedback system that considers all the energy input to a product during its life and all the energy which has been saved due to maintenance and refurbishment applications.

Before a detailed analysis can be conducted under SCM, several assumptions have to be made. One major assumption is that maintenance procedures prolong the life of a product, thus avoiding the Embodied Energy involved in the procurement of new products. This allows the accounting system to harvest the energy saved. Further assumptions can be seen in appendix A3.

5.9.3 The Cyclic Nature of the Phase 2 Life Cycle

The product enters the usage cycle and is in-service for a certain length of time after which it enters the first maintenance process. Once maintained the product is returned to the usage element to perform its second in-service period. This cycle continues until eventually after, perhaps the fifth in-service period (5th Usage Life [UL]) the product needs a major overhaul and enters the refurbishment process where the product is stripped to its basic components. Sacrificial parts are removed and replaced by new parts. Part worn components are also removed, being replaced by new components.

The aim of refurbishment is to return the product to the usage cycle in an “as-new” state of serviceability.

The cycle of *usage-maintenance-usage-maintenance-refurbishment-usage* is treated as a single cycle where refurbishment is the end of one cycle and the beginning of the next as indicated below in the sequence list and in the diagram in figure 5.22.

1. manufacture
2. primary usage
3. maintenance (usage-maintenance cycle may happen several times)
4. recycle sacrificial components
5. refurbishment (almost new, the product re-enters the usage element once again) recycle sacrificial components and reuse those components possessing residual life
6. second usage cycle after refurbishment
7. maintenance (usage-maintenance cycle may happen several times)
8. second refurbishment (this may happen several times depending on the product)
9. recycle (at the end of its life the product and/or its components are sent to recycle)

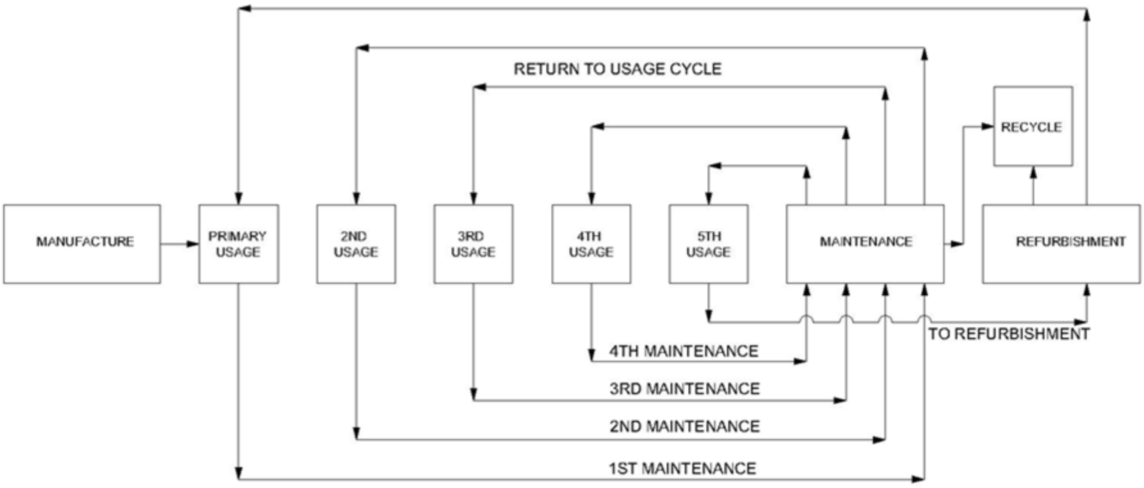


Figure 5.22: Detail Process of the Usage-Maintenance/Refurbishment Cycle

After maintenance the product is returned to its second usage element where it performs its service for another service life. Since maintenance has extended the product life it can be said that a single value of EPS has been saved. The energy used in the maintenance process is minimal when compared to the saving of the EPS, but still needs to be added as negative energy to the energy balance sheet. After performing its serviceable function for a length of time the product is then returned to the second maintenance process.

The usage/maintenance cycle may happen several times but eventually the product will need major refurbishment which is much more intensive than the maintenance process and requires a certain level of energy input to accomplish although this energy input should be accounted for, it is small compared to the energy that has been saved through prolonging the product life. The cycle can be seen much simplified in figure 5.23.

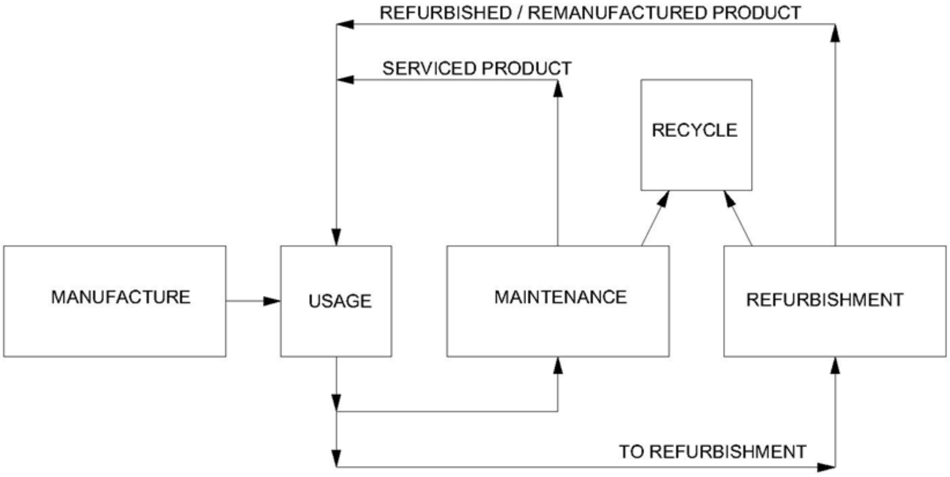


Figure 5.23: General Process Usage Maintenance/Refurbishment Cycle Feed Forward and Feed Backward of Components

The above models in figures 5.22 and 5.23 merely show the general process of usage, maintenance and refurbishment, however components are fed back into the usage element of the life cycle and other parts at the end of their life are fed forward into the recycle process.

The refurbishment process removes the sacrificial components to be recycled but the refurbishment programme also removes components which still possess residual life. These are then fed backwards for reuse into the maintenance process so that they can be reused for at least one serviceable life. The refurbishment engineers need to define the residual life of reusable components.

5.9.4 Energy Accounting (Formulation of the Energy Balance Sheet)

In the models shown above, component flow has been used to define the cycles but energy is required to fulfil each process and therefore the energy accounting cycle lies alongside the mass flow models thus presented. This can be seen in figure 5.24 and shows the role of energy within the feed forward and feed backward of products and components.

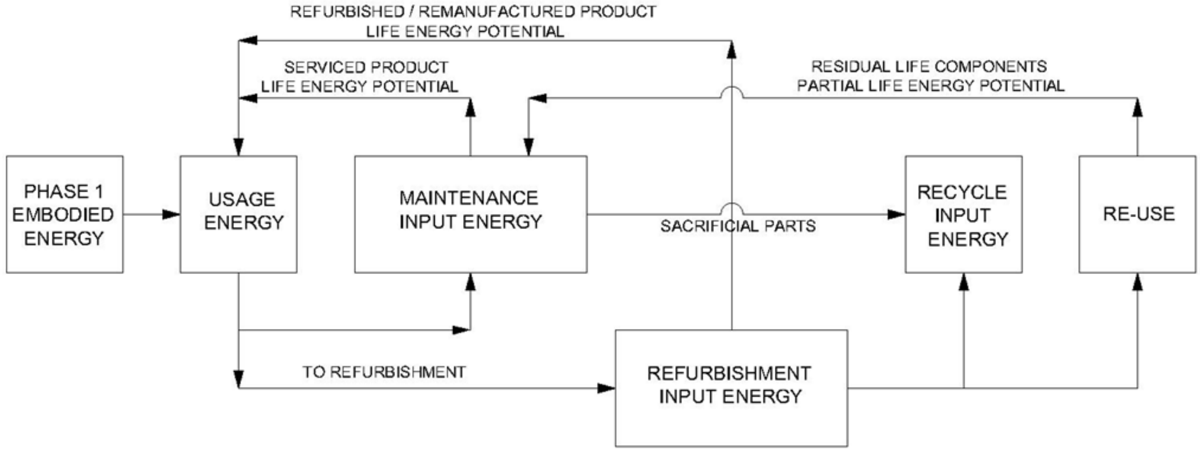


Figure 5.24: Energy Input to the Usage-Maintenance-Refurbishment Cycle

5.9.5 Explanation of Figure 5.24 Elements

5.9.5.1 Phase 1 Embodied Energy

The Embodied Energy within the product, as it leaves the factory, is the result of all the energy applied during material sourcing, design, manufacturing and any incurred in transport.

5.9.5.2 Usage Energy

The energy applied whilst product is in use may vary between products. A passive device such as a solar panel or a gearbox (when taken in isolation) may not use energy. A solar panel can actually generate energy. A vehicle, on the other hand, uses chemically stored energy (petrol, diesel during use. Energy required between service intervals should be calculated to give a used Embodied Energy value.

As an example, a truck has service intervals of around 10,000 miles (16,130km or 16,130,000m) The energy coefficient for the truck is the energy used per m for a specific size of truck.

14 t truck energy Coefficient = 5.26 Mj/m Kojima [5.15]

Find Energy Used by Truck between Service Intervals

Energy used = distance x Coefficient = $16{,}130 \times 10^3 \times 5.26 \times 10^6$ = **8,484Gj**

5.9.5.3 Maintenance Process Energy (M_E)

Maintenance may take a few days (depending on the product) and the energy thus used should be attributed to a portion of the factory overhead taking into consideration the number of days the factory is open (365 days in this case) and the number of products serviced per year. The latter value may be converted to mass (kg) if multiple, variant products were serviced.

$$M_E = \frac{\text{Annual factory energy overhead} \times \text{No days for maintenance}}{\text{Annual product throughput} \times 365}$$

Since maintenance returns the product to the usage process in a serviceable condition the product's life has been extended. More appropriately the procurement of a new product has been avoided thus saving a single value of EPS which can be combined within the energy accounting system as positive energy (energy saved).

The usage-maintenance cycle may take place several times and with each cycle a small amount of energy will be using maintenance and perhaps a larger amount of energy will be saved by avoiding new product procurement. The maintenance process removes sacrificial parts such as bearings and seals but eventually non-sacrificial parts may begin to wear and refurbishment is required.

5.9.5.4 Refurbishment

Refurbishment is a deeper, longer process, often taking weeks rather than days. Energy required in refurbishment is therefore greater than that required for maintenance, but the use of a proportion of the factory overhead is still valid and can be included in energy accounting as negative energy (energy used).

$$R_E = \frac{\text{Annual factory energy overhead} \times \text{No days for Refurbishment}}{\text{Annual product throughput} \times 365}$$

The act of refurbishment returns the product to the usage cycle in an "as-new" condition thus avoiding the procurement of a new product and saving a single value of EPS.

The refurbishment process creates what is, effectively a new product allowing the usage-maintenance cycle to continue once again through several cycles, at the end of which the product will again be refurbished.

5.9.5.5 End of Life

The product will eventually become so worn and unserviceable that the refurbishment process is unable to return the product to a serviceable condition. It is also possible that it may be too costly to return the product to serviceability, or that the product has been surpassed by new technology.

At the end of a product's life, energy will be expended in order to separate and recycle products. This energy is likely to be a relatively low value but it should be included as a proportion of the factory's overhead just as energy values are derived for maintenance and refurbishment.

Idealistically everything should have the potential to be recycled but realistically there will be items which are not cost effective to recycle. These items can potentially be incinerated thereby extracting calorific energy.

5.9.5.6 Reusable Components (residual life energy)

The aim of the refurbishment programme is to return the product to service as if it were a new product. The refurbishment programme replaces part worn components with new components, but the part worn components still possess residual energy. Such components can be deemed “fit to reuse” if they are expected to be serviceable for at least one period of usage where the next maintenance period will remove the completely worn component (end of life component) and feed it forward to recycling. The residual life energy should be considered as a bonus since every reused component would normally have been recycled after having been removed from the main product. The value of residual life energy can therefore be added to the energy accounting system as positive energy.

5.9.6 Calculation of Residual Life

Residual life calculation may be straightforward for some components. For instance, life of bearings may be calculated based on already accrued rotational cycles and loadings compared against design expectations. There is always a risk that a part worn component may fail prematurely. For example, some would argue that bearings should be removed and recycled at every maintenance instance to prevent failure in the middle of a cycle. This is normally considered to be good maintenance practice.

5.9.6.1 High Risk Reuse

Often the cost of maintenance and parts replacement is proportional to the amount of energy expended. The frugal maintenance engineer may clean and reuse components thinking that he is saving money (energy), but should that component fail in service the cost might be extreme when considering lost production and unscheduled maintenance. A reused, critical, high risk component failure such as that of an aircraft engine bearing may prove fatal. Policies should be installed to list all high risk components and specify an appropriate maintenance/removal schedule. The example below examines a practical high risk reuse case study and highlights the risks of reuse of critical components.

5.9.6.2 Example: Offshore Wind Turbine

Large bearings may be expensive to replace so it is tempting to reuse bearings if they still possess residual life, but replacement costs need to be weighed against the cost of downtime and risk of failure. The following example of a wind turbine bearing shows the monetary risks involved in using a component to the end of its life.

Offshore wind turbines, see figure 5.25 have a generating capacity of, typically, 5 MW that can reach as much as 8 MW according to Wind Power Magazine [5.17]. Donnelly [5.16] suggests that offshore wind farm maintenance can cost as much as 25% of the original procurement cost but also suggests that an average maintenance figure is around 0.03 Euro kilowatt-hour.

Calculation of Typical Maintenance Cost
typical generation capacity = 5 MW
average maintenance cost = 0.03 Euro/kilowatt-hour
time period = 1 hour

1 kWh = 1 kW every hour = 0.03 Euro service cost

Maintenance cost = $5 \times 10^6 \times 0.03$ = **<u>150,000 Euro</u>**

The cost of a bearing could be as much as 10,000 Euro which is a small cost relative to the loss of energy generation and unscheduled maintenance should a bearing fail.

Figure 5.25: Offshore Wind Generator Farm, Sheringham Shoal, UK [5.18]

Energy evaluations follow the cost evaluation in that the energy expended in replacing the bearing is greater than the Residual Embodied Energy (REE), therefore it is energy efficient to replace the bearing during a scheduled maintenance period than to try and eke out the remaining energy and risk failure between scheduled maintenance sessions.

5.9.6.3 Component Reuse (Low Risk)

Some sacrificial components may be considered low risk such as vehicle suspension system components, rubber grippers, part worn tyres, etc. These may be reused with relative confidence since even their premature failure would not prove to be catastrophic to the system or expensive to replace.

The product type will determine which components are able to be reused with consideration of safety, cost and energy harvesting. Many vehicle breakers take apart the end of life vehicles in order to retrieve part worn components. These components include almost anything that can be removed without damage, such as wing mirrors, boot lids, bonnet lid, tyres, suspension systems, latches, side windows, etc. The list is extensive.

In a normal maintenance environment, when part worn components are removed; decisions need to be made as to whether these components should be recycled or reused. A formal decision method can be seen in figure 5.28 for the brick and block clamp components shown in figure 5.26 and figure 5.27

Figure 5.26: Brick and Block Clamp courtesy HE&A Ltd

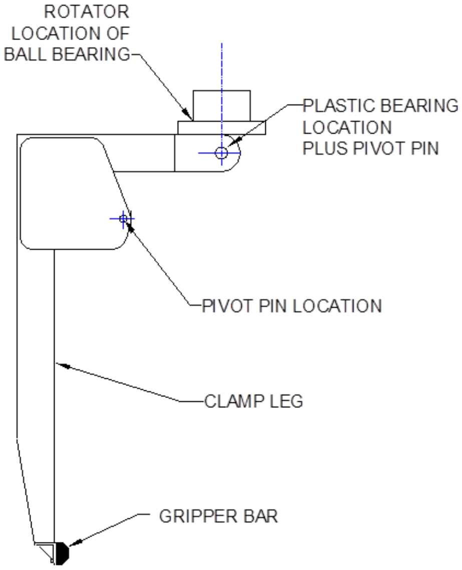
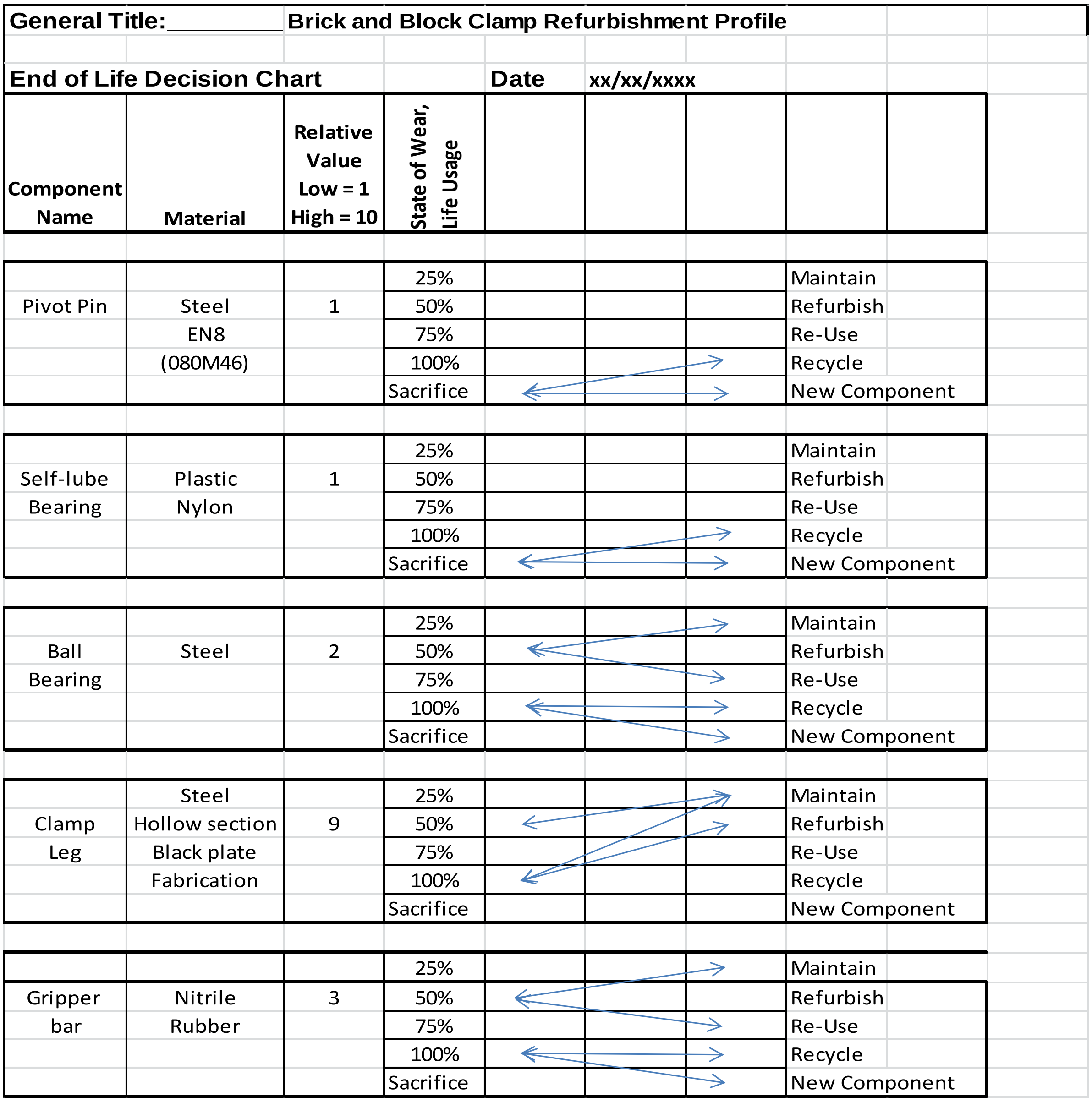


Figure 5.27: Schematic of the Brick and Block Clamp Courtesy HE&A Ltd

The chart shown in figure 5.28 shows the maintenance decisions and indicates how various components may be redirected on removal from the main product. This becomes a record that includes part numbers which can be used as feedback to the TDCMS and design team.

Analysis of the chart in figure 5.28 shows that the smaller sacrificial parts are often discarded whilst the larger components are repaired and reused. These decisions are often made on the basis of cost, but *reuse prudence* should also be a consideration as indicated by the example in section 5.9.6.2.



General Title:_________ Brick and Block Clamp Refurbishment Profile

End of Life Decision Chart Date xx/xx/xxxx

Component Name	Material	Relative Value Low = 1 High = 10	State of Wear, Life Usage				
			25%				Maintain
Pivot Pin	Steel	1	50%				Refurbish
	EN8		75%				Re-Use
	(080M46)		100%				Recycle
			Sacrifice				New Component
			25%				Maintain
Self-lube	Plastic	1	50%				Refurbish
Bearing	Nylon		75%				Re-Use
			100%				Recycle
			Sacrifice				New Component
			25%				Maintain
Ball	Steel	2	50%				Refurbish
Bearing			75%				Re-Use
			100%				Recycle
			Sacrifice				New Component
	Steel		25%				Maintain
Clamp	Hollow section	9	50%				Refurbish
Leg	Black plate		75%				Re-Use
	Fabrication		100%				Recycle
			Sacrifice				New Component
			25%				Maintain
Gripper	Nitrile	3	50%				Refurbish
bar	Rubber		75%				Re-Use
			100%				Recycle
			Sacrifice				New Component

Figure 5.28: Reuse/End of Life Decision Chart [5.6]

5.9.7 Residual Life Evaluation

There are two elements to residual life evaluation:

- estimation of residual Embodied Energy for energy accounting purposes
- estimation of residual component life based on maintenance cycles, wear rate, etc.

5.9.7.1 Residual Embodied Energy evaluation can be based on the energy of primary source (EPS). If a component takes 100 Mj to manufacture and it is estimated that 50% of its life has been used then there is 50 Mj residual Embodied Energy remaining. The component can be reused or recycled. Reuse of the component should use most or all of the residual Embodied Energy, whilst recycling the component means that any residual Embodied Energy will be lost in accounting terms.

5.9.7.2 Residual component life evaluation depends upon the component and its use. If it is to be reused, then it should be able to fulfil at least one lifetime of usage prior to the next maintenance process *(Usage Life) (UL).* It is easy to envisage the maintenance engineer estimating the residual life of a component without using any predictive methodology. The application of judgement or pure guesswork by an individual carries an element of risk of component failure during use, no matter how skilled the person may be, even if that judgement is based on previous statistical analysis. Wherever possible, the life evaluation of a component should be a calculated value.

The reuse of a bearing can be calculated based on duty cycles already accrued compared to the future duty requirement. The reuse of a simple rubber gripper may merely require a wear depth measurement. These wear parameters will have been specified at the design stage. The role of the designer is to calculate design life and specify when certain components should be changed by the maintenance team. It is possible that the product may not be used as the designer specified and it falls to the maintenance staff to inspect components making on-the-spot decisions for reuse or recycling whilst referring to design life recommendations. If there is any doubt as to the serviceability of a component, it should be removed and recycled.

The design function will also specify that some components, such as seals, should never be reused whilst others, such as hydraulic motors, may be replaced by refurbished motors. The role of the design function here is to remove elements of doubt from the maintenance decision team. The unpredictability of use by the consumer, however, means that there has to be some flexibility built in to the maintenance decision process.

5.9.8 Phase 2 Life Cycle SCM Audit Approach

The end of life decision chart shown in figure 5.28 is useful but it does not show the result of the end of life decisions, nor does it account for residual Embodied Energy or the Embodied Energy of new parts, nor several other factors including loss of residual embodied energy when parts are recycled. An accurate appraisal of Phase 2 Life Cycle energies input and energies harvested requires consideration of several data types, the manipulation of which have to be driven by the sequence of maintenance process events. Maintenance and refurbishment practices are core to this process since both represent ideal points in the life cycle to take measurements, derive usage information, and calculate the energies remaining, used and harvested. When the SCM audit is taken at maintenance intervals throughout the life cycle, a “snapshot” of the product performance can be gathered. When the major components are recycled, at the end of a product’s life this “snapshot” then becomes a full life cycle analysis of the product.

The SCM audit analysis flowchart is shown in figure 5.29 and indicates five columns; information, process, generated data, calculated data and energy balance sheet. The energy balance sheet is subdivided into input and harvested energy, the sum of which culminate in input energy throughout the life cycle, Sustainable Life Value (SLV Ph1 & Ph2), and the Sustainable Giveback Value (SGBV)

The audit's approach is driven by the maintenance/refurbishment process, elements of which have to take place before information can be generated and calculations performed. During the life cycle process information is generated, including number of installed parts, accrued Usage Lives (UL's), number of parts used, number of recycled parts, recycled steel mass and recycled other material mass.

The generated data can then be combined with original information such as, Energy of Primary Source (EPS) so that calculation of positive and negative energies can be performed. For instance, the Embodied Energy for the number of installed parts can be calculated and represents energy input to the product since each part will possess its own EPS (Embodied Energy). This energy value will appear as negative energy on the balance sheet.

A major contributor to the positive energy is that of "Reused Cumulative EPS". This harvested energy is derived through the product being returned to usage after being serviced by the maintenance process, thus avoiding the procurement of new products. The energy thus saved can therefore be added to the positive side of the balance sheet.

Remaining Residual Embodied Energy is added to the positive side of the balance sheet since this Residual Embodied Energy (REE) is that energy remaining in each component. This is linked to the design life of each component. For instance, when the design life of a component is only half complete, the component should have used only half its original EPS, which means that the REE remaining is 50% of the original EPS. If the component is reused until its expected life has expired, the REE will be zero. If the component is recycled before its design life has expired then the remaining residual energy will be lost. This aspect is considered as "Recycled REE" (H_{REC}) and will appear as negative energy on the balance sheet.

The remaining calculations relate to the energy required to convert component materials into raw material for recycling. This includes information input such as the proportion of 26% of EPS for the rendering of steel scrap to usable raw steel material. Other materials such as plastic, rubber, glass can be treated in similar fashion.

The end of life decision chart shown in figure 5.28 has now been modified with a great deal of detail and its position in the life cycle where measurements and decisions can take place. These modifications convert the end of life decision chart into SCM energy measurement and decision/recording system.

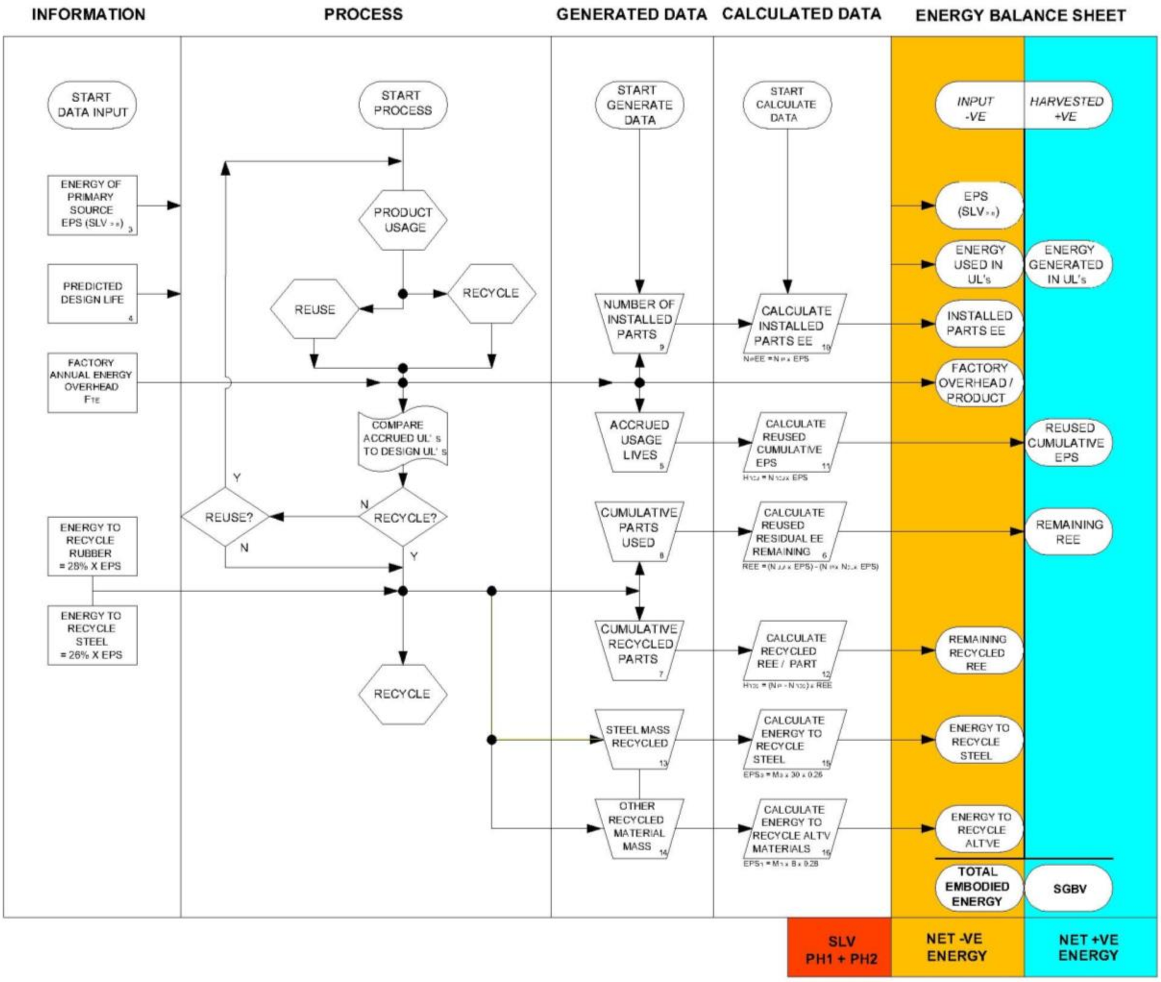


Figure 5.29: Flowchart for SCM Audit Measurement System

Note! The number in the bottom right-hand corner of each Flowchart element refers to the column number heading in the algorithm chart in figure 5.30.

5.9.9 Sustainability Centred Maintenance Algorithm (SCMA)

The measurement of Phase 2 Life Cycle Embodied Energy is complex and increases in complexity when considering the variability in a component's design life, usage or abuse and many other aspects of a product which is outside the direct influence of the TDCMS and the design team. An algorithm has been devised that can absorb and manipulate these complex data inputs. The advantage is that measurements are taken and information is gleaned as the product is maintained or refurbished. This is practical, real-life, in-the-field data and can be used to give accurate feedback information to the TDCMS and also to create energy data that will be used in the energy balance sheet.

The SCM algorithm chart shown in figure 5.30 is derived from the parts list for the product and should include a full description of each component plus drawing numbers or parts numbers if the components are bought from an outside source. The original parts list for the product should be extended to accommodate the computation of values necessary for the energy balance sheet.

During the design process, life expectancy will have been calculated and specified for each component, thus giving maintenance engineers a guide for the design life of each component. This will ensure recycling/reuse decision-making is based on design criteria rather than pure judgement. The modified chart includes several extra parameters laid down by the design function which include:

1. product life expectancy expressed in Usage Lives (UL) cycles between maintenance/refurbishment periods. The gearbox had a total product life of 15 UL's.
2. number of life cycles each individual component is expected to survive. The taper roller bearings in figure 5.35 have an individual life of 2 UL's

The energy balance sheet requires the computation of several parameters which take into account the number of usage lives accrued, the number of components reused or recycled and the energies involved. Furthermore the energy required to recycle various materials is also included. Parameters are defined below. Note: The numeration of paragraphs in 5.9.9.1 represent column heading numbers in the Sustainability Centred Maintenance Algorithm (SCMA), figure 5.30.

5.9.9.1 Definitions of Chart Headings, figure 5.30

1. *Decision:* the decision of the maintenance engineer to recycle or reuse a component based on predicted design life and life in service.

2. *End of life status*: the fate of the component; either reused, recycled or maintained

3. *Energy of Primary Source (EPS*): Embodied Energy within individual components, comprising sourcing, design and manufacturing energies. Information supplied by the design function. EPS is used in Phase 2 Life Cycle to distinguish between SLV_{PH1} used as the total Embodied Energy product in Phase 1 Life Cycle.

4. *Design life usage cycles (N_{DL}):* expected life of each component specified by the design function

5. *Number of usage lives accrued (N_{ULA})* : entered by the maintenance engineer at each maintenance interval, this is the cumulative number of usage lives experienced by the product/component.

6. Residual Embodied Energy (REE): energy residing each component after usage lives have been experienced.

REE = Energy within Original Parts - Used Lives Accrued Embodied Energy ………..(5.16)

$$REE = (N_{IP} \times N_{DL} \times EPS) - (N_{ULA} \times EPS) \text{ (joules)} \qquad \text{………..(5.17)}$$

7*. Recycled Parts Cumulative Number (N_{REC}):* number of parts forwarded for recycling, recorded by the maintenance engineer

8. *Reused parts cumulative number (N_{REU}):* number of parts fed backwards for reuse. Entered by the maintenance engineer

9. *Cumulative Number of Installed Parts(N_{IP}):* additions made and entered by the maintenance engineer

10. Installed parts Embodied Energy ($N_{IP}EE$): The Cumulative Embodied Energy from all components

$N_{IP}EE$ = Number of Installed Parts x Energy of Primary Source ………..(5.18)

$N_{IP}EE = N_{IP} \times EPS$ (joules) ……….(5.19)

11. *Cumulative energy +ve reused (H_{REU}):* energy harvested by reusing components

H_{REU} = Number of Reused Parts x Energy of Primary Source …………(5.20)

$H_{REU} = N_{REU} \times EPS$ (joules) …………(5.21)

12. *Cumulative energy -ve recycled (H_{REC}):* energy lost by recycling components still possessing residual energy

H_{REC} = (Number of Installed Parts - Number of Recycled Parts) x Residual Embodied Energy ……..…(5.22)

$H_{REC} = (N_{IP} – N_{REC}) \times REE$ (joules) ..………(5.23)

13. *Steel mass (kg) (M_S):* mass of individual steel components: specified by design or completed by the maintenance engineer

14. *Other mass (kg) (M_R):* component mass of other materials: specified by design or completed by the maintenance engineer (M_R Rubber), (M_P Plastic)

15. *Energy needed for recycling steel (EPS_S)*: recycling steel requires 26% of EPS (EPS_S)

EPS_S = Component Mass x Energy of Primary Source x Energy Needed for Recycling ………(5.24)

$EPS_S = M_S \times EPS \times 0.26$ (joules) ……..(5.25)

16. Energy needed for recycling other (EPS_R): Recycling rubber requires 8.1% of EPS

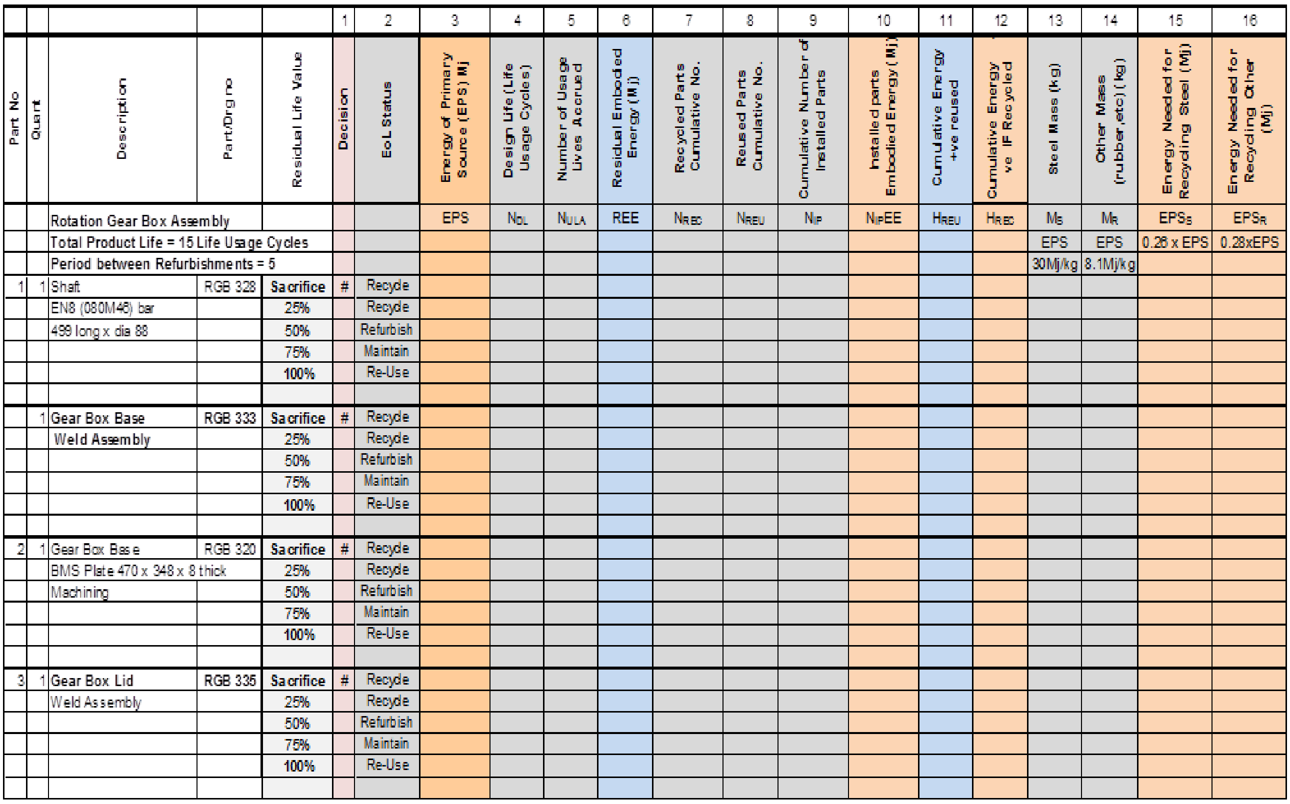
EPS_R = Component Mass x Energy of Primary Source x Energy Needed for Recycling ……..(5.26)

$EPS_R = M_R \times EPS \times 8.1$ (joules) ……..(5.27)

The End of Life (EoL) decision will determine the direction of the component, to recycling or reuse. The fate of the Residual Embodied Energy (REE) also resides in the SCM decision chart. If a component retains some residual life yet is deemed unserviceable, it is therefore sent to recycling and its REE is lost. This will register on the energy balance sheet as negative energy. Once the end of life decision has been made the REE can be determined and combined with the energy balance sheet.

5.9.9.2 Cumulative Parts Recycled/Reused

During the lifetime of the product, several parts, such as bearings, might have been removed and replaced. The tally of components is entered in the column headed "Cumulative Parts Recycled" or "Cumulative Parts Reused" depending on their direction when the EoL decision was made. The cumulative energy is entered in the column headed "Cumulative Energy +ve for reused and -ve for recycled". If components are reused then the REE is added to the positive side of the energy balance since this is energy that the component still possesses. Should there be REE in parts that are recycled, then that energy will be effectively lost and should be entered on the energy balance as negative energy.



					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Part No	Quant	Description	Part/Drg no	Residual Life Value	Decision	EoL Status	Energy of Primary Source (EPS) Mj	Design Life (Life Usage Cycles)	Number of Usage Lives Accrued	Residual Embodied Energy (Mj)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Cumulative Number of Installed Parts	Installed parts Embodied Energy (Mj)	Cumulative Energy +ve reused	Cumulative Energy -ve IF Recycled	Steel Mass (kg)	Other Mass (rubber,etc) (kg)	Energy Needed for Recycling Steel (Mj)	Energy Needed for Recycling Other (Mj)
		Rotation Gear Box Assembly					EPS	N_{DL}	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	M_S	M_R	EPS_S	EPS_R
		Total Product Life = 15 Life Usage Cycles															EPS	EPS	0.26 x EPS	0.28xEPS
		Period between Refurbishments = 5															30Mj/kg	8.1Mj/kg		
1	1	Shaft	RGB 328	Sacrifice	#	Recycle														
		EN8 (080M46) bar		25%		Recycle														
		499 long x dia 88		50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
	1	Gear Box Base	RGB 333	Sacrifice	#	Recycle														
		Weld Assembly		25%		Recycle														
				50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
2	1	Gear Box Base	RGB 320	Sacrifice	#	Recycle														
		BMS Plate 470 x 348 x 8 thick		25%		Recycle														
		Machining		50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
3	1	Gear Box Lid	RGB 335	Sacrifice	#	Recycle														
		Weld Assembly		25%		Recycle														
				50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														

Figure 5.30: Sustainability Centred Maintenance Algorithm (SCMA) Chart

Note! SCMA shows sample of parts list for a rotation gearbox in the case study below

5.9.9.3 Cumulative Replacement Parts

Newly installed components, new parts or replacing worn parts, will possess their own value of Embodied Energy. This can be considered as energy input to the product (negative energy entry on the balance sheet). The quantities of components and their respective energy values are added to the SCM chart under the columns “Cumulative Number of Replacement Parts” and “Replacement Parts Embodied Energy”

5.9.9.4 Energy Needed for Recycling

When components are recycled, energy is required to convert the components into original material. For instance, steel requires 26%, Ashby [5.2] , of the EPS to return it to raw product; aluminium requires just 5%, Ashby [5.2] of the EPS and rubber requires 28% of its EPS, Amari [5.26]. This is calculated using the mass of the product and the EPS of the material. It is entered into the negative side of the energy balance sheet since this is considered an energy input.

The flowchart for SCM Audit Measurement System shows how these calculated and derived energies are eventually combined as positive or negative entries in the energy balance sheet.

5.9.10 Maintenance/Refurbishment Factory Energy Application

During maintenance and refurbishment energy is applied as factory overhead and should be entered as a negative energy input on the energy balance sheet. The energy input is calculated as a proportion of the total energy overhead of the maintenance premises. A careful proportioning of activity needs to be considered since the overhead may be shared between maintenance, refurbishment and other manufacturing processes. To complete the calculation, several items of information are required as input as follows:

F_{TE}: total factory annual energy usage (factory overhead)
F_{DAYS}: number of days/year the factory is in use.
$M_{DAYS:}$ average time, days, applied to the maintenance procedure
F_{DAYS}: average time, days, applied to the refurbishment procedure
M_{O}: intended number of maintenance occurrences
R_{O}: intended number of refurbishment occurrences
P_{Q}: quantity of products maintained per year

The above input data can be taken from the factory database. The factory overhead (F_{TE}) may be available data but would otherwise require calculating. This requires the input energies in the various forms that the factory may use. The most common factory energy forms are listed as follows:

E_{ELEC}: electrical energy
E_{GP}: piped gas energy
E_{GB}: bottled gas energy
E_{COAL}: energy directly derived from coal
E_{OIL}: energy derived directly from oil

$F_{TE} = E_{ELEC} + E_{GP} + E_{GB} + E_{COAL} + E_{OIL}$ (Mj) ………..(5.28)

5.9.10.1 Maintenance Energy Applied per Product

M_{EI}: Maintenance Energy / Product can now be calculated

$$M_{EI} = \frac{\text{Maintenance Occurrences x Maintenance Period x Factory Overhead}}{\text{Factory Working Days}} \qquad \text{………..(5.29)}$$

$$M_{EI} = \frac{M_O \text{ x } M_{DAYS} \text{ x } F_{TE}}{F_{DAYS}} \quad \text{(Mj)} \qquad \text{…………(5.30)}$$

The energy applied during refurbishment can be similarly calculated

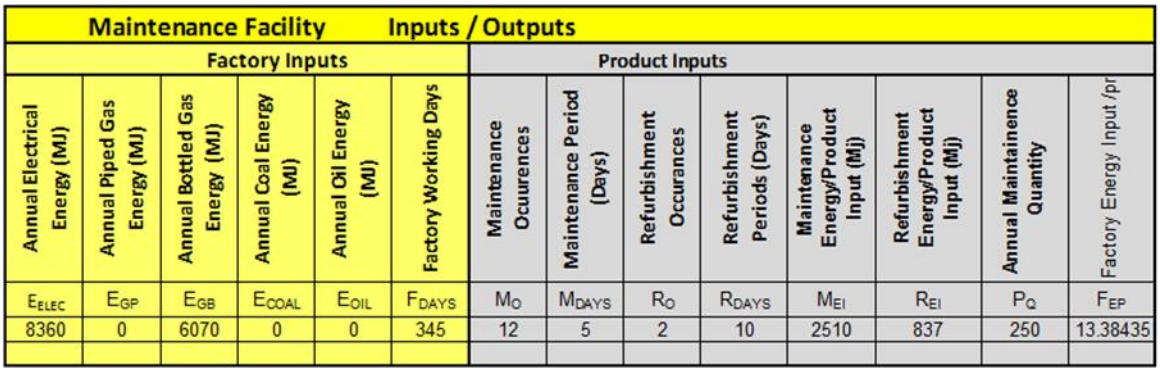
5.9.10.2 Refurbishment Energy Applied per Product

R_{EI}: Refurbishment Energy / Product can now be calculated

$$R_{EI} = \frac{\text{Refurbishment Occurrences x Refurbishment Period x Factory Overhead}}{\text{Factory Working Days}} \qquad \text{..………..(5.31)}$$

$$R_{EI} = \frac{R_O \text{ x } R_{DAYS} \text{ x } F_{TE}}{F_{DAYS}} \quad \text{(Mj)} \qquad \text{…………(5.32)}$$

The energies accrued by the factory overhead during maintenance and refurbishment was the subject of a separate algorithm. This builds into the energy balance sheet as shown in the SCM audit flowchart, figure 5.29. The factory overhead algorithm is shown in figure 5.31

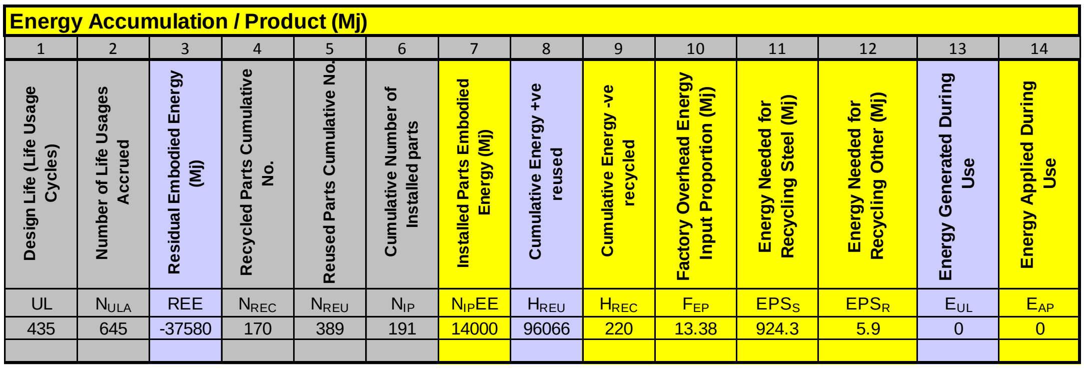


Maintenance Facility Inputs / Outputs													
Factory Inputs						Product Inputs							
Annual Electrical Energy (MJ)	Annual Piped Gas Energy (MJ)	Annual Bottled Gas Energy (MJ)	Annual Coal Energy (MJ)	Annual Oil Energy (MJ)	Factory Working Days	Maintenance Ocuurences	Maintenance Period (Days)	Refurbishment Occurances	Refurbishment Periods (Days)	Maintenance Energy/Product Input (Mj)	Refurbishment Energy/Product Input (Mj)	Annual Maintainence Quantity	Factory Energy Input /pr
E_{ELEC}	E_{GP}	E_{GB}	E_{COAL}	E_{OIL}	F_{DAYS}	M_O	M_{DAYS}	R_O	R_{DAYS}	M_{EI}	R_{EI}	P_Q	F_{EP}
8360	0	6070	0	0	345	12	5	2	10	2510	837	250	13.38435

Figure 5.31: Factory Overhead Algorithm (extracted from gearbox case study 3)

5.9.11 Energy Accumulation Algorithm

The values calculated for energy application to the product can now be amalgamated with the energy applied from the factory overhead in preparation for the energy balance sheet to be formulated. The energy accumulation algorithm can be seen in figure 5.32.



Energy Accumulation / Product (Mj)													
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Design Life (Life Usage Cycles)	Number of Life Usages Accrued	Residual Embodied Energy (Mj)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Cumulative Number of Installed parts	Installed Parts Embodied Energy (Mj)	Cumulative Energy +ve reused	Cumulative Energy -ve recycled	Factory Overhead Energy Input Proportion (Mj)	Energy Needed for Recycling Steel (Mj)	Energy Needed for Recycling Other (Mj)	Energy Generated During Use	Energy Applied During Use
UL	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	F_{EP}	EPS_S	EPS_R	E_{UL}	E_{AP}
435	645	-37580	170	389	191	14000	96066	220	13.38	924.3	5.9	0	0

Figure 5.32: Energy Accumulation per Product Algorithm (extracted from case study 3)

The table in figure 5.30 represents the accumulation of energy during Phase 1 and Phase 2 Life Cycle and is a precursor to creating the energy balance sheet. The data shown is drawn from the SCMA or the factory overhead energy and comprises generated data from the journey through the life cycle, or calculated data. The latter value represents energy input and energy harvested and is entered on the energy balance sheet. Columns 1, 2, 4, 5 and 6 show generated data. Columns 3, 8 and 13 indicate harvested, positive energy whilst columns 7, 9, 10, 11, 12 and 14 represent energy input which is negative energy.

The table shows the values at the end of life of the gearbox in the case study, section 5.13. The negative value in column 3 indicated that a large value of REE is lost when the gearbox comes to the end of its life. Within the system boundary, ISO14044 [5.28], of the gearbox and its components, energy that is gained or lost must be accounted for.

The negative value of REE = -37580 Mj is within the boundary and is deemed to be lost as the gearbox reaches the end of its life and is recycled in its entirety. In reality most of the REE belongs to a hydraulic motor which is refurbished and reused in another product. The hydraulic motor has its own boundary and contains its own REE. The second product to which the hydraulic motor is fitted will gain by the lower REE offered.

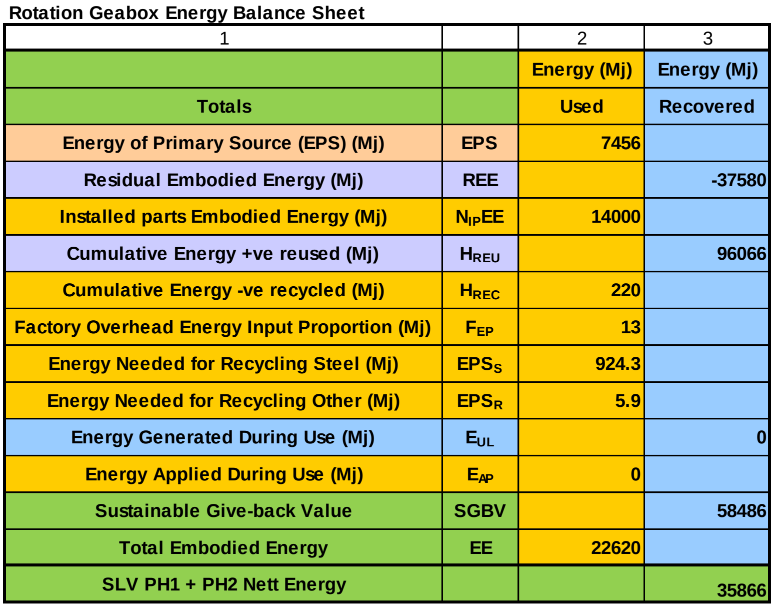
5.9.12 Energy Balance Sheet

The energy balance sheet is the culmination of the energies input to the product and harvested during both Phase 1 and Phase 2 Life Cycle and is shown below in figure 5.33 for the gearbox in the case study, section 5.10. EPS is the Embodied Energy carried by the product from Phase 1 Life Cycle. As input energy this is entered on the negative side of the balance sheet. REE is on the positive side of the balance sheet and shows a negative result. This has been specifically dealt with above but it should be noted that this is the end of life tally of energies and the REE in this case is lost, hence the negative value. During the life of the product, when a “snapshot” is taken at each maintenance/refurbishment occurrence, this will show a positive figure since it represents the REE that is available to be used.

Other input energies and harvested energy values have been explained above but the addition of the columns results in specific values, Total Embodied Energy, SLV Ph1 & Ph2 and SGBV that have been the goal of the product life cycle analysis. Total Embodied Energy represents the entire energy input during the life of the product for both Phase 1 and Phase 2 life cycles. The design team should endeavour to reduce this value by analysing the elements that input energy, such as material sourcing, manufacture, transport, operational efficiency, longevity enhancement, etc.

SGBV is the sum of all the harvested energies and should include saved energy (by reusing products rather than buying new) and generated energy (such as that generated by a PV panel). These are positive energies that the product supplies and can be used to offset the negative, input energies. The design team should endeavour to maximise this value by creating longer lived products, selecting appropriate components, employing generating schemes in designs, eg., incorporating solar panels in the roof of vehicles.

SLV Ph1 & Ph2 is the net value of energy after input energy and harvested energies have been combined. This is the true worth of the energy value for the product and covers the entire life cycle of the product from sourcing through to disposal. It also covers any energy which might be harvested though this is likely to be from Phase 2 Life Cycle only. In this case the generated energy value is zero. A product such as the gearbox in the case study is passive in terms of energy usage. It does not use energy as does a vehicle (petrol, diesel), nor does it generate energy such as a photovoltaic panel. A gearbox merely converts hydraulic energy into mechanical energy. Admittedly there will be losses but these are negligible compared to the Embodied Energy values and those energies that are harvested. Though there is provision for generated energy and energy used in the energy balance sheet, the passive gearbox returns nil energy used and nil energy harvested.



Rotation Geabox Energy Balance Sheet

1		2	3
		Energy (Mj)	Energy (Mj)
Totals		Used	Recovered
Energy of Primary Source (EPS) (Mj)	EPS	7456	
Residual Embodied Energy (Mj)	REE		-37580
Installed parts Embodied Energy (Mj)	$N_{IP}EE$	14000	
Cumulative Energy +ve reused (Mj)	H_{REU}		96066
Cumulative Energy -ve recycled (Mj)	H_{REC}	220	
Factory Overhead Energy Input Proportion (Mj)	F_{EP}	13	
Energy Needed for Recycling Steel (Mj)	EPS_S	924.3	
Energy Needed for Recycling Other (Mj)	EPS_R	5.9	
Energy Generated During Use (Mj)	E_{UL}		0
Energy Applied During Use (Mj)	E_{AP}	0	
Sustainable Give-back Value	SGBV		58486
Total Embodied Energy	EE	22620	
SLV PH1 + PH2 Nett Energy			35866

Figure 5.33: Energy Balance Sheet (extracted from the case study in section 5.13)

The net energy figure shown in figure 5.33 can be considered by the TDCMS and by the design team as a target to improve. The figure of 35,866 Mj may be used as a comparator against competitors' products. Competition between manufacturers will help to improve this figure in the same way as design and manufacture teams strive to reduce costs.

The analysis of each of the sections will lead to improvements. For instance, the value of 140,000 Mj for installed parts is a target to be reduced and achieved by selecting components with a better Embodied Energy profile. The energy needed for recycling steel could be reduced by manufacturing lower weight products since the greater mass of the recycled product, the greater energy will be absorbed. The EPS of 7,456 Mj may be reduced by better initial manufacturing techniques, using recycled materials, reducing transport costs by sourcing locally, etc.

The negative value of REE has been explained above, but ideally should not appear in the energy balance sheet since it reduces the positive, net energy value at the end of life of a product. It is incumbent on the design team to specify components whose life ends when the main product life ends thereby reducing the REE to zero.

The *cumulative energy value* of 96,066 Mj represents energy harvested by prolonging the life of the product and continually returning it to service thus avoiding the procurement of new products. The EPS, thus saved is added to the positive cumulative energy value and is one of the major components of the SGBV. The responsibility of the design team is therefore to improve the longevity of a product through better maintenance and refurbishment and selecting better materials and components that will naturally lead to a longer product life.

5.10 Case Study 3: Gearbox Components

Figure 5.34 shows a small, independent water well rock drill which used the gearbox in the case study. The rotation gearbox is a self-contained product around which can be prescribed a boundary as directed in ISO14044 [5.28] and is discrete product to which the SCMA can be applied.

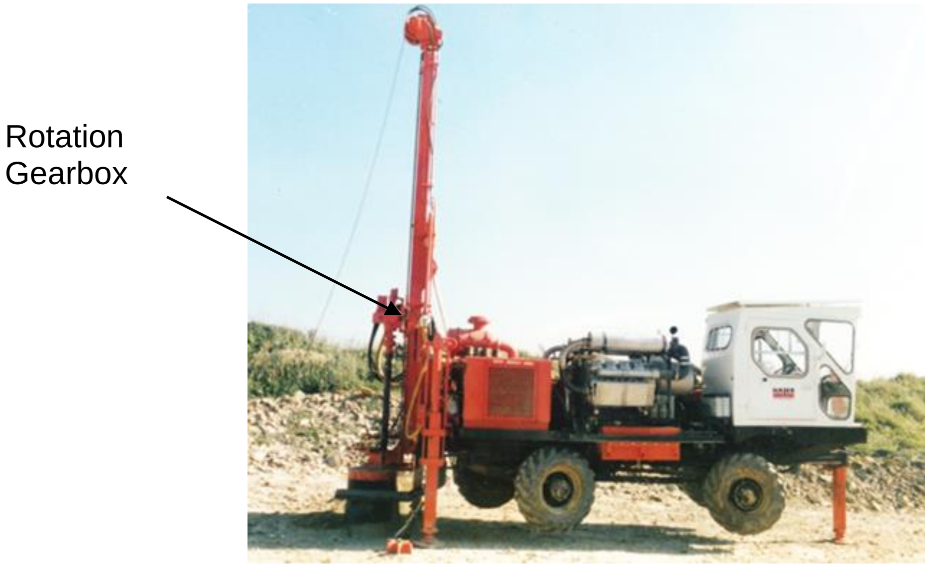


Figure 5.34 Self-Contained Rock Drill Showing Rotation Gearbox Location

The gearbox comprises a fabricated steel case, a hydraulic motor driving a pinion spur gear and driven spur gear, both of which are mounted on a shaft running in bearings and seals. Various other components ensure the normal operation of the gearbox.

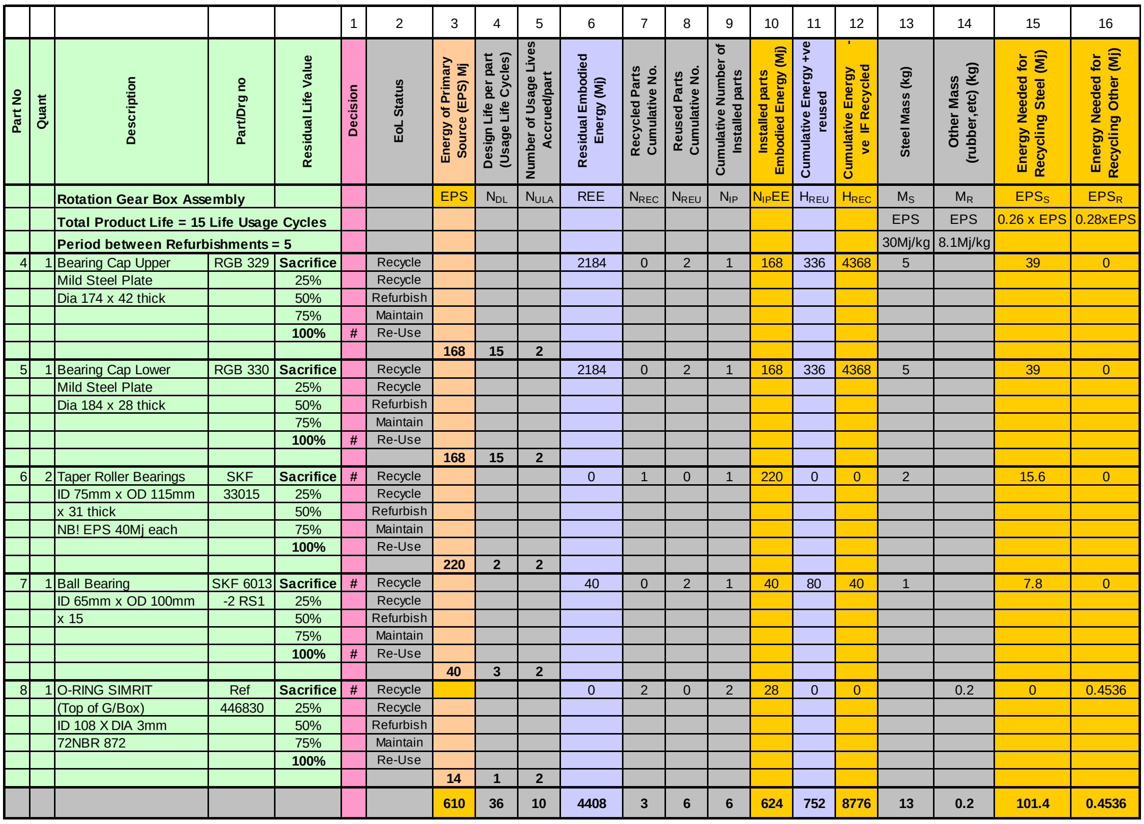
The SCMA chart below in figure 5.35 analyses selected components employed within the rotation gearbox. This “snapshot” after 2 Usage Lives (UL’s) is taken at the second maintenance period. At the head of the chart, figure 5.35, the designers have indicated a total product design life of 15 Usage Life cycles.

The maintenance engineer must consider each component in turn to determine the original design life. In the case of item 4 the original design life is 15 UL’s. Since this is the second maintenance period and only two UL’s have been expended. Item 4, *Bearing Cap Upper*, can be reused having 2,184 Mj of residual energy remaining.

Item 6 relates to two taper roller bearings whose combined Embodied Energy value is 220 Mj. Their design life is 2 UL’s. Since this is the second maintenance period at the end of the second UL the REE value is considered to be exhausted resulting in both bearings being recycled with the energy balance sheet returning zero Embodied Energy. The recycled taper roller bearings require replacement with two new bearings of combined Embodied Energy value of 220 Mj. The number of new bearings has been entered under column 9 “Cumulative Number of Installed Parts” and the energy value has been entered as 220 Mj under column 10 “Installed Parts Embodied Energy”.

Item 7 is a single row ball bearing whose design life is three Usage Lives. Since the bearing has only experienced 2 UL’s it is reused for a third and final usage period.

Item 8 is an O-ring. The general maintenance policy is to replace all seals at every maintenance period. The O-ring has therefore been removed and recycled.



					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Part No	**Quant**	**Description**	**Part/Drg no**	**Residual Life Value**	**Decision**	**EoL Status**	**Energy of Primary Source (EPS) Mj**	**Design Life per part (Usage Life Cycles)**	**Number of Usage Lives Accrued/part**	**Residual Embodied Energy (Mj)**	**Recycled Parts Cumulative No.**	**Reused Parts Cumulative No.**	**Cumulative Number of Installed parts**	**Installed parts Embodied Energy (Mj)**	**Cumulative Energy +ve reused**	**Cumulative Energy -ve IF Recycled**	**Steel Mass (kg)**	**Other Mass (rubber,etc) (kg)**	**Energy Needed for Recycling Steel (Mj)**	**Energy Needed for Recycling Other (Mj)**
		Rotation Gear Box Assembly					EPS	N_{DL}	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	M_S	M_R	EPS_S	EPS_R
		Total Product Life = 15 Life Usage Cycles															EPS	EPS	0.26 x EPS	0.28xEPS
		Period between Refurbishments = 5															30Mj/kg	8.1Mj/kg		
4	1	Bearing Cap Upper	RGB 329	**Sacrifice**		Recycle				2184	0	2	1	168	336	4368	5		39	0
		Mild Steel Plate		25%		Recycle														
		Dia 174 x 42 thick		50%		Refurbish														
				75%		Maintain														
				100%	#	Re-Use														
							168	**15**	**2**											
5	1	Bearing Cap Lower	RGB 330	**Sacrifice**		Recycle				2184	0	2	1	168	336	4368	5		39	0
		Mild Steel Plate		25%		Recycle														
		Dia 184 x 28 thick		50%		Refurbish														
				75%		Maintain														
				100%	#	Re-Use														
							168	**15**	**2**											
6	2	Taper Roller Bearings	SKF	**Sacrifice**	#	Recycle				0	1	0	1	220	0	0	2		15.6	0
		ID 75mm x OD 115mm	33015	25%		Recycle														
		x 31 thick		50%		Refurbish														
		NB! EPS 40Mj each		75%		Maintain														
				100%		Re-Use														
							220	**2**	**2**											
7	1	Ball Bearing	SKF 6013	**Sacrifice**	#	Recycle				40	0	2	1	40	80	40	1		7.8	0
		ID 65mm x OD 100mm	-2 RS1	25%		Recycle														
		x 15		50%		Refurbish														
				75%		Maintain														
				100%	#	Re-Use														
							40	**3**	**2**											
8	1	O-RING SIMRIT	Ref	**Sacrifice**	#	Recycle				0	2	0	2	28	0	0		0.2	0	0.4536
		(Top of G/Box)	446830	25%		Recycle														
		ID 108 X DIA 3mm		50%		Refurbish														
		72NBR 872		75%		Maintain														
				100%		Re-Use														
							14	**1**	**2**											
							610	**36**	**10**	**4408**	**3**	**6**	**6**	**624**	**752**	**8776**	**13**	**0.2**	**101.4**	**0.4536**

Figure 5.35: SCM Chart: Sample of Gearbox Components after 2 Usage Lives

Information Sources

Energy required for bearing manufacture SKF [5.19]

Energy required for rubber manufacture WCE [5.21]

Energy required for rubber recycling Amari [5.26]

It is quite possible that the maintenance engineer may consider that an item can no longer fulfil one UL even though its design life is not exhausted. The component is therefore sent for recycling prematurely. Any REE value in the column 12 is lost energy and has therefore to be added to the energy balance sheet as negative energy.

The maintenance engineer is faced with several decisions and tasks:

1. to recycle or reuse a component
2. the determination of the REE
3. recording decisions
4. recording REE

Element 1 above can be prescribed by the expected design life but may need some discretion by the maintenance engineer.

Element 2 above is more straightforward since the maintenance engineer can deduce the Residual Embodied Energy from the usage parameters and also from the EPS value supplied by the design team.

Elements 3 and 4 are recorded on the SCM chart.

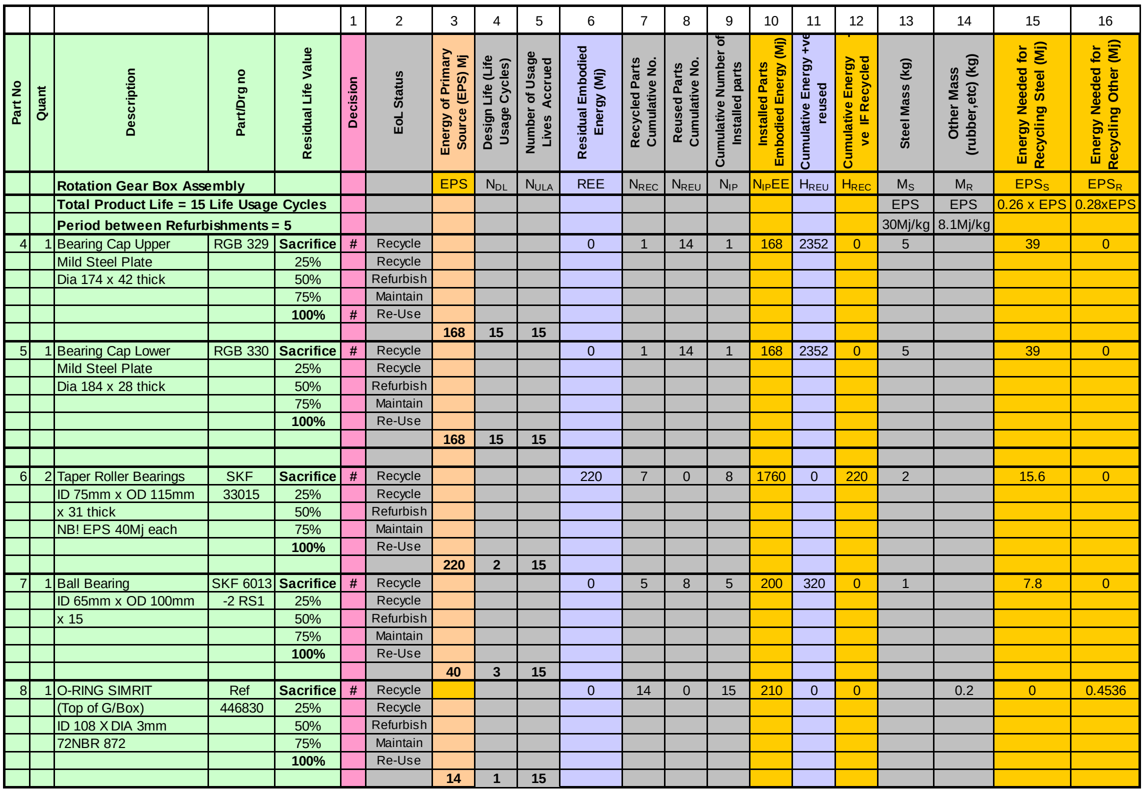
5.10.1 Case Study 3: Recording and Feedback of Information

The information thus recorded is useful to the maintenance function for control, ordering new components, assessing recycling components, etc., but other life cycle functions also require such information. In particular, the Total Design Control Management Scheme (TDCMS) and the design function requires feedback from maintenance and refurbishment since this information shows usage trends and gives valuable information to the designers and especially those members of the design team who are responsible for sourcing, manufacture, usage, maintenance and end of life management.

5.10.2 Case Study 3: End of Useful Life

After each maintenance period the SMC data can be reviewed to give a Phase 2 Life Cycle progress report used to see trends in the effectiveness of individual components. This data can give valuable “in-the-field” feedback to the designers who may use the information to influence new designs.

A full picture can be gained at the end of the product’s life, which in the case of the gearbox, is 15 UL’s. Figure 5.36 shows the same sample of components as shown in figure 5.35. These have now endured 15 UL’s amounting to 12 maintenance periods and 2 refurbishments before recycling.



					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Part No	Quant	Description	Part/Drg no	Residual Life Value	Decision	EoL Status	Energy of Primary Source (EPS) Mj	Design Life (Life Usage Cycles)	Number of Usage Lives Accrued	Residual Embodied Energy (Mj)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Cumulative Number of Installed parts	Installed Parts Embodied Energy (Mj)	Cumulative Energy +ve reused	Cumulative Energy -ve IF Recycled	Steel Mass (kg)	Other Mass (rubber,etc) (kg)	Energy Needed for Recycling Steel (Mj)	Energy Needed for Recycling Other (Mj)
		Rotation Gear Box Assembly					EPS	N_{DL}	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	M_S	M_R	EPS_S	EPS_R
		Total Product Life = 15 Life Usage Cycles															EPS	EPS	0.26 x EPS	0.28xEPS
		Period between Refurbishments = 5															30Mj/kg	8.1Mj/kg		
4	1	Bearing Cap Upper	RGB 329	**Sacrifice**	#	Recycle				0	1	14	1	168	2352	0	5		39	0
		Mild Steel Plate		25%		Recycle														
		Dia 174 x 42 thick		50%		Refurbish														
				75%		Maintain														
				100%	#	Re-Use														
							168	**15**	**15**											
5	1	Bearing Cap Lower	RGB 330	**Sacrifice**	#	Recycle				0	1	14	1	168	2352	0	5		39	0
		Mild Steel Plate		25%		Recycle														
		Dia 184 x 28 thick		50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
							168	**15**	**15**											
6	2	Taper Roller Bearings	SKF	**Sacrifice**	#	Recycle				220	7	0	8	1760	0	220	2		15.6	0
		ID 75mm x OD 115mm	33015	25%		Recycle														
		x 31 thick		50%		Refurbish														
		NB! EPS 40Mj each		75%		Maintain														
				100%		Re-Use														
							220	**2**	**15**											
7	1	Ball Bearing	SKF 6013	**Sacrifice**	#	Recycle				0	5	8	5	200	320	0	1		7.8	0
		ID 65mm x OD 100mm	-2 RS1	25%		Recycle														
		x 15		50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
							40	**3**	**15**											
8	1	O-RING SIMRIT	Ref	**Sacrifice**	#	Recycle				0	14	0	15	210	0	0		0.2	0	0.4536
		(Top of G/Box)	446830	25%		Recycle														
		ID 108 X DIA 3mm		50%		Refurbish														
		72NBR 872		75%		Maintain														
				100%		Re-Use														
							14	**1**	**15**											

Figure 5.36: Sample Gearbox Components End of Life SCM Chart (15 Life Usages)

The values in columns 1,2,3,4,5,7,8 and 9 represent information input. The data displayed in columns 6 and 11 documents energy harvested or saved, whilst columns 3,10,12 and 16 represent energy input. The accumulation of these values can be applied to the energy balance sheet. It is significant that most of the values in column 6 (REE) show a value of zero. This indicates that each component has outlived its useful life and has used its residual Embodied Energy in entirety. The Item 6 bearing, however, possesses 220 Mj of REE at the point the whole product is being directed for recycling. The bearing may be reused in a separate product, but is likely to be recycled along with the original product in which case the REE will be lost. As indicated in column 12 (H_{REC}), energy lost through recycling, shows that the REE will be lost in recycling. Since the bearing has not been reused, column 11 (R_{EU}), energy harvested by reusing components, returns a zero value. Significantly column 11 (R_{EU}), accrues all the Embodied Energy (EPS) that has been saved by reusing components thus avoiding the procurement of new components. These accrued values will be used directly in the energy balance sheet.

Note: An energy appraisal of the entire gearbox and components can be seen in the appendix A5A2.

5.10.3 Case Study 3: Factory Overheads

The chart shown in figure 5.36 describes the component flow and energy input/output during the maintenance and refurbishment processes. Energy is also applied in the form of factory overhead during those processes and should be included as input energy on the energy balance sheet.

The calculation of energy input to the maintenance and refurbishment processes is a proportion of the total energy overhead of the factory or maintenance premises. This overhead may be shared between maintenance, refurbishment and other manufacturing processes so that a careful proportioning of activity needs to be considered. The gearbox case study assumes that the factory is dedicated to maintenance and refurbishment only. Several other assumptions are listed as follows:

- the factory is in use for 345 days per year
- the maintenance procedure takes an average of 5 days
- the refurbishment procedure takes an average of 10 days
- there are 12 maintenance occurrences during the productive life
- there are 2 refurbishment occurrences during the productive life

Annual factory energy usage has been taken from information supplied by HEA Ltd of Sowerby Bridge, UK. This is a factory of appropriate size and with similar processes to those required for refurbishment of gearboxes.

Electricity: Total usage	= 8,360 Mj/year
Bottled Gas: Total usage	= 6,070 Mj/year
total energy used:	= 14,430 Mj/year

HEA limited information extracted from 5.8.4 block clamp case study.
The maintenance and refurbishment energy value can now be computed

Maintenance Energy / Gearbox (M_{EI})

$$M_{EI} = \frac{\text{Number maint' procedures x average maint' days x annual factory energy O/head}}{\text{factory operational days}} \quad \text{.........5.29}$$

$$M_{EI} = \frac{12 \times 5 \times 14{,}430}{345} = \underline{\mathbf{2{,}510\ Mj\ /\ Gearbox}}$$

Refurbishment Energy (R_{EI})

$$R_{EI} = \frac{\text{Number refurb' procedures x average refurb' days x annual factory energy O/head}}{\text{factory operational days}} \quad \text{.........5.31}$$

$$R_{EI} = \frac{2 \times 10 \times 14{,}430}{345} = \underline{\mathbf{837\ Mj}}$$

Total Energy Used in Maintenance and Refurbishment

$$\text{Total Energy} = M_{EI} + R_{EI} = 2{,}510 + 837 = \underline{\mathbf{3{,}347\ Mj}}$$

A portion of the algorithm used to compute this figure can be seen in figure 5.29

5.10.4 Case Study 3: Energy Input/output During Use

Products such as vehicles require energy input to power them during their UL where energy in the form of petrol (gasoline) or diesel is used to provide motive power. Power may also be derived from electric engines or hydrogen engines, etc. Whatever the power source of the energy used, it should be entered into the energy balance sheet.

In the case of vehicle the energy input can be derived using parameters of:

- distance travelled between maintenance intervals
- energy/kilometre coefficient

Energy input = Distance x Number of Usage Lives x Energy Coefficient

Eg. Energy coefficient 14 tonne truck = 5.26×10^{-06} Mj/m Kojima K [5.15]

The energy thus derived should be added to the negative side of the energy balance sheet since it is energy input to the product.

The case study of the rotation gearbox is an example of a passive device that does not require input energy, merely converting energy via a hydraulic motor into mechanical rotational energy. Energy therefore passes through the gearbox to the drilling operation. It is considered that any losses within the gearbox are negligible when compared to the energy values during Phase 1 and Phase 2 Life Cycles.

The energy balance sheet for the gearbox can be seen in figure 5.33. It is important to note that the gearbox is neither an energy generator nor an energy user which means that these two elements within the energy balance sheet are returned as zero.

5.10.5 Case Study 3: Energy Balance Sheet (Phase 2 Life Cycle)

The energy balance sheet shown in figure 5.33 is the amalgamation of the analysis set out in the algorithms represented in figures 5.31 and 5.32 and represents the energy input and energy saved or collected during Phase 2 Life Cycle whilst incorporating the energy input during Phase 1 Life Cycle in the form of Energy of Primary Source (EPS). The data thus presented represents the energy balance for the entire life of the gearbox after 15 UL's.

Information gathered from the maintenance and refurbishment periods throughout the life of a product can generate trends leading to longevity and functional efficiency of individual components. Armed with the information presented in the energy balance sheet and in the preceding algorithmic data the designers can select long lived components and design-in strategies which allow UL's to become longer, thus extending the entire Phase 2 life of the product and improving the SGBV.

The balance sheet energy value is a tool by which the sustainable efficiency of the product can be measured. It is common practice to use cost as a measurement device but this does not always consider the energy input and cannot measure the energy saved.

Engineers are conditioned to think in terms of monetary values and it is inevitable that these energy balances will be converted to costs. There follows a cost conversion based on the energy balance sheet in figure 5.33. The cost of energy has applied data published by the Department for Energy and Climate Change (DECC), a UK Government Department. [5.27]

Average energy cost = £106.33 £/MWh

Generic Equation

$$\text{Energy cost} = \frac{\text{energy applied x cost/MWh}}{\text{conversion factor MWh -Joules}}$$

Energy Input

$$\text{Cost of Input Energy} = \frac{22{,}620 \times 106.33}{3.6 \times 10^{3}} = \textbf{\underline{£668.11}}$$

Energy Saved/Harvested

$$\text{Cost of Energy Saved} = \frac{58{,}486 \times 106.33}{3.6 \times 10^{3}} = \textbf{\underline{£1,727.45}}$$

Net Energy

$$\text{Cost of Net Energy} = 1{,}727.45 - 668.11 = \textbf{\underline{£1,059.34}}$$

The conversion to monetary value creates a more understandable perspective and shows there can be great savings made to the cost-focused engineer.

This figure may seem a small value when compared to the cost of the gearbox but the factory maintains 250 gearboxes per year which accrues to an annual saving of £264,835 per year.

During the life of a product, engineers strive to reduce energy input by reducing haulage distances, buying energy from the cheapest supplier, applying insulation to factories and applying the quickest and lowest energy manufacturing techniques. These measures and many others are valid but engineers and businessmen rarely account for the Embodied Energy that can be saved or harvested during the entire life cycle of a product. The model and case study thus presented shows how energy can be harvested and accounted for by increasing longevity through maintenance and refurbishment and by avoiding the necessity to procure new products with their incumbent Energy of Primary Source (EPS).

5.11 Consolidation of Phase 1 and Phase 2 Embodied Energy

The calculation of the entire life-cycle Embodied Energy is an addition of both Phase 1 Life Cycle and Phase 2 Life Cycle Embodied Energies. The Embodied Energy accrued during Phase 1 Life Cycle, from material sourcing to manufacture is generally energy input and can be termed as Energy of Primary Source (EPS), but Phase 2 Embodied Energy can be input, saved or harvested energy depending on the product, its variations in use and the subsequent maintenance and disposal methods. This fluidity of application complicates the energy input/output data acquisition but is nevertheless considered in section 5.9 onwards.

Sections 5.7 and 5.8 defines methods that measure energy input during Phase 1 Life Cycle, and uses a single product manufactured from steel. Products assembled from a multiplicity of components with varying materials require a different approach in that all the major components need to be addressed separately and added to the energy input total. This approach has been taken with the rotation gearbox case study. Appendix A5 A2 shows the total value of the Embodied Energy (EPS) of the constituent components as 7,456 Mj. Separating the components also allows the consideration of multiple materials in particular parts of the analysis.

5.12 Case Study 4: Stone Tumbler

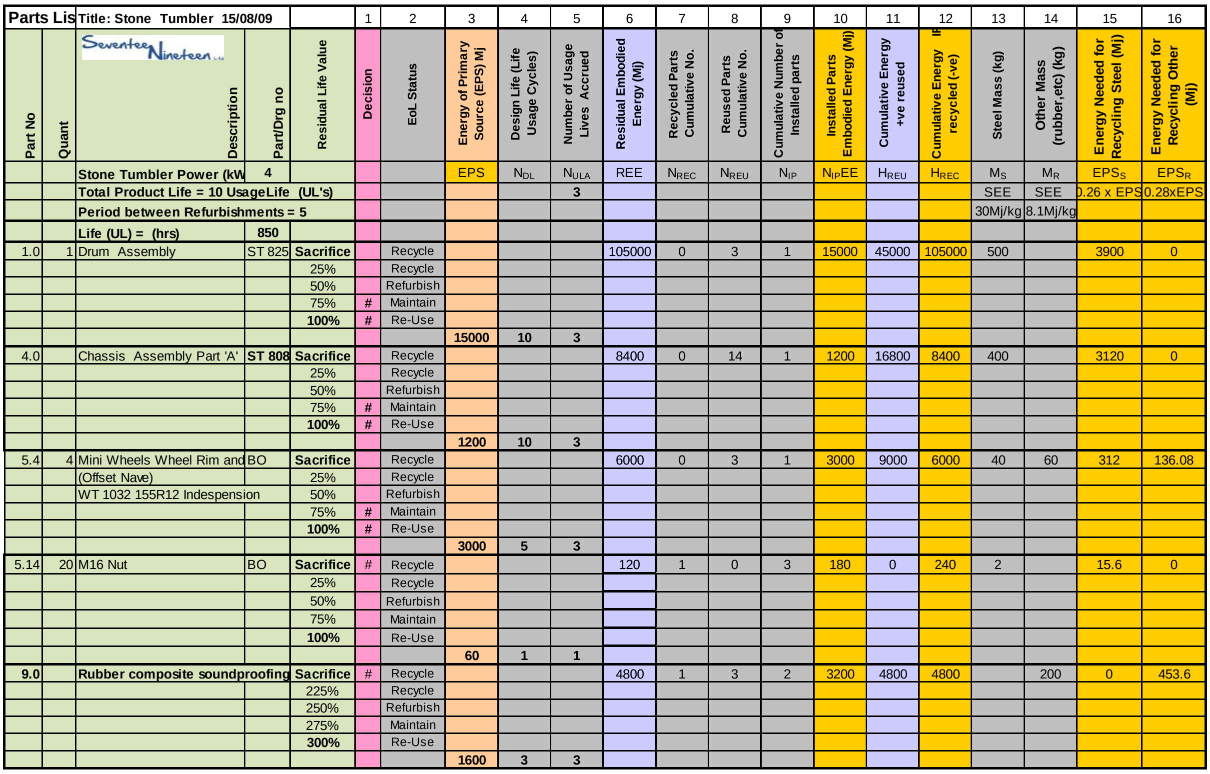
A second case study is presented of a stone tumbler which is a machine used in quarries to dull the edges of cut stone; see Figure 5.37. This example has been inserted to show that the SCM audit system is compatible with a diverse range of products. The Stone Tumbler, unlike the gearbox in case study 3, requires energy for operation during its useful life and this has to be accounted for in the final energy balance sheet.

Figure 5.37: Stone Tumbler

In operation the drum of the Stone Tumbler is set at an angle of approximately 10° whereupon cut stone blocks are placed in the drum at the higher end. As the drum rotates the cut stone blocks grind against themselves thus blunting the sharp edges. The blocks gradually work their way to the lower end where they can be collected. The drum is 1 m diameter and 3 m long and rotates, supported by a set of tyres which are driven by a 4 kW electric motor.

5.12.1 Case Study 4: Application of SCM and the SCMA

The SCMA chart below in figure 5.38 analyses example components that form part of the assembly. This “snapshot” after 3 Usage Lives (UL’s) is taken at the third maintenance period.



Parts Lis		Title: Stone Tumbler 15/08/09			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Part No	Quant	Seventeen Nineteen Ltd Description	Part/Drg no	Residual Life Value	Decision	EoL Status	Energy of Primary Source (EPS) Mj	Design Life (Life Usage Cycles)	Number of Usage Lives Accrued	Residual Embodied Energy (Mj)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Cumulative Number of Installed parts	Installed Parts Embodied Energy (Mj)	Cumulative Energy +ve reused	Cumulative Energy IF recycled (-ve)	Steel Mass (kg)	Other Mass (rubber,etc) (kg)	Energy Needed for Recycling Steel (Mj)	Energy Needed for Recycling Other (Mj)
		Stone Tumbler Power (kW	**4**				EPS	N_{DL}	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	M_S	M_R	EPS_S	EPS_R
		Total Product Life = 10 UsageLife (UL's)							**3**								SEE	SEE	0.26 x EPS	0.28xEPS
		Period between Refurbishments = 5															30Mj/kg	8.1Mj/kg		
		Life (UL) = (hrs)	**850**																	
1.0	1	Drum Assembly	ST 825	**Sacrifice**		Recycle				105000	0	3	1	15000	45000	105000	500		3900	0
				25%		Recycle														
				50%		Refurbish														
				75%	#	Maintain														
				100%	#	Re-Use														
							15000	**10**	**3**											
4.0		Chassis Assembly Part 'A'	**ST 808**	**Sacrifice**		Recycle				8400	0	14	1	1200	16800	8400	400		3120	0
				25%		Recycle														
				50%		Refurbish														
				75%	#	Maintain														
				100%	#	Re-Use														
							1200	**10**	**3**											
5.4	4	Mini Wheels Wheel Rim and	BO	**Sacrifice**		Recycle				6000	0	3	1	3000	9000	6000	40	60	312	136.08
		(Offset Nave)		25%		Recycle														
		WT 1032 155R12 Indespension		50%		Refurbish														
				75%	#	Maintain														
				100%	#	Re-Use														
							3000	**5**	**3**											
5.14	20	M16 Nut	BO	**Sacrifice**	#	Recycle				120	1	0	3	180	0	240	2		15.6	0
				25%		Recycle														
				50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
							60	**1**	**1**											
9.0		**Rubber composite soundproofing**		**Sacrifice**	#	Recycle				4800	1	3	2	3200	4800	4800		200	0	453.6
				225%		Recycle														
				250%		Refurbish														
				275%		Maintain														
				300%		Re-Use														
							1600	**3**	**3**											

Figure 5.38: SCM Chart: Sample of Stone Tumbler Components after 3 Usage Lives

Information Sources

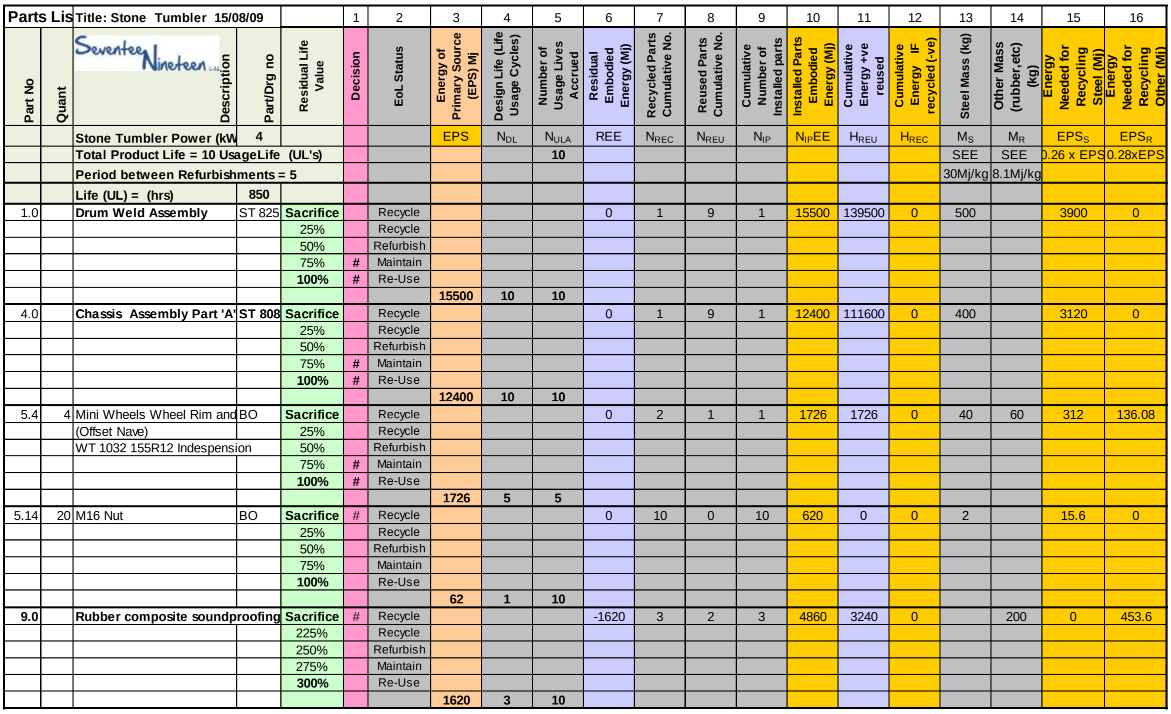
Energy required for rubber manufacture WCE [5.21]

Energy required for rubber recycling Amari [5.26]

The stone tumbler is driven by a 4 kW motor and has a total design life of 10 Usage lives (UL) A representative selection of components is shown in figure 5.38. A single UL is stated at 850 hours and refurbishment is to take place after five UL's. The major components, item 1, Drum Assembly and item 4, Chassis Assembly are expected to last the full 10 UL's. After 5 UL's the stone tumbler unit will be refurbished and should be thoroughly checked for exceptional wear above that which might be expected during normal use. For instance, cracks may appear in the welds which will require re-welding or items may be bent out of shape and need replacing or repairing.

Item 5.4 constitutes four support wheels which are vehicle wheels and include standard road rubber tyres. These have been given a design life of five UL's and will be replaced during refurbishment but otherwise maintained in a normal maintenance period. Part 5.14 is a quantity of M16 nuts. It is good practice to replace these during every maintenance process. The old nuts can be recycled. Item 9 is rubber composite sheeting which lines the drum to reduce the noise. This component has an arduous duty and is expected to have a life of just 3 UL's.

Figure 5.38 is a "snapshot" of the stone tumbler status after three UL's. Column 6 shows values of Residual Embodied Energy (REE) and is the value of Embodied Energy still remaining in the components. As the components are reused to the end of their life, this value will reduce to zero before recycling. Column 10 is a calculation of the Embodied Energy within the installed parts and is an accumulation of the original Energy of Primary Source (EPS). This value will increase as new parts replace end of life parts. Column 11 is the accumulation of harvested energy. When parts are reused the procurement of new components is avoided which also avoids expenditure of Energy of Primary Source. This saved energy can be accrued to offset input energy and is accounted for in column 12 which shows values of REE. Item 5.34, Audi-Mini car wheels, possess 6000 Mj of energy which would be lost if recycled at this point. In fact they have another two UL's before they are recycled which will use the remainder of the Embodied Energy.



Parts Lis		Title: Stone Tumbler 15/08/09			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Part No	Quant	SeventeeNineteen Ltd Description	Part/Drg no	Residual Life Value	Decision	EoL Status	Energy of Primary Source (EPS) Mj	Design Life (Life Usage Cycles)	Number of Usage Lives Accrued	Residual Embodied Energy (Mj)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Cumulative Number of Installed parts	Installed Parts Embodied Energy (Mj)	Cumulative Energy +ve reused	Cumulative Energy IF recycled (-ve)	Steel Mass (kg)	Other Mass (rubber,etc) (kg)	Energy Needed for Recycling Steel (Mj)	Energy Needed for Recycling Other (Mj)
		Stone Tumbler Power (kW	**4**				EPS	N_{DL}	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	M_S	M_R	EPS_S	EPS_R
		Total Product Life = 10 UsageLife (UL's)							**10**								SEE	SEE	0.26 x EPS	0.28xEPS
		Period between Refurbishments = 5															30Mj/kg	8.1Mj/kg		
		Life (UL) = (hrs)	**850**																	
1.0		**Drum Weld Assembly**	ST 825	**Sacrifice**		Recycle				0	1	9	1	15500	139500	0	500		3900	0
				25%		Recycle														
				50%		Refurbish														
				75%	#	Maintain														
				100%	#	Re-Use														
							15500	**10**	**10**											
4.0		**Chassis Assembly Part 'A'**	**ST 808**	**Sacrifice**		Recycle				0	1	9	1	12400	111600	0	400		3120	0
				25%		Recycle														
				50%		Refurbish														
				75%	#	Maintain														
				100%	#	Re-Use														
							12400	**10**	**10**											
5.4	4	Mini Wheels Wheel Rim and	BO	**Sacrifice**		Recycle				0	2	1	1	1726	1726	0	40	60	312	136.08
		(Offset Nave)		25%		Recycle														
		WT 1032 155R12 Indespension		50%		Refurbish														
				75%	#	Maintain														
				100%	#	Re-Use														
							1726	**5**	**5**											
5.14	20	M16 Nut	BO	**Sacrifice**	#	Recycle				0	10	0	10	620	0	0	2		15.6	0
				25%		Recycle														
				50%		Refurbish														
				75%		Maintain														
				100%		Re-Use														
							62	**1**	**10**											
9.0		**Rubber composite soundproofing**		**Sacrifice**	#	Recycle				-1620	3	2	3	4860	3240	0		200	0	453.6
				225%		Recycle														
				250%		Refurbish														
				275%		Maintain														
				300%		Re-Use														
							1620	**3**	**10**											

Figure 5.39: SCM Chart: Sample of Stone Tumbler Components after 10 Usage Lives

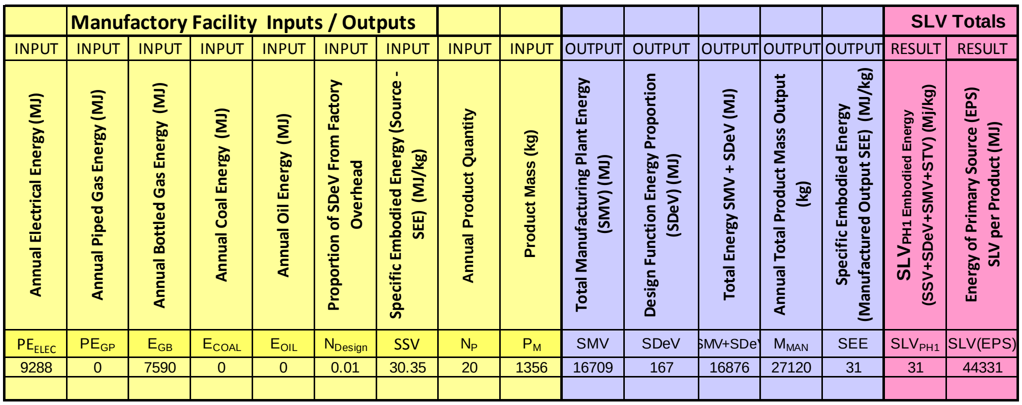
Figure 5.39 shows the same sample components after the designated life of the stone tumbler has completed 10 UL's. This shows that the Residual Embodied Energy has reduced to zero, having used the energy in a full life cycle. Attention should be drawn to Item 9, Rubber Composite Soundproofing. This shows an REE value of -1600 Mj. The stone tumbler rig is being recycled after 10 Usage lives but there is still Residual Embodied Energy worth a single UL within the composite rubber soundproofing which will be lost if recycled with the rest of the stone tumbler. The energy balance sheet shown in figure 5.42 assumes that the rubber composite has been sacrificed and its REE lost. Column 11 shows the cumulative energy which is harvested by reusing components. This value has grown during the life of the stone tumbler, as components have been reused and energy saved.

5.12.2 Case Study 4: Energy Balance Sheet: Accumulation of Data

Note: Factory energy supplied by HE&A Ltd, Sowerby Bridge, Halifax, West Yorkshire

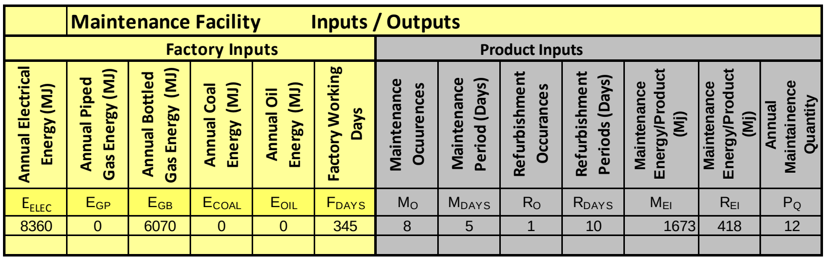
A great deal of data has been accumulated during Phase 1 Life Cycle and also in Phase 2 Life Cycle during the maintenance and refurbishment periods. This information can now be collated. Figure 5.40(a) shows data taken from the manufacturing of the stone tumbler and considers material sourcing, design and manufacture with incumbent transport energy values the most useful value to carry forward to the energy balance sheet is the Energy of Primary Source (EPS).

Also shown in figure 5.40(b) is the energy expended by the maintenance facility. As with the gearbox, case study consideration has been given to the number of days the company works per year, the number of average days used in maintenance and those in refurbishment. The average energy expended per product in maintenance is calculated from a proportion of the factory energy usage overhead.



	Manufactory Facility Inputs / Outputs														SLV Totals	
INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	RESULT	RESULT	
Annual Electrical Energy (MJ)	Annual Piped Gas Energy (MJ)	Annual Bottled Gas Energy (MJ)	Annual Coal Energy (MJ)	Annual Oil Energy (MJ)	Proportion of SDeV From Factory Overhead	Specific Embodied Energy (Source - SEE) (MJ/kg)	Annual Product Quantity	Product Mass (kg)	Total Manufacturing Plant Energy (SMV) (MJ)	Design Function Energy Proportion (SDeV) (MJ)	Total Energy SMV + SDeV (MJ)	Annual Total Product Mass Output (kg)	Specific Embodied Energy (Manufactured Output SEE) (MJ/kg)	SLV_{PH1} Embodied Energy (SSV+SDeV+SMV+STV) (MJ/kg)	Energy of Primary Source (EPS) SLV per Product (MJ)
PE_{ELEC}	PE_{GP}	E_{GB}	E_{COAL}	E_{OIL}	N_{Design}	SSV	N_P	P_M	SMV	SDeV	SMV+SDe	M_{MAN}	SEE	SLV_{PH1}	SLV(EPS)
9288	0	7590	0	0	0.01	30.35	20	1356	16709	167	16876	27120	31	31	44331

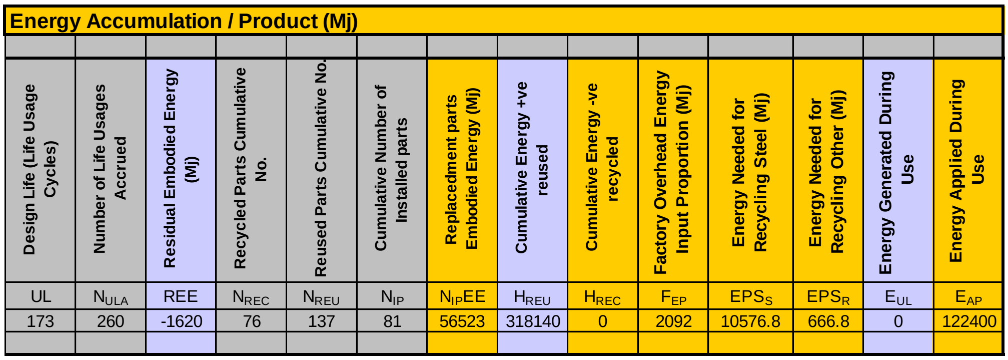
(a) Phase 1 Embodied Energy: Material Sourcing through to Manufacture: Derivation of EPS



	Maintenance Facility Inputs / Outputs												
Factory Inputs						Product Inputs							
Annual Electrical Energy (MJ)	Annual Piped Gas Energy (MJ)	Annual Bottled Gas Energy (MJ)	Annual Coal Energy (MJ)	Annual Oil Energy (MJ)	Factory Working Days	Maintenance Ocuurences	Maintenance Period (Days)	Refurbishment Occurances	Refurbishment Periods (Days)	Maintenance Energy/Product (Mj)	Maintenance Energy/Product (Mj)	Annual Maintainence Quantity
E_{ELEC}	E_{GP}	E_{GB}	E_{COAL}	E_{OIL}	F_{DAYS}	M_O	M_{DAYS}	R_O	R_{DAYS}	M_{EI}	R_{EI}	P_Q
8360	0	6070	0	0	345	8	5	1	10	1673	418	12

(b) Phase 2 Embodied Energy: Derivation of Phase 2 Energies

Figure 5.40: Stone Tumbler: Addition of the Manufacturing Energy and Maintenance Energy

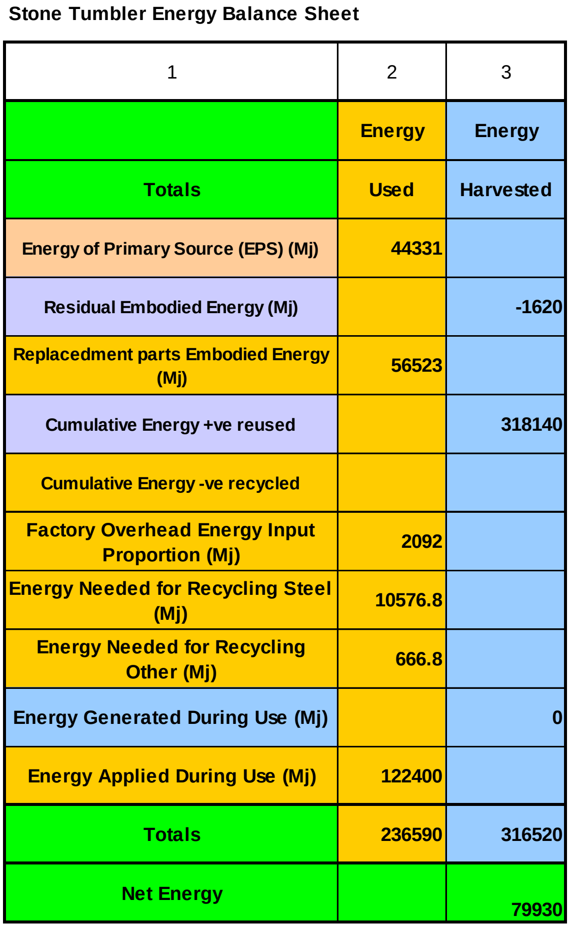


Energy Accumulation / Product (Mj)													
Design Life (Life Usage Cycles)	Number of Life Usages Accrued	Residual Embodied Energy (Mj)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Cumulative Number of Installed parts	Replacedment parts Embodied Energy (Mj)	Cumulative Energy +ve reused	Cumulative Energy -ve recycled	Factory Overhead Energy Input Proportion (Mj)	Energy Needed for Recycling Steel (Mj)	Energy Needed for Recycling Other (Mj)	Energy Generated During Use	Energy Applied During Use
UL	N_{ULA}	REE	N_{REC}	N_{REU}	N_{IP}	$N_{IP}EE$	H_{REU}	H_{REC}	F_{EP}	EPS_S	EPS_R	E_{UL}	E_{AP}
173	260	-1620	76	137	81	56523	318140	0	2092	10576.8	666.8	0	122400

(c) Entire Life Cycle Energy Accumulation Leading to Energy Balance Sheet

Figure 5.41: Life Cycle Energy Accumulation (Prior to Balance Sheet Entry)

Figure 5.39 shows a representative sample of components, but there are 27 components and sub-assemblies within the stone tumbler. The life cycle values can be seen in figure 5.41 which accumulates the data prior to insertion into the energy balance sheet. It should be noted that HREC "Cumulative –ve Energy Recycled" is an information that shows the value of Residual Embodied Energy in components which are about be recycled. The REE will therefore be lost upon recycling. The value has been omitted from the energy balance sheet since it is accounted for as Residual Embodied Energy.



Stone Tumbler Energy Balance Sheet

1	2	3
	Energy	Energy
Totals	Used	Harvested
Energy of Primary Source (EPS) (Mj)	44331	
Residual Embodied Energy (Mj)		-1620
Replacedment parts Embodied Energy (Mj)	56523	
Cumulative Energy +ve reused		318140
Cumulative Energy -ve recycled		
Factory Overhead Energy Input Proportion (Mj)	2092	
Energy Needed for Recycling Steel (Mj)	10576.8	
Energy Needed for Recycling Other (Mj)	666.8	
Energy Generated During Use (Mj)		0
Energy Applied During Use (Mj)	122400	
Totals	236590	316520
Net Energy		79930

Figure 5.42: Energy Balance Sheet for the Stone Tumbler

The energy balance sheet can be seen in figure 5.42 and accrues all the energy input and energy harvested during the life cycle of the stone tumbler. The values are taken from figure 5.40 and figure 5.41. Harvested energy has offset the input energy to give a net energy surplus of 79,930 Mj. This value is the culmination of the energy applied to the Stone Tumbler during its entire life and can be used as a marketing tool to compare with other similar products and also to gauge the sustainability of the process and in that sense can be used as input data to help influence decisions made under the umbrella of the Triple Bottom Line.

Column 2 shows energy applied to the stone tumbler and incorporates Energy of Primary Source from Phase 1 Life Cycle. All other entries in Column 2 represent energy input whilst all those entries in column 3 represents the energy harvested. Column 3 shows a negative value for Residual Embodied Energy due to the premature recycling of Item 5.9 Rubber Composite Soundproofing, where 1620 Mj are lost due to item 5.9 not completing its full UL and REE still remains.

The stone tumbler is different to the gearbox case study in that energy has to be expended in order for it to be used. The energy (power) to drive the drum comes from a 4 kW motor and needs to be accommodated in the energy balance sheet. The operating parameters are as follows:

motor power	4 kW
total design life	10 UL
expected hours per UL	850 hrs
conversion Kw to Mj	1 Kw = 3.6 Mj

Find Energy Applied During Entire Life Cycle

Energy = Power x UL time expended x Design Life x Conversion factor

Energy = 4 x 850 x 10 x 3.6 x 10^6 = **122,400 Mj**

This is accounted for on the negative side of the balance sheet in figure 5.42.

5.13 Energy Accounting Algorithm

The energy accounting algorithm provided by CES EduPack (Granta Design Ltd) [5.11] was used as a comparator for elements of the life cycle as the EPS Phase 1 algorithm was developed. Commercial packages such as this are useful but tend to be too broad in their approach by making assumptions which do not allow detailed analysis.

The algorithm to define Energy of Primary Source (EPS) can now stand alone as a detailed Embodied Energy measurement device that can be combined with Phase 2 Life Cycle Embodied Energy. The results from the algorithm for the combined energies from Phase 1 Life Cycle and Phase 2 Life Cycle can be seen in figure 5.33 for the gearbox case study and in figure 5.42 for the stone tumbler Case study.

Figures 5.31 and 5.40 for the gearbox and stone tumbler respectively, derive the energy input and energy saved during the Phase 2 Life Cycle. The working premise is that in maintaining a product the procurement of a new product is being avoided and therefore the EPS of a new product is also avoided. This is saved energy and can be added to the energy balance sheet as positive energy.

The charts in figure 5.32 and 5.41, combines all the energy input to the products with all the energy saved to create an energy accumulation sheet prior to the formulation of the energy balance sheets for both case studies, which is shown in figure 5.33 and figure 5.42

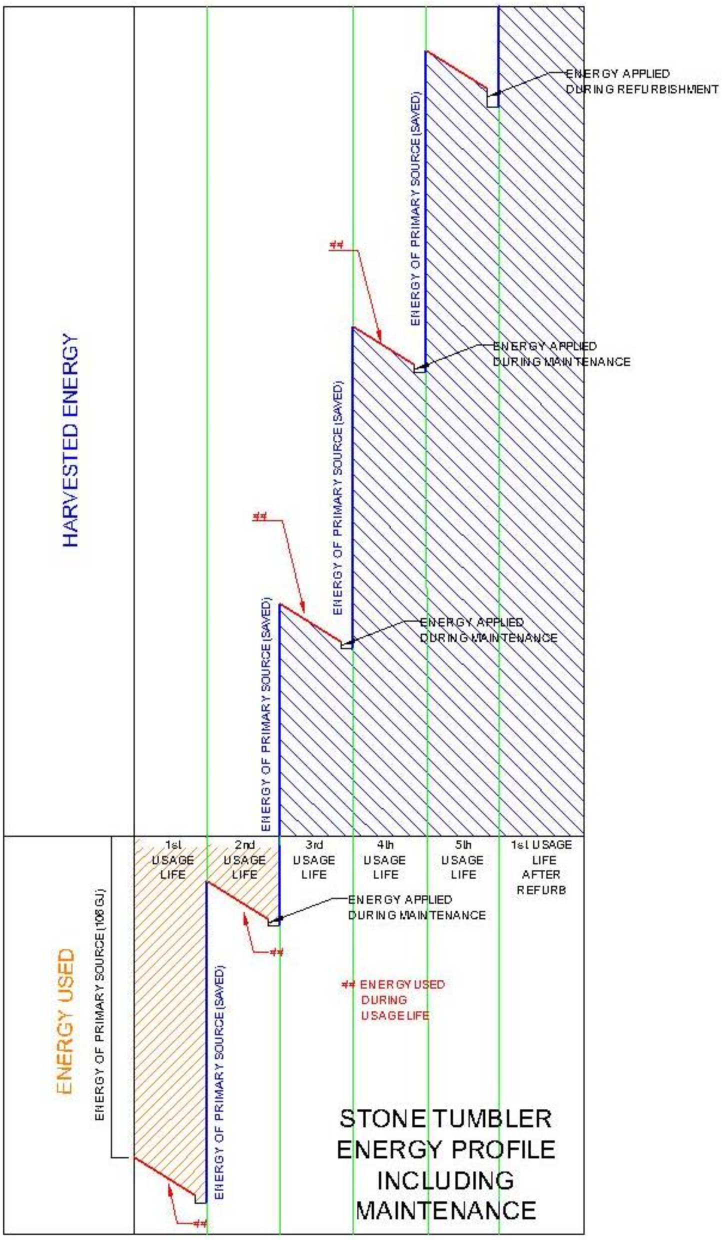


Figure 5.43: Energy Profile Description and Break Even Chart

It is useful to show graphically the energy input and that harvested during the life cycle of the stone tumbler. This can be seen in figure 5.43. During manufacture Embodied Energy is expended on the stone tumbler resulting in the Energy of Primary Source (EPS). When the product enters service in its first usage life the stone tumbler uses energy in the form of power to its electric motor which increases the energy used. Energy is also used during maintenance but that very process saves (harvests) a single EPS by avoiding the procurement of a new product. This goes some way to offsetting the energy used.

During the second usage life energy is again expended through the electric motor and again energy is used during maintenance at the end of the second usage life. The energy saved due to the maintenance process offsets the energy used and for the first time enters a positive energy balance. The cycle is repeated until five usage lives have been applied whereupon refurbishment takes place. This takes more energy than a single maintenance process but still returns the stone tumbler to be used in a nearly new condition. The stone tumbler can now commence first usage life after refurbishment and continues around the maintenance usage cycle saving EPS with every cycle.

5.14 Energy Balance Sheet Application

The end result of the net energy balance is SLV Ph1 & Ph2. This valuable bottom line figure can be used in several ways:

- as a marketing tool to pit against similar products.
- as a target for the design team to improve
- as an index value which can be listed on an eco-label such as Energy Star

As a marketing tool the value can help cement companies' "green" credentials by producing a product that can beat the Embodied Energy value of a competitor's similar product. The design teams will strive to improve the overall SLV, thus competitively reducing the Embodied Energy and/or increasing the harvested energy. There are several eco-labels which have stringent requirements before allowing products to share their logo. The SLV Ph1 & Ph2 value will help define the level of sustainability that a product possesses.

These applications are the front face of the SLV but the real importance lies under the surface with the information that the process generates. The SCM process coupled with the SCMA algorithm provides valuable in-the-field information to the TDC MS and the design team so that new products can be modified and the entire life cycle controlled more efficiently. When behaviour of the product and consumer is determined using real time information, designs can both accommodate the behaviour and influence future behaviour. This aspect fulfils item 5 of the measurement requirements put forward by Subhas and Sikhdar [5.41].

1. select sustainability parameters with system boundary
2. indicators or metrics selection must be quantifiable
3. prioritise indicators and metrics for precision and quality
4. conduct an analysis that provides quantified data
5. use methodologies that combine and collate information suitable for appropriate decision-making

Information feedback is only one aspect since the direction of components towards recycling or reuse can be audited and controlled with information feedback to the TDCMS. Information such as this does not currently return to the manufacturer since products often enter the market with no system in place where performance, usage or disposal possibilities can be fed back.

The end result of the process may be a valuable quantity of net energy, but the important elements lie within the process and the information it generates. The benefits of the measurement process are as follows:

- measurement of Embodied Energy leads to better life cycle control. The basic management premise “Measure it to control it”, applies.
- energy values within process elements allows close analysis of the life cycle elements
- feedback information to TDC MS and design teams is essential for component functional improvement
- energy feedback information is necessary for design iterations leading to reduction in Embodied Energy
- component reuse information leads to better control of component usage thereby helping to ensure components fulfil their useful life, thus ideally reducing REE to zero before recycling
- component recycling information improves recyclability and assists design teams to ensure a high percentage of easy-to-recycle components are designed into the product
- information generated by the SCM leads to the design of longer life parts and the selection of Embodied Energy efficient components.
- Feedback information gives the design team the opportunity to design longevity into the product
- feedback information of time taken in maintenance ensures better designed-in maintenance procedures resulting in shorter maintenance times and lower maintenance energy input

These benefits help the design team and the TDCM management team control the entire life cycle of a product through information feedback and design iteration of better, lower Embodied Energy products.

5.15 Validation of Data Input

It is important to ensure that any data input to the algorithm is accurate and validated since crude, inaccurate data will result in imprecise output. Measures should therefore be taken to ensure that all data has been validated and is taken from an appropriate source.

It is also important to realise that a fool proof data validation system is difficult to generate unless the system is actually applied in an industrial context where specific, real-time data is available by tuning the SLV process to a particular factory or plant. In accordance with ISO14001 and ISO14044 a validation scheme can be incorporated when the SLV sustainability measurement system is first set up. The Standards suggest procedures and outline classifications of data.

5.15.1 Data Collection

The initial procedure should be to establish a boundary around the process or environment at which the measurement is to be targeted. The ISO Standards then suggest data classifications, listed as follows:

1. energy inputs, raw material inputs, ancillary inputs and other physical inputs
2. products, coal-products and waste
3. emissions to air, discharges to water and soil

4. other environmental impacts

Data collection can be resource intensive and the Standards suggest that practical constraints on data collection should be considered and documented. It should be noted that whilst items three and four above are extremely important elements which any industrial system should reduce to a minimum, in the context of this research project these outputs could be considered as waste energy output that could be recycled since they would be likely to carry heat and chemical energy into the environment.

5.15.2 Data Calculation

The standards also offer suggestions for operational data calculation including

1. data validation
2. relationship of data to processes
3. relating of data to a functioning unit or system

The calculation of energy flows should take into account the different fuels and electricity sources used, including efficiency of conversion and distribution of energy flow, as well as the efficiencies associated with the energy flow.

The data validation process that follows is extracted from the active columns in figure 5.40(a & b) and Figure 5.41 and is the Embodied Energy accumulation for Phase 1 and Phase 2 Life Cycle applied to the case study for the stone tumbler.

5.15.3 Specific Embodied Energy (SEE)

Description: the value of Embodied Energy (Mj) expended on the product during sourcing from extraction through converting to a usable product e.g. steel hollow section, *I* section beam, etc.
Validation action: certificated material such as timber should possess appropriate information but for uncertificated material such as steel, the SEE needs to be determined since Embodied Energy input varies in efficiency between processing plants, countries and distance transported. The accurate determination of sourcing data may require an investigation through suppliers to the original source of the material whereupon a true value can be determined.

5.15.4 Sustainable Design Value (SDeV)

Description: the value of Embodied Energy applied to the product during the design process
Validation action: the determination of an accurate energy value may take several forms depending on the situation.
Validation action 1: After setting up a control volume around the design facility the process of determining and compiling the energy usage of all appliances within the design and development area should be conducted. Furthermore an apportioning of heating energy and any other energy using devices should be undertaken.

Other methods may be applied when considering the variations in premises. For instance, in some companies the manufacturing facility is closed down for annual maintenance, but the design function may still be fully employed. In these situations an energy reading can be taken of the design facility whilst it is isolated from the rest of the factory.

5.15.5 Sustainable Manufacturing Value (SMV)

Description: the SMV is the energy value expended on the product during manufacturing. It is normally expressed in energy per unit mass or (Mj/kg). A factory is a complicated energy usage environment and whilst production engineers will attempt to reduce energy usage machine by machine the SMV needs to consider not just manufacturing facility but all the support facilities such as offices and transport. To this end a total energy value can be obtained through utility bills and additional purchases of energy such as diesel, bottles of propane and/or other gas.

Validation action: draw a control volume around the manufacturing facility and monitor energy usage bi-annually separating summer energy usage from winter energy usage. Ensure all energy usage is accounted for in terms of electricity, gas, solar, geothermal, acetylene, propane, methane, coal, etc. In some companies components may be transported into the plant for assembly onto the product. The energy expenditure needs to be accrued and may be attributed to the sending company or to the receiving company but should not be counted twice. The appropriation of this energy will depend on the company policy. If it is added to the sending company the Embodied Energy value will be applied to the component whilst adoption by the receiving company will add the Embodied Energy value to the final product. Transport values can be monitored by analysing fuel usage.

5.15.6 Sustainable Usage Value (SUV)

Description: the SUV is the value of energy used during a lifetime of usage. For a vehicle this will be the value of energy embodied in the petrol or diesel consumed. Conversely the product, such as a solar panel may generate energy. The SUV can therefore be positive or negative energy applied to the product life cycle.

Validation Action: determine the form of energy input during use. Some products may use electric motors whereupon duration should be monitored in seconds then multiplied by the power rating of the rotor, giving energy in Mj. For fossil fuelled products (cars or trucks) fuel usage in litres may be monitored or perhaps miles covered in Ltr/km. When the application is considered the most convenient or most accurate medium may be selected.

Products such as solar panels generate energy. This may be monitored and accrued as positive energy directly included in the energy balance sheet. Other products such as flywheel storage devices can be considered to store energy which would otherwise be lost. This saved energy may therefore be monitored and included as positive energy in the energy balance sheet. Practical application is required for precise measurement.

5.15.7 Sustainable Maintenance Value (SMaV)

Description: SMaV is the input energy attributed to carrying out maintenance and refurbishment work on the product and includes factory overhead such as heating and power. In carrying out maintenance work and returning the product to full service, the procurement of a new product has been avoided and its Energy of Primary Source (EPS) can be considered as saved or harvested energy. The SMaV can therefore constitute positive or negative energy.

Validation action: to determine positive (harvested energy) it is necessary to define an accurate Specific Embodied Energy value (SEE) as described above which can be defined as the energy per kilogram of product. In order to use this effectively an accurate product mass needs to be defined.

To determine the maintenance input energy the factory energy overhead may be used and proportioned according to the number of days the product has spent in the maintenance plant coupled with the throughput of the number of products. The data thus used can be gleaned from the recorded data, research data and factory policy documents.

Maintenance Energy

$$M_{EI} = \frac{\text{Number maint' procedures x average maint' days x annual factory energy O/head}}{\text{factory operational days}} \quad \ldots\ldots\ldots 5.29$$

During the maintenance process components such as seals and bearings may be changed which can be considered as sacrificial components but when replaced require their EPS adding to the maintenance value.

It is important that data is recorded accurately. Included in the data acquisition is information such as, the number of times maintenance has been performed on a particular product or the number of times a bearing has been replaced.

5.15.8 Sustainable Disposal Value (SDV)

Description: the SDV is the value of energy required to reprocess components into usable raw material. This is often only a small proportion of the EPS (e.g. 26% for steel and 5% for aluminium)

Validation action: the mass (kg) of discrete materials should be determined so that energy required in recycling can be calculated. Recycling facilities may possess different efficiencies and so the target facility should be selected for its efficiency in converting end of life materials and components into new, usable product. This can be done by taking the annual energy overhead of the plant and dividing by the output product mass thus creating an SEE (Mj/kg) for the recycling plant.

The above validation actions are guidelines based on directions extracted from ISO Standards; ISO14001 and ISO14044 and are intended as guidelines for good practice. A detailed data validation scheme can only be put in place when the sustainability measurement system is applied to a manufacturing plant with a specific range of products.

5.16 Sensitivity Analysis

During the manufacture of a product energy input may vary but this can be broken down often into seasonal variations. It is useful to assume that the energy required for manufacture of most industrial products will be the same whether manufactured in summer or winter. In the majority of cases it may be assumed that the energy fluctuations are due to extra heating of the manufacturing plant during the winter months. There follows a sensitivity analysis of the stone tumbler manufactory where consideration was given to the heating of the factory during the winter months between 1st October and 31st of March.

Sensitivity action: analysis has been centred on the methods of heating the factory. Energy accumulation readings would normally be taken bi-annually accounting for summer and winter heating. Office heating proved to be increased during winter but was a negligible part of the entire energy usage and was therefore added to the general factory annual energy usage. Heating the manufacturing space of the factory, however, was a significant increased energy value. Large propane powered space heaters (47 kg propane bottles) were used throughout the work areas. The annual usage was 12 propane gas bottles of 47 kg, three of which were used for manufacturing purposes during the summer months whilst a total of nine bottles were used during the winter months, 3 bottles for manufacturing and 6 bottles for heating. (Data from HE&A Ltd Sowerby Bridge, UK)

5.16.1 Determination of Energy (Mj) Available in Each 47 kg Propane Bottle

1 Ltr Propane = 0.51kg

A single 47kg bottle contains $\frac{47}{0.51}$ = 92.2 Ltr Propane

Energy Value of Propane = 25.3 Mj/Ltr

Energy Value per 47 kg bottle = 92.2 x 25.3 = **2,331.6 Mj**

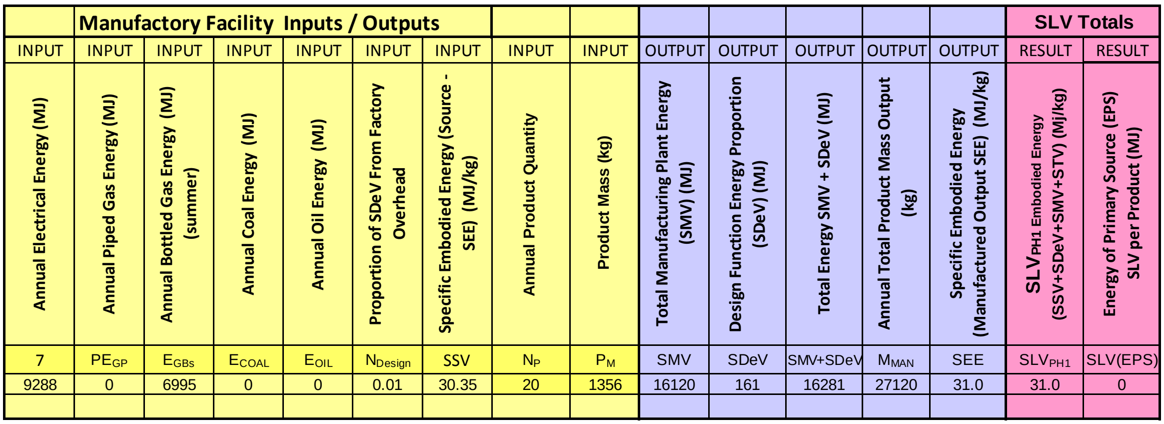
Propane Energy Usage Summer
3 x 47kg bottles x 2331.6 = **6,995 Mj**

Propane Energy Usage Winter
9 x 47kg bottles x 2,331.6 = **20,984 Mj**

Difference between Summer usage and winter usage
20,984 – 6,995 = **13,989 Mj**

This data has been inserted into the Phase 1 Life Cycle algorithm to determine the Energy of Primary Source (EPS). The significant outcome value is the Specific Embodied Energy (SEE) which is applied to the mass of each component to derive an energy value. This is later inserted into the energy balance sheet.

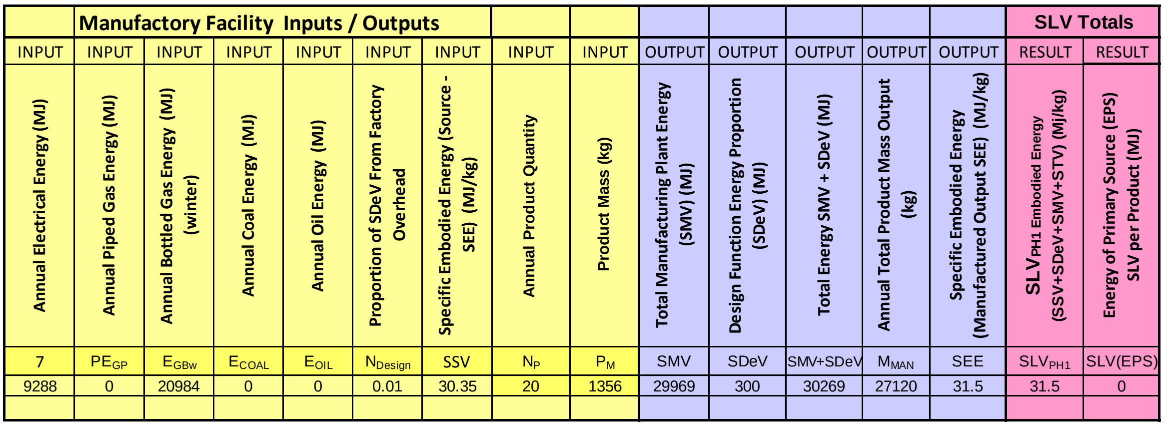
It can be seen in figure 5.44 that the summer energy usage value for bottled gas energy is 6,995 Mj creating an SEE value of 31.0 Mj/kg. Figure 5.45 shows that the winter energy usage value has increased to 20,984 Mj with an incumbent SEE value of 31.5 Mj/kg.



	Manufactory Facility Inputs / Outputs													SLV Totals	
INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	RESULT	RESULT
Annual Electrical Energy (MJ)	Annual Piped Gas Energy (MJ)	Annual Bottled Gas Energy (MJ) (summer)	Annual Coal Energy (MJ)	Annual Oil Energy (MJ)	Proportion of SDeV From Factory Overhead	Specific Embodied Energy (Source - SEE) (MJ/kg)	Annual Product Quantity	Product Mass (kg)	Total Manufacturing Plant Energy (SMV) (MJ)	Design Function Energy Proportion (SDeV) (MJ)	Total Energy SMV + SDeV (MJ)	Annual Total Product Mass Output (kg)	Specific Embodied Energy (Manufactured Output SEE) (MJ/kg)	SLV_{PH1} Embodied Energy (SSV+SDeV+SMV+STV) (Mj/kg)	Energy of Primary Source (EPS) SLV per Product (MJ)
7	PE_{GP}	E_{GBs}	E_{COAL}	E_{OIL}	N_{Design}	SSV	N_P	P_M	SMV	SDeV	SMV+SDeV	M_{MAN}	SEE	SLV_{PH1}	SLV(EPS)
9288	0	6995	0	0	0.01	30.35	20	1356	16120	161	16281	27120	31.0	31.0	0

(a) Phase 1 Embodied Energy: Material Sourcing through to Manufacture: Derivation of EPS (Summer)

Figure 5.44: Derivation of Energy of Primary Source (EPS) Summer Usage



	Manufactory Facility Inputs / Outputs													SLV Totals	
INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	INPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT	RESULT	RESULT
Annual Electrical Energy (MJ)	Annual Piped Gas Energy (MJ)	Annual Bottled Gas Energy (MJ) (winter)	Annual Coal Energy (MJ)	Annual Oil Energy (MJ)	Proportion of SDeV From Factory Overhead	Specific Embodied Energy (Source - SEE) (MJ/kg)	Annual Product Quantity	Product Mass (kg)	Total Manufacturing Plant Energy (SMV) (MJ)	Design Function Energy Proportion (SDeV) (MJ)	Total Energy SMV + SDeV (MJ)	Annual Total Product Mass Output (kg)	Specific Embodied Energy (Manufactured Output SEE) (MJ/kg)	SLV_{PH1} Embodied Energy (SSV+SDeV+SMV+STV) (Mj/kg)	Energy of Primary Source (EPS) SLV per Product (MJ)
7	PE_{GP}	E_{GBw}	E_{COAL}	E_{OIL}	N_{Design}	SSV	N_P	P_M	SMV	SDeV	SMV+SDeV	M_{MAN}	SEE	SLV_{PH1}	SLV(EPS)
9288	0	20984	0	0	0.01	30.35	20	1356	29969	300	30269	27120	31.5	31.5	0

(a) Phase 1 Embodied Energy: Material Sourcing through to Manufacture: Derivation of EPS (Winter)

Figure 5.45: Derivation of Energy of Primary Source (EPS) Winter Usage

The conclusion that can be drawn is that increase energy usage, in this case to heat the factory, has had an impact on the Specific Embodied Energy value. Whilst it is appropriate to take energy values from the factory overhead to benefit the product SLV a sensitivity analysis such as that shown above indicates where reductions in manufacturing energy usage can be applied. The increase in energy usage through gas cylinders during winter months has actually increased the Embodied Energy applied to the product.

Footnote: the factory at HE and A Ltd is a traditional manufacturing plant with a large open space filled with machine tools and a poorly insulated roof and walls. This analysis indicated to the management staff that a great deal of energy was being used and lost through poor insulation. The findings were a quantifiable indicator of wasted energy and prompted the management to create discrete containment rooms around specific manufacturing areas and though data is not available at the time of writing, it was expected that these would make a significant improvement to the factory energy usage.

The sensitivity analysis conducted above is a single example of a practical application of the approach taken to derive SLV for Phase 1 Life Cycle other similar analyses could be undertaken by production staff when tuning the SLV approach to specific factories.

5.17 The Triple Bottom Line and the Position of SLV Phase 1 and Phase 2

SLV Phase 1 and Phase 2 can be integrated into and further develop other researchers work. John Elkington [5.42] in 1994 coined the Phrase "Triple Bottom Line" and proposes that all three elements need to be engaged if sustainability and reduction in liability to the planet is to be improved. Significantly he suggests that sustainability is the catalyst that binds all three bottom line elements. The TBL approach was first published in 1994 and takes its lead from Brundtland [5.43] which introduced the concept of Sustainable Development. The TBL is captured pictorially in figure 5.46 and indicates how sustainability links the three elements.

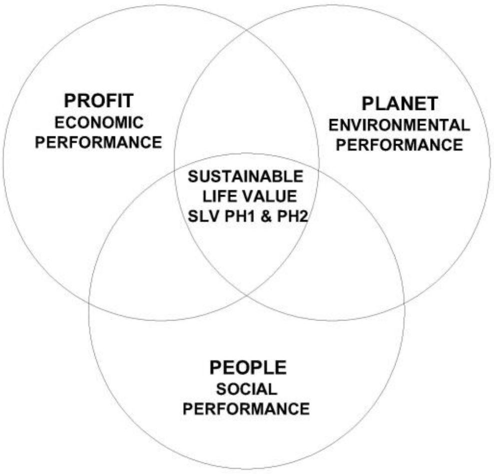


Figure 5.46: Graphical Representation of the Triple Bottom Line

Sustainability means many things to many people depending on the subject area, their particular goals and the level of the investigation. For instance, a sustainability investigation may be focused on an urban community or perhaps a whole country in which case measurement results will tend to be combined into an index. Several researchers have made significant proposals. Moran [5.44] used the Human Development Index (HDI) to measure human well-being nation by nation. Moles [5.37] investigated the sustainability of urban districts and attempted to gauge the urban metabolism using various measurement parameters such as energy usage, carbon dioxide output, food tonnage consumed, cost of living, and many more, eventually using 174 measurement parameters which were eventually combined into a single index.

Mohannad [5.38] suggests that a sustainability measurement approach by producing a product sustainability index (PRODSI) which compiles several measured parameters. The starting point is the need for an index and populating the index with appropriate measurements. The research outlined in this chapter approaches the measurement requirement from the product level where distinct measurements are taken of Embodied Energy and harvested energy. The information can then be used directly or be fed into an appropriate index.

Figure 5.46 also shows the influence of product by product measurement in the form of the Sustainable Life Value (SLV Ph1 & Ph2) as devised within the SLV model. It is acknowledged that the final value of SLV Ph1 & Ph2 is an important value but the real value lies in the entire complex SLV Ph1 & Ph2 system incorporating management techniques, measurement methodologies, algorithms, etc. and is the resource which contributes to the TBL.

Figure 5.47 shows the influence on the TBL by the Sustainable Life Value system and methodology. The detail elements that lie behind the three pillars of the 3BL can be quite diverse depending on the subject area and measurement device. The elements within figure 5.47 were selected from a publication by Slaper [5.45] who specifically related product influences to the 3BL.

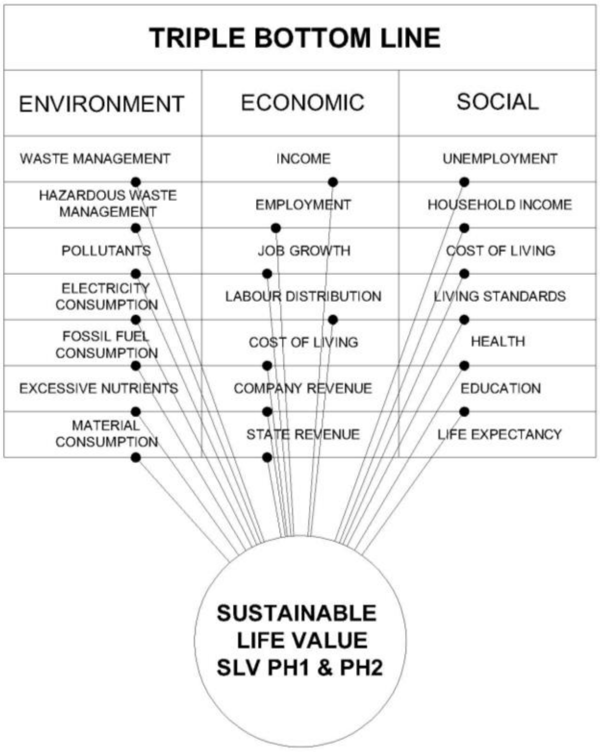


Figure 5.47: The Influence of the Sustainable Life Value on the Triple Bottom Line

It is useful to explore the influence of SLV Ph1 & Ph2 on some of the TBL sub-elements. The influence of the SLV system on the environmental elements is the most obvious since it promotes reduced energy input in the form of Embodied Energy and in doing so reduces material input to a product. A reduction in material use will also help to reduce waste, pollutants and also hazardous waste since the reduction in material usage means a reduction in processing and a reduction in harmful by-products. The focus on reducing input energy and usage energy will naturally help to reduce energy consumption. A reduction in mass, improvements in engine technology, replacement of fossil fuel powered units to more environmentally friendly powered units will inevitably lead to a reduction in fossil fuel consumption.

In economic terms the focus on reducing the Embodied Energy and energy when in use naturally leads to cost benefits. Material sourcing is notoriously a high energy element of the life cycle Ashby [5.2]. Local sourcing of materials that transport energy is reduced leading to lower fuel consumption and reduced transport costs. Local sourcing also creates a richer local economy leading to job growth, greater employment, locally improved cost of living and a stable income for workers.

From a social point of view a local economy improves employment and improves household income while reducing the cost of living. Moles [5.37] investigated several small local urban areas and reported that a stable local economy improves living standards and stability. O'Reagan [5.46] applied slightly different metrics to Moles but established similar conclusions. The extrapolation of these ideas suggests that the focus of a reduction in Embodied Energy by designers and manufacturers will lead to an improved local economy with the benefits described above.

The hypothesis submitted is that the benefits of reducing Embodied Energy in products are much greater than the mere reduction of energy. Within the Sustainable Life Value model the focus on reducing Embodied Energy and creating situations where energy can be harvested focuses engineers on the methodology of achieving those goals and in so doing spreads a positive influence which affects the three pillars of the TBL. It is submitted that the SLV model and the system that allows it to function spreads across environmental, economic and social boundaries shown graphically in figure 5.46.

5.18 Global Data Access

The Sustainable Life Value (SLV) process generates a great deal of useful and valuable information and for this information to be fully utilised it needs to be distributed to management teams, design teams and to other interested parties who are concerned with different aspects of the product life cycle. It is most important to ensure dissemination of information so that the information can be used to advantage. After leaving the factory, products, may be used globally so data dissemination and retrieval systems also need to be global. Cayzer and Priest [5.50] suggested that data should not be static or flow in one direction but data retrieved from a life cycle analysis should flow backwards as well as forwards so that the data is interactive and free-flowing.

The Total Design Management Control Strategy (TDCMS) is effectively a closed loop management system which operates at a detailed product level. Matsokis & Kiritsis [3.47] extended the use of Product Life-cycle Management (PLM) into the usage, refurbishing and disposal so that closed-loop life cycle management (CL2M) could be achieved. The objective of CL2M is to be able to continually improve design, manufacturing, use and end of life handling of products and maintain the most energy efficient resource level. Matsokis & Kiritsis suggest that it is easy to discern activity, environmental or otherwise, on an aggregate level but at the detailed level, accurate data is required. The main aim of the PLM system is to utilise precise data, and interconnect functions and systems within the life cycle elements of a product using distributed information transmission systems such as RFID, wireless, hard wire, laser, etc.

The PLM data acquisition and distribution structure is ideal to combine with the TDCMS. The PLM system is able to capture the information gathered by the Sustainable Life Value scheme and disseminate it to appropriate elements within the TDCMS structure. Kiritsis [5.48] admits that the technology is in its infancy, but, with such a system in place, producers will be provided with complete data about modes of use and conditions of retirement and disposal of their products. He further suggests that designers will be able to exploit expertise and know-how of other players in the product life cycle, thus improving product designs. It is clear that TDCMS can work effectively alongside PLM where TDCMS and the Sustainable Life Value scheme can supply the detailed product information which PLM can disseminate.

Framling [5.49] improved on Kiritsis [5.48] within PLM, by suggesting that intelligent products are necessary for sustainability and that the use of computer aided technologies can allow communication between intelligent products and other information systems. Framling's proposal enhances the suggestion by Cayzer and Priest who recommended that data should be free-flowing and interactive. According to Framling the communication between devices and systems can improve energy efficiency by reducing energy consumption, extrapolating user behaviour and integrating energy supply and demand. Products operating within the SLV scheme could benefit greatly from the intelligent information sharing concept where certain behavioural information could be fed back to a central TDCMS location for instantaneous retrieval and application to new products and to products already in use.

Analysis of maintenance and refurbishment information can reveal flaws and problems with the current product so that, for instance, new materials may be sourced, longer lasting components may be located and more efficient manufacture techniques may be instigated. Each element of the product life cycle can benefit from this shared information.

Modern “Cloud” technology suggested by Kiritsis et al [5.47, 5.48 and 5.49] allows the installation of a centralised database to be established with global write and read access. In this case the gathered SCM information under the umbrella TDCMS can run alongside the PLM systems and relates to the:

- flow of components, feed forward and feed backwards,
- flow of sustainability information to all functions within the life cycle envelope
- accounting of used and harvested energy leading to the energy balance.

5.17 Conclusions

The measurement of sustainability can take many forms. This research project proposes using Embodied Energy as the metric for measuring sustainability throughout the life cycle a product. Phase 1 Life Cycle represents measurement of Embodied Energy during the journey of the product from material sourcing to leaving the factory including transport between processes and may include energy expended on transport to the customer. Phase 2 Life Cycle commences when the product reaches the consumer and represents the measurement of Embodied Energy during product use, maintenance and disposal. During Phase 2 Life Cycle it is also possible to harvest energy from energy saved or energy generated. The proposed energy accounting model and algorithm accrues all the energy applied to a product during its life cycle and energy that can be harvested.

During the design process the design team can recommend ideal conditions for use, maintenance and disposal but cannot predict customer applied variations in use or disposal. As a new product is being designed, Phase 2 Embodied Energy can only be predicted since new products that do not possess a usage track record. When the product is in use, then accurate feedback information allows the TDCMS and design team to accurately define the SLV for both Phase 1 and Phase 2 Life Cycles

The SLV_{PH1} value was initially shown in the TDCM strategy in figure 5.12 and can be used as a marketing tool for comparison with competitors' products. The certification process could be similar to the CE marking process (European conformity standard) as individual companies make justified and analytically supported claims of Certified Embodied Energy Value (CEEV) for their product.

To retain a competitive edge, companies would find it necessary to redesign their products to achieve a lower CEEV thereby initiating the reduction of Embodied Energy values for new products. In the case study, section 5.8, an exercise was conducted to reduce the manufacturing energy applied to the product, achieving a significant cost reduction as well a reduction in SLV. There was much more the factory could do to reduce the energy used in manufacture, but small energy savings, eventually build to create an efficiently manufactured product. In practice the exercise focused the management team on ways they could reduce energy so additional improvements in the future can be anticipated.

5.17.1 Phase 1 Life Cycle: Embodied Energy Derivation

The analysis presented should be considered as generic. Refinement towards a particular component and product will enhance accuracy but requires the addition of elements such as the Embodied Energy of individual components, recycled materials input, and the possible reuse of waste product plus the Embodied Energy applied during the waste products' incumbent transport.

The two Phase 1 case studies presented demonstrate the application of the different aspects of the audit system. The first is a sustainability audit of a kinetic energy storage battery flywheel rotor which is a concept design which represents the first opportunity in the design process to apply a sustainability audit.

The second case study of a brick and block clamp is a practical exercise based on a functioning company producing an existing component. The energy data has been derived directly from the company's energy overhead. This is typical of a final sustainability audit and allows the company to see precisely where their energy had been applied. Though the company was very concerned with cost savings the exercise really focused on energy savings and in particular the impact on the Embodied Energy of each brick and block clamp.

Commercial energy accounting algorithms such as CES EduPack (Granta Design Ltd) [5.11] are useful but tend to be broad in their approach making assumptions which do not allow detailed analysis. CES EduPack was used as a comparator for elements of the life cycle as the SLV Phase 1 algorithm was developed which can now be used as a stand-alone algorithm.

5.17.2 Phase 2 Life-Cycle: Embodied Energy Derivation and SLV Phase 1& Phase 2

The Embodied Energy derivation for Phase 2 Life Cycle is complicated for most products since they are at the mercy of the consumer who may, or may not use the product as the designer intended. For this reason the measurement of Embodied Energy during Phase 2 Life Cycle is also complicated.

It is generally considered that maintenance and refurbishment extends the life of products and it is these two elements of the Phase 2 Life Cycle which have been used as integral processes where energy measurements can be taken and logged, and decisions made relating to recycling and reuse of components. The algorithms thus presented accrue and combine all energy inputs to the product and all energies that can be harvested. The Phase 2 algorithm is based on maintenance and refurbishment processes and applies sustainability principles as a central focus. The process runs along-side normal maintenance techniques and is termed Sustainability Centred Maintenance (SCM).

The Phase 2 algorithm combines SLV Phase 1 energy data with Phase 2 energy inputs and harvested energy. The end result is a complete energy profile that can be formulated for the entire product cycle. This is shown in figure 5.33 for the gearbox case study and figure 5.42 for the stone tumbler case study. The complete life cycle data can then be combined into an Embodied Energy balance sheet which, for the rotation gearbox case study, can be seen in figure 5.33 and figure 5.42 for the stone tumbler. Input energy in the form of Embodied Energy is collated and represents all the energy the product has used during its entire life cycle. The positive side of the balance sheet shows the Sustainable Giveback Value (SGBV) which represents all the energy that has been harvested. The result of combining the positive and negative energy is the net energy representing the true Embodied Energy value and is the SLV Phase 1 & Phase 2.

5.19.3 The Role of Maintenance and Refurbishment

Maintenance and refurbishment are very practical elements of Phase 2 Life Cycle and it is the maintenance engineers who have to make decisions to reuse or recycle components. Some components may fail before their design life is complete and some components may last until the end of life of the product. Flexibility has therefore been built into the data entry system to accommodate this usage uncertainty.

Maintenance and refurbishment processes have been used as appropriate points for data collection during Phase 2 Life Cycle. This data can be used by the design function to judge usage trends and, if necessary, make changes to current design projects. End of life data is also generated during the maintenance process which is important input to the design function since data will influence the direction and composition of future designs.

5.19.4 Data Distribution

The data generated from the SLV scheme is valuable in-the-field data and must be disseminated if the goals of creating the data are to be realised. Modern Internet and cloud technology can be employed to create a global data network allowing input from globally distributed maintenance centres and data access from globally distributed design functions. Researchers such as Kiritsis, Framlington and others [5.47, 5.48 and 5.49] suggested using closed loop PLM which is the control of information from intelligent products. It is clear that the TDCMS is effectively a closed loop PLM system and can generate the detailed information that the Kiritsis et al model does not possess. A complete system could be formed by combining the PLM platform with the TDCMS strategy.

5.19.5 The Sustainable Life Value Scheme and its Influence on the Triple Bottom Line

The original framework selected on which to build the sustainable life value model was that of life cycle analysis (LCA) however for the analysis to be effective this needed to influence the more global strategy of the Triple Bottom Line (TBL). The suggested SLV scheme operates at the product level where precise measurements of Embodied Energy are possible that can be used to influence the product creation and management process.

The hypothesis submitted is that the benefits of reducing Embodied Energy in products are much greater than the mere reduction of energy. Within the Sustainable Life Value model the focus on reducing Embodied Energy and creating situations where energy can be harvested focuses engineers on the methodology of achieving those goals and in so doing spreads a positive influence which affects the three pillars of the TBL. It is submitted that the SLV model and the system that allows it to function spreads across environmental, economic and social boundaries shown graphically in figure 5.47. By focusing on a single metric that can measure all products and services it has been possible to produce a system that can describe the level of sustainability in those products and services. The proposed comprehensive measurement system can provide information and influence higher, more global levels of sustainability measurement.

5.19.6 Viewpoint Change

The professional approach to most businesses, enterprises and individuals such as engineers is to create products which are low cost. In many cases cost reduction starts as efficient manufacturing practices often laid down by the design office. An aspect of cost reduction for the manufacturing engineer relates to the efficient running of machine tools, low energy factories and reduced transfer using vehicles. Reduction in energy to reduce cost is very valid but the refocus of Embodied Energy reduction and LCA allows the engineer to embrace many other aspects of energy reduction. This could involve materials sourcing, using a local economy, applying “smart factory” doctrines where energy efficient factories, computer planning techniques, smart products, etc., help to reduce overall energy input. This refocus may also lead to inbuilt energy harvesting techniques such as solar panels placed in every vehicle roof or mini wind generators placed in a vehicle wheel cavity. A refocus on reduction of Embodied Energy opens up a new vista of possibilities where efficient application and gleaning of energy can lead to fewer resource implications and an increased in cost efficiencies.

5.20 Glossary Specifically Relating to Columns in the SCMA

Definitions of Terms

1. *residual life value;* is the value of energy that remains at the current maintenance period and is based on the design life set out by the design function.

2. *decision;* represents the decision made by the maintenance engineer
3. *EOL status;* shows the direction of the component towards recycling, maintenance or reuse.

4. *Energy of Primary Source (EPS);* Embodied Energy possessed by a new component upon leaving the factory ready for use.

5. *design life (usage cycles);* is the life expectancy designated by the design function for the whole product and for each individual component.

6. *number of Usage Lives (UL) accrued;* at the point of maintenance or refurbishment the product/component will have completed and accrued several UL's

7. *residual Embodied Energy;* based on the design life set by the design function, the residual Embodied Energy can be calculated by proportioning the life expended against the original life expectancy and relating this to the EPS.

8. *recycled parts cumulative number;* the additive number of specific component parts recycled during the life of a product. This figure assists in calculating the wasted Embodied Energy in recycling parts which possess residual life.

9. *reused parts cumulative number;* the additive number of specific component parts reused during the life of a product. This figure assists in calculating the energy gained through the reuse process

10. *cumulative number of replaced parts;* the additive number of specific component parts used to replace those recycled. This figure assists in the calculating the energy input to the product from new parts.

11. *replacement parts Embodied Energy;* the actual energy input by using new parts.

12. *cumulative energy +ve reused;* the additive energy saved by reusing components

13. *cumulative energy -ve recycled;* energy lost due to recycling components which still possess residual embodied energy.

14. *steel mass (kg);* component mass

15. *other mass (rubber, etc.) (kg);* mass of components other than steel

16. *energy needed for recycling Steel (Mj);* calculated value for recycling a mass of steel

17. *energy needed for recycling other (Mj);* calculated value for recycling a mass other than steel

CHAPTER 6
TOTAL DESIGN CONTROL MANAGEMENT STRATEGY

6.1 Introduction

The creation of new products within the principles of sustainability requires a particular management approach that transcends the usual pure design approach. There needs to be a broader umbrella than the pure design function can offer. The proposed umbrella management process controls the systems that apply the principles of sustainability to the entire life cycle of a product. The design process, however, provides the core framework for the Management of Sustainability, its implementation and its measurement. This follows on from work by researchers such as Chapas [6.18] who put forward the case for an LCA, multidisciplinary management team based around design that uses certification and environmental standards.

This management strategy builds on work previously published by Johnson & Mishra [6.7] who introduce a "Sustainable Life Value" model to create a "Total Design Control Management Strategy" (TDCMS) for managing the implementation of the principles of sustainability within the product creation process. The fundamental feature of this strategy is that the design function overviews, specifies and applies the principles of sustainability through the entire life of the product within the TDCMS management umbrella.

6.2 Origins of Approach

The Brundtland Commission report, published in 1987, entitled "Our Common Future" [6.17] introduced the concept of sustainable development as “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.* Thus sustainability was added to the driving forces of political, social and financial equity. The commission defined three “pillars” (3P’s) of sustainable development:

- Economic growth
- Environmental protection
- Social equality

This was developed by Elkington and others into the concept of the *triple bottom line*, [6.1] where corporations could benchmark their performance as producers of goods and services in all three areas by measuring:

- profit
- interaction with stakeholders
- net effect on the environment

At first sight, it would appear counter-intuitive for a company to focus on their environmental impact, particularly where this could have an apparently detrimental effect on their bottom line or profit, which was the first and still most important of the “3Ps”. However, changes in public attitudes in the developed world have begun to manifest themselves in the form of legislation and market pressure. Seung [6.19] reviews economic aspects of environmental impact and makes the point that pressure for sustainable products has come from consumers in recent years. Golden [6.22]

Consumers are increasingly showing trends which review energy efficiency ratings for domestic appliances or fuel efficiency for vehicles and make purchasing decisions based on recycled material content or end-of-life destination for product packaging. Energy Saving Trust [6.20] and Energy Star [6.21] both suggest this trend has increased pace in recent years. It therefore behoves any good company to ensure that it is viewed as meeting or exceeding these demands to enable capture of a share of the most lucrative market segments.

True sustainability could be defined as *Development and use of products and services where ZERO resources are taken from the Earth.* In Chapter 1, section 1.2, it was established that true sustainability can never be achieved but reducing negative environmental impact is still a desirable goal. Traverso [1.32].

6.3 Total Design Control Management Strategy (TDCMS)

6.3.1 TDCMS Overview

Total Design Control is a management strategy that considers the entire life of a product so that the principles of sustainability can be implemented from sourcing through end-of-life disposal. It is intended that the strategy be applied at the design stage of the product creation process and that the design team should be composed of appropriate specialists who can influence the design of the newly created product. Each *Life Phase* is therefore scrutinised for energy usage so that the principles of sustainability can be applied.

6.3.2 The Life Phases of a Manufactured Product

The life analysis of a typical product shows that there are six phases which can be influenced by the design function put forward by Johnson & Mishra [6.7] as previously shown in Chapter 4 figure 4.3 in the Design Objectives Model.

The model shows how the six phases can be linked and coordinated by the design function. The implementation of the model requires thought and consideration for each of the phases during the process of product design. For instance, it is the design function that can specify the sustainable sourcing of the material and in other parts of the design provide an easily maintainable device by creating easy access and interchangeable, sacrificial components. Furthermore design can determine the method of manufacture and facilitate simpler end of life disposal where easy separation of variant materials is incorporated.

6.4 The Concept of Embodied Energy as a Measurement Device [6.2]

The measurement of sustainability is particularly difficult due to its many facets and broad scope and may take several forms depending on the required outcome of the quantification process. Some evaluations may use carbon footprint, where others such as Ecolabel or Blue Angel use a complex mix of consumed resources along with pollution emitted during the product life cycle. Since the creation of physical products requires energy at every life phase and it is proposed in chapter 4 that Embodied Energy, measured in joules, is the optimum metric, Ashby [6.2].

In order to form a product from original source material, energy is applied during the various processes including manufacturing and transport. This total amount of energy can therefore be termed "Embodied Energy" and allows the designer to apply a sustainable efficiency rating to his work.

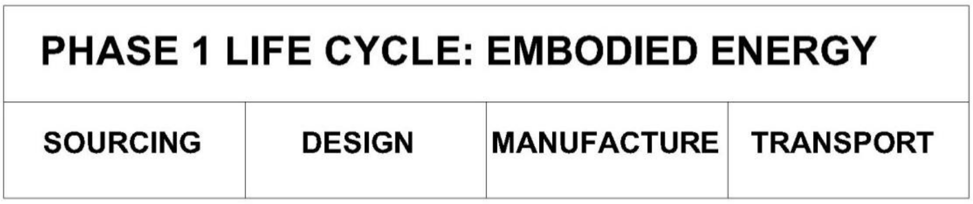
The design objectives model, figure 4.3 and Johnson, Gibson [6.3], Johnson, Mishra [6.7], shows variables for Embodied Energy at each life phase and assigns a name for each based on when it occurs in the life cycle of the product. This abridged list was introduced in Chapter 3. Definitions can be found in the general glossary

- SSV: Sustainable Source Value
- SDeV: Sustainable Design Value
- SMV: Sustainable Manufacturing Value
- SUV: Sustainable Use Value
- SMaV: Sustainable Maintenance Value
- SDV: Sustainable Disposal Value
- SGBV: Sustainable Giveback Value

6.5 Phases 1 and 2 of the Entire Life of a Product

Embodied Energy is applied throughout the life of the product, especially during Phase 1 Life Cycle which is the period from sourcing material through to the product leaving the factory. This phase sees high levels of Embodied Energy input.

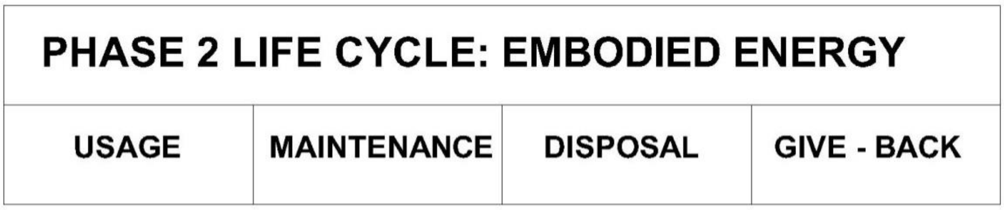
Phase 1 Life Cycle amalgamates the Embodied Energy required in material sourcing, sustainable design, sustainable manufacture, and sustainable transport. See figure 6.1. During this phase energy is reasonably easy to measure and enables the derivation of a Phase 1 Sustainable Life Value (PH_1SLV) (joules)



PHASE 1 LIFE CYCLE: EMBODIED ENERGY			
SOURCING	DESIGN	MANUFACTURE	TRANSPORT

Figure 6.1: Component Elements of Phase 1 Life-Cycle

Phase 2 Life-Cycle encompasses: usage, maintenance, disposal and the new element of “Sustainable Giveback” (SGBV). See figure 6.2. During Phase 2 Life-Cycle the product is in use and may or may not have energy input depending on the product and its use. A large vehicle will use energy as diesel oil during its useful life, whilst a passive photovoltaic solar panel will actually generate energy.



PHASE 2 LIFE CYCLE: EMBODIED ENERGY			
USAGE	MAINTENANCE	DISPOSAL	GIVE - BACK

Figure 6.2: Component Elements of Phase 2 Life-Cycle

Phase 2 Life-Cycle considers the life phases of usage, maintenance, disposal and "Give-Back". Phase 2 Life-Cycle Embodied Energy is much more difficult to quantify since the product is now in the hands of the consumer who may use the product at different rates, may not maintain the product as recommended, and may not dispose of the product as planned.

"Give-back" is an energy accounting value and represents the value of energy which can be harvested by employing life extending and energy gleaning techniques such as maintenance, low usage, sustainable end of life disposal, etc.

Phase 2 Life-Cycle Embodied Energy is the focus of work that can be viewed in Chapter 5 which presents an energy measurement method and Chapter 7 where a specific management program is incorporated to coordinate materials and information feedback.

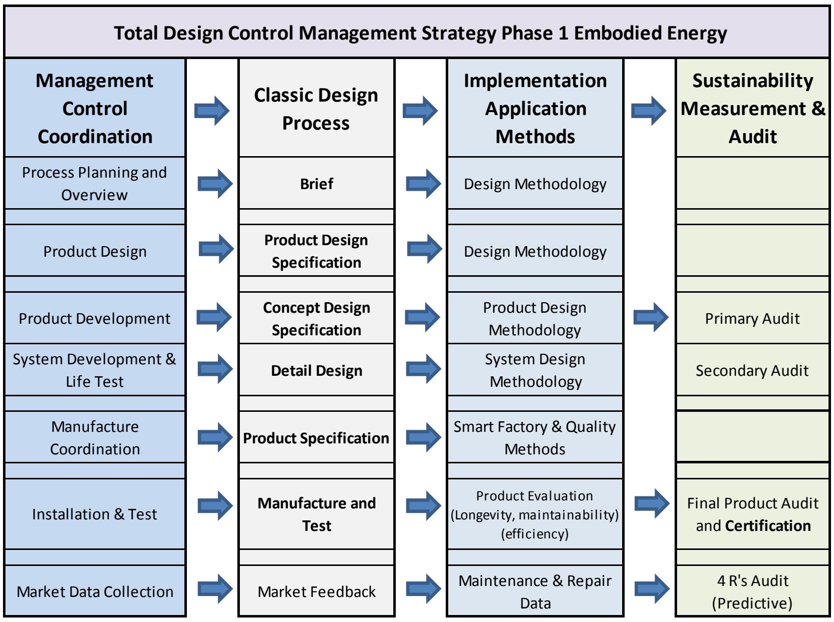
6.6 Total Design Control Management Strategy (TDCMS)(influenced by Rahimi 6.5])

Total Design Control is a management approach that combines the classic design process with techniques and measurement devices that can control and reduce the Embodied Energy within a product.

Since the design is the major influence during all six life phases of the product, it is therefore argued that there should be designed-in features that actively reduce Embodied Energy and encourage energy harvesting. In order to accomplish this task the design function has to embrace disciplines normally considered to belong to other 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.

Such a core design team would therefore be in “Total Design Control” of the six life phases, coordinating and applying sustainability principles. The quantification of energy at each life phase enables analysis of the Embodied Energy and eventual reduction to an optimum, more sustainable level.

The Total Design Control Management Strategy (TDCMS) can be seen in figure 6.3. This strategy links management control elements to the *Classic Design Process*, which forms a route through the product creation process allowing the TDCMS to be implemented, triggered by each stage of the design process. As the design process progresses management control and coordination elements are triggered for each new stage. Implementation and application methods are fundamental to the design process and should be applied by the design team at an appropriate point. Sustainability measurement first takes place when the concept design has been formulated. This is the first time in the creation process that a product has taken shape, be it merely sketches and specifications.



Total Design Control Management Strategy Phase 1 Embodied Energy

Management Control Coordination	Classic Design Process	Implementation Application Methods	Sustainability Measurement & Audit
Process Planning and Overview	**Brief**	Design Methodology	
Product Design	**Product Design Specification**	Design Methodology	
Product Development	**Concept Design Specification**	Product Design Methodology	Primary Audit
System Development & Life Test	**Detail Design**	System Design Methodology	Secondary Audit
Manufacture Coordination	**Product Specification**	Smart Factory & Quality Methods	
Installation & Test	**Manufacture and Test**	Product Evaluation (Longevity, maintainability) (efficiency)	Final Product Audit and **Certification**
Market Data Collection	Market Feedback	Maintenance & Repair Data	4 R's Audit (Predictive)

Figure 6.3: Total Design Control Management Strategy

There are four elements to the TDC management strategy:

- Classic design process
- Management control and coordination,
- Implementation and application methods,
- Sustainability Measurement and audit

6.7 Sustainability Measurement

The measurement of sustainability involves the quantification of the Embodied Energy within a product in Joules. An energy audit is taken at various stages as the product progresses through the design process to provide feedback. Predicted and measured Embodied Energy can then be compared and, if necessary, partial redesign may be applied to the product to reduce further the Embodied Energy.

In order to understand how to measure the energy added to and hence embodied in a product it is necessary to follow the mass flow from primary extraction through the various manipulation processes. The transport of the material from one process to the next is also considered in the calculation. Adding energy values applied to the product through all the life phases generates the Specific Embodied Energy (SEE)
(SEE = joules/kg) as shown in figure 6.4.

$$\boxed{\mathbf{SEE}} = \boxed{\text{SSV}} + \boxed{\text{SDeV}} + \boxed{\text{SMV}} + \boxed{\text{SUV}} + \boxed{\text{SMaV}} + \boxed{\text{SDV}}$$

Figure 6.4: Specific Embodied Energy (SEE)

The SEE can be eventually refined to a Sustainable Life Value (SLV) of pure energy (joules) by multiplying the SEE by the product mass as follows:

$$\text{SSV} = \text{SEE} \times \text{Product Mass} = \text{joules}$$

$$\text{SSV} = \frac{\text{Joules} \times \cancel{\text{kg}}}{\cancel{\text{Kg}}} = \text{joules}$$

6.8 Classic Design Process

When a product is designed there is a general process which starts when the designer receives the brief which describes the product need. After the designer gathers sufficient information to develop a complete understanding of the requirements of the project, he mentally processes the design, eventually developing the Product Design Specification (PDS).

The next stage is conceptual design, within which several alternative design options may be considered by comparing parameters. This phase culminates in the concept design and is represented by the Concept Design Specification (CDS).

Once the designer has received acceptance of the concept design, product is designed in detail by precisely defining the overall product and its components, selecting materials etc. This culminates in a Final Design Specification (FDS) specification that normally includes detailed drawings and specific data for purchase and manufacture. Manufacture, assembly, and test are then the final phase before the product is shipped to the customer.

The general classic design process can be described in a flowchart, figure 6.5, where the general process in any design creation can be seen as an iterative development. Note should be taken of the various phases which, when complete, are summarised in a specification. For instance, Phase 1, investigation phase is summarised in the Product Design Specification (PDS). The completion of Phase 2 investigation is summarised as a Concept Design Specification (CDS). These specifications effectively form "way markers" which are convenient points from which to take a sustainability audit.

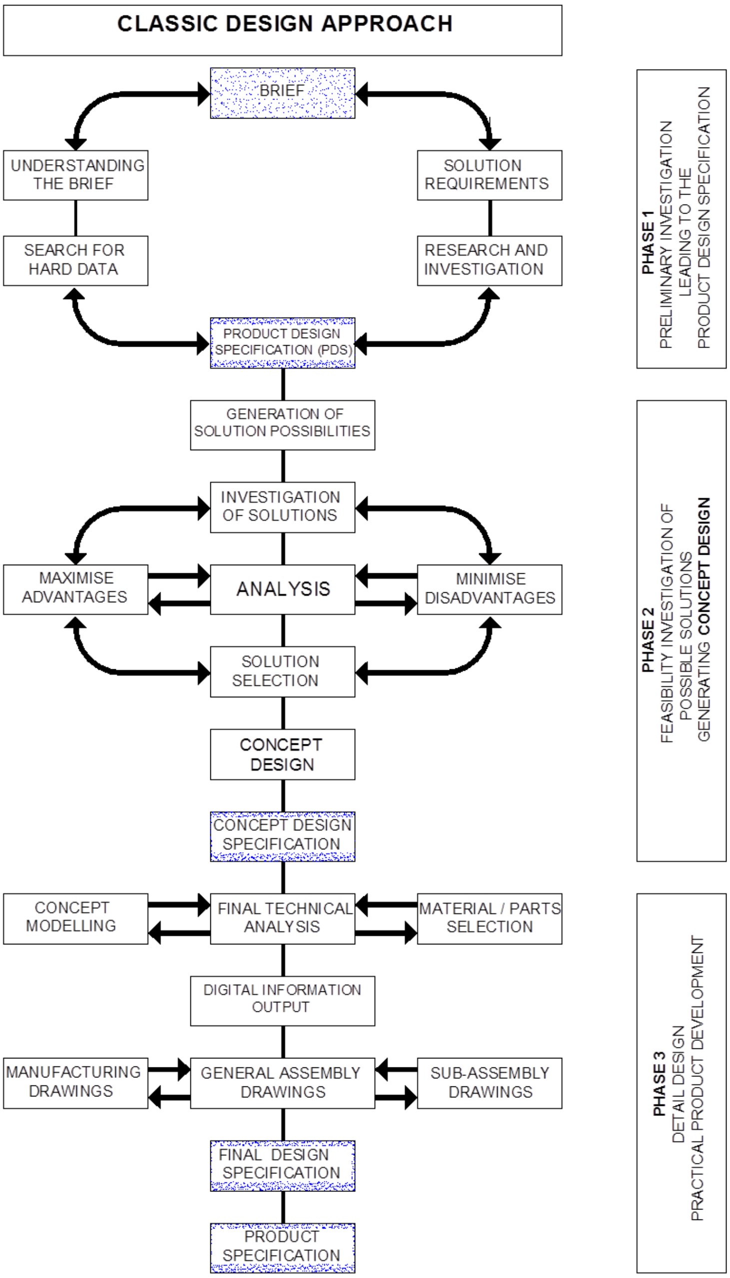


Figure 6.5: Classic Design Process, Johnson and Gibson[6.3]

6.8.1 Level One: 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 6.5. 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.

6.8.2 Level 2: Design (Concept Design Specification)

The PDS is used to formulate and synthesise several possible ideas through the various processes of idea generation to create the concept design with its precise description in the Concept Design Specification (CDS) which should match the PDS in objectives. The CDS incurs relatively low cost with minimal environmental impact involving comparatively few resources. At the point where manufacture of the product begins, much of the initial Embodied Energy and much of the creation costs are incurred. The concept design and in particular the CDS is closely scrutinised by entrepreneurs and/or management before resources are committed.

6.8.3 Level Three: Detail Design (leading to Product Specification)

Once the CDS has been accepted, the feasible theoretical design is converted into a “specified” design. This detail-oriented 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 of precise technical output (usually drawings), allowing precise manufacture. The Product Specification (PS) is also produced at this stage which as a factual list of metrics and performance characteristics and should closely match the PDS.

6.8.4 Level Four: Manufacturing and Test

The next stage is to manufacture and test the product based on the precise technical information from level three. After material sourcing, this is often the most energy intensive phase and hence one of the most expensive. Shipping to the customer completes this phase.

6.8.5 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 to design is returned via the data collection throughout the product usage and maintenance phases.

6.8.6 Installation and Testing

Installation and testing takes place after manufacture and includes 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 and ships require specialised delivery, installation and testing before handing over to the customer. With smaller items such as toasters, computers, furniture, bicycles, etc., the customer expects that the items will be serviceable as soon as they are removed from the packaging.

6.9 Management Control and Coordination (influenced by Elkington [6.1])

In the early days of the Industrial Revolution, successful manufacturing companies were typically led by innovative and entrepreneurial individuals, whose motives and ethics became the motives and ethics of the company. Successful companies are often personality-led, but the majority of companies with institutional shareholders tend to be either finance-led or possibly marketing-led. This leads to a focus on the financial bottom line, where the design function assumes the role of reducing the cost of each generation of new products by taking advantage of new materials and methods, whilst being mindful of the customers' needs and desires as determined by marketing.

In order to meet the demands of all three components of the 3BL (Triple Bottom Line), the design function is pivotal Chapas[6.18] and is especially necessary to optimise the sustainability of a company's products or systems, Luttrop et al [6.24]. Design is uniquely placed to determine the in-built or designed-in sustainability of an engineered product or system, through choices in materials, materials sourcing, manufacturing methods, ease of assembly and maintenance, usage and disposal. These choices will help determine the Embodied Energy of the product or system, which can then be used as a comparative measure to judge the ecological contribution of the product or system. Pojasek [6.25] advocating using indicators and metrics within a sustainability management environment to improve efficiencies in company operations.

The shoulders of a single designer would indeed need to be broad to carry such a herculean weight, so a systematic management process using a design team is proposed which would normally require input from marketing, procurement, production, quality, maintenance or customer care, and finance. Design team compilation is discussed in Chapter 4. Nonetheless, each design team must have a "champion" to:

- advise on issues of sustainability across the product life cycle
- liaise with other specialists, such as manufacturing and procurement to ensure optimum performance of external components and internal manufacturing processes
- ensure that improvements in sustainability are seen to benefit the producer of the product or system as well as the customer and the environment
- set up and use measurement metrics
- audit the process and provide regular feedback on a product-by-product and a global basis

This champion, (TDC Manager) co-ordinates or manages the TDC Systems. He or she will be responsible for structuring the system, ensuring full participation by stakeholders external to the design team or function, and designing and managing the audit process.

Dramatic changes in the approach to quality were introduced by Taguchi in the 1950s and 1960s. More recently these were followed by proposals by Johnson, Gibson [6.3], [6.4], and the need for well-supported Quality Management System (QMS). This kind of cultural shift within a design and manufacturing organisation will only be effective if the TDC manager reports directly to senior management who is committed to the implementation of the TDC strategy. The need to promote this new way of thinking will inevitably lead to challenges from those entrenched in past methods. The proposed structure ensures that the TDC manager has a co-ordinating and influencing role across the management matrix, whilst being supported by a direct reporting line to senior management, as shown in figure 6.6. Silvius [6.31] outlined methods and systems where project management techniques could be integrated with sustainability requirements.

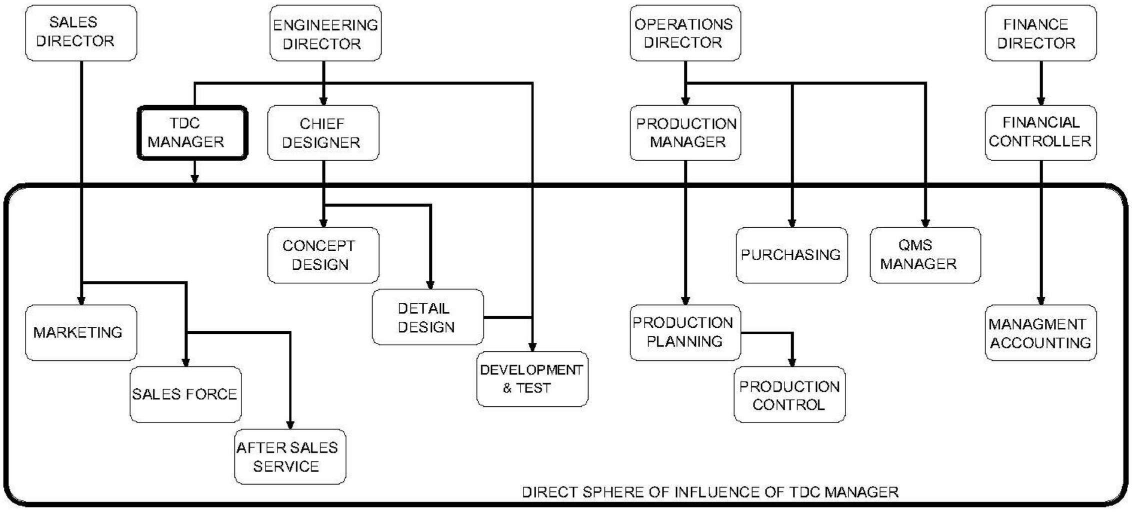


Figure 6.6: Management Structure of a Typical Engineering Company, Showing Position of TDC Manager

Figure 6.6 describes the role of the TDC Manager and his position within the design team. Taking each TDC management task in turn, the coordinating role has been examined in more detail.

6.9.1 Coordination

The design of the product can be considered to be the primary process leading all the other elements of the management strategy. Until stage by stage elements of the design have been accomplished, the project cannot progress and hence design activity is crucial to leading the process. Karkkainen [6.26] suggested a "Product Centric" approach over the entire product life cycle and proposed a management coordination at the level of each individual product. Ronkko [6.27] expanded the work of Karkkainen by proposing an enterprise Information system to improve information gathering and feedback. Further improvements were suggested by Framling [6.28], Matsokis [6.29] and Kiritsis [6.30] who are advocates of a Product Life Cycle (PLM) management strategy where information from products in the field is communicated between products and also to information collection nodes, thus ensuring feedback of information is efficient and automatic.

6.9.2 Process Planning and Overview

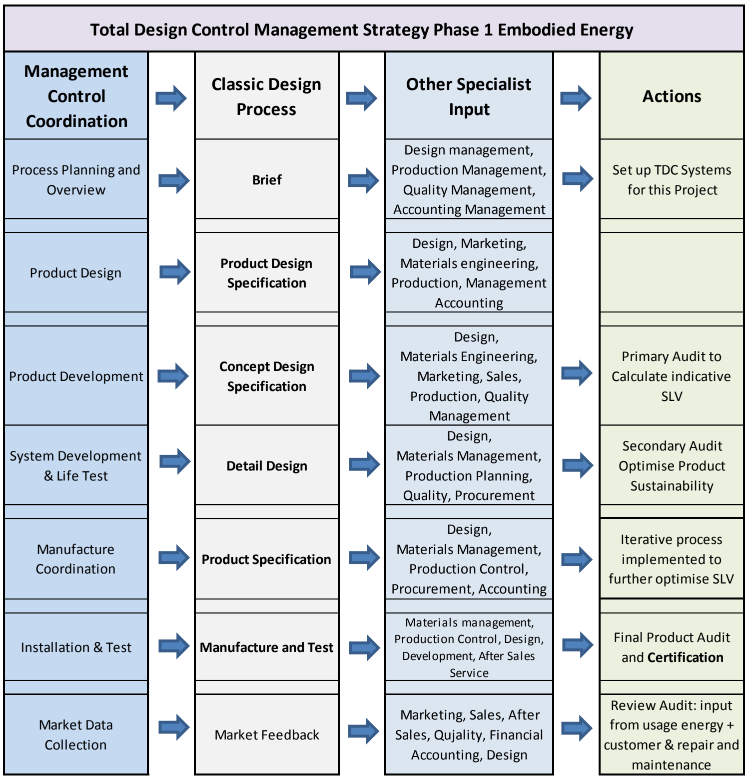
The elements in the management control and coordination column of figure 6.7 closely relates to the elements of the design process. At the beginning of the project several tasks must be sequentially accomplished. Major tasks is are listed as follows:

1. review the brief (usually generated by the marketing function)
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, examine the design brief in detail so that work can be focused on variant design facets.

From a sustainability point of view, elements 4 and 5 above are crucial since these areas define the team and its expertise. Figure 6.8, shown later shows the composition of a typical product design team indicating the expertise required from sourcing materials to product disposal. After the design team has been assembled the brief can be investigated so that it is intimately understood.

6.9.3 Design Brief

As a new product or system design project is conceived, the TDC manager must set up the systems including organising regular coordination meetings and events and aligning the audit timing with the design project management perhaps using standard planning techniques such as Gantt charts and network analysis.



Total Design Control Management Strategy Phase 1 Embodied Energy

Management Control Coordination	Classic Design Process	Other Specialist Input	Actions
Process Planning and Overview	**Brief**	Design management, Production Management, Quality Management, Accounting Management	Set up TDC Systems for this Project
Product Design	**Product Design Specification**	Design, Marketing, Materials engineering, Production, Management Accounting	
Product Development	**Concept Design Specification**	Design, Materials Engineering, Marketing, Sales, Production, Quality Management	Primary Audit to Calculate indicative SLV
System Development & Life Test	**Detail Design**	Design, Materials Management, Production Planning, Quality, Procurement	Secondary Audit Optimise Product Sustainability
Manufacture Coordination	**Product Specification**	Design, Materials Management, Production Control, Procurement, Accounting	Iterative process implemented to further optimise SLV
Installation & Test	**Manufacture and Test**	Materials management, Production Control, Design, Development, After Sales Service	Final Product Audit and **Certification**
Market Data Collection	Market Feedback	Marketing, Sales, After Sales, Qujality, Financial Accounting, Design	Review Audit: input from usage energy + customer & repair and maintenance

Figure 6.7: The Role of the TDC Manager across the Phases

6.9.4 Brief Leading to Product Design Specification

As the design specification is drawn up for the product, the TDC manager must ensure that the design and marketing teams seek input from materials and production experts, and work with management accounting functions to set up appropriate auditing systems.

6.9.5 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. Johnson and Gibson [6.3].Though all team members will have contributed to this concept design, it is a management responsibility to ensure it fulfils the product’s required future performance and also the values of sustainability throughout its life. 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.

6.9.6 Concept Design

During the concept design phase, the audit tools can be used to provide an iterative feedback loop that helps drive materials selections and decisions to make or buy components, cast or forge components, etc. There is a need for good coordination skills on the part of the TDC manager to ensure that valid inputs are made by all areas of expertise within the company, and possibly to introduce external expertise where required whilst allowing the design team the space and scope to bring their skills and experience to bear in the design process. Using the combined input information and the outline product design concept, the TDC manager can conduct the primary audit and hence give an indication of the likely sustainability impact of the proposed product, product range, or system

6.9.7 Detail Design

The management element now overviews the conversion of the concept into a real product and is linked to the process by the “Detail Design” stage. 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 it is at this stage that much of the environmental impact and monetary cost is established. The selection of components or specific materials influences the way of 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.

Careful management control will also specify manufacturing methods. For instance, since much of the Embodied Energy is applied during manufacture, the selection of appropriate manufacturing techniques falls within TDC influence as outlined by Corbett et al [6.9] who suggested that up to 80% of the manufacturing cost was applied at the design stage. It follows that much of the energy expenditure of manufacture is also designated during the design process.

As the design process moves forwards, the same auditing process is then applied to individual components, whereby relevant methods are applied to ensure optimised Embodied Energy, strength to mass ratios, and sourcing and manufacturing efficiency, without losing sight of the original design brief as defined by the design and marketing teams within the PDS. Auditing Embodied Energy, component by component, at this stage will give a more detailed and realistic energy value

6.9.8 Product Specification

Once the detailed design and parts lists are complete, the key focus of coordination moves to materials management, manufacturing, and procurement, with feed-back inputs both to and from the design team as issues are revealed during prototyping or first-batch production. The management accounts team once more becomes involved in quantifying the cost effects of manufacturing and procurement decisions.

6.9.9 Manufacture and Test

Within the selected TDC Team there would normally be manufacturing experts who can influence the designers to take advantage of efficient manufacturing techniques. At this point in the product creation process the influence of the manufacturing increases. 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 [6.8].

During the physical process of manufacturing and testing, and subsequent launch into the market, the TDC manager must continue to liaise with materials management, manufacturing, and procurement teams and with sales, after-sales, and marketing to gain initial indications of performance in service and customer perceptions. As these are typically used to make minor adjustments and refinements to the “first-to-the-market” test products, the TDC manager needs to ensure that the sustainability impact of these amendments and adjustments is noted and recorded.

As the manufacture and test procedures are completed and the product is ready to be shipped to the customer, the Final Sustainability Audit (FSA) should be carried out. It is this audit that will provide the data for the “Certificate of Sustainability” which states the value of Embedded Energy within the product.

6.9.10 Installation and Testing

Installation and testing involves shipping the product to the customer and ensuring correct performance after manufacture. Many products are tested before they leave the factory and can simply be purchased from the retail outlet where the customer expects the product to be serviceable with only cursory installation such as inserting the plug into the electric wall socket. Large technical products such as diesel engines or coolers require special delivery, installation and testing (commissioning) before handing to the customer.

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.

6.9.11 Market Feedback

As market feedback information is returned while following the product’s extended use-in-service and eventual end of life disposal, the actual, rather than estimated, values for the Phase 2 Life Cycle Embodied Energy can be calculated. At this point, the figures from the FSA audit can be validated and improved, and the lessons learned can be fed back to the design team, specifically into the materials sourcing, design and manufacture aspects of the product in order to:

a) seek further improvements in the design perhaps creating the Mk2 product
b) inform the design process of new design requirements possibly resulting in further new products

6.9.12 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 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 and also 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 construction plant such as a digger may use 110 litres/hr (396MJ/hr), of diesel fuel, DSS [6.14]. Armed with this information the TDC team can refine the design using a more efficient diesel engine which may burn only 100 litres/hr (373MJ/hr), DSS [6.14].

Remote data feedback was initially championed by Ohno [6.32] who introduced the kanban system at Toyota. This technique has been improved and by the introduction of Product Life-Cycle Management (PLM) by Matsokis and Kiritsis [6.29] who extended PLM into product usage, refurbishing and disposal thus creating a closed loop's life cycle data management system. This system was later consolidated by kiritsis [6.30] who advocated real time data sharing through Internet links. Framling [6.28] enhanced PLM still further by advocating Smart products that communicated with each other and that those products should converse with a central data node. Protagonists would then be able to access data in real-time on a global basis. Framling suggests that the technology is available but not yet coordinated. It would be useful to introduce these "future" systems into the TDCM management strategy.

6.10 Design Implementation and Application Methods

6.10.1 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).

6.10.2 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”, QFD, Akayo [6.15] or TRIZ, Chen et al [6.16]. There may also be substantial research to obtain information relevant to the new product.

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 should have an input. These specialists can contribute extra information and ideas enabling the design of the product to be fine-tuned thus reducing the amount of 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 1000 units. If there were a packaging specialist on the design team he/she could recommend subtle changes in product shape which would reduce the volume of the product and packaging thereby increasing the capacity of the container to perhaps 1500 units. This clearly means that there would be less energy per product 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 Concept Design Specification (CDS).

6.10.3 System Design Methodology

Though designers create the technical information in drawings, models, analysis, etc., the other specialists within the group also have an input. Since this phase specifies materials, components, shape, and manufacturing methods, specialists in manufacturing engineering, 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 Factory" methods thus reducing Embodied Energy. Logistics engineers may suggest weight reduction techniques and purchasing engineers will have the knowledge to locate recycled materials.

6.10.4 Manufacturing Techniques

Corbett and Dooner [6.9] suggested that 80% of the manufacturing cost is developed at the design stage indicating that the design function specifies manufacturing techniques, methods, materials, etc. without consultation with manufacturing personnel. However, seeking the advice of manufacturing engineers at this stage would allow application of techniques that reduce manufacturing time leading to reductions in the Embodied Energy usually first quantified in the design stage. An example of this would be the inclusion of a simple flange on a gearbox which could be gripped by the machine tool. Much setting-up time (locating and clamping on the machine tool) would be saved by this modest design inclusion and is an element which a pure design specialist may not consider.

Some manufacturing methods that contribute to design efficiency 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
- design for easy assembly
- design for easy dis-assembly (this also assists with ease of maintenance)
- minimise handling

Cooperation combines specialist expertise in bringing together many of the above elements and creating new design approaches with the goal of reducing the Embodied Energy in the product.

6.10.5 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. The evaluation needs to consider what a potential customer purchasing a vehicle will want to know about its performance characteristics, but the evaluation should also include aspects and values of sustainability.

Longevity: a long lived product avoids the need to purchase new products thereby *saving* Embodied Energy.

Maintenance: for some products such as vehicles, maintenance is standard since it is realised by users that maintenance will prolong the life of the vehicle. Maintenance, however, is not always easy to accomplish or is even considered by the consumer who, faced with a broken appliance, may merely consign it to the bin. If easy maintenance is built into products then those products have a better chance of achieving 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 information should be fed back to the design team to modify the product.

6.10.6 Maintenance and Repair Data

The data obtained through maintenance and repair has to be returned via the data collection system and evaluated within the maintenance element. Cayzer et al [6.33] advises that data should be checked for accuracy. He suggests that questionable data may be constructed from; estimates, inbuilt assumptions, inaccurate collection methods, uncertainty or skewed. He suggests that a sustainability hub might be useful together and check incoming information.

This feedback data is vital for the design iteration process and the management control and coordination element. Review of data can be used to 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.

Several techniques that can enhance sustainability within a product are already in standard use and are aligned with reducing cost, but often the designer is preoccupied with manufacturing cost and may not consider the environmental costs of usage, maintenance, or disposal which are the life elements within Phase 2 Life-Cycle: Embodied Energy.

When each of the life phases is considered in turn, a reduction in Embodied Energy should be the reward. The examples below indicate where Embodied Energy can be reduced phase by phase:
Data from Johnson and Gibson [6.3]

Sustainable Sourcing

- Use recycled materials
- Use local materials
- Minimise the material to be re-moved
- Re-use components
- Use certified sustainable materials where possible

Sustainable Design Approach

- Optimise for particular usage
- Reduce time to manufacture and assembly
- Include modules where possible
- Use 3D modelling in preference to building prototypes
- Design for ease of manufacture
- Design-in easy assembly
- Design-in easy disassembly for maintenance and material separation at disposal
- Minimise the number of parts
- Design multi-use parts
- Reduce mass

Sustainable Manufacture

- Minimise parts
- Use multifunctional parts
- Reduce machining
- Reduce weld length when fabricating
- Minimise handling
- Aim at assembly from one direction
- Work within a smart factory environment

Sustainable Usage Application

- Introduce fuel efficient engine and transmission systems
- Design-in reduced mass, this reduces fuel consumption, material sourcing, etc.
- Use natural energy sources, e.g. wind, solar
- Operate machinery within design parameters
- Use modules for speedy change of usage
- Keep well maintained for optimum performance

Maintenance for Sustainability

- Increase the life of the product through maintenance
- Predict component life for planned maintenance
- Design-in easy removal of components
- Design-in serviceability in the field rather than a workshop
- Design-in lubrication delivery systems
- Ensure sacrificial components (bearings, seals, etc.) are easy to replace

Disposal for Sustainability

- Reduce the components sent to landfill
- Design-in components that can be separated easily into material classes
- Reuse components which are not yet at the end of their life
- Recycle materials gleaned from end of life products
- Capture residual caloric value (When materials and components are truly the end of their life, they may still retain calorific value). Rather than consign to landfill, these component can be used to generate heat/steam/electricity

This list is not exhaustive but it shows that when the life cycle of products are considered as six elements, it is possible to see how the design function can influence and coordinate reduced energy input or reduced energy use.

6.11 Design Team Composition

The design function is in a unique position 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 Total Design Control development team can be seen in figure 6.8. Johnson and Gibson [6.3]

Such a core design team would therefore influence the design and coordinate the six phases by applying sustainability principles. The measurement of energy at each life phase enables analysis of the Embodied Energy and its eventual reduction.

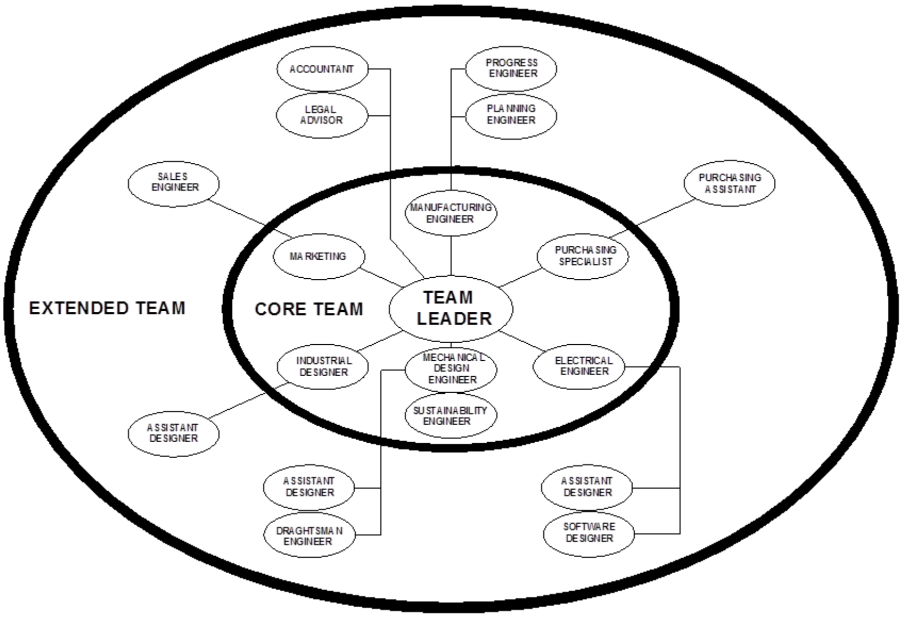


Figure 6.8: The Composition of the Product Development Team: Johnson and Gibson [6.3]

Though there are core members of the product development team there may need to be secondary team members who can assist in developing the product according to design objectives across the life-cycle of the product. Figure 6.9 shows the main design objectives that need to be coordinated in each of the six life phases.

Though the model in figure 6.8 refers to personalities it is equally valid to createa design team relating to skill sets. Indeed this approach lends itself to multi-disciplinary personnel within the team. It should also be noted that the range of skills required to design products across the entire life cycle is unlikely to be possessed by a single person. Indeed, during the construction of the design team the team leader should avoid requiring team members to take on duties in which they are only partially skilled.

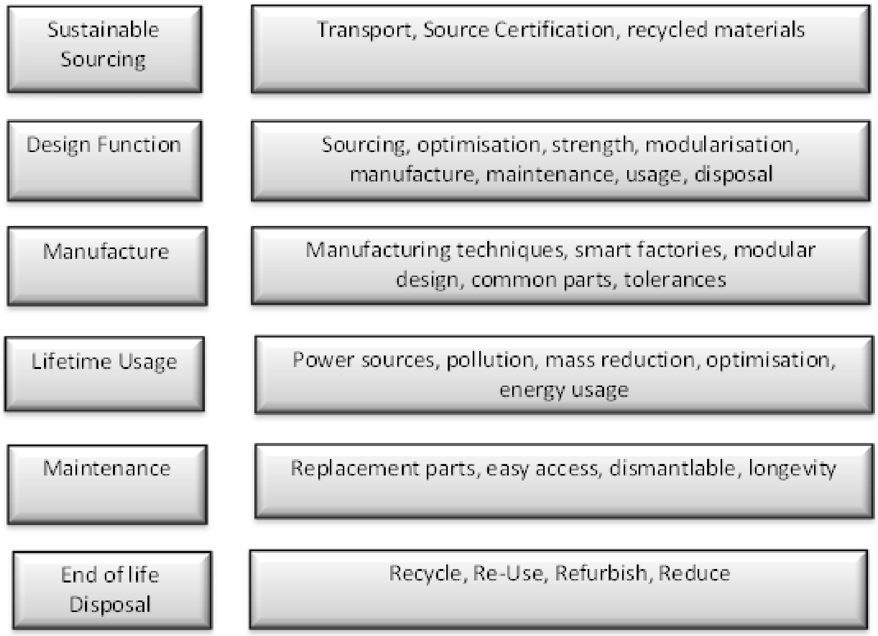


Figure 6.9: Design Objectives Model

6.11.1 Design Team Implementation within the TDC Management Strategy

The TDCMS shown in figure 6.7 links management control elements to the Classic Design Process, forming a process association guide. The use of the Classic Design Process serves as a guide for the implementation techniques and measurement methods and allowing the formulation of an overall control strategy using market and maintenance information as a feedback parameter.

When linked to the design process there are four facets to the TDC management strategy: Management Control and Coordination; Classic Design Process; Application of Sustainable Design Techniques and Sustainability Measurement.

There are now three separate goals for the team leader when setting up the project.

- Select product development team members
- Determine the skills of those team members to accommodate the design objectives
- Determine management control and coordination of the four facets of the TDCMS program

When these 3 elements are integrated and linked to the guidance set out in ISO14001, a robust management strategy is the result which allows improved sustainable product development.

6.12 Sustainability Measurement and Audit

The measurement device (metric) is dependent on the required outcome. Some researchers may use carbon footprint while others may use sulphur as the indicator. The sustainability measurement strategy proposed uses Embodied Energy as the metric, since energy is the commodity that is applied or gained during every life phase

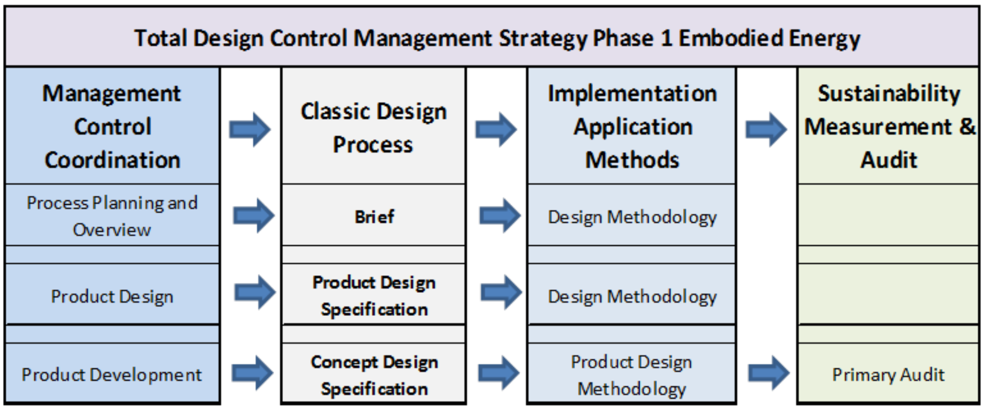
The TDCMS model thus proposed serves well as a guidance tool, but for it to be a truly effective measure of sustainable design, the output must include a feed-back into the management strategy to take advantage of performance improvement indicators. Kerkkainen [6.26] and Ronkko [6.27] put forward the "product centric" approach where information from individual components was fed back to appropriate elements of the life-cycle management process. This fits well with the approach to PLM by Kiritsis [6.30] and Framling [6.28] in advocating their smart product data feedback methodology.

It is therefore critical that a concise feedback and quantification method is adopted if the designer is to measure the sustainable efficiency of his design. Furthermore it is also key to the success of the audit process that audits occur at several key stages as shown in figure 6.3.

6.12.1 The Primary Audit

The primary audit can take place only when the *concept design* has been formulated and is the first estimate of the product’s Embodied Energy. The concept design is really a feasibility proposal that has estimated sizes, masses energy uses etc. The concept also possesses tentatively allocated components, strengths of chassis calculated, running costs, etc. and is an excellent point at which to conduct a relatively accurate concept audit which should give an Embodied Energy value close to that of the final product. This is the point at which a feasible, conceptual design has been placed on the table for evaluation by the client/company.

Such an audit will also highlight where more work needs to be done to further reduce Embodied Energy. Figure 6.10 shows the Total Design Control Management Strategy and the position at which the primary audit should take place. The Primary Audit will indicate the value of energy required to complete the product and hence indicate the level of sustainability. This is merely a first estimation measurement but will allow comparisons to be made with other similar products.



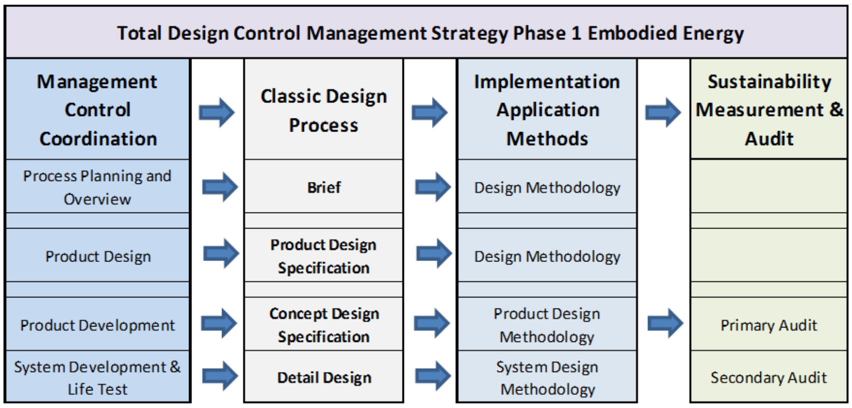
Total Design Control Management Strategy Phase 1 Embodied Energy

Management Control Coordination	Classic Design Process	Implementation Application Methods	Sustainability Measurement & Audit
Process Planning and Overview	**Brief**	Design Methodology	
Product Design	**Product Design Specification**	Design Methodology	
Product Development	**Concept Design Specification**	Product Design Methodology	Primary Audit

Figure 6.10: The Position of the Primary Audit within the TDCMS

6.12.2 The 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 specified in detail allowing a more accurate analysis and, hopefully, revealing 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 elements in an attempt to reduce Embodied Energy further before manufacturing commences. Figure 6.11 shows the position of the secondary audit within the TDCMS



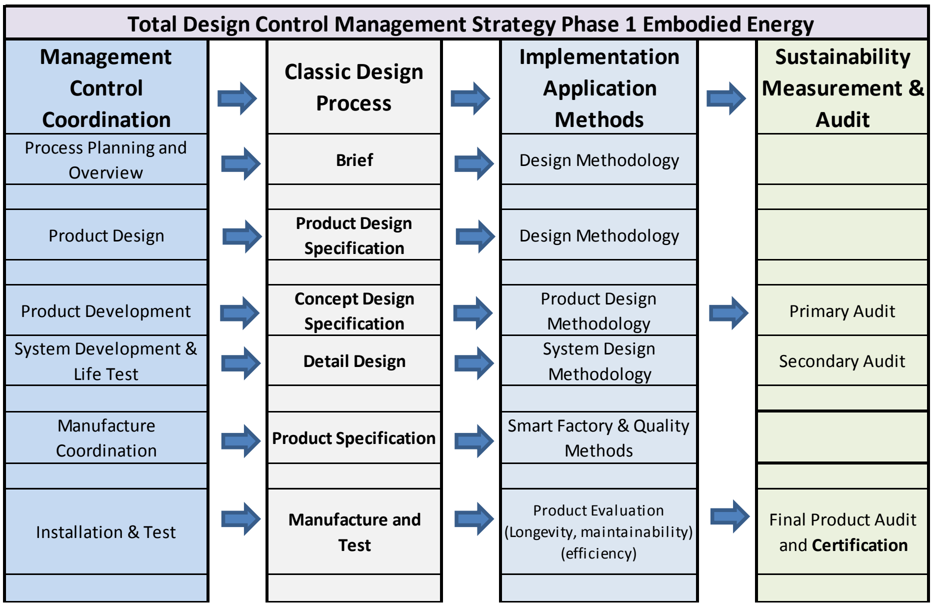
Total Design Control Management Strategy Phase 1 Embodied Energy

Management Control Coordination	Classic Design Process	Implementation Application Methods	Sustainability Measurement & Audit
Process Planning and Overview	**Brief**	Design Methodology	
Product Design	**Product Design Specification**	Design Methodology	
Product Development	**Concept Design Specification**	Product Design Methodology	Primary Audit
System Development & Life Test	**Detail Design**	System Design Methodology	Secondary Audit

Figure 6.11: The Position of the Secondary Audit within the TDCMS

6.12.3 Final Product Audit and Certification

As the product leaves the factory a final product audit should be taken to set a final value for the Embodied Energy for the newly manufactured product. This value could be used as a comparator to other similar products at the "just manufactured stage". Transport may be included, especially if great distances are being traversed in order to deliver the product of the customer. Figure 6.12 shows the position of the Final Product Audit within the Total Design Control Management Strategy.



Total Design Control Management Strategy Phase 1 Embodied Energy

Management Control Coordination	Classic Design Process	Implementation Application Methods	Sustainability Measurement & Audit
Process Planning and Overview	**Brief**	Design Methodology	
Product Design	**Product Design Specification**	Design Methodology	
Product Development	**Concept Design Specification**	Product Design Methodology	Primary Audit
System Development & Life Test	**Detail Design**	System Design Methodology	Secondary Audit
Manufacture Coordination	**Product Specification**	Smart Factory & Quality Methods	
Installation & Test	**Manufacture and Test**	Product Evaluation (Longevity, maintainability) (efficiency)	Final Product Audit and **Certification**

Figure 6.12: The Position of the Final Product Audit within the TDCMS

This Final Product Audit is a refinement of the Primary and Secondary Audits and should therefore be the most accurate. The accuracy of this audit enables it to be used as a certification parameter where an SLV can be specified. Discerning customers can then compare the SLV certification to other similar products and make their choice based on the lowest value.

6.13 ISO 14001:2004, ISO 14040: 2006 Environmental Management Systems Requirements

Skerlos et al [6.34] provided a framework for conceptualising sustainable design challenges. Some of the elements included establishing targets, metrics and strategies within sustainable design methods, but also advocated applying appropriate standards and certification. The following sections overview ISO standards and suggests their combination with TDCMS.

6.13.1 Standards Overview

The International Standards Organisation (ISO) is based in Europe but was set up to provide a worldwide, cohesive standards organisation. The TDCMS uses various ISO Environmental Standards as a platform on which to base the management strategy.

The TDCMS is intended to provide a Product Creation Organisation (PCO) within the management system and also a measurement capability for controlled sustainable development of its products. It is important that this management strategy complies with the guidance elements set out in ISO14001, ISO14040 and ISO14044 [6.11, 6.12, 6.13] since compliance with this standard injects a robust level of quality and consistency to the TDCMS process. Furthermore adherence to these standards enhances credibility within peer groups and also with the consuming public.

The TDCMS is intended to provide 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 (perhaps from international agreements and protocols) and information relating to, in this case, the reduction of Embodied Energy during the product creation process.

The standards in this range provide a platform for environmental management systems but also for implementation of practical environmental applications.

In general ISO14001 along with its updated version due to be released in October 2014 offers a platform for on-the-ground management of the environmental sustainability programme. This detailed, practical approach is particularly suitable to act as a platform strategy for TDCMS.

ISO14040 and ISO14044 offer a higher level management, data retrieval, and quality assessment structure based on LCA. This is applied in Chapter 7 where a Sustainability Enhancement Program (SEP) is proposed.

6.13.2 ISO14001: Environmental Management System Requirements

Within this standard much of the responsibility for environmental management implementation is placed on the management team and requires that the "organisation" applies, maintains and audits such a policy.

The standard sets out elements which must be installed in such an environmental management policy. Some of the major items are listed as follows:

- planning
- implementation and operation
- communication
- documentation
- operational control
- monitoring and measurement
- internal auditing

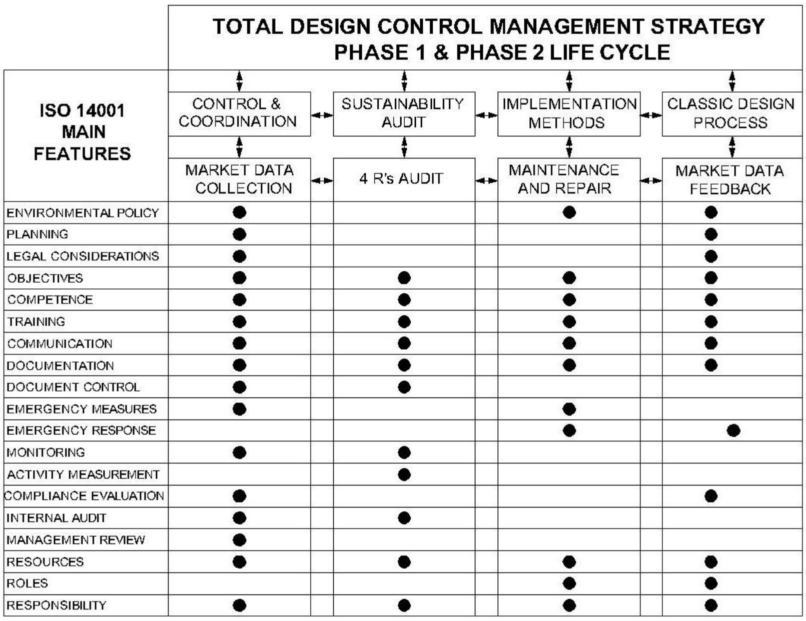
These are a selection of the elements outlined in the Standard that also match the requirements of the TDCMS.

The requirements follow a fairly logical procedure where planning is the first element before implementation and operation of the system can take place. There needs to be communication between entities along with the documentation of performance parameters.

Elements which are just as important as the core features mentioned above relate to the control of the management system, control of documents, operational control and being in control of emergencies. Here there needs to be some form of preparedness and planned response.

There is a third tier of monitoring and measurement where evaluation and compliance with the Standard takes place and in the case of nonconformity, corrective action can be implemented. The control of records is necessary for an internal audit system which can then be monitored by the management team. Annex A of the Standard explains how and why the suggested elements can be applied.

It is useful to link the requirements of ISO14001, noted above, to the main management elements set out in the TDCMS. To this end a chart linking compliant components of TDCMS to the ISO14001 Standard is set out in figure 6.13.



TOTAL DESIGN CONTROL MANAGEMENT STRATEGY
PHASE 1 & PHASE 2 LIFE CYCLE

ISO 14001 MAIN FEATURES	CONTROL & COORDINATION	SUSTAINABILITY AUDIT	IMPLEMENTATION METHODS	CLASSIC DESIGN PROCESS
	MARKET DATA COLLECTION	4 R's AUDIT	MAINTENANCE AND REPAIR	MARKET DATA FEEDBACK
ENVIRONMENTAL POLICY	●		●	●
PLANNING	●			●
LEGAL CONSIDERATIONS	●			●
OBJECTIVES	●	●	●	●
COMPETENCE	●	●	●	●
TRAINING	●	●	●	●
COMMUNICATION	●	●	●	●
DOCUMENTATION	●	●	●	●
DOCUMENT CONTROL	●	●		
EMERGENCY MEASURES	●		●	
EMERGENCY RESPONSE			●	●
MONITORING	●	●		
ACTIVITY MEASUREMENT		●		
COMPLIANCE EVALUATION	●			●
INTERNAL AUDIT	●	●		
MANAGEMENT REVIEW	●			
RESOURCES	●	●	●	●
ROLES			●	●
RESPONSIBILITY	●	●	●	●

Figure 6.13: Compliant Elements of TDCMS with ISO14001

The chart in figure 6.13 has taken the requirements of the ISO14001 Standard and matched them to the main elements of the TDCMS. It can be seen that the Control and Coordination element of the TDCMS is heavily involved with the requirements of the Standard. The sustainability audit, Implementation and design elements are also influenced to a lesser degree depending on their function.

The authors of the Standard have linked many aspects of ISO14001 to ISO9001 which is a Standard related to quality assurance and management techniques. In Annex B of ISO14001 there is a table of comparative elements elegantly showing that companies that have adopted ISO9001 have already achieved quality management structures which are synchronous with ISO14001. Annex B clearly shows that there is a great deal of equivalence in terms of process approach, scope and quality management systems, quality policies, management commitment, responsibility, and authority, to name just a few.

ISO14001 which was released in October 2014 has been updated to meet new environmental challenges and includes revisions which conform to new ISO management standards requirements. Included in the forthcoming document is a high-level management structure and though the context is close to the ISO14001 2004 version, it is clear that management systems developed under the revised version are intended to mesh with other ISO management strategies.

Since sustainability in industry is an overarching concept integral within many diverse industries, it seems appropriate that an environmental management strategy should also mesh with management strategies in diverse industries.

The TDCMS has been put forward as a relevant operational management scheme to assist in the sustainable creation of products. In the TDCMS methodology, in order for products to be improved, there has to be feedback from across the life cycle of the product. The new ISO14001 reflects this need in its management systems and suggests that upgrading is required when new inputs emerge and when new output elements are necessary.

Feedback to the design function has always been necessary so that new design iterations could take place. The TDCMS incorporates information feedback, and could not operate successfully without such data.

6.14 The “Green Badge”

Currently, many companies are clamouring for a "Green Badge" recognisable by the consumer and based on scientific rather than qualitative principles. Clearly, there are a number of measurement and certification systems in use at present, including carbon foot printing estimates from Energy Star, Blue Angel and EU Ecolabel, further described in Chapter 4. With the exception of carbon foot printing, most of these comparisons use a mixture of quantitative and qualitative data typically including :

- Resource consumption – water, base material etc., in some cases including efficiency of extraction issues.
- Energy efficiency
- Packaging and distribution aspects
- Consumption of energy and water during the product’s working life (aimed particularly at domestic appliances)
- Ease of recovery and recycling
- Health issues

The recognition level for these labels varies across time and place, but whilst general awareness levels of the issues involved are improving, the plethora of “competing” labels and claims are tending to confuse rather than educate the consumer.

The term *greenwashing* TerraChoice [6.6] was coined to describe the way some companies and organisations would use terms such as “only natural ingredients” or “responsibly sourced product” to enhance their product or company without actually changing their design, sourcing or production philosophy.

The TerraChoice organisation has been reviewed in Chapter 4, but has produced a series of reports on greenwashing. In their latest review in 2010, they noted a general improvement in the way companies were approaching the sustainability agenda.

Any measurement and certification system must embrace the entire life of the product, from sourcing to its end of life fate, and must be calculated using a sensibly derived algorithm or series of algorithms using traceable data.

As an example, the adoption of SLV Certification as part of a recognised sustainability measurement system means that companies can genuinely compete for the “Green Badge” against their rivals. Furthermore the competition between rival companies will tend to make those companies strive more and more for lower and lower SLV values.

6.15 Phase 2 Life Cycle Embodied Energy

The measurement and prediction of Embodied Energy in Phase 1 of the Life Cycle can be achieved reasonably accurately since these are measured values. The value of Phase 2 Embodied Energy, however, is more unpredictable since during this phase the product is in the hands of the consumer who could use and abuse the product in unexpected ways. Maintenance and end of life disposal is also in the hands of the consumer who may not know how to dispose of the product or may be indifferent to the best sustainable disposal methods. A combined strategy has been developed in order to accurately measure the applied energy and harvested energy in the Phase 2 Life Cycle. This is developed and is shown in detail In Chapter 5.

6.15.1 Market Feedback

Data feedback from the marketplace is often hard to determine but is an important factor in influencing a products' design and performance when revisiting a design. Feedback of such information to the design team may be ad-hoc and sketchy but careful organisation may glean accurate information. Phase 2 Life Cycle energy accruing methodology shown in Chapter 5 also develops systems where information can be fed back to the TDCMS but also products can also be fed back for reduce or fed forward for recycling. The energy harvesting is also therefore recorded and fed to the TDCMS so that future products can benefit. The TDCMS data feedback system would benefit by combination with the work by Kerkkainen [6.26] and Ronkko [6.27] with the introduction of their PLM system.

6.16 Conclusion

It has been shown that the employment of a Total Design Control Management Strategy within the design and manufacture process can influence a product’s life cycle by dividing the life of the product into six life phases and implementing a minimum energy application strategy to each phase.

This is best achieved through the imposition of good design practice. Clearly, some of the methods already applied as best practice are already in use on a daily basis in order to reduce costs. There is, however, so much more the designer can accomplish by including elements across all the product life phases normally considered to be out of the designers' control.

The TDCMS would be merely guidance if it weren't for the measurement element which feeds back to the Total Design Management Control to trigger the re-evaluation of certain design elements to improve/reduce the Embodied Energy value. In this way the Sustainable Life Value (SLV) metric can be used as an accurate comparator and marketing tool for each product.

The Total Design Control Management Strategy can influence the whole life of the product from materials sourcing through to end of life disposal. Design techniques and consideration of life phases during Phase 1 and Phase 2 will inevitably lead to a more sustainable product; however, the current Embodied Energy measurement process can only be applied accurately to measured values during the Phase 1 Life Cycle period.

Due to the vagaries of usage in Phase 2, Embodied Energy can only be predictive during the design process and may, at Phase 1 Life Cycle stage, only estimate the ideal *Available Sustainability*. A substantial Phase 2 Life Cycle management and energy accounting system has been developed and can be seen in detail in Chapter 5. This process bases the management and information harvesting strategy at the point in the product life cycle where products are maintained and refurbished. Here data can be collected and energy measurements taken.

The inclusion of ISO14001 Standard as a platform gives some harmony to the TDCMS in terms of organisation and implementation. Furthermore ISO Standards have been devised so that they are cohesive between diverse standards originating from the same stable. ISO14001, for instance, will therefore mesh with ISO9001 quality standard. Chapter 7 explores the use of other ISO standards within the Sustainability Enhancement Program (SEP) which will also mesh seamlessly with ISO14001.

Many organisations apply themselves to various ISO standards in order to achieve credibility and a level of quality. When TDCMS is applied to ISO14001 credibility, quality and coherence can be achieved along with compliance with ISO9001 Quality Standards.

CHAPTER 7
SUSTAINABILITY ENHANCEMENT PROGRAM
AN UMBRELLA MANAGEMENT MODEL

7.1 Overview

The need for sustainable products is growing annually due to pressures from governments and consumers alike MTS [7.16], but often product creators are either resistant or uninformed as to how to engage with the sustainable creation processes. A cohesive management strategy would be of great benefit that could inform industrialists and provide the tools for the implementation of a sustainable approach to product design and the product life cycle. The instigation of ISO 14001 series standards [7.12, 7.13 and 7.14] are available to form the basis of such a cohesive management strategy.

This chapter builds on previous work Johnson et al [7.3, 7.4, 7.5] and Chapters 3, 4, 5, & 6, enhancing the commonly used Life Cycle Analysis (LCA) and triple bottom line (3BL) creating a complete management strategy termed the Sustainability Enhancement Program, (SEP). This incorporates ISO Standards as an operating platform. Embodied Energy, Ashby [7.1] is used as a metric by SEP so that the value of energy within products can be measured and reduced in the future product iterations. SEP is integrated with Total Design Control Management Strategy (TDCMS) and Sustainability Centred Maintenance (SCM) to form an executive management approach.

7.2 Introduction

Life Cycle Analysis describes the process from material sourcing through to end of life disposal for a product. The current proposal is to improve the life cycle analysis structure by adding three novel elements, sustainable design, sustainable maintenance and sustainable giveback. The whole of the product life cycle can now be split into the seven elements, listed below:

1. sustainable sourcing
2. sustainable design
3. sustainable manufacture
4. sustainable usage
5. sustainable maintenance
6. sustainable disposal
7. sustainable giveback

The first six elements are actual life events during the life cycle of a product. The Seventh Element “sustainable giveback” is part of the measurement strategy were energy harvested from Phase 2 Life Cycle can be used to offset the Embodied Energy applied during the life of the product.

Maintenance has long been used for as the standard method of improving the longevity of a product though has rarely been used as an implement to improve or measure sustainability. The energy harvested in prolonging the life of a product can be used to offset the energy used in the creation and implementation of the original product. This constitutes “Giveback” which can also include energy saved in recycling materials and reusing components. Giveback and maintenance are novel concepts in terms of sustainability and have been introduced in previous work Johnson et al [7.5]. These elements are explained in detail in Chapters 4, & 5. It has also been previously proposed that a metric of Embodied Energy should be used in order to quantify the value of sustainability in each phase of the life cycle.

It is within the ability of the design function in any product creation process to overview all seven phases and design-in features that will reduce Embodied Energy input. To this end this chapter builds on a Total Design Control Management Strategy (TDCMS) seen in Chapter 6.

It is convenient to break down a product life-cycle into two phases. Phase 1 Life Cycle covers the Embodied Energy input from sourcing material to the instant when the product leaves the factory. This distinction has been made because energy input up to this point can be measured reasonably accurately. During the design process Phase 2 Life Cycle embodied energy cannot be measured and is a predictive exercise. Chapter 5 deals with the measurement of Phase 2 Life Cycle Embodied Energy and harvested energy. Elements which comprise Phase 1 Life Cycle can be seen in figure 7.1, whilst elements that comprise Phase 2 Life Cycle are shown in figure 7.2.

PHASE 1 LIFE CYCLE: EMBODIED ENERGY			
SOURCING	DESIGN	MANUFACTURE	TRANSPORT

Figure 7.1: Phase 1 Life Cycle Elements

PHASE 2 LIFE CYCLE: EMBODIED ENERGY			
USAGE	MAINTENANCE	DISPOSAL	GIVE - BACK

Figure 7.2: Phase 2 Life Cycle Elements

7.3 Introduction of Total Design Control Management Strategy (TDCMS)

The Total Design Control Management Strategy (TDCMS) explained in Chapter 6, influences the whole life cycle of a product but has the most impact on Phase 1 Life Cycle where measurement and direct management of Embodied Energy is more defined.

Phase 2 Life Cycle is harder to measure than Phase 1 Life Cycle since the product is in the hands of the consumer who may or may not use and discard the product as the designer originally intended. Nevertheless there needs to be systems in place so that there is data feedback from Phase 2

Elements to the TDCMS enabling product iteration and improvement during revisions in future Phase 1 Life Cycles.

7.3.1 Market Feedback

Data feedback from the marketplace is often hard to determine but is an important factor in influencing a product's design and performance when revisiting a design. Feedback of such information to the design team may be ad-hoc and sketchy but careful organisation may glean accurate market information. The manufacturers of high value products such as passenger vehicles are able to apply a complex feedback system through maintenance franchises that naturally feedback repair and maintenance information to the manufacturer. This information is therefore used to improve the product and determine trends for new products.

As the product passes through each stage of the Phase 2 Life Cycle, the system should allow information to flow back into the TDCMS. This usually happens when the product is maintained. Maintenance procedures collect information which can be fed back to the TDCMS and, furthermore, allows the replacement of elements such as sacrificial components so that there is not only information flow but mass/component flow into and out-of the maintenance process. Figure 7.3 shows a diagram defining maintenance as a primary hub feature of the Phase 2 Life Cycle.

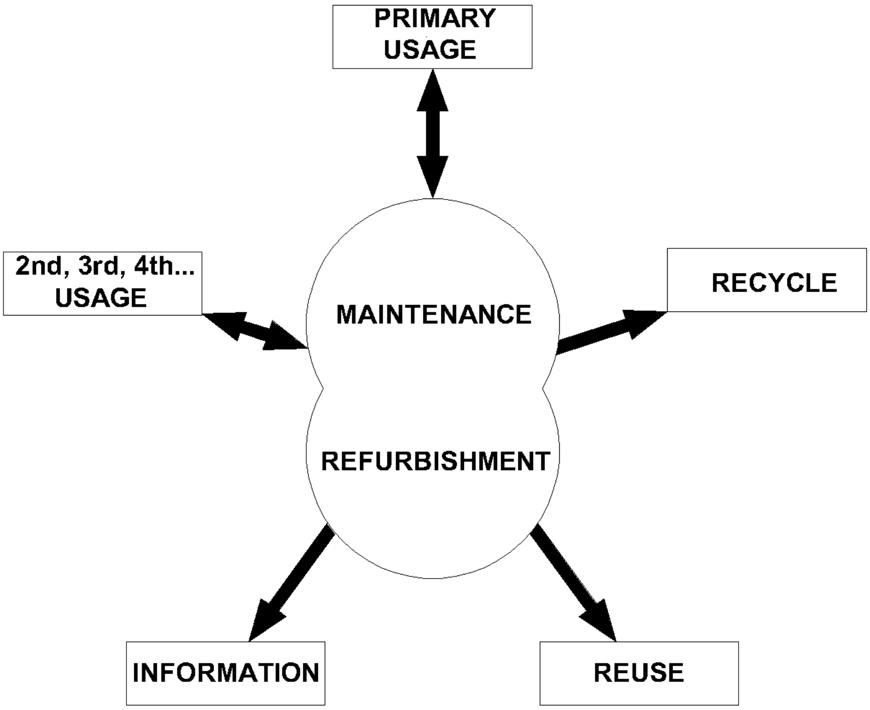
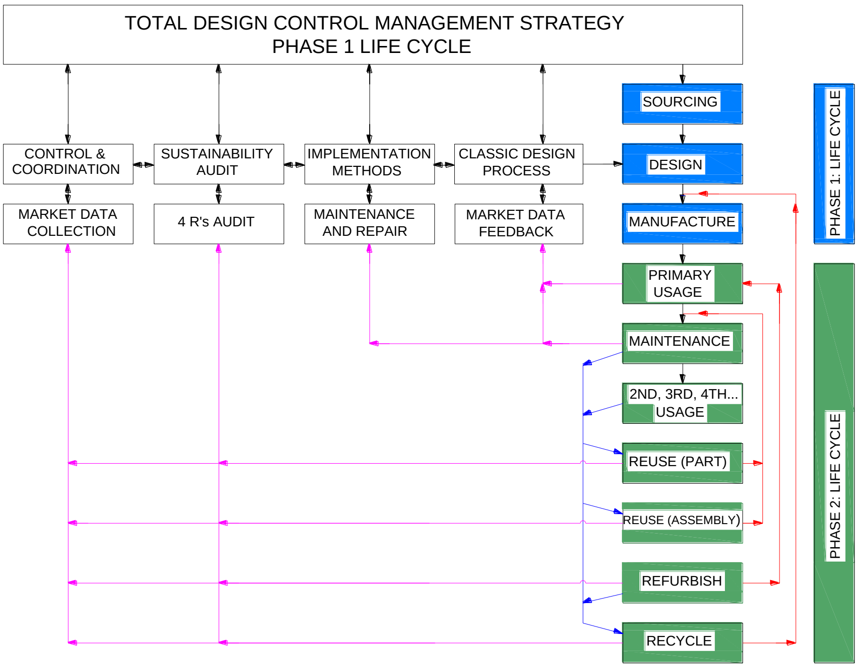


Figure 7.3: Maintenance and Refurbishment as a Hub Element of Phase 2 Life Cycle

After several maintenance procedures the product may require refurbishment which is effectively maintenance at a much deeper level and requires that major parts are completely renewed or repaired so that the product is returned to service in an "as-new" condition. Refurbishment creates data to feed-back information to the TDCMS and the design function, but there is also a major flow of parts and materials into, as well as, out during the process. Partly used components and assemblies may also be collected and passed back to the maintenance procedure so that they can be reused. Also at the refurbishment stage, parts which are no longer useful can be collected and recycled. Refurbishment processes have therefore been incorporated as part of the hub element also shown in figure 7.3.

Takata [7.6] suggested planning of the product life cycle using “circular manufacturing” techniques. This integrates maintenance strategies with reuse of components that still possess residual life. The goal of circular manufacturing is to gather for reuse all those components and materials which possess residual life (material feedback) and send forward end-of-life components for recycling (material feed forward). Kerley [7.11] reported on his investigations relating to the maintenance of aircraft jet engines suggesting that the design function needed to design-in maintenance strategies. He further added that information from the maintenance process needed to be fed back to the design team, indicating the implication of a wider management process. These notions have been integrated into the TDCMS.

In consideration of the need for the TDCMS to record and assimilate information to engage new design strategies, the processes from sourcing to manufacture (Phase 1 Life Cycle) and from usage to disposal (Phase 2 Life Cycle) have been compiled into the TDCMS Flow Control Process set out in figure 7.4.



Key: Blue arrows: materials feed forward: Red arrows: materials feed backwards

Magenta arrows: information feedback

Figure 7.4: TDCMS Flow Control Process

The Phase 2 Life Cycle is shown so that the usage, maintenance, and refurbishment processes are set out in a systematic order. These are then linked to the Phase 1 Life Cycle elements that define their position within the TDCMS as a whole system.

The diagram in figure 7.4 shows that there are essentially three evidential elements emanating from the Phase 2 Life Cycle process:

- materials feed forward
- materials feed backward
- data feedback

Processes such as maintenance and refurbishment will remove worn and partly worn components and feed them forward to be reused or recycled. There may also be a feedback element where part-worn components and newly refurbished products are re-introduced to the usage chain.

Data feedback is a necessary requirement since without this the design of new components has no input and no impetus for improvement for a design with further reduction in Embodied Energy.

7.3.2 Materials Feed Forward

When maintenance is undertaken on a product, sacrificial components such as bearings and seals are removed and replaced. Depending on their condition the removed sacrificial elements may be reused or recycled. In this case material from maintenance is fed forward towards the end of the life cycle. Maintenance may be performed several times thereby extending the life of the product and feeding material forward.

At some point the product will require a major overhaul. This refurbishment is a much deeper process than maintenance and replaces components that normally are not replaced during ordinary maintenance activities. The process may involve dismantling the whole product and perhaps re-machining components or welding elements which are showing signs of fatigue cracking or wear. The outcome is that the product is returned to use in an almost-new condition. The process generates many used components which may be reused or perhaps fed forwards for recycling.

7.3.3 Materials Feed Backwards

Feeding materials backwards within the usage-maintenance-refurbishment process allows the maximum use to be gained from the residual life of components, assemblies, and products. This important part of the Embodied Energy reduction process avoids the need to procure new components, thus avoiding expenditure of Energy of Primary Source (EPS). Many materials can be reused after being removed from the parent product during the maintenance or refurbishment process. These smaller elements may have some useful life remaining and can be fed backwards and reused within the Phase 2 Life Cycle.

Products that have been maintained can be fed backwards to enter the usage cycle once again. Some products, such as vehicles, can be maintained almost indefinitely and experience several life extensions, being fed back into the usage cycle after each maintenance procedure.

Refurbishment is a second major feed backward process for materials since the whole product is renewed and re-presented as almost-new thus re-entering the usage/maintenance cycle once again. Components and assemblies which are removed during both the maintenance and refurbishment may still possess some useful life. These can also be fed backwards to an appropriate stage within Phase 2 Life Cycle. Feed backwards is used to great advantage within the vehicle industry. Here many partly used components are removed from end-of-life vehicles and resold to supplement damaged components on similar mark vehicles. This avoids the requirement for procuring new components, saving the Energy of Primary Source (EPS).

7.3.4 Data Feedback

Perhaps one of the most difficult aspects of the TDCMS to achieve is that of data feedback yet it can be argued that it is one of the most important since it reflects real usage and possibly real difficulties in executing the Embodied Energy reduction plan. Data feedback informs the design team of usage trends, maintenance aspects, sacrificial component requirements, etc.

Armed with this data the design team can create new products with improved features. It should be emphasised that elements of this process are successfully undertaken in several industries but is largely used to enhance the “customer experience”. This could mean more engine power or adding a second handle to make the device more portable or whatever changes might make the product more appealing to the consumer.

The data is also used to improve sustainability where modifications aimed at reducing Phase 2 Embodied Energy can be made. For instance; lengthy, time-consumptive maintenance periods may be the result of components that are difficult to access or there may be sacrificial components which are difficult to remove. Changes in the product design can then be made to improve access and improve component removal rates. Here the process of returning information would be instantly accomplished using PLM presented by Framling [7.17] and Kiritsis et al [7.18] who proposed that Smart products could communicate with each other and with data nodes.

Rolls-Royce (RR) Kerley [7.11], have recently changed their aircraft engine marketing strategy. Instead of selling the engines with the completed aircraft the engines are now leased which means that RR is responsible for maintenance and refurbishment. RR now controls materials input and outflow both to and from the engine but, more importantly, information flows back to the management structure and into the design function. Though in its early stages, there have already been design changes to allow speedier, simpler engine maintenance. These changes have been driven by safety and cost concerns rather than any perceived Embodied Energy Reduction (EER), but it shows that such systems already exist and can be used to apply EER with a slight change in management approach.

Data taken from refurbishment, later in the Phase 2 Life Cycle, can be used to determine which components wear the quickest and those components that are partly worn and may be fed back to be reused. Recycling rates can also be assessed linking ease of recycling and the energy required for recycling and comparing that to the energy saved by avoidance of the primary sourcing of materials.

The fed-back data from all aspects of the Phase 2 Life Cycle can then be analysed and used on several levels:

- To compare the actual Embodied Energy to that originally predicted by the design function
- To enhance the product through design iteration thereby reducing Embodied Energy in future products
- To improve maintenance time and techniques through more sensitive design
- To identify high wear components and improve their longevity by better design or by selecting more robust components

7.4 Predicted Phase 2 Life Cycle Embodied Energy

When the product leaves the factory, it enters into the realm of the consumer where the Embodied Energy can only be forecast by the design team since the future of the product is largely out of the direct control. Nevertheless, it is important that the creation team predicts the Embodied Energy performance through each of the Phase 2 Life Cycle elements.

The application of a maintenance/refurbishment system is a sustainability tool aimed at controlling the input of Embodied Energy and regaining the “Give-Back” energy through the extended life of the product and making full use of any residual life of partly used components. The latter is achieved through re-use and refurbishment.

The graph in figure 7.5 shows the product leaving the factory and entering the Phase 2 Life Cycle at which point it already possesses Phase 1 Life Cycle Embodied Energy. In use, many typical products will inevitably use energy but this can be offset through increased longevity due to maintenance. Increased life reduces the need to procure new products with their incumbent EPS. A small input of maintenance energy can offset a large value of Phase 1 Embodied Energy.

The graph in figure 7.5 shows a decreasing Embodied Energy trend but this depends on the product. A photovoltaic panel which requires zero energy input in use will generally show a diminishing Embodied Energy trend since longevity through maintenance will create “Giveback” energy which can offset the energy used in creation. Giveback energy will also be improved by including the generation of energy by the PV panel.

A large energy usage in products such as construction plant may not be totally offset by the maintenance process since energy in the form of diesel fuel is being applied whilst the machine is being used. Since “Giveback” may not provide enough energy to offset the whole of the energy required in usage the graph will therefore show a rising Embodied Energy trend. Nevertheless, by using a design with planned maintenance, its life could be extended and a certain portion of Embodied Energy of original source will have been saved.

Significantly figure 7.5 also indicates that a non-maintained item will merely continue to absorb energy and eventually come to an earlier end of life than optimal.

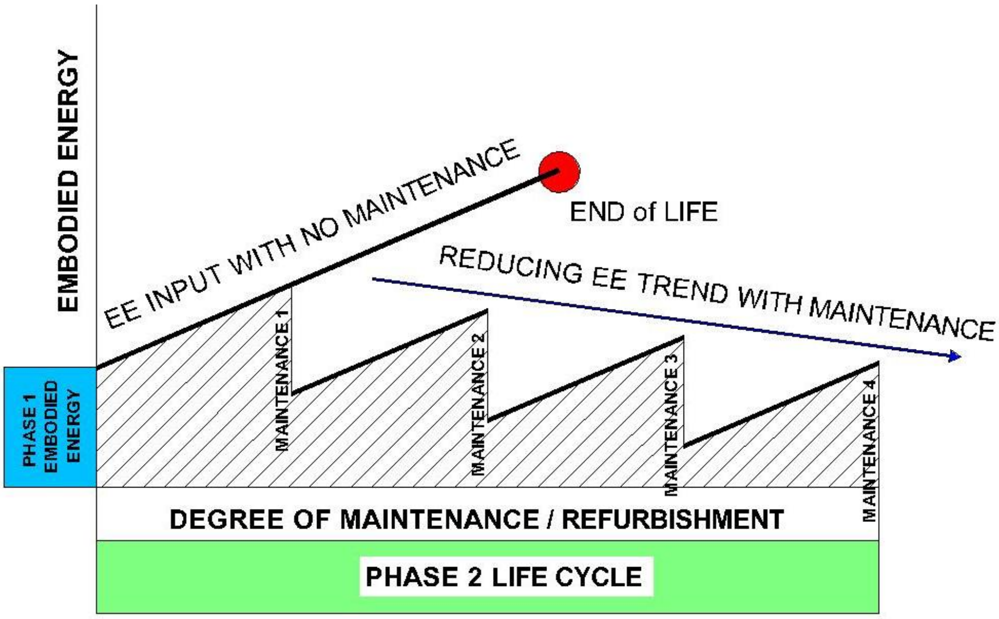


Figure 7.5: Phase 2 Life Cycle Embodied Energy Trend

It is most likely that such an exercise will predict Embodied Energy usage and energy harvesting in the most idealistic situations. This is excusable when creating a new product because there is no data upon which to base realistic projections. It is a different situation with a product that is already in the field where maintenance, refurbishment, and replacement of parts is already underway and an efficient information feedback system allows the creation team to compare actual Embodied Energy data with their original predictions. It can be expected that the original predictions of Embodied Energy may differ from the practical data being returned from the field. Armed with the practical data from the field the design team can now implement design iterations and component changes which will improve performance and reduce Embodied Energy for future products in the field.

7.5 Reliability Centred Maintenance Introduction and the Role of SCM

In order to achieve clarity in the various levels of management program and the various standards that are used please refer to the overview diagram in figure 7.11.

It is clear that the logistics of implementing the Phase 2 Life Cycle element of the TDCMS is a complex task, complicated further by the global nature of products and their multiplicity of components. It makes sense, therefore, to embrace convenient points within the Phase 2 Life Cycle where measurements and other data can be gathered. Current maintenance and refurbishment best practices offer these “way points” since these are important elements within any life cycle and form core processors within Phase 2 Life Cycle product control.

Reliability Centred Maintenance (RCM) has been used and applied for several decades by such notables as the US Navy Submarine Service [7.9] and the Royal Navy [7.10] along with various aircraft manufacturers, Kerley [7.11]. and other operators Rahimi et al [7.19]. As the title suggests, the process is focused on *reliability* through efficient maintenance techniques, providing a framework that defines a complete maintenance regime. This is explained by Sandam [7.7]

The tools of the maintenance regime are as follows:

- Planned Preventative Maintenance (PPM)
- Predictive Testing and Inspection (PTI)
- Reactive Maintenance (Repair when failed) (RM)
- Proactive Maintenance (PM)

In practice these four features provide the mechanism for maintenance engineers to maintain the function of equipment, keep large systems operational and ensure reliability. According to Allen [7.9] some other key elements of this approach are that it:

- Acknowledges design limitations
- Driven by safety and economic concerns
- Treats a system as a “living system”

The system creates an efficient environment where possible failures are identified and dealt with in a planned manner. Furthermore information and, in some cases, components are fed back to be reused.

The system, according to Sandam [7.7] defines failure modes and defines failure risks as follows:

- High Risk: life support systems and components that can cause significant disruption or prohibit the primary use of the product
- Medium Risk: diagnostic instruments and components that can fail with limited redundancy; e.g. a single headlight bulb failure in a vehicle will allow the vehicle to be used even if with reduced efficiency.
- Low Risk: components that make the overall system comfortable, e.g. interior vehicle lighting that are not essential for the primary use of the product

7.5.1 Sustainability Centred Maintenance (SCM)

The application of SCM requires a slight shift in approach to the maintenance/refurbishment process. SCM does not replace formal maintenance; it merely complements and runs alongside the maintenance process. In so doing SCM is able to refocus the approach to the maintenance process thereby creating an environment where sustainability values can be implemented. This can be accomplished by the setting up of a feed forward-feedback system and actively encouraging maintenance personnel to make component life decisions based on sustainability reasoning. Maintenance personnel will therefore need to consider reuse of components and the point at which a component needs to be recycled. Furthermore, information is gathered at each maintenance/refurbishment occasion to be fed back through the TDCMS process to the design team and others in the life cycle analysis arena. Thus, SCM is a complimentary tool to maintenance programs whether formal or informal.

RCM is a formal system defined by BS EN ISO60300 3 11: 2009 [7.15] and has been put forward as an appropriate formal maintenance and refurbishment system. It should be noted that maintenance and refurbishment are often carried out using less formal systems, perhaps applying an internal company methodology or in the case of a passenger vehicle alerting the owner to effect a service after a certain interval. It is intended that SCM should complement and enhance any maintenance system.

7.5.2 BS EN ISO60300 3 11: 2009 Dependability Management: An application guide to Reliability Centred Maintenance (RCM) [7.15]

This standard has been reviewed in Chapter 3 but it is useful to overview its aims

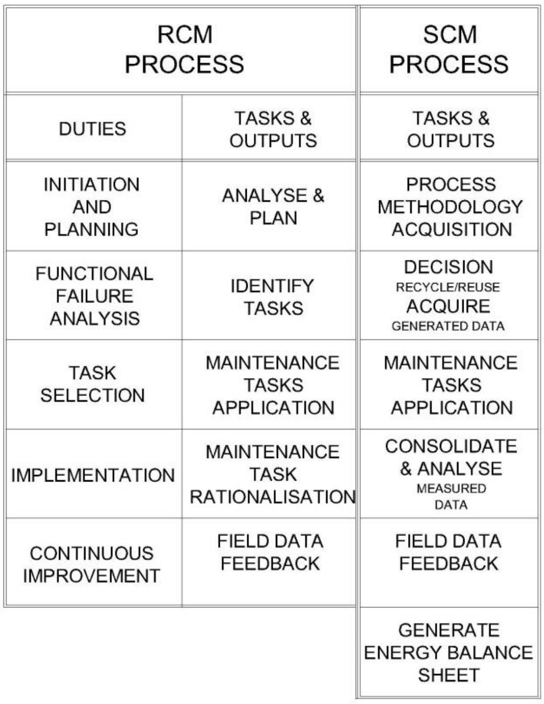
7.5.1.1 Scope

This Standard provides guidelines for the development of failure management policies using Reliability Centred Maintenance (RCM) techniques.

The RCM method was initially devised for physical systems such as vehicles, ships, aircraft, etc., but since each system is treated as a living entity, RCM can also be extended to service systems. The methodology behind RCM is that a whole system is taken and broken down into its relative sub-systems, sub-sub-systems. This approach complements the approach taken in Chapter 5 were SCM is applied to several case studies, each product being broken down into its individual components. The RCM process combines effectively five major elements as follows:

1. RCM initiation and planning
2. functional failure analysis
3. task selection
4. implementation
5. iteration and improvement

The tasks applied by the SCM complement the RCM program as can be seen in figure 8.5 which shows the overall RCM process and the complementary SCM program which allows the RCM process to continue unhindered but extracts information at each stage in the maintenance process so that analysis can be performed and finally an energy balance can be generated.



RCM PROCESS		SCM PROCESS
DUTIES	TASKS & OUTPUTS	TASKS & OUTPUTS
INITIATION AND PLANNING	ANALYSE & PLAN	PROCESS METHODOLOGY ACQUISITION
FUNCTIONAL FAILURE ANALYSIS	IDENTIFY TASKS	DECISION RECYCLE/REUSE ACQUIRE GENERATED DATA
TASK SELECTION	MAINTENANCE TASKS APPLICATION	MAINTENANCE TASKS APPLICATION
IMPLEMENTATION	MAINTENANCE TASK RATIONALISATION	CONSOLIDATE & ANALYSE MEASURED DATA
CONTINUOUS IMPROVEMENT	FIELD DATA FEEDBACK	FIELD DATA FEEDBACK
		GENERATE ENERGY BALANCE SHEET

Figure 7.6: Combined SCM and RCM Profiles [7.15]

Though the RCM process has been used as a convenient framework, other maintenance processes should follow a similar format. In this way SCM can adapt to formal or informal maintenance and refurbishment processes.

The Standard [7.15] outlines an efficient maintenance program in terms of these objectives:

- to maintain the function of an item at the required dependability and performance level within its operating parameters
- to obtain the information necessary for design improvement or to isolate those items whose reliability proved to be inadequate.
- To accomplish these goals at a minimum Life Cycle Cost (LCC) to include maintenance costs and residual failure costs.
- To obtain information necessary for on-going maintenance programs which, through revisions improves on the initial program

RCM, as well as most maintenance programs are focused on ensuring the product is serviceable. In this case SCM creates a much needed information control and feedback system to the life cycle management team (TDCMS). Further SCM objectives can therefore be added as follows:

- gather generated data (number of times component has been reused, etc)
- create a formal decision process for reuse or recycling
- allow life expectancy values to be attached to individual components
- through life expectancy analyse the residual Embodied Energy value
- analyse and calculate the harvested energy

- accrue all the life cycle input energy to the product
- combine input energy and harvested energy into a single energy balance
- collect life cycle data to feedback to TDCMS
- collect data component feed forward to recycling
- collect data components feed backwards to reuse

Statements within the Standard [7.15] recognise that maintenance cannot correct design deficiencies and can only minimise deterioration by restoring the component to the service level allowed within the current design. The statements are quite meaningful since it underlines the fact that RCM concentrates on maintenance and increased longevity rather than design improvement. The introduction of SCM creates a complimentary system that feeds back to the design function, thus allowing products to be improved.

The incorporation of SCM and maintenance processes within the TDCMS framework combines tried and tested maintenance programs with the requirements of a sustainability management and feedback program.

The application of ISO Standards to the combined SCM/Maintenance/TDCMS allows snug integration of the two systems and with it credibility and efficiency. Furthermore adherence to an aspect of ISO management systems ensures that there is meshing with other ISO management systems such as those laid down in ISO14001, ISO14040 and ISO14044 and ISO9000.

7.5.3 SCM Incorporation into Phase 2 Life Cycle

Maintenance programs are developed to ensure that maintenance is predictive, reactive, and efficient with the aim of sustaining systems that should be long lived where the motivation is normally safety and cost reduction. Properly applied the system can be very efficient, but information and material flow is often confined to the closeted cocoon of the maintenance process. It is interesting to note that “design limitations”, Sandham [7.7] are acknowledged but there is little provision for feedback to the design function to enable design improvements. Furthermore within many maintenance systems including the RCM system there is minimal provision for end-of-life equipment disposal. The incorporation of SCM systems would alleviate this shortcoming.

ISO60300 [7.15] suggests that the implementation of RCM improves maintenance effectiveness and provides a mechanism for managing maintenance. This is exactly what is required within the TDCMS program. Many of the references quoted above relating to RCM explain their activity within maintenance practices but do not mention feedback to the design function. ISO60300, however, states in several places that information feedback to the design function is necessary for improvement of new products.

Potential benefits are summarised as follows:

1. system dependability can be increased
2. overall costs can be reduced
3. a fully documented audit trail is produced
4. processes are put in place to review and revise failure management policies
5. a management tool is provided which gives control and direction to the managers

The general RCM program is aimed at improving dependability and reliability. A further goal is that of reducing maintenance costs. The priority here is to improve maintenance procedures, efficiency of maintenance, improved safety and improved reliability but by including SCM into a Phase 2 Life Cycle sustainability programme the standard five benefits mentioned above can be increased, offering further benefits.

6. Increasing longevity to improve the Sustainability Life Value (SLV)
7. Increasing longevity to reduce overall Embodied Energy
8. Adherence to an Embodied Energy Reduction Program encompasses energy expenditure hitherto not considered e.g. smart factories, sustainable transport, local sourcing, re-use of components, use of recycled materials, etc.
9. Reduced monetary costs by the avoidance of purchasing new equipment

The advantage of using RCM and other maintenance programs within the Phase 2 Life Cycle is that the core component of maintenance is already defined and well established in great detail in terms of operation and application.

It is therefore proposed that the standard RCM and other individual maintenance processes be modified to encompass SCM where the focus is broadened to include Embodied Energy reduction through reuse and recycle programs and improved longevity of the system and components.

To this end the Total Design Control Management Process has been modified so that maintenance and refurbishment practices becomes a central component. The new program integrates SCM with TDCMS with influences across both Phase 1 Life Cycle and Phase 2 Life Cycle**.** The whole system can be seen in figure 7.7, which is modified from figure 7.4.

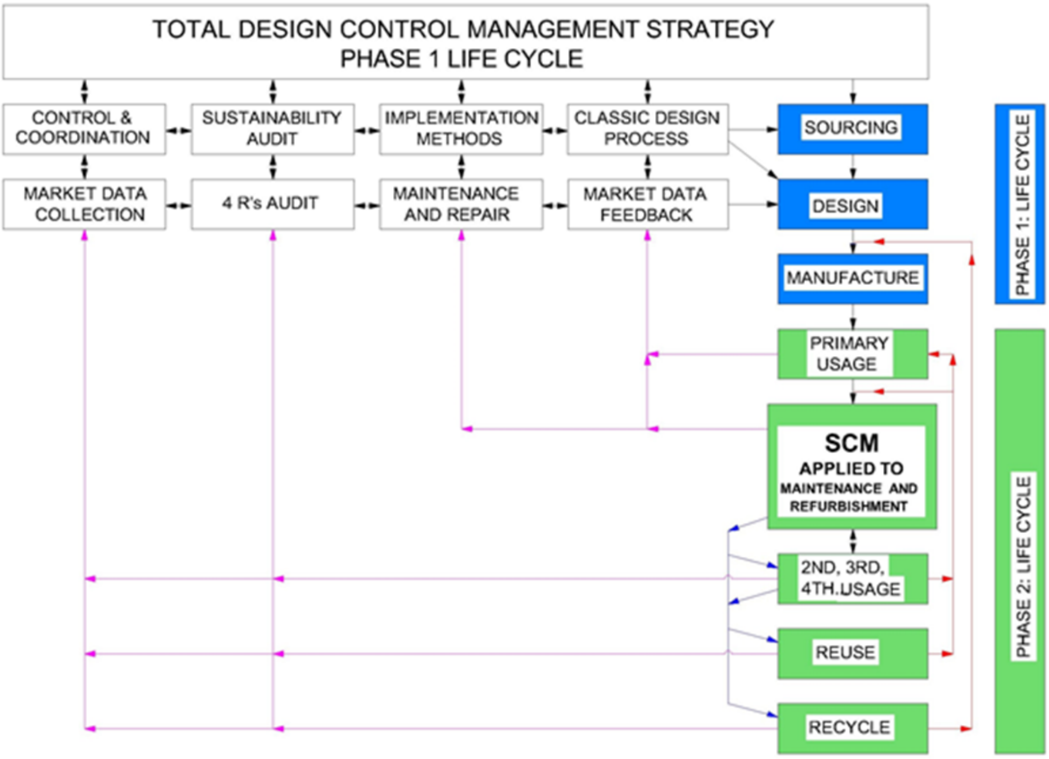


Figure 7.7: SCM / TDCM Incorporation Model

Within TDCMS there is more emphasis on feed forward of materials than the original RCM process allows. This encourages end-of-life disposal and feedback of materials for reuse and recycling.

The original concept of RCM tends to be a closed system where information does not flow out to other elements such as design. A major improvement of TDCMS is that data is now fed back to the various elements of the TDCMS model.

This data should include:

- Time required for maintenance (from which Embodied Energy usage can be defined)
- Time required for refurbishment (from which Embodied Energy usage can be defined)
- Quantification and specification of replaced components
- Establishing an Embodied Energy Value of replacement parts
- Reason for replacement
- Listing of parts that have been repaired (re-welded/re-machined)
- List of destination of replaced components (recycle, reuse)

The above general list is not exhaustive and could be improved when the details of maintenance/refurbishment, the product and the industry sector is considered. The aim of this information feedback is to inform the design function so that design improvements can be made through the design iteration process.

7.6 The Benefits of Combining TDCMS and SCM Maintenance Systems

In general the aim of a general maintenance program including RCM is to reduce monetary expenditure although other elements such as safety may take precedence over saving money. The introduction of Embodied Energy Reduction (EER) enhances and improves the standard maintenance program by creating a feedback route of real-life data to the design team and the TDCMS management team. The normal attributes of maintenance and refurbishment are listed as follows:

- reduce cost expenditure
- improve longevity
- improve reliability
- improve safety

The incorporation of a modified SCM maintenance strategy within the Phase 2 Life Cycle adapts the TDCMS model, so that EER can be based on a current SCM system. TDCMS can therefore be enhanced and made practicable by the qualities listed above plus the attributes brought to TDCMS by the focus on reduction of Embodied Energy. These attributes are listed below:

Attributes of the Embodied Energy Reduction Programme

- reduce Embodied Energy usage
    - increase in the life of a product
    - reusing or recycling components
    - reducing the time to apply maintenance or refurbishment
    - reducing the need to purchase new products (with the incumbent EPS)
- information feedback (to the design function and the TDCMS management team)
- Create an information absorptive environment to encourage regeneration and iteration of products leading to their EE improvement.
- Reduce the Embodied Energy applied to new products

Implementation of an efficient maintenance program will have previously reduced Embodied Energy by default where energy reduction usually aimed at reducing direct energy application such as transport energy or energy powering machine tools where reduction is directly linked to its cost.

The implication of incorporating SCM, EER and TDCMS goes much further in that *ALL* energy use, within the product boundary, is considered and accounted for in focusing on the goal of improving the energy input efficiency and longevity of the product. This could include such elements as implementing smart factories, sustainable transport, localised sourcing, etc.

The reduction of input energy is synonymous with reducing cash expenditure. It is also true that the implementation of an EER strategy and the incumbent systems can be quite costly. It was noted by Allen [7.9] however, that the cost of Initial RCM systems implementation was regained over time and eventually provided significant savings.

7.7 Evolution of a Sustainability Enhancement Program (SEP)

A program such as the integration of SCM within the TDCMS cannot be applied piecemeal. Pojasek [7.20] maintained that it was necessary for the success of any management strategy to be applied with corporate commitment at all levels and with appropriate planning methodology, implementation techniques, personnel training, and programme updating

Any large and complex program such as SEP requires a plan of implementation and running procedure. The characteristics of such a system can be seen in figure 7.8 and include:

- management commitment
- SEP implementation strategy
- establishment of SEP program systems
- establishment of a SEP system boundary
- compliance with ISO standards and regulations
- Embodied Energy Reduction capability
- planning of maintenance and refurbishment procedures
- updating of SEP procedures

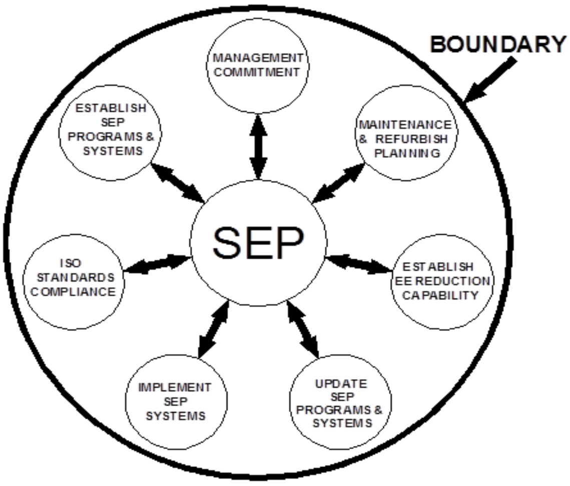


Figure 7.8: Characteristics of Sustainability Enhancement Programme

7.8 Benefits of SEP Implementation

There are several benefits of implementing such a system. Design and the management team have full knowledge of the product in service and can implement a life cycle overview interpretation pertaining to new products. Products are no longer isolated in the usage environment since information feedback informs the TDCMS team of impending problems as the following example outlines.

The vehicle industry has occasionally recalled for repair many millions of vehicles because a fault has been discovered whilst the vehicle is in use or being maintained. Toyota has recently recalled 6.4

million vehicles worldwide due to an airbag fault BBC News [7.8] and would only have implemented the recall after developing a design solution.

Continuous monitoring of a product, such as that applied by Toyota, within the Phase 2 Life Cycle creates an environment of continuous process improvement. Toyota, as with many other similar companies, appear to apply management systems which have some parallel elements to the TDCMS and SEP strategy, but the motivation is reducing costs, reducing complaints, improving safety, and perhaps improvement of reputation. EER is not usually considered a priority.

The introduction of a SEP strategy would cover all the motivational elements listed above plus reduce Embodied Energy within the Phase 2 Life Cycle. SEP techniques can then be tailored to a particular product integrating elements such as maintenance, refurbishment, recycling, and reuse into a cohesive strategy

7.9 ISO European Standards

Any new environmental management system requires adherence to legislation and the most appropriate standards. The ISO Standards ISO14001, ISO14040 and ISO14044 [7.12, 7.13, 7.14] represent some of the most modern environmental management thinking and it is proposed that these guidelines should be applied to an overall management control system dedicated to reducing EER in components, products and systems. This overview system is termed Sustainability Enhancement Program (SEP) and provides an umbrella management system that controls and operates practical elements such as “what is done” as well as systemic elements which deals with procedures. The incorporation of ISO standards is directly appropriate to SEP methodology. The management overview diagram can be seen in figure 7.9.

The implementation and methodology requirements set out in the ISO standards can now be incorporated with the aims and procedures of the SEP. It is clear that the ISO14040 [7.13] relates to SEP systemic control and incorporates background policies, aims, data processing, quality and relevance through impact assessment.

ISO14001 [7.12] relates more to the practical system operation and blends with the TDCMS. As explained in Chapter 6 there are overlap elements between the various standards, but it is clear that ISO14001 relates in practical terms to the TDCMS planning, operation, implementation, monitoring, etc.

7.9.1 ISO14000 Series Standards Overview

7.9.1.1 ISO 14001: 2004 Environmental Management Systems Requirements: [7.12]

This Standard sets out requirements for managing environmental systems. In particular when implementing TDCMS many of the requirements for such a system are proposed in the "requirements" of the standard. Much of the responsibility for implementing an environmental management policy such as TDCMS is placed on the management team of the organisation for applying, maintaining and auditing such a policy.

The standard outlines elements which must be installed in such an environmental management policy. Some of the major items are listed as follows:

- planning
- implementation and operation
- communication
- documentation
- operational control
- monitoring and measurement
- internal audit

These are merely a few of the complexities required by the standard, but match the objectives and requirements of the TDCMS management system.

7.9.1.2 ISO 14040: 2006 Environmental Management — Life Cycle Assessment — Principles and Framework: [7.13]

This Standard provides more of an overview of the aims and scope of an environmental management policy and the blends with the SEP model scope and aims. Within such an environmental management policy the Standard projects the use of a Life Cycle Assessment (LCA) which should have 4 components:

- goal and scope definition,
- inventory analysis,
- impact assessment
- interpretation.

These four elements are very useful as a management overview tool and whose incorporation within SEP ensures that the environmental enhancement is properly targeted.

Interestingly there is no cost implication mentioned which is perhaps a symptom of an altruistic approach. In this cost-sensitive commercial world, institutions will only implement energy reduction programs if there is a financial or marketing benefit. The ISO Standard uses the metric of energy in order to quantify the various processes which is exactly what is being proposed throughout this work.

7.9.1.3 ISO14044 2006 Environmental Management LCA Requirements and Guidelines [7.14]

ISO 14044 should be used in conjunction with ISO14040 [7.13] which compliments ISO14040 by providing detail on "how" LCA can be achieved. Early paragraphs provide the same overview and approach as ISO14040 but the Standard goes on to specify further details such as system boundary.

The system boundary determines which unit processes should be included within the product LCA and explains that consistency with the overall goal is necessary and the criteria used for inclusion should be identified and explained.

The elements included within the boundary may comprise mass, energy, and some form of environmental significance. The standard is flexible, allowing institutions to select their own measurement criteria such as carbon dioxide, sulphur, carbon monoxide, etc. Significantly the Standard also suggests that energy input (Embodied Energy) may also be used as a major measurement device. The standard also defines data quality and data presentation methods. Cayzer and Priest [7.21] sounded a cautionary note in their article which suggested that some data can be “questionable” and that organisations may modify data to suit their own purposes.

7.9.1.4 Life Cycle Inventory Analysis (LCI) [7.14]

The initial plan for conducting the Life Cycle Inventory of an LCA is defined within the goals and scope of the study. The inventory however should be performed using specified operational steps as explained in figure 7.9.

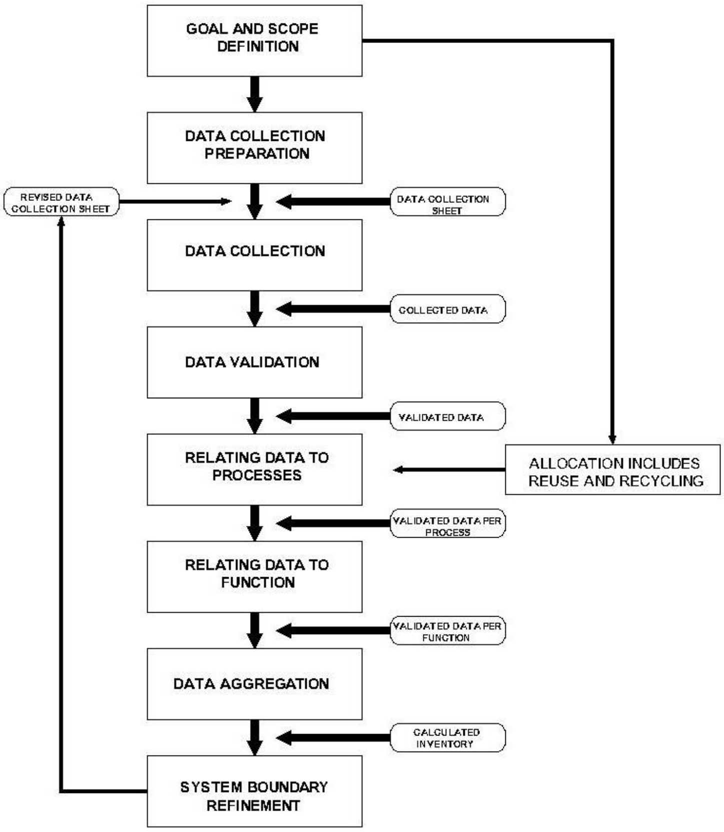


Figure 7.9: Operational Steps of a Life Cycle Inventory Analysis

The Standard specifies that both qualitative and quantitative data may be used, but care should be taken to ensure the data is necessary and valid. Various rules and definitions are clarified as requirements within the Standard including defining each function, process, boundary, and method of data collection and calculation.

As can be seen from the diagram in figure 7.9 this overview level of structural management requires detailed attention to collection of data and its validation with reference to particular processes and functions

After the raw data has been collected, it requires manipulation and presentation in a meaningful fashion. The standard applies mandatory processes such as:

- selection of impact categories
- category indicators
- characterisation models
- assignment of LCI results to the selected impact categories (classification)
- calculation of category indicator results (characterisation)

The diagram in figure 7.10 shows how the SEP and TDCMS management systems are applied within the envelope of both ISO's. The Standards also require a control boundary, also shown. This ensures that spurious inputs are eradicated and the Embodied Energy relating to a particular product or system is not contaminated.

The ISO standards correctly applied complies in full with the approach taken by the SEP management model and the TDCMS. The use of Embodied Energy as a metric ensures that there is a quantitative value that can be used throughout the system as currency in Embodied Energy Reduction.

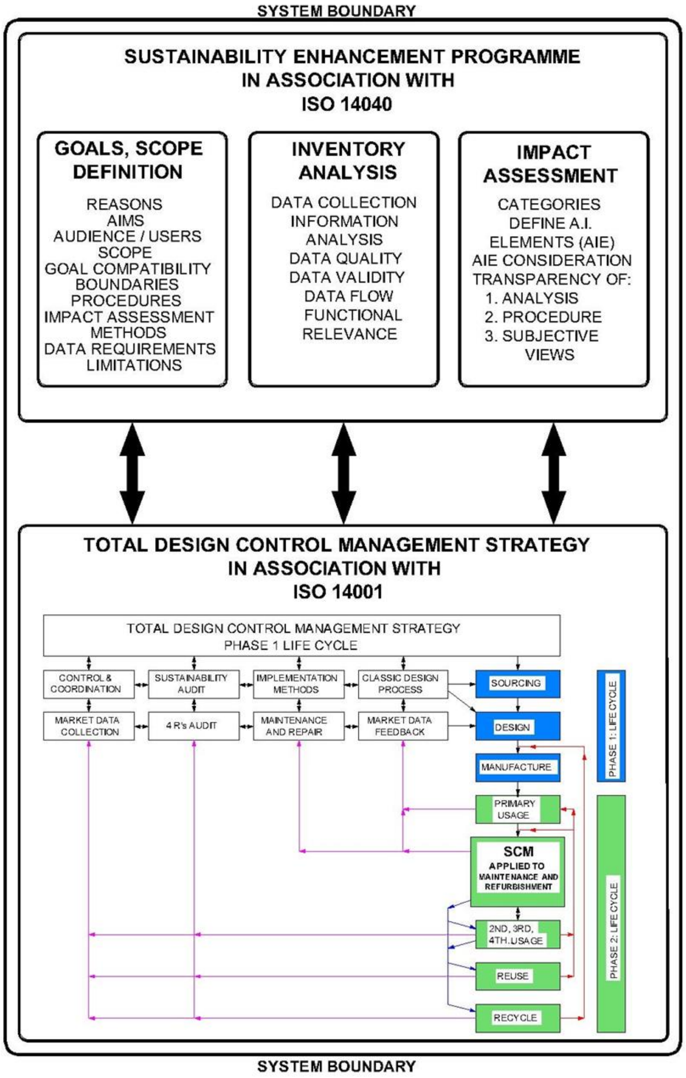


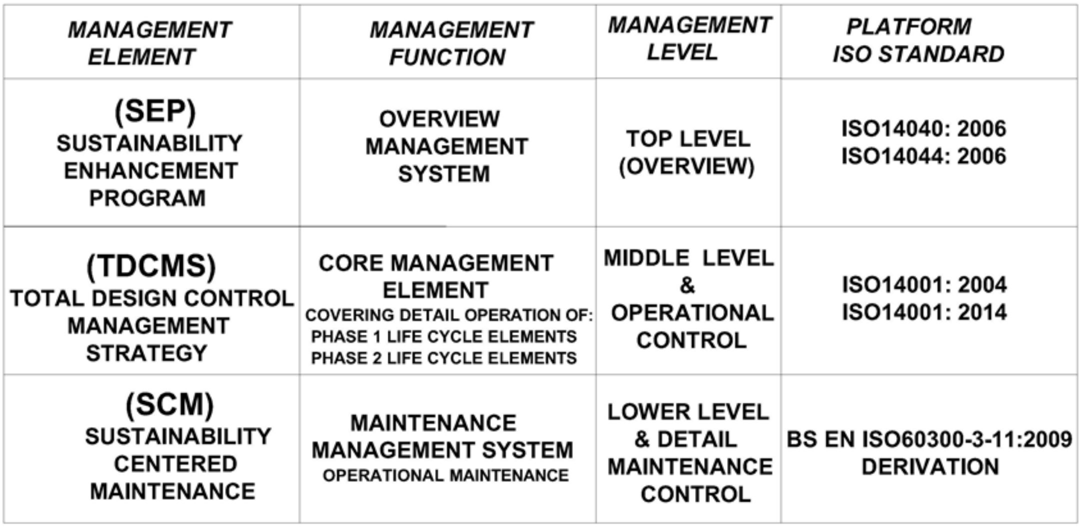
Figure 7.10: Sustainability Enhancement Program Incorporated with ISO Standards

7.10 SEP Management Systems Overview

Within the SEP program there are three levels of management systems running together and meshing cohesively. Shown as follows:

SEP	(Sustainability Enhancement Program)
TDCMS	(Total Design Control Management System)
SCM	(Sustainability Centred Maintenance)

Each management system uses the platform of a particular ISO standard. The diagram in figure 7.11 defines the standard that relates to the management level.



MANAGEMENT ELEMENT	*MANAGEMENT FUNCTION*	*MANAGEMENT LEVEL*	*PLATFORM ISO STANDARD*
(SEP) SUSTAINABILITY ENHANCEMENT PROGRAM	OVERVIEW MANAGEMENT SYSTEM	TOP LEVEL (OVERVIEW)	ISO14040: 2006 ISO14044: 2006
(TDCMS) TOTAL DESIGN CONTROL MANAGEMENT STRATEGY	CORE MANAGEMENT ELEMENT COVERING DETAIL OPERATION OF: PHASE 1 LIFE CYCLE ELEMENTS PHASE 2 LIFE CYCLE ELEMENTS	MIDDLE LEVEL & OPERATIONAL CONTROL	ISO14001: 2004 ISO14001: 2014
(SCM) SUSTAINABILITY CENTERED MAINTENANCE	MAINTENANCE MANAGEMENT SYSTEM OPERATIONAL MAINTENANCE	LOWER LEVEL & DETAIL MAINTENANCE CONTROL	BS EN ISO60300-3-11:2009 DERIVATION

Figure 7.11: Management Levels within SEP Related to ISO Standards

ISO Standards have been intentionally used to platform the various management levels within the SEP program for several reasons:

- each standard offers precisely the management characteristics required for the level of management
- ISO Standards are part of a systemic family which cohesively mesh with other similar standards such as ISO9000 Quality Management.
- Distinct output from one management level is acceptable to another management level simply because adherence to the ISO standards defines the data type, control, and data route.

7.11 Conclusion: SEP Implementation

The Phase 2 Life Cycle Model is already used in part in several industries although only a few industries, e.g. vehicles, aircraft, military have developed cohesive overview systems. When these systems are applied as suggested in the Phase 2 Life Cycle model, the goal is to improve the longevity of the system which improves reliability, safety, and cost. There may be attempts to reduce directly applied energy but generally Embodied Energy reduction is rarely considered

Few industries, apply Phase 2 Life Cycle systems in order to reduce Embodied Energy. Commercially, cost is a major motivator and even though there may be good sustainability solutions available, they will only be implemented if they are cost-effective.

With the SCM system, there are high risk, medium risk and low risk elements relating to the Embodied Energy Program. High-risk items threaten the serviceability of the product and have to be maintained no matter what the cost in monetary terms or in Embodied Energy terms. In an idealistic situation low risk items such as a light bulb should be replaced and recycled however it may be necessary to avoid maintaining such items simply because it will be too costly to implement. Furthermore it may require more energy to replace the bulb than is being saved. Low risk items could be replaced in a Standard maintenance programme rather than on an ad hoc basis.

It is within the designer's ability to overview the whole life cycle of a product from sourcing materials to end-of-life disposal. In order to perform this task properly there needs to be a management process in place which has become known as the Total Design Control Management System (TDCMS). To function properly, TDCMS requires feedback of information from the product during its Phase 2 life.

Phase 1 Life Cycle Embodied Energy covers the product until it leaves the factory. Its Embodied Energy can be measured since this is pure energy input to the product. Phase 2 Life Cycle Embodied Energy is much more difficult to predict, however, with a strategic model such as SEP and TDCMS there can be materials feed-forward, feed-backwards, and more importantly dataflow from the field into the TDCMS. The Sustainability Enhancement Program combines Phase 1 Embodied Energy measurement and Phase 2 Embodied Energy prediction/measurement so that information is fed back to the TDCMS. This then allows the design team and other life cycle protagonists to make changes and iterate the design to become more Embodied Energy efficient with each modification.

The core Phase 2 Life Cycle elements are those of maintenance and refurbishment from which feedback data is derived. In order to create a cohesive maintenance and refurbishment management environment within TDCMS, Sustainability Centred Maintenance (SCM) practices have been incorporated which complement the RCM standard ISO60300 [7.15]. This Standard not only provides a consistent management and data logging environment but with the incorporation of SCM can now specify feedback data to the design function. This Standard therefore functions at an operational level within the broader management strategy of other ISO Standards of the ISO14000 [7.12] series.

The incorporation of the ISO Standards 14001 [7.12], 14040 [7.13] and 14044 [7.14] have been used as base platforms and have guided the evolution of the whole umbrella management system that evolved into SEP. The ISO Standards have defined management processes, goals, boundaries, and procedures and have been developed to be cohesive.

SEP has developed into an executive level management component with TDCMS as the day-to-day operational information management system covering both Phase 1 Life Cycle and Phase 2 Life

Cycle. Within TDCMS lies the operational management system of SCM covering the core activities of maintenance/refurbishment within the Phase 2 Life Cycle element. Each management tier is platformed on ISO standards that are cohesive and interactive.

CHAPTER 8
SUMMARY

8.0 Summary to: Sustainability and Its Incorporation into the Mechanical Engineering Design Process

The original aim for this research project was to provide a means of measuring sustainability primarily so that the designer creating the components on the CAD system would be able to define the sustainability value of his newly designed product.

Sustainability is such an enormous and broad ranging subject that it was necessary to focus on a particular theme, which in this case is product creation where the product is first designed, then manufactured and finally put into service.

As the project unfolded it became clear that the product's Life Cycle Analysis (LCA) was the key to creating a framework for a sustainability measurement program and was prescribed by researchers such as Landolfo [8.5], Ashby [8.1], Granta Design [8.6], Heiskanen [8.7], Hauschild [8.8] and Wanyama [8.9] who all put forward LCA as an appropriate framework. But it was significant that researchers tended to spend their efforts on the easier to define elements of the life cycle, such as end of life disposal (recycling and reuse). The literature survey was fundamental in determining the life-cycle elements that were most popular and highlighted those that were less well served.

8.1 The Product Life Cycle Base Framework

The original life cycle analysis typically possessed only four elements, USEPA [8.13] These are listed as follows:

1. material sourcing
2. manufacture
3. usage
4. end of life disposal

The novel version proposed has expanded the original four elements into six elements to which a sustainability measurement program could be applied. The two new elements are maintenance and design both of which affect consumed energy during the product's life cycle. A maintained product can be returned to service thereby avoiding the purchase of new equipment with its incumbent environmental resource drain. This is an Embodied Energy saving and can offset the input energy to manufacture the product. Though product maintenance is a normal practice it is rarely used in the sustainability discussion. Every product needs to be designed and it has been proposed by several practitioners that design should be central to the achievement of product sustainability. These practitioners include, Lutrop[8.21], Periera [8.14], Ashby [8.1], Granta Design [8.6], Byggeth et al

[8.15], Rose [8.16], Zwolinski et al [8.17], Ueda et al [8.18], Spicer et al [8.19], Yu SY [8.20]. Such an important life cycle element cannot be overlooked and has been added to the elements of the LCA. The overview diagram can be seen in figure 8.1.

8.2 Triple Bottom Line (TBL) Higher Level Framework

The LCA created an excellent base framework and proved to be suitable for assessing the detail of a product on its journey through its life but the results could also be applied in high-level decision-making. The work presented by Chapas [8.10], Mayyas [8.11] and Mohannad [8.12] suggested that work at the detail level would be best served by a framework of LCA but these researchers and others also prescribed that the combination of LCA with TBL and various standards would serve as a complete system. In this way information generated at the LCA level could be used in a global sense by practitioners of TBL. TBL was therefore incorporated into the sustainability application stratagem.

8.3 The Measurement Device

Measurement methodology in many industries tends to aim towards a required outcome. For instance, refurbishment of catalytic converters might require a metric of carbon monoxide reduction, Gozde Kizilboga et al [8.27] or the refurbishment of diesel engines may require a metric of carbon dioxide reduction to assess efficiency.

Since the sustainability metric has to cater for almost any product, specific metrics such as carbon dioxide are unlikely to cover the whole life cycle of a product and its use assumes that all the energy used is from fossil fuels. Research revealed that one commodity was input (or sometimes output) throughout the entire life cycle of a product. That commodity was energy (Joules) or more specifically Embodied Energy as originally set out by Ashby [8.1]. Antiohos [8.22] also applied Embodied Energy to building materials. Ashby et al [8.23] applied Embodied Energy as a measure of sustainability across the product life-cycle. Mayyas [8.11], Pope [8.24], and Patxi [8.25] are other notable researchers who successfully applied Embodied Energy as the metric of choice. Embodied Energy is a metric that can be efficiently applied across the entire life cycle and has therefore been selected for the sustainability measurement process within LCA. The use of Embodied energy has several benefits:

- Embodied Energy could be applied to any product or any service.
- Embodied Energy is relatively easy to convert from any energy storage commodity, such as, coal, nuclear, petrol, diesel, wind, solar, etc.
- Embodied Energy can be used to measure all six life-cycle elements
- Embodied Energy can be used as a currency to define the value of sustainability for a product
- Harvested energy value can be used to offset the input of Embodied Energy thereby using this value as an accounting device

As the metric development progressed it became clear that some products such as PV panels create energy during their useful life whilst other products, such as vehicles, use energy. Furthermore, a product at the end of its life might give up energy if the calorific value is extracted by burning. During the recycling process a material may be reformed which avoids extracting raw material from the Earth. This saves the extraction energy (Energy of Primary Source or EPS). For instance aluminium requires only 5% of EPS. Steel requires around 26% EPS to be recycled. This means that for recycled aluminium there is a 95% EPS saving and for steel the value is 74%

A full life cycle measurement package has been proposed to measure Embodied Energy across the entire product life cycle. Harvested energy in the form of energy saved and energy generated constitutes the give-back element and can be used to offset energy input to the product. The life cycle measurement strategy then combines to give "Sustainable Life Value" (SLV) and includes seven items which are listed as follows and shown in figure 8.1:

1. SSV: Sustainable Source Value: Embodied Energy required to source and process the material.
2. SDeV: Sustainable Design Value: Embodied Energy required in the product design process
3. SMV: Sustainable Manufacturing Value: Embodied Energy required to manufacture the product
4. SUV: Sustainable Use Value: Embodied Energy used by the product during its useful life
5. SMaV: Sustainable Maintenance Value: Embodied Energy required during maintenance processes
6. SDV: Sustainable Disposal Value: Embodied Energy required to dispose of the product
7. SGBV: Sustainable Giveback Value: Embodied Energy gleaned or saved

8.4 ISO Standards

It became clear that a management structure was required to guide and control the system that drives the measurement process. This was generated as a Total Design Control Management Strategy (TDCMS) and is discussed below. A review of standards revealed that the ISO14000 series, [8.2], [8.3], and [8.4], comprise several comprehensive standards and deal with aspects of application, measurement and management of sustainability. Furthermore within the set of standards, methodologies are specified which allow seamless meshing within the set but also with other management standards such as ISO9001. These are discussed and introduced below in more detail.

The LCA discussed in sections 8.2 to 8.4 above can now be modified with the additions of elements of design and that of maintenance. This updated, novel LCA also shows the relationship to the TBL and includes the input from ISO standards and the *Sustainable Giveback Value,* a new energy accounting element. The whole model vision is shown in figure 8.1.

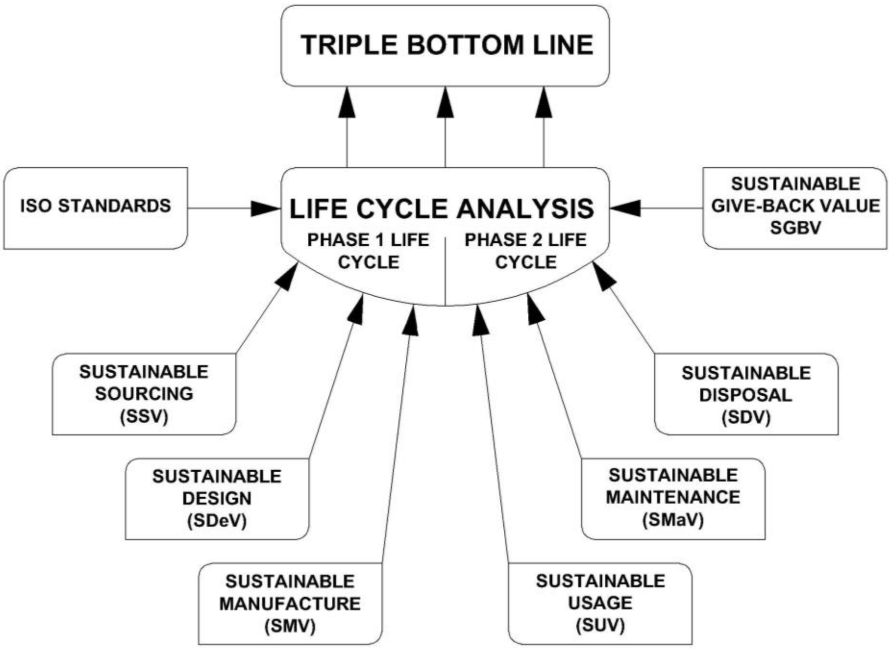


Figure 8.1: Novel System Vision: Life Cycle Analysis with Life Elements

8.5 Phase 1 and Phase 2 Life Cycle

The creation process (Phase 1), consisting of sourcing, design, manufacture and vicarious transport is a process that requires input of Embodied Energy which can be measured. Once the product leaves the factory it is in the hands of the consumer (Phase 2) who may or may not treat the product as the designer intended in terms of usage, maintenance and end of life disposal. A distinction was therefore made between life-cycle elements that embraced input Embodied Energy that could be measured and the elements of the life cycle that were more unpredictable.

Giveback is important since it can be used to offset the original energy required to manufacture the product. For instance if a product, through maintenance, has its life extended for example five times, it has avoided the use of 4 x EPS. (The first creation will always cost energy). This can therefore be offset against the original EPS and any energy applied during product use such as fuel used to power a vehicle.

The LCA elements that fell neatly into pure input Embodied Energy were sourcing, design, manufacturing and vicarious transport. These were termed as Phase 1 Life-Cycle Embodied Energy and are the first four elements of the Life-Cycle process. Phase 2 Life-Cycle Embodied Energy included: Usage, Maintenance, End of Life Disposal and Giveback.

When products are being created the only LCA element that can overview the entire life cycle is the Design Function. A lone designer cannot efficiently perform this cross-discipline task since there are too many specialist considerations required to embrace the whole life cycle. It is proposed that there should be a design team comprising specialists from the entire life cycle such as; sourcing, maintenance, production, packaging and marketing, to name but a few. If the specialist team contributes at the design stage of a product then elements can be included in the design which will enhance the whole life cycle and reduce its Embodied Energy content.

The design team can design-in elements to improve the Embodied Energy throughout the life cycle, Phase 2 Life Cycle is still unpredictable and requires a different approach to energy measurement to that used in Phase 1 Life-Cycle. The dilemma was in selecting a point in the Phase 2 Life-Cycle where measurements and data could be collected. The natural point emerged to be during the maintenance/refurbishment process when worn components are removed and replaced with new or reused components. Data can be collected and collated to give a "snapshot" of product performance using energy values as the measurement data. At the products' end of life, similar data can be collected to create the energy balance sheet which includes all the Embodied Energy and all the harvested energy, a net energy value being the result. The system described is that of maintaining products with a focus of sustainability which compliments the normal maintenance task of maintaining reliability. This new focus can be termed Sustainability Centred Maintenance (SCM) and provides a system whereby the maintenance engineer can assess the product and its assembled components in terms of Embodied Energy value and review the direction after maintenance; feedback to be reused or feed-forward to be recycled. SCM also provides a data acquisition system which feeds back information to the TDCMS and design team. SCM is intended to complement rather than replacestandard maintenance procedures.

The net energy balance figure thus generated, can be used as a benchmark to be reduced in future products or as a marketing tool to compare with similar competitors' products. The net energy value can be used as a direct measurement of a product’s available sustainability. The LCA information thus generated can be fed into the TBL to assist in influencing economic, social and environmental issues.

Though the net energy balance is useful, the most important aspect of the Phase 2 Life-Cycle measurement process is the SCM system model and its application which allows continuous feedback of real-time information to the TDCMS in the design team.

It became clear that there needed to be a management structure included in the measurement process, but this requires a corporate overview since it would need to involve high-level management down to base level workers who would implement the process. More importantly feedback to the design team was required from products already in the field. This required resource commitment which could only be sanctioned by institutional management.

Since the design team was therefore in "total control" of the whole life process the management system was termed Total Design Control Management System (TDCMS) and to function efficiently, it requires feedback of information as the product is used during its Phase 2 Life-Cycle.

The overview management strategy, TDCMS combines Phase 1 Life Cycle and Phase 2 Life Cycle in an overall Embodied Energy Reduction program known as The Sustainability Enhancement Program (SEP). SEP combines Phase 1 Embodied Energy measurement and Phase 2 Embodied Energy prediction/measurement so that information is fed back to the TDCMS which is then able to influence/control/enhance new products through better design and manufacture.

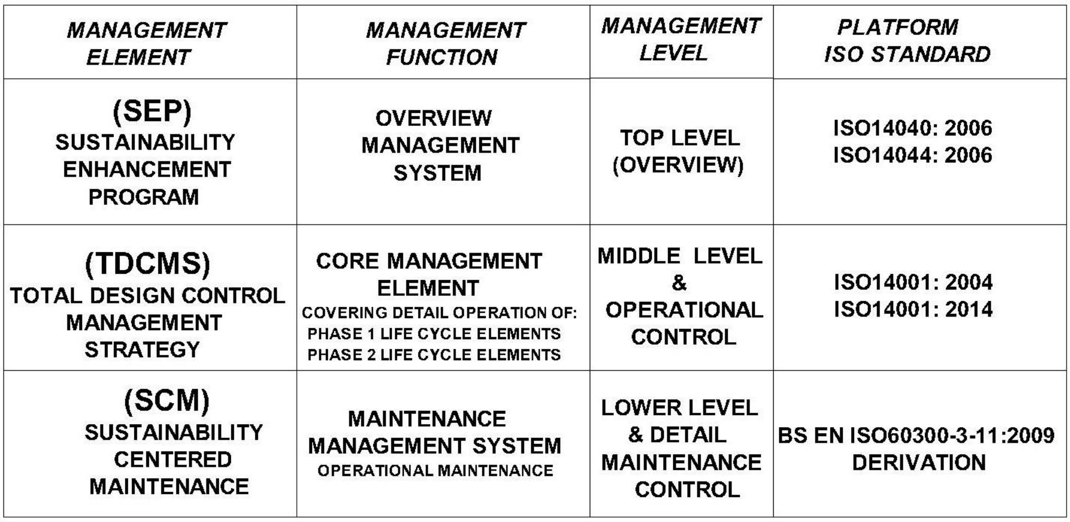
Phase 1 Life Cycle covers the product until it leaves the factory. Its Embodied Energy can be measured since this is pure energy input to the product. Phase 2 Life-Cycle Embodied Energy is much more difficult to predict, however by application of a strategic management model such as SEP and TDCMS and implementation through SCM there can be materials feed-forward, feed-backwards and more importantly dataflow from the field into the TDCMS. This then allows the design team to make changes and iterate the design to become more Embodied Energy efficient with each modification.

Maintenance and refurbishment is a fundamental process within Phase 2 Life-Cycle and has been elevated to a core element. It is intended that normal maintenance processes should still take place but should be complemented by SCM which will refocus the maintenance effort onto Embodied Energy efficiency where parts can be reused and end of life parts recycled. New bearings, seals, etc., can replace recycled parts allowing refurbished products to re-enter the usage chain. Perhaps one of the most important outcomes of the maintenance function is feedback information directed to the design function. Such an important core activity therefore requires a suitable core management process and therefore Sustainability Centred Maintenance (SCM) has been incorporated within the TDCMS.

The integration of ISO Standards 14001, 14040 and 14044 has been used as a base platform and has guided the evolution of the whole umbrella management system that developed into TDCMS and SEP. Furthermore SCM has been linked to specific maintenance programs such as "Reliability

Centred Maintenance" (RCM) which is categorised and platformed by the use of ISO60300 Dependability Management [8.26]. The ISO Standards prescribe defined management processes, goals, boundaries and procedures and have been developed to be cohesive and intermeshing. They are also compatible with the ISO9000 quality standard to which many large institutions adhere.

These three levels of management process complete with their relationship to the ISO standards can be seen in figure 8.2



MANAGEMENT ELEMENT	*MANAGEMENT FUNCTION*	*MANAGEMENT LEVEL*	*PLATFORM ISO STANDARD*
(SEP) SUSTAINABILITY ENHANCEMENT PROGRAM	OVERVIEW MANAGEMENT SYSTEM	TOP LEVEL (OVERVIEW)	ISO14040: 2006 ISO14044: 2006
(TDCMS) TOTAL DESIGN CONTROL MANAGEMENT STRATEGY	CORE MANAGEMENT ELEMENT COVERING DETAIL OPERATION OF: PHASE 1 LIFE CYCLE ELEMENTS PHASE 2 LIFE CYCLE ELEMENTS	MIDDLE LEVEL & OPERATIONAL CONTROL	ISO14001: 2004 ISO14001: 2014
(SCM) SUSTAINABILITY CENTERED MAINTENANCE	MAINTENANCE MANAGEMENT SYSTEM OPERATIONAL MAINTENANCE	LOWER LEVEL & DETAIL MAINTENANCE CONTROL	BS EN ISO60300-3-11:2009 DERIVATION

Figure 8.2: ISO Standards Linked to the Three Level Sustainability Management System

In conclusion, a three level management system has been developed, shown in figure 8.2 which incorporates a sustainability measurement system that can be used by the engineering designer who is creating the product. The end result is that a Sustainability Life Value (SLV) can be allocated to the product. The Sustainability Life Value can then become a marketing tool when compared to other similar products, offering a competitive edge in terms of SLV or more succinctly the value of Embodied Energy within that particular product.

8.6 Conclusions to Sustainability and Its Incorporation into the Mechanical Engineering Design Process

Sustainability is such a broad subject that researchers have often been superficial in their assessments simply because they have attempted to cover too much. In the case of this particular project, the intention was to create aims sufficiently narrow that project depth could be achieved.

The general aim of the research project was to formulate and define a method of measuring sustainability so that the mechanical engineer in the process of designing products could attach a sustainability value to the design. Though this has been attempted previously the focus has been in many cases to create an index, Gabi [8.28], Eco-rucksack [8.34], or to consider only part of the life cycle was, Paxti [8.25], or that the application was in a different industrial sector, Yohanis et al [8.30]. Addressing a gap in the approach to sustainability measurement then became the focus of this project.

Sustainability is well established within the built environment and geographic sciences but mechanical engineering is a relative late-comer to the sustainability party. The major dilemma was in determining a measurement parameter. There are a multitude of labels, indicators, and parameters such as carbon dioxide or sulphur that were possibilities but many of these are quite specific to a particular industry or product. The general aim of the research considered that the design engineer requires a measurement parameter while working in any industry and on any kind of product. The measurement device (metric) therefore had to be universally acceptable across industries.

The most favoured universal metric was energy, measured in joules. This theory was supported by the discovery that several researchers also applied energy as a measurement device, perhaps the most prominent being Ashby [8.1] who dubbed the metric as “Embodied Energy”. Ashby et al [8.23] also applied Embodied Energy as a measure of sustainability across the product life-cycle. Antiohos [8.22] applied Embodied Energy to building materials. Mayyas [8.11], Pope [8.24], and Patxi [8.25] are other notable researchers who successfully applied Embodied Energy. Several ISO Standards [8.2, 8.3, 8.4] also use Life Cycle Analysis (LCA) with energy as the measurement parameter.

The initial literature survey revealed that many researchers also used the Life Cycle Analysis (LCA) approach. These researchers included Luttrop [8.21], Pope [8.24], Paxti et al [8.25] and Ashby [8.1] amongst others. This approach considers the entire product life cycle from sourcing through disposal but it was quickly discovered there were some elements that were not usually considered. These included design, maintenance and the new term “Sustainable Giveback Value” (SGBV). Though maintenance is used as a matter of course to improve the life of a product, it has rarely been used in the sustainability debate even though extending the life of a product actually avoids procuring new products thus resulting in lower environmental impact. Elements in the new Life Cycle Analysis are therefore listed below with prefixes suggesting these are also measurement values:

1. SSV: Sustainable Sourcing value

2. SDeV: Sustainable Design Value
3. SMV: Sustainable Manufacture Value
4. SUV: Sustainable Usage Value
5. SMaV: Sustainable Maintenance Value
6. SDV: Sustainable Disposal Value
7. SGBV: Sustainable Giveback Value

Elements 1 to 6 are phases through which the product passes through its entire life. Element 7, SGBV, is actually a measurement accounting device introduced to accumulate energy gleaned or saved. This can then be offset against the Embodied Energy used on the product thereby introducing an energy accounting system.

The literature survey and subsequent research forays into current publications confirmed the nature and direction of the research project. Chapter 2 sets out the aims of the project and relates them to the chapters in the thesis. These aims and subsequent achievements are explained below chapter by chapter.

8.6.1 Chapter 3: Standards Survey

This chapter is a survey of current environmental standards and proved useful for integrating appropriate values and management techniques into the management structures discussed below.

8.6.2 Chapter 4: Design for Sustainability

Design for sustainability is reasonable well covered by numerous publications from such notables as; Chapas [8.10], Mayas [8.11], Periera [8.14], Patxi [8.25], and Luttrop [8.21] amongst others. Taking their lead this chapter confirms that new product sustainability can only be achieved by an overview of the entire product life cycle. The best placed function is the design function. From the designers overview the standard LCA model was enhanced by novel elements including Sustainable Design, Sustainable Maintenance and Sustainable Giveback Value. The chapter subdivides the elements of the novel LCA into those elements which can be directly measured Phase 1 Life Cycle and those elements that suffer the vagaries of customer use and require special attention to gather any form of measurement data. This is Phase 2 Life-Cycle. The chapter confirmed Design for Sustainability (DfS) as proposed by Pope [8.24] and Johnson et al [8.31] and went on to briefly explain the methodologies that the designer can apply to achieve DfS. Achievements for this chapter are listed as follows:

1. *Life Cycle Enhancement*: This chapter describes improvements to the original life cycle with the addition of novel elements of Sustainable Design (SDeV), Sustainable Maintenance (SMaV), Sustainable Giveback Value (SGBV). These elements form part of the LCA group but are also measurement elements to which a value of energy may be attributed.

2. *Sustainability Measurement Methodology:* Chapter 4 describes and proposes a methodology for measuring sustainability consolidating the input energy applied throughout the product life cycle and combining the energy which may be harvested, usually in Phase 2 Life-Cycle.

3. *Sustainability Audit:* Using the classic design process this chapter proposes a sustainability audit at three points during the design process.
   The primary audit takes place as the concept is formulated.
   The secondary audit takes place when the product has been specified (drawings, models, analysis) but has not yet been manufactured. This is a more precise audit since it uses component specifications.

   The third audit is after testing and just prior to the product leaving the factory. This is the most accurate of the three audits since it uses measured energy input data. It also predicts the Embodied Energy profile during Phase 2 Life-Cycle.

4. *Applies a Key Process of Maintenance*: This chapter proposes maintenance as the key process from which measurements can be taken and information can be gleaned and fed back to the design team. Furthermore control of components can be applied for recycling and for re-use.

5. *Practical Design for Sustainability Methods:* This chapter describes practical methodologies that can be used by the designer to achieve DfS.

8.6.3 Chapter 5: The Measurement of Sustainability

The development of the measurement for sustainability was conducted in two phases which considered the energy which can be measured directly during Phase 1 Life Cycle and the particular situation of Phase 2 Life-Cycle which required certain systems in place before measurement and other data could be recorded.

Part One (The Measurement of Phase 1 Life Cycle Embodied Energy)

1. *Embodied Energy Metric:* The measurement parameter of Embodied Energy (input energy) was applied to materials from sourcing through processing, through to manufacture and eventual product creation. The Embodied Energy value was termed Sustainability Life Value for phase 1 (SLV_{PH1})

2. *Phase 1 and Phase 2 Life-Cycle:* The entire enhanced life cycle model is subdivided into Phase 1 and Phase 2 to allow convenient measurements and/or methodologies to be applied

3. *Enhanced Life Cycle Model:* Chapter 5 applies the enhanced life cycle model incorporating Sustainable Design Value as one of the measurement parameters during Phase 1 Life Cycle

4. *Total Design Control Management Strategy (TDCMS):* The implementation of design influence and control over the entire product life cycle drives the management strategy TDCMS. This shadows the classic design approach in managing the processes involved in the creation of a new product and overviewing and influencing the product during Phase 2 Life-Cycle.

5. *Detailed Measurement Methodology:* This chapter defines a detailed measurement method for Phase 1 Life-Cycle using Embodied Energy as the preferred metric.

6. *Phase 1 Life Cycle Measurement Algorithm:* This chapter explains the creation and application of a detailed computer-based algorithm that accrues and defines Embodied Energy applied during Phase 1 Life-Cycle. The result is SLV_{PH1} which is a practical energy measurement, later applied to the energy balance sheet as "Energy of Primary Source" (EPS).

Part Two (Phase 2 Life-Cycle: Measurement of Embodied Energy and Harvested Energy)
(Introduces management systems, measurement techniques and case study applications)

1. *Sustainability Centred Maintenance (SCM):* This chapter defines SCM, and explains the methodology of a detailed control and data acquisition system based on maintenance and refurbishment that records measurements of energy and other occurrences such as number of components renewed or number of components reused. The process incorporates feedback and feed forward of materials and components and feedback of information to the design team and the TDCMS

2. *Phase 2 Life-Cycle Measurement Algorithm:* This chapter defines a computer-based algorithm which accrues all the energy in Phase 2 Life-Cycle, both input energy and harvested energy, and adds it to the Embodied Energy applied during Phase 1 Life-Cycle.

3. *Sustainable Giveback Value (SGBV):* This new term is introduced to the enhanced and novel LCA. SGBV is an accounting value that enables harvested energy to offset input energy and is used in the energy balance sheet.

4. *Energy Balance Sheet:* An energy balance sheet is created that accrues all energies input to the product and all the energies generated or saved. The energies that are saved or generated are termed harvested energies and are used to offset the input energies on the energy balance sheet. The result is a net energy balance for the entire product life cycle. (SLV Ph1 & Ph2) stop

5. *TDCMS Information Feedback:* The methodology projects how the information generated during the entire life cycle process can be used and applied at a detailed level by its feedback to the TDCMS and on a more global level by its application to the Triple Bottom Line.

8.6.4 Chapter 6: Total Design Control
(Describes Total Design Control Management Strategy (TDCMS))

The development of the novel life cycle analysis model and the application of a measurement system led to the requirement of some form of management system. This approach developed from work by Corbett and Dooner [8.33] who proposed design for manufacture strategies. The TDCMS can be considered as a design for sustainability strategy.

1. *Total Design Control Management Strategy:* A management system is created which puts design influence in control of the LCA and influences the elements of the entire product life cycle.

2. *Team Approach:* The TDCMS proposes that a team approach has to be taken for DfS to be applied.

3. *Total Design Control Management Strategy Definition:* The TDCMS is defined as a novel management strategy with the purpose of managing the product life cycle.

4. *The Design Process as the Key:* This section identifies the design process as the key to guiding the management and control (TDCMS) of the entire product life cycle.

5. *Design Function Drives Sustainability Processes*: TDCMS operations are activated by steps in the classic design approach.

6. *Sustainability Audits Triggered by Design Specifications:* Sustainability audits on occurrence of concept design specification, detail design specification and product design specification.

7. *TDCMS Management Structure Defined:* The TDCMS management structure is identified to incorporate the design process, Design for Sustainability (DfS) and audit systems.

8. *Design Team Composition:* The composition of the TDCMS design team is outlined.

9. *Environmental Standards Integration:* TDCMS is integrated with environmental standards (ISO14001) [8.2]. Integration offers quality systems, quality management structures, integrity and cohesiveness with other management standards

8.6.5 Chapter 7: Sustainability Enhancement Program (SEP) (and executive level sustainability management programme)

SEP was developed from the requirement to involve executive management in the application of sustainability methodology. The need to divert funds towards such a program may be as recommended by ISO14044 [8.4] who prescribes a “top down management system”

1. *Sustainability Enhancement Program (SEP) introduced:* The executive tier of management is defined as part of the total management package.

2. *Integration of SEP, TDCMS and SCM:* The entire management package, its integration and operation is defined.

3. *Environmental Standards Integration:* SEP is integrated with ISO14044, Environmental Management [8.4] and ISO 60300, Dependability Management and RCM. [8.32] and further incorporates Sustainability Centred Maintenance

4. *Entire Management Structure Defined:* The entire management system from SEP through TDCMS to SCM is defined and links the whole management strategy to Phase 1 and Phase 2 Life-Cycle

8.7 Research Achievements (in brief)

- identification of six (seven if SGBV is included) sustainability elements within the Life Cycle of a product from material sourcing to eventual disposal

- introduction of novel sustainability elements of maintenance, design and give back which hitherto have been rarely included in general sustainability models

- introduction of practical elements which the applied design engineer can implement

- defining a system to establish a quantitative value for sustainability

- defining and creating a computer based quantitative system for the application of the Principles of Sustainability for new products and services

- introduction of a three tier management system from executive level to application level

- introduction of an Embodied Energy accounting system using SGBV to offset accumulated Embodied Energy.

8.8 Commercial Sustainability Measurement Packages

Several commercial sustainability packages were reviewed. Some are very sophisticated but it was observed that much of the collected data is aimed at higher management levels for decision-making purposes, even though the data originated at a detail/product level. The current approach advocated by Eco-IT [8.35], Eco-Rucksack [8.34]. IEC [8.36] and Open-ICA [8.37] is often focused on resource consumption within energy based and carbon-based models and tends to be qualitative and is intended to guide rather than offer precise data. Within such databases are measurement elements such as carbon, toxicity, resource depletion and are directed towards providing typical information such as carbon emissions data.

Complex algorithms have been developed such as that offered by Granta Design [8.6], but often these models are broad in approach resulting in information that is also broad and barely usable at product level. Concerns were raised by several researchers including Moles [8.38] and several other researchers including Gurav Ameta [8.39], Singh [8.41], Moran [8.42] and Babcicky [8.43], about the accuracy of manipulated data which was generally aimed at higher level decision-making. The methodology proposed in this project uses specific measurement data that is applied directly to products which drives the eventual changes in those products. The results will be shown as more sustainably efficient products.

8.9 Data Application and Targeting

Life Cycle Analysis (LCA) was selected as the base framework on which to build a Sustainable Life Value (SLV) model. The suggested SLV scheme operates at the product level where precise measurements of Embodied Energy are possible and can be used to influence the product creation and management process. Though information was intended to be used at the detail/product level, the information could also be used to influence a more global strategy of the Triple Bottom Line (TBL).

The submitted proposal offers the extra benefits of influencing the individuals who work within the product life cycle envelope. Within the Sustainable Life Value model, the focus on reducing Embodied Energy and creating situations where energy can be harvested focuses engineers on the methodology of achieving those goals and in so doing spreads a positive influence which affects the three pillars of the TBL. It is submitted that the SLV model and its operating system spreads across environmental, economic and social boundaries by focusing on a single metric that can measure across the range of products and services. Taking a lead from Subhas and Sikhdar [8.44], who proposed the five elements of sustainability measurement it has been possible to create a comprehensive measurement system that can provide information and influence higher, more global levels of sustainability measurement.

8.10 Waste

Throughout this work the working hypothesis has been that there should be no waste. The assumption has been that all materials can be recycled. This is an idealistic target and falls within the Cradle to Cradle (C2C) idealistic framework. Anders [8.45] explained the differences between absolute targets and idealistic targets and criticised C2C has been “highly idealistic”. This research has generally assumed the idealistic target of zero waste, but has also assumed that waste will be inevitable. The target is to reduce the waste as much as possible and any waste that cannot be reused or recycled can be dealt with in a sympathetic way, perhaps extracting calorific value.

8.11 SLV Programme Benefits

The benefits of the Sustainable Life Value programme lay mostly in the process and the feedback of information. The end result of the energy balance sheet is useful as a comparator value. The main benefits are listed as follows:

Simplification

- complex systems made simple through use of algorithms
- information for input is readily available

Flexibility

- SCM can adapt to ad-hoc maintenance systems as well as more formal systems such as RCM
- SLV program designed to be adaptable to almost any applications environment or system
- system application reveals information that can be used for design iteration

Practicality

- accurate information at product/detail level
- practical approach to measurements and information
- SCM creates a practical system within maintenance
- results of analysis are practical and can be used through SCM by TDCMS and the design team

Scope

- stand-alone or can be incorporated into a larger system
- incorporates LCA from sourcing through to disposal
- incorporates methods that measure life cycle performance during Phase 2 Life Cycle
- creates a net energy balance value

Applicability

- aimed at the practical designer to give a precise value of sustainability for each product
- information can be used for decision-making at detail, company, national and global levels.
- base framework of LCA allows feeding information through to a global Triple Bottom Line higher level framework
- results of the system and the net energy balance value can be used to influence new designs and high-level decisions
- information can be used to apply for a “Green Badge” such as Energy Star, Bateman [8.29]

CHAPTER 9
CONCLUSIONS

9.0 Research Conclusions Overview

The Sustainable Life Value (SLV) program evolved by expanding the original product life cycle of sourcing, manufacture, usage and disposal into the six elements shown in figure 9.1. As the model evolved an algorithm was devised to accumulate and manipulate data from across the product life cycle. Implementation of the SLV program involved an executive-to-base level management coordination system governed by ISO standards. Figure 9.1 shows the Sustainable Life Value programme in its entirety. The central column indicates the evolution of the programme. The right hand column shows the management elements and their location in the whole scheme, whilst the left hand column indicates the evolution of the measurement algorithm culminating in the energy balance sheet.

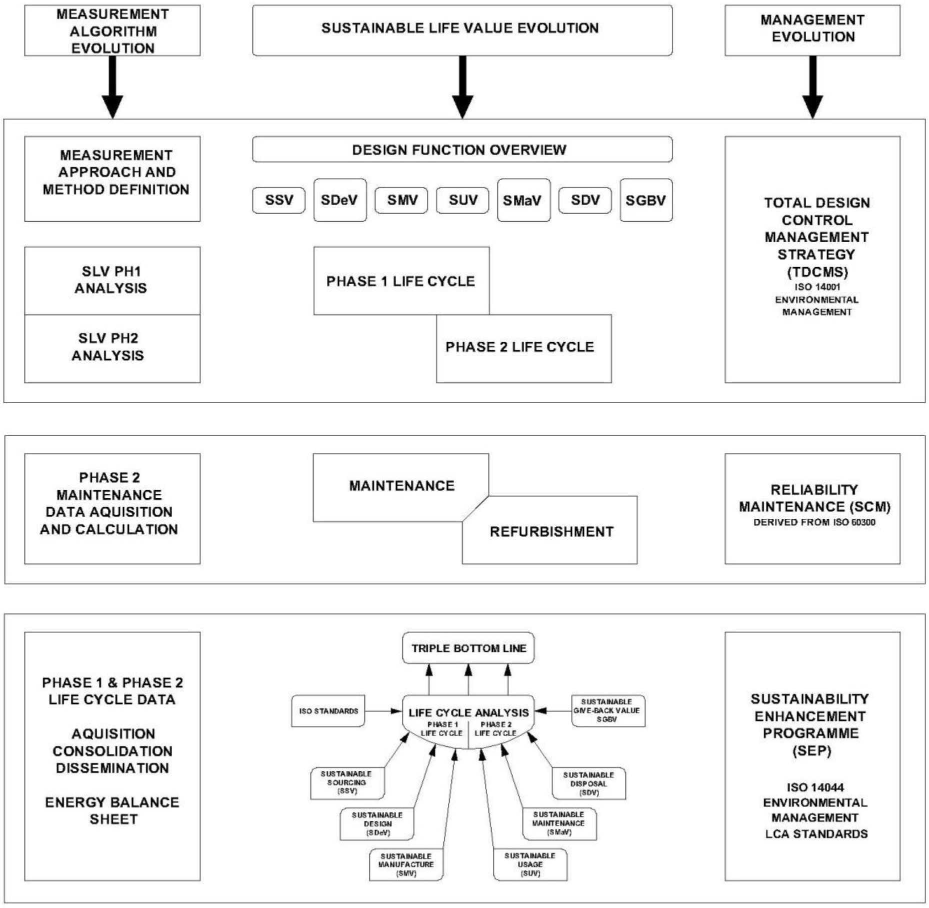


Figure 9.1: Sustainability Life Value: Programme Overview

9.1 Sustainable Life Value (SLV) Scheme Evolution

The evolution of the Sustainable Life Value scheme originally focused on enhancements to the basic Life Cycle Analysis (LCA) by introducing novel elements of Sustainable Design Value (SDeV), Sustainable Maintenance Value (SMaV) and Sustainable Giveback Value (SGBV). In a parallel process, a means of measuring sustainability was incorporated using input energy. It became clear that the newly improved LCA could be broken down into two major phases:

Phase 1 LCA covered material sourcing through to product manufacture where energy input could be relatively easily measured. The value of energy input was termed “Embodied Energy”, Ashby [9.1]. As the product exited the factory it was imbued with a value of Sustainable Life Value Phase 1 Embodied Energy (SLV_{PH1EE}) (joules) or more conveniently termed “Energy of Primary Source” (EPS) (joules).

Phase 2 LCA covered the period from first usage through to disposal where the product lay in the hands of the consumer. The product would be subject to variations in use by the consumer which led to difficulties in predicting behaviour. Furthermore energy input proved to be difficult to measure and required the development of a methodology to accommodate these consumer imposed variations.

Maintenance and refurbishment activities became key points in Phase 2 Life Cycle where products could be analysed for usage, new component introduction, reuse of components and recycling of components. Furthermore the act of returning a product to the usage cycle avoided the procurement of new products and thus further avoiding the energy input (EPS) required during Phase 1 Life Cycle. This constituted energy saved (harvested) and could be used to offset the energy input to a product. The linking of the new LCA approach to the Triple Bottom Line (TBL) enabled information, generated in the SLV program, to be used as an influence factor in sustainability or environmental analysis. Figure 9.2 indicates the influence position of the Sustainable Life Value within the Triple Bottom Line complex.

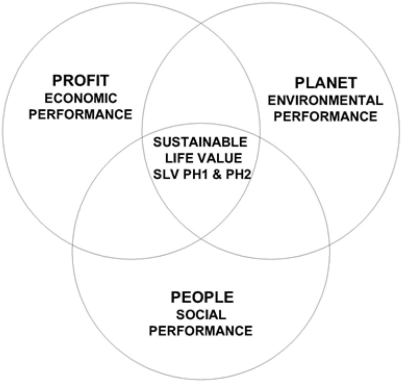


Figure 9.2: Graphical Representation of the Triple Bottom Line

Information collected during maintenance and refurbishment activities is raw (clean) data that has not been manipulated to suit an information presentation process. Its accuracy can be considered valuable in influencing elements of the Triple Bottom Line as shown in figure 9.3 which is also used to influence various societal levels from factory level through regional, national and eventually global level. Figure 9.4 indicates the position of SLV raw data, its influence within the Triple Bottom Line and links those values to societal levels.

The Triple Bottom Line is influenced by the SLV program, figure 9.3, by applying the generated data to the elements of all three fields, i.e. environmental, economic and social. It should be noted that it is not just SLV program data but the integration and functioning of the SLV program that also provides improvements in the Triple Bottom Line through feedback to the management coordination system.

There are several parts of the SLV program that contribute towards such improvements, perhaps one of the most useful examples being Design for Sustainability (DfS). The designer is in a unique position to overview the entire product life cycle from sourcing to disposal and can design-into the product elements that will reduce Embodied Energy in terms of material sourcing, manufacturing, usage, maintenance and disposal.

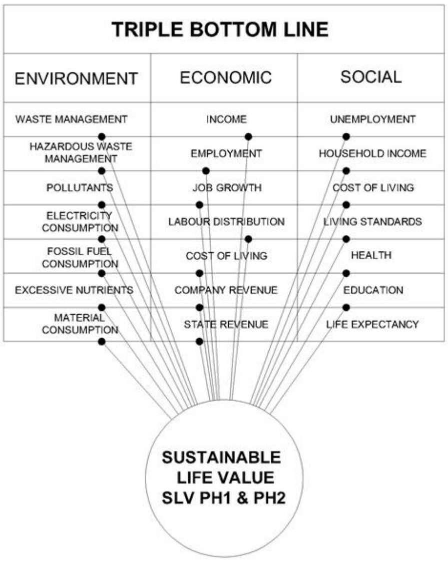


Figure 9.3: The Influence of the Sustainable Life Value on the Triple Bottom Line

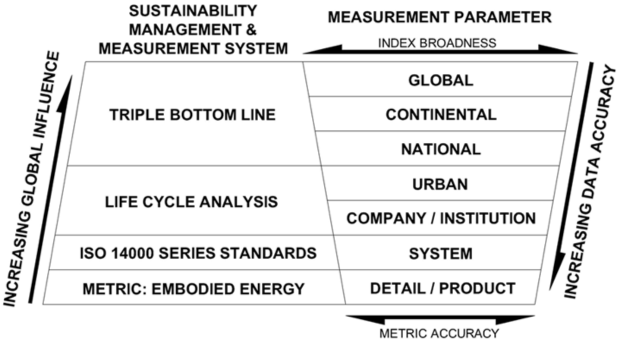


Figure 9.4: Sustainability System Vision Linked to the Sustainability Measurement Profile and Influence to Societal Levels

The SLV program, can feed generated data through the life cycle analysis to the Triple Bottom Line, but as figure 9.4 shows, such data may influence strategic thinking above the company/institutional level through to global level.

9.2 Evolution of the SLV Algorithm

From the beginning of the project it was clear that there would be large volumes of generated data and data manipulation and presentation. As each stage of the SLV scheme developed, a stage of the SLV algorithm was also developed.

9.2.1 The Phase 1 Life Cycle SLV Algorithm

Measurement of energy input to a product can be complex and in reviewing commercial packages such as Granta Design [9.2] and Energy Star [9.3], it became clear that their approach to energy measurement was more of an overview using energy input from general manufacturing techniques, rather than using precise data. The SLV algorithm thus developed, collected data from actual processes allowing the system to be tuned to a particular product and a particular manufacturing process. The tuneable data acquisition system allows direct input from specific manufacturing plant, linking the final EPS to a particular factory. The result is accurate data which can be used to ascertain the efficiency of particular factories and a means of assessing the energy footprint of those factories.

The end result of the algorithm is the derived EPS that can be added to later elements of the algorithm which assesses the energy input and energy harvested from the Phase 2 Life Cycle of a product.

9.2.2 Phase 2 Life Cycle SLV Algorithm

The maintenance or refurbishment occurrence became the opportunity with which to assess the product in terms of; energy used, residual energy, Embodied Energy in newly fitted parts and several other energy inputs and gleanings. Assessing these factors and many more became complex and required an algorithm that could accommodate input data, generated data and perform calculations to derive energy values. An overview flowchart for the process can be seen in figure 9.5

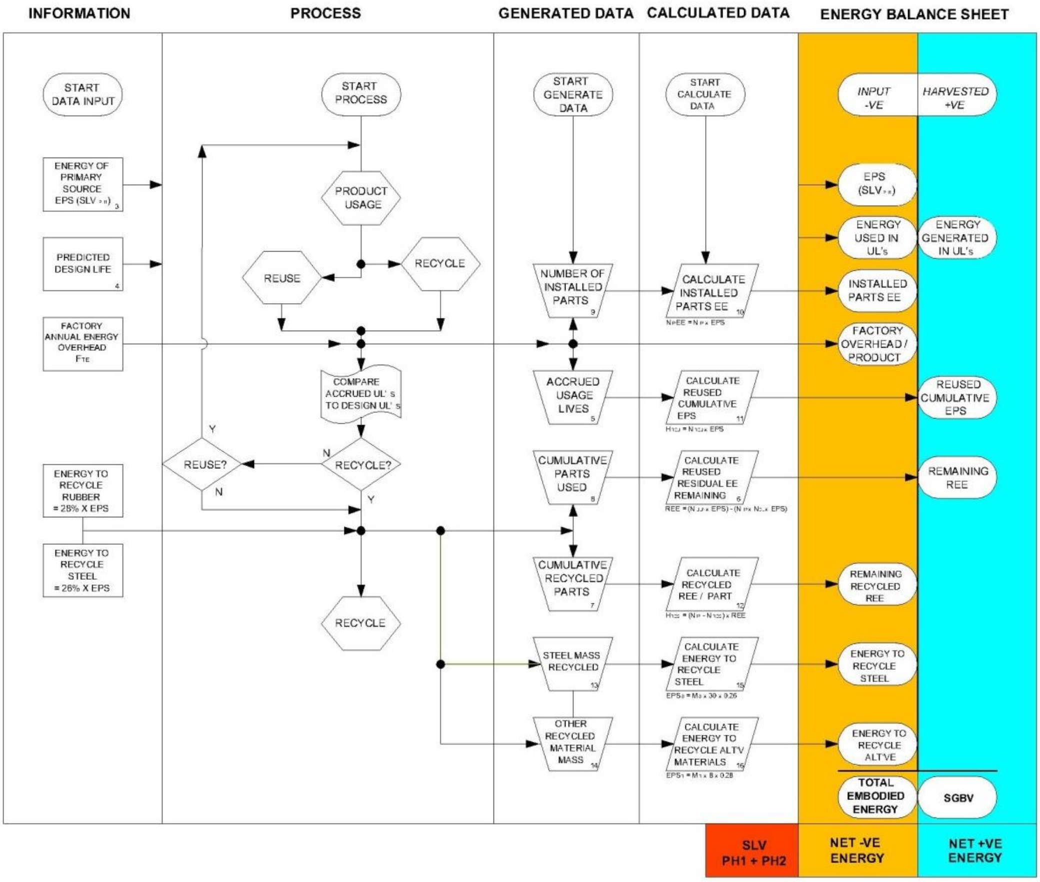
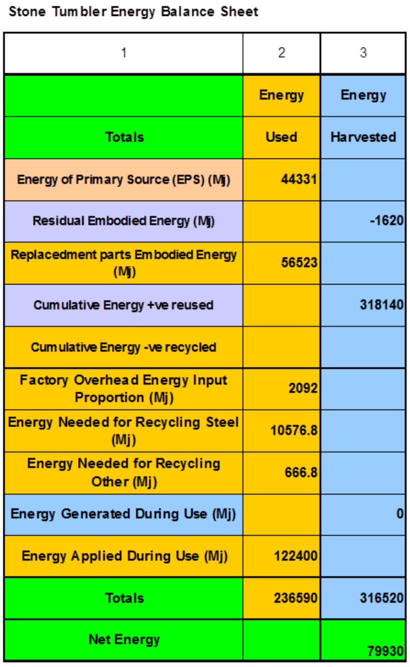


Figure 9.5: Flowchart for the SLV Audit Measurement System

Input information to the algorithm, figure 9.5 included; EPS, predicted design life, factory overhead, etc. Generated data included; number of installed parts, accrued usage lives, cumulative recycled parts, etc. These data and others were used in calculations to derive such values as: installed parts Embodied Energy, residual Embodied Energy, harvested energy, etc.

The consolidation of EPS and energies applied and harvested in Phase 2 Life Cycle during usage, maintenance and disposal could then be compiled into an energy balance sheet, an example of which can be seen in figure 9.6.



Stone Tumbler Energy Balance Sheet

1	2	3
	Energy	Energy
Totals	Used	Harvested
Energy of Primary Source (EPS) (Mj)	44331	
Residual Embodied Energy (Mj)		-1620
Replacedment parts Embodied Energy (Mj)	56523	
Cumulative Energy +ve reused		318140
Cumulative Energy -ve recycled		
Factory Overhead Energy Input Proportion (Mj)	2092	
Energy Needed for Recycling Steel (Mj)	10576.8	
Energy Needed for Recycling Other (Mj)	666.8	
Energy Generated During Use (Mj)		0
Energy Applied During Use (Mj)	122400	
Totals	236590	316520
Net Energy		79930

Figure 9.6: Example of the Energy Balance Sheet for the Stone Tumbler Case Study

The energy balance sheet represents the entire product life cycle and includes energy input (column 2) and energy harvested (column 3). In this case there is a positive net energy balance which can be used as an alternative product comparator or marketing tool. Though the end result is useful, the true benefits of the SLV programme lie in the methodology and its information feedback to all the elements of the life cycle where functionaries can use the data to improve energy input or energy harvested.

9.3 Management Coordination

From the early stages of the project there was a perceived need for management elements in terms of coordination, responsibility and authority.

9.3.1 Total Design Control Management System (TDCMS)

Design was recognised as the overview function for the entire life cycle and as such required feedback from all life cycle elements. A mid-management coordination system was devised to coordinate, mainly Phase 1 Life Cycle elements, but extended into Phase 2 Life Cycle elements in order to coordinate and receive feedback from products in the field. This became known as the "Total Design Control Management System" (TDCMS) and was regulated by ISO14001Environmental Management Systems [9.4]. The application of the ISO Standard to TDCMS imbued qualities of coordination, feedback, record-keeping, data acquisition and data validation.

9.3.2 Sustainability Centred Maintenance (SCM)

One of the essential areas of data acquisition was during maintenance events within Phase 2 Life Cycle. Maintenance is a frequent occurrence, especially with medium to high value products but is rarely used in context with sustainability even though maintaining products extends their life thus avoiding extraction of new materials from the Earth. In the framework of the SLV program, maintenance became the convenient data collection event which coordinated data acquisition, yet the data collection process had to sit alongside maintenance processes already in place. Sustainability Centred Maintenance (SCM) management coordination system was therefore devised and based on Reliability Centred Maintenance methodology governed by ISO60300 Dependability Management [9.5]. As with ISO14001 this Standard imbues qualities of coordination, feedback, record-keeping, data acquisition and data validation.

The SCM data coordination system became part of the TDCMS scheme providing data collection means with feedback to all elements of the product life cycle. Figure 9.7 indicates its position within the TDCMS scheme.

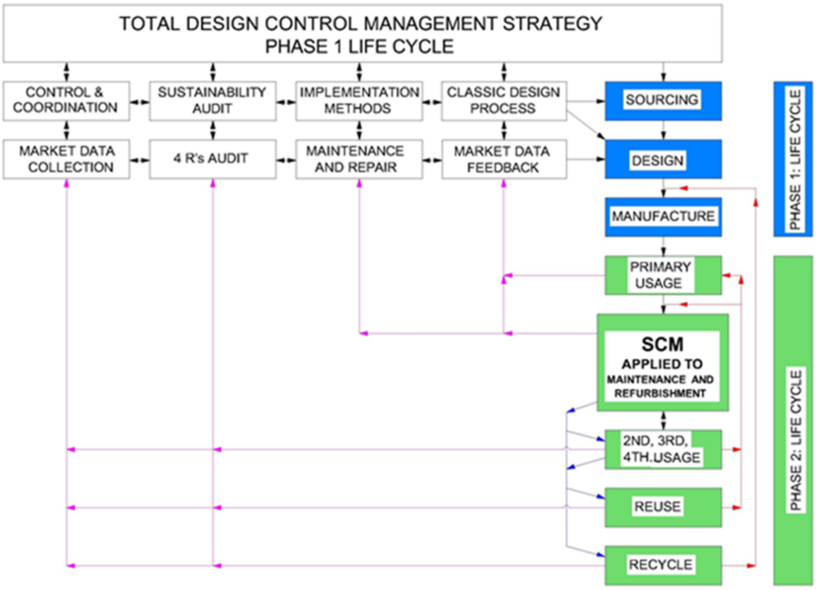


Figure 9.7: The TDCMS Scheme Showing the Position of SCM

The management schemes presented thus far have concentrated on coordination and responsibility for the entire SLV program but authority to perform these management tasks was only lightly covered. The Sustainability Enhancement Program (SEP) was therefore devised to address the shortfall.

9.3.3 Sustainability Enhancement Program (SEP)

The SLV program is aimed at installation in companies or institutions where management commitment is paramount for the implementation of funding, training and program execution. Executive management recognition gives authority and is accommodated in the SLV program by the inclusion of an umbrella executive management suite termed Sustainability Enhancement Program. SEP coordinates the strategic functions of the SLV program and is regulated by ISO14040 Environmental Management: Life Cycle Assessment [9.6] and ISO14044 Environmental Management

LCA Requirements [9.7], which lay down guidelines as to strategic coordination, feedback, record-keeping, data acquisition and data validation. The entire management system can be seen in figure 9.8.

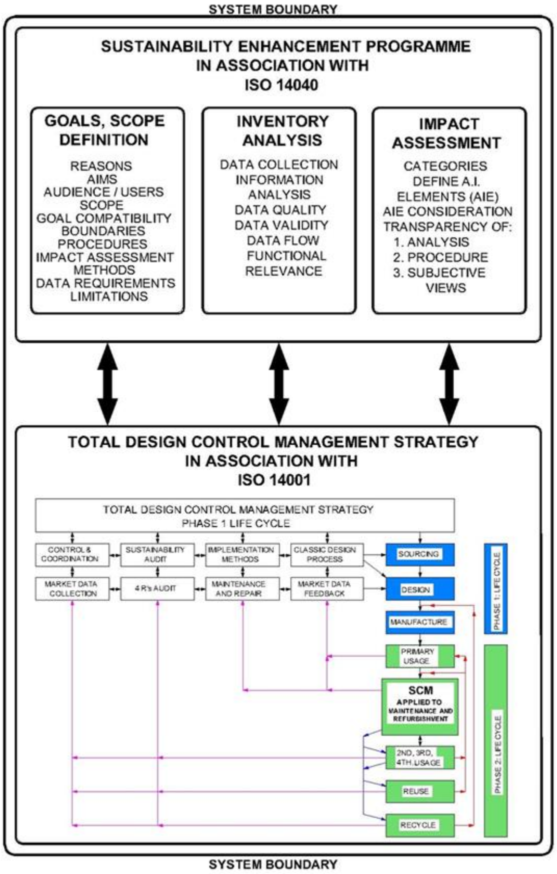


Figure 9.8 Sustainability Enhancement Program incorporating TDCMS and SCM

The complete SLV program thus presented is a coordinated system supported by a comprehensive algorithm and a synchronised top-down management system. It is put forward that such a complete system will enhance a company profile and offers the possibility of improvements to the energy used in the product life cycle and an opportunity for functionaries to examine methods of sourcing, design, manufacture, usage, maintenance and disposal. This fine tuning of energy input and energy harvested across the entire life cycle is possible due to measurement data being made available to all.

9.4 Achievement of Aims

Below is a useful abridgement which lists the achievement of the aims originally set out in Chapter 2.

Frameworks

- The LCA model - improved with additional novel elements
- LCA and TBL frameworks - combined into a cohesive system

Methods and Models

- Maintenance processes now included as an energy harvesting source through extended product life.
- Practical application of Design for Sustainability. (DfS)
- Design iterations can be influenced through real-time LCA data

Measurement and Audit

- Embodied Energy - primary metric
- A design activated audit method has been devised.
- An energy accounting algorithm has been devised resulting in an energy balance sheet.

Management Systems Introduced for:

- Putting the design function in control can influence the entire life cycle
- Detailed data collection & dissemination to the entire life cycle
- Integration with ISO environmental management standards

9.5 Subject Advancement

Below is a summary of the subject advancement provided by this research project.

General System

- Detailed sustainability measurement across the entire product life cycle
- Complete system model integrates: management, process, measurement and data control
- Product life cycle model improved with novel elements
- LCA and TBL closely linked to achieve influence from product level through company, regional, national and global levels.

Design

- Design process is the system regulator
- Design iteration achieved from real time data feedback
- Design for Sustainability (DfS) applied to the entire life cycle especially Phase 2 life cycle

Algorithm

- Algorithm: records, analyses, calculates, consolidates and disseminates data
- Integrated algorithm across the entire product life cycle
- Embodied Energy metric applied across the entire product life cycle
- Energy accounting system provides a net energy balance

Data

- Primary data fed-back to Design / Management
- Detailed data obtained at a product level
- Integrated dataflow across the entire life cycle
- Real-time measurements
- Data can be used for “Green Badge” application

Coordination

- Cohesive management strategy regulated by ISO standards
    - SEP - umbrella executive management suite
    - TDCMS - middle management suite-coordinates design, material flow, data flow
    - SCM - base management suite-retrieves data from Phase 2 Life Cycle maintenance processes
- ***SCM - adaptable to specific manufacturing plants***
- A cohesive system for the measurement of sustainability has been devised and includes:
    - Integrated System and Model
    - Audit and Measurement Algorithm
    - Integrated Management System - SEP, TDCMS, SCM
    - ISO Environmental Management Standards

9.6 Future Work

The current research project has provided a means of measuring the value of sustainability in the creation of new products. The program has been developed alongside a value accreditation system and coordinated by a top to bottom management coordination system. Though this first development phase is considered to be complete, further work is required to bring the program to fruition as a practical sustainability measurement tool. The major enhancements needed are discussed below:

1. Develop a commercial interactive algorithm with a user-friendly front end
2. Determine data for alternative materials e.g. aluminium, copper, plastics, concrete and other materials relative to a particular product
3. Introduce a pilot study with a suitable company
4. Explore data dissemination through Cloud based technology based on a “Wikipedia” type framework
5. Explore and define adaptive information feedback and retrieval methods using “Big” data approaches, e.g. Closed Loop Product Life-cycle Management (PLM) put forward by researchers Kiritsis [9.8] and Framling [9.9]

9.6.1 Development of a Commercial Interactive Algorithm

The current algorithm exists as a suite of several fully functioning but separate algorithms. There is a requirement to create a user-friendly but interactive "front end" so that users can be prompted for information which will automatically be inserted into appropriate positions within the algorithms for data accumulation, analysis and eventual output. Output information is also an important feature of the program since this data needs to be disseminated in alternative formats to functionaries representing different aspects of the product life cycle. Future work will entail consolidating the current analytical "engine" and introducing a user-friendly input interface and a suitably flexible data output system.

9.6.2 Determination of Alternative Materials Data

The current project provided materials data, mostly EPS and recycling energy requirements, relating to steel and rubber compounds which reflected the fact that steel is one of the most widely used engineering materials and that the various case studies used both steel and rubber in various components. Other engineering materials include aluminium, stainless steel, copper, various plastics, concrete, etc. It is quite possible that on implementation into a manufacturing company there may be specialist materials requiring new data. Further work is therefore proposed to determine EPS/recycling data for mainstream materials such as stainless steel, aluminium and various plastics but the flexibility of the SLV system gives the opportunity for specialist materials data to be incorporated.

9.6.3 Introduce the S LV Program as a Pilot Study into a Company

Institutional (company) data and systems can be so varied that validation techniques for one company will not be appropriate in another company. True validation can only be achieved in practice, by implementing the S LV program into a company thereby testing its flexibility in overcoming particular company idiosyncrasies. The SLV program was designed to be flexible with strategic guidance built-in through the management strategy and the compliance with the ISO Standards. These accommodate diverse manufacturing practices, management systems, data approval processes and data dissemination methods.

9.6.3.1 Data Validation

Crude and inaccurate data input to the S LV algorithm will merely lead to inaccurate data output. It is important to validate any data that is input to the system. Section 5.15 draws attention to the validation of data input and its importance but strategic data validation guidance can also be found in the quoted ISO Standards as follows:

ISO14001	Section 4.5, Checking	[9.4]
ISO14040	Section 5.2.4 Data Quality Requirements	[9.6]
	Section 5.3, Data Calculation	
	Section 6.0 Reporting	
ISO14044	Section 4.2.3.6 Data Quality Requirements	[9.7]

True data validation can only be applied to specific data during implementation of the SLV program. It is strongly recommended that any implementation adheres to the guidelines set out in various ISO Standards.

9.6.4 Exploration of Cloud Based Technology for Information Dissemination

The SLV program data output is intended to be disseminated to all functionaries within the life cycle phases. Further work in this area could take the form of exploring the possibility of creating a Cloud-based database, possibly along the lines of the Wikipedia format but with appropriate controls and access rights. This would mean that life cycle functionaries could extract specific data from a global source that pertain to their particular area.

9.6.5 Adaptive Information Feedback

Adaptive information feedback has been introduced by Kiritsis [9.8] and Framling [9.9] who have developed a system of "Closed Loop Product Life Cycle Management" (PLM). This system involves automatic reading of information from the product, often imbued with "smart" properties so that data can be directly fed through a "Big Data" system to various life cycle functionary’s’ databases which are automatically updated. Further work would involve exploring the system and linking it to particular manufacturing companies who may have differing requirements for information retrieval and input to their systems.

9.7 And Finally

It is natural for costs to be applied as a measure of product success or failure. Changing the emphasis to an energy valuation system and to reducing energy input could bring many other benefits including cost reduction. The proposed research hypothesis suggests that a reduction in Embodied Energy and an increase in harvested energy is a measure of the sustainability of a product which can have far-reaching effects and inherently means that there are fewer resources given up by Earth. This project has created a method where a quantifiable value of sustainability using energy as the metric can be integrated into product development to influence the product’s entire life cycle.

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10.10 A.D.Johnson Publications

Books

A.D.Johnson: '*Foundations of Mechanical Engineering'*
'Foundations of Mechanical Engineering: Study Guide'
Undergraduate (Year 1) Mechanics including Statics, Dynamics, Thermodynamics and Fluids
Published by Taylor and Francis 1997

A.D.Johnson, A.Gibson: *Engineering Design with Sustainability* Projected Publish Date: 2014 February:

An undergraduate text specifically for Mechanical Engineering Designers. This proposes Total Design Control of the whole life of a product allowing the designer to apply Sustainable Engineering practice thereby creating sustainable products from cradle to grave. This subject has not been published previously and is described as "Groundbreaking" by the publisher "Elsevier"

Conference and Journal publications

1. Johnson A.D., Kelly PF Chandler JR: *The Design of a Low Cost System for the Automatic Location and Clamping of Components within a Flexible Manufacturing Cell.* Production Research association Conference 1989
2. Johnson A.D., Sherwin K: *A Design-Build-Test Project for First Year Students* International Journal of Mechanical Engineering Education, Vol 21, No1. 1991
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13. Johnson AD: *Product Sustainability within Phase 2 Life Cycle Embodied Energy: an Approach to Derivation*: Journal of Renewable and Sustainable Energy: Accepted but with modifications December 2014

APPENDIX

CHAPTER 1
APPENDIX

A 1.1 Institution of Mechanical Engineers Code of Conduct

Extracts taken from the institution's By-laws of 9th of April 2008-2009

By-Law 30
All members shall conduct their professional work and relationships integrity and objectivity and with due regard for the welfare of the people, organisations and environment should they interact.

Pursuant to By-law 32: *Amended and approved by the trustee board on 13 July 2009*
members are specifically referred to By-law 33, which sets out the core of ethical obligations for all members of the institution. The following regulations are founded on the principles contained within this By-law understatement of ethical principles published by EC(UK)2007

CR1 Members shall act with care and competence in all matters relating to their duties

CR2 Members shall maintain up-to-date knowledge and skills and assist the development in others.

CR3 Members shall perform services only in areas of current competence.

CR4 Members shall not knowingly mislead nor allow others to be misled in engineering matters.

CR5 Members shall present and review engineering evidence, theory and interpretation honestly, accurately and without bias quantify all risks.

CR6 Members shall be alert to the ways in which their duties derived from and effect the work of other people; respect the rights and reputations of others.

CR7 Members shall avoid deceptive acts and take steps to prevent corrupt practices of professional misconduct; declare conflicts of interest.

CR8 Members shall reject bribery stop

CR9 Members shall act for each employee or client in a reliable and trustworthy manner.

CR10 Members shall ensure that all work is lawful and justified.

CR11 Members shall recognise the importance of socio-economic and environmental factors and shall minimise and justify any adverse effect on wealth creation, the natural environment and social justice by ensuring that all developments, throughout the life, use best practice and economic solutions to meet the needs of the present without compromising the ability of future generations to meet their own needs.

CR12 Members shall act honourably, responsibly, and lawfully source to uphold the reputation, standing and dignity of the profession in general and the Institution in particular.

CR13 Identify and be aware of the issues at engineering raises for society; listen to the aspirations and concerns of others.

CR14 Actively promote public awareness of the impact and benefits of engineering achievements.

CR15 Issue public statements only in an objective and truthful manner.

A 1.2 American Society of Mechanical Engineers: Extract from "Code of Ethics of Engineers"

SOCIETY POLICY

ETHICS

ASME requires ethical practice by each of its members and has adopted the following Code of Ethics of Engineers as referenced in the ASME Constitution, Article C2.1.1.

CODE OF ETHICS OF ENGINEERS

The Fundamental Principles

Engineers uphold and advance the integrity, honor and dignity of the engineering profession by:

I. using their knowledge and skill for the enhancement of human welfare;

II. being honest and impartial, and serving with fidelity their clients (including their employers) and the public; and

III. striving to increase the competence and prestige of the engineering profession.

The Fundamental Canons

1. Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.

2. Engineers shall perform services only in the areas of their competence; they shall build their professional reputation on the merit of their services and shall not compete unfairly with others.

3. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional and ethical development of those engineers under their supervision.

4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest or the appearance of conflicts of interest.

5. Engineers shall respect the proprietary information and intellectual property rights of others, including charitable organizations and professional societies in the engineering field.

6. Engineers shall associate only with reputable persons or organizations.2 P-15.7
2/1/12

7. Engineers shall issue public statements only in an objective and truthful manner and shall avoid any conduct which brings discredit upon the profession.

8. Engineers shall consider environmental impact and sustainable development in the performance of their professional duties.

9. Engineers shall not seek ethical sanction against another engineer unless there is good reason to do so under the relevant codes, policies and procedures governing that engineer’s ethical conduct.

10. Engineers who are members of the Society shall endeavor to abide by the Constitution, By-Laws and Policies of the Society, and they shall disclose knowledge of any matter involving another member’s alleged violation of this Code of Ethics or the Society’s Conflicts of Interest Policy in a prompt, complete and truthful manner to the chair of the Ethics Committee.

The Ethics Committee maintains an archive of interpretations to the ASME Code of Ethics (P-15.7).

These interpretations shall serve as guidance to the user of the ASME Code of Ethics and are available on the Committee’s website or upon request.

Responsibility: Committee of Past Presidents/Ethics Committee

Reassigned from Centers Board of Directors/Center for Career and Professional Advancement/Committee on Ethical Standards and Review

Reassigned from Centers Board of Directors/Center for Professional Development, Practice and Ethics/Committee on Ethical Standards and Review 4/23/09

Reassigned from Council and Member Affairs/Board on Professional Practice & Ethics 6/1/05

Adopted: March 7, 1976

A 1.3 The Royal Society of Engineers Codes of Practice

Accuracy and rigour

Professional engineers have a duty to ensure that they acquire and use wisely and faithfully the knowledge that is relevant to the engineering skills needed in their work in the service of others.

They should:

- always act with care and competence

- perform services only in areas of current competence

- keep their knowledge and skills Up to date and assist the development of engineering knowledge and skills in others

- not knowingly mislead or allow others to be misled about engineering matters

- present and review engineering evidence, theory and interpretation honestly, accurately and without bias

- identify and evaluate and, where possible, quantify risks.

Honesty and integrity

Professional engineers should adopt the highest standards of professional conduct, openness, fairness and honesty.

They should:

- be alert to the ways in which their work might affect others and duly respect the rights and reputations of other parties

- avoid deceptive acts, take steps to prevent corrupt practices or professional misconduct, and declare conflicts of interest

- reject bribery or improper influence

- act for each employer or client in a reliable and trustworthy manner.

Respect for life, law and the public good

Professional engineers should give due weight to all relevant law, facts and published guidance, and the wider public interest.

They should:

- ensure that all work is lawful and justified

- minimise and justify any adverse effect on society or on the natural environment for their own, and succeeding generations

- take due account of the limited availability of natural and human resources;

- hold paramount the health and safety of others

- act honourably, responsibly and lawfully and uphold the reputation, standing and dignity of the profession.

Responsible leadership: listening and informing

Professional engineers should aspire to high standards of leadership in the exploitation and management of technology. They hold a privileged and trusted position in society, and are expected to demonstrate that they are seeking to serve wider society and to be sensitive to public concerns.

They should:

- be aware of the issues that engineering and technology raise for society, and listen to the aspirations and concerns of others

- actively promote public awareness and understanding of the impact and benefits of engineering achievements

- be objective and truthful in any statement made in their professional capacity

CHAPTER 3
APPENDIX

A3.1 Energy Analysis

Approximate figures

Every dwelling in the UK was fitted with solar panels:

Energy = $23.4 \times 10^6 \times 1124 \times 10^3 = \underline{26.3 \times 10^{12}\text{Wh/year}}$

Every car was fitted with solar panels:

Energy = $28.7 \times 106 \times 141 \times 10^3 = \underline{4.04 \times 10^{12}\text{ Wh/year}}$

Power consumption of UK per year [A2.4] : $\underline{11.63 \times 10^{15}\text{ Wh/year}}$

$$\varepsilon = \frac{(26.3 \times 10^{12} + 4.04 \times 10^{12}) \times 100}{11.63 \times 10^{15}} = 0.26\%$$

That is 0.26% of total UK Power Use

Value = at 10cents/kWh [A3.4]

$$\text{Value} = \frac{26.3 \times 10^{12} + 4.04 \times 10^{12}}{1000} \times 0.1 = \underline{\textbf{\$3.034 Billion (£1.8 Billion)}}$$

Number of Dwellings in the UK = 23.4 million [A3.2]

House PV Panels 4m x 2m: average 1124KWh/year energy output [A3.3]

Number of cars 28.7million [A3.1]

Car PV Panels 1m x 1m: 141KWH/year energy output [A3.3]

CHAPTER 4
APPENDIX

A4.1 Forest Products Certification

FSC Controlled Wood Certification
Controlled Wood certification enables forest management companies to demonstrate that their wood products have been controlled to avoid sourcing wood that has been illegally harvested, harvested in violation of traditional and civil rights, harvested in forests where high conservation values are threatened by management activities, harvested in forests being converted to plantations or non-forest use, and harvested from forests where genetically modified trees are planted. Controlled Wood certification involves a five-year contract with annual auditing

Forest Products Certification
The Rainforest Alliance is the world's leading Forest Stewardship Council (FSC) Forest Management certifier, with more than 20 years of certification experience. We've worked in over 70 countries and all forest types, with small businesses, indigenous communities and Fortune 500 companies alike.

With the launch of the Smart Wood program in 1989, the Rainforest Alliance developed the world's first global forestry certification program and the first to rely on market forces to conserve forests. We are one of the founders of the Forest Stewardship Council (FSC), the most respected forestry standard-setter in the world. We are now the largest FSC-accredited certifier and have certified the greatest number of community and indigenous operations to FSC standards. Today, Rainforest Alliance certification and auditing services are managed and implemented within our RA-Cert Division. All related staff and personnel responsible for audit design, evaluation, and certification/verification/validation decisions are under the purview of the RA-Cert Division, hereafter referred to as Rainforest Alliance.
Beyond our unsurpassed experience and global expertise, the Rainforest Alliance also offers:

Transparency and Credibility: By collaborating with a reputable, independent nonprofit conservation organization, which operates with transparency, you can more effectively communicate the credibility of your sustainability efforts.

Use of the Rainforest Alliance Certified™ Seal: In addition to the FSC trademarks, our clients also earn the exclusive opportunity to use the Rainforest Alliance Certified™ seal on certified products and in promotional materials.
Local Knowledge: Through our network of field offices we have an intimate understanding of local and regional issues.

A Practical Approach to Certification: We can introduce you and your suppliers to the requirements for Forest Stewardship Council (FSC) certification and use of the Rainforest Alliance Certified seal -- and we'll work with you to ensure a rigorous and efficient evaluation process that can lead to certification.

Useful Addresses

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A4.2 Calculation of Welding Costs [4.8, 4.16]

Welding costs can vary enormously with the thickness of material, the size of welding rod and the power required. For this example the chassis shown below was fabricated from 100 mm x 80 mm Rectangular Hollow Section. Calculations are largely based on the mass the deposition rate and the total mass of welding rod deposited. The example uses a medium duty weld type with medium power.

Barckhoff, Kerluke and Lynn [4.8] suggested that labour was the major cost of welding at 85% of the total cost. The pie chart below, figure A4.1 shows the percentage cost of the major elements of a welding application.

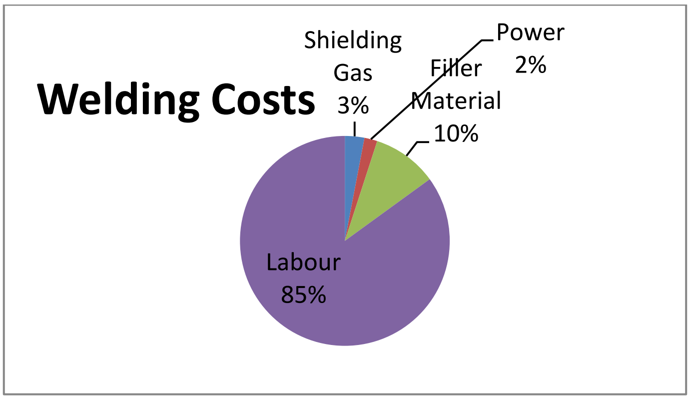


Figure A4.1: Percentage Costs of the Major Elements of a Welding Application

It can be seen that power consumption is only 2% of the cost but it should be noted that power equates to embedded energy and any reduction in power will lead to a reduction in the embedded energy within a fabrication.

The example below relates to a chassis of approximately 2 tonnes. The exercise is to reduce the amount of welding the chassis the chassis comprises rectangular hollow section with corners strengthened by webs. The average throat thickness (weld size) has been set at 6 mm. The calculations below are based on a medium electrode size and the mass of electrode deposited during the welding process.

The chassis set out in figure A4.2 indicates the welded joints which were dimensioned at 6mm throat. Figure A4.3 shows the throat dimensions of a typical fillet weld.

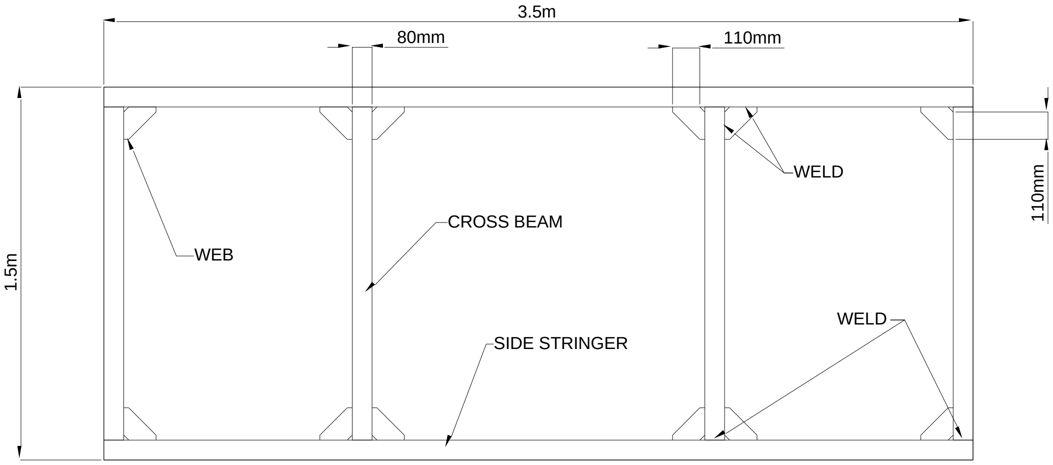


Figure A3.2: Item of Plant Chassis Showing Welded Joints

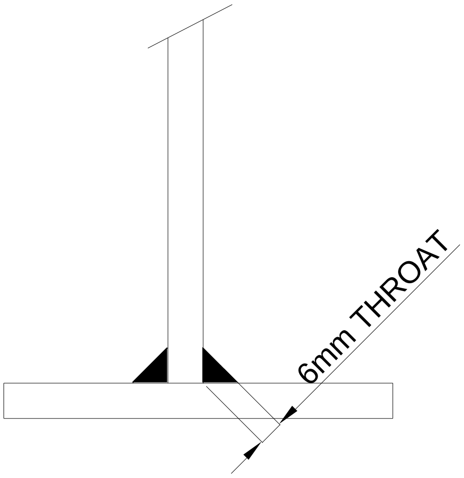


Figure A4.3: Throat Dimensions of a Typical Fillet Weld

Main Chassis Welded Joints
Find Mass of Welds
Density of Steel = 7850kg/m^3
Mass = Volume x Steel Density
Mass = Length x area x ρ
Mass = 8 x [(0.1 x 0.08) x 2] x 0.006^2 x 7850 = **<u>0.814kg</u>**

Fillet Weld Joints for the Web
Find Mass of Welds
Density of Steel = 7850kg/m^3
Mass = Volume x Steel Density
Mass = Length x area x ρ
Mass = 3 x 16 x 0.11 x 0.006^2 x 7850 = **<u>1.49kg</u>**

<u>Total Mass of Weld in the Original Fabrication 2.03kg = 5.82lbs</u>

New Chassis Weld Details

New Weld regime

- reduce the general Weld throat to 3 mm
- use continuous Welds in fabricating the rectangular hollow section
- use intermittent welds: 50/50 say 25mm weld / 25mm gap

Main Chassis New Welded Joints

Find Mass of Welds

Density of Steel = 7850kg/m^3

Mass = Volume x Steel Density

Mass = Length x area x ρ

Mass = 8 x [(0.1 x 0.08) x 2] x 0.003^2 x 7850 = **<u>0.2kg</u>**

New Fillet Weld Joints for the Web

Find Mass of Welds

Density of Steel = 7850kg/m^3

Mass = Volume x Steel Density

Mass = Length x area x ρ

Mass = 3 x 16 x 0.11 x 0.003^2 x 7850 = **<u>0.187kg</u>**

<u>Total Mass of Weld in the New Fabrication 0.387kg = 0.85lbs</u>

The charts below in figures A4.4 and A4.5 give estimates of the time taken to lay down a mass of Weld and an indication cost implications.

Time Needed (mins) to Deposit 1 lb of Weld Filler					
Rod Size	**Operating Factor**				
	60%	50%	40%	30%	20%
1/8"	30.4	36.5	45.6	60.8	91.2
5.32"	23.4	28.1	35.1	46.8	70.2
3/16"	16.8	20.2	25.2	33.6	50.4
7/32"	14.9	17.9	22.4	29.8	44.7
1/4"	12.2	14.6	18.2	24.3	36.5

Figure A4.4: Time Taken to Deposit One lb of Weld Metal [4.16]

Total Cost ($/lb) of Deposition with $50 Labour & O/Head rate					
Rod Size	**Operating Factor**				
	60%	50%	40%	30%	20%
1/8"	$29.91	$34.97	$42.97	$55.24	$80.57
5.32"	$24.03	$27.02	$33.77	$43.52	$62.73
3/16"	$18.63	$21.43	$25.63	$32.63	$46.35
7/32"	$17.05	$19.54	$23.26	$29.47	$41.61
1/4"	£14.80	$16.83	$19.87	$24.94	$34.80

Figure A4.5: Approximate Cost Estimation per lb of Weld Metal Deposited [4.16]

Original Fabrication Times and Costs
using 1/8" welding rod diameter
using 40% operating factor

Time Taken
One lb of weld takes 45.6 min to be deposited
5.82lbs deposited

Time = 45.6 x 5.82 = **<u>265.4 Mins = 4.42 hrs</u>**

Total Cost
$42.57 / lb deposited
5.82 lbs deposited

Cost = 42.57 x 5.82 = **<u>$247.76</u>**

New Fabrication Times and Costs

Time Taken
One lb of weld takes 45.6 min to be deposited
0.85lbs deposited

Time = 45.6 x 0.85 = **38.76 Mins = 0.65 hrs**

Total Cost
$42.57 / lb deposited
0.85 lbs deposited

Cost = 42.57 x 0.85 = **$36.18**

Percentage Reductions

Time

$$\text{Time reduction} = \frac{265.4 - 38.76}{265.4} = \mathbf{0.854 \text{ or } 85.4\% \text{ reduction in time}}$$

Cost

$$\text{Cost Reduction} = \frac{247.76 - 36.18}{247.76} = \mathbf{0.854 \text{ or } 85.4\% \text{ reduction in cost}}$$

Energy
Power setting = 125A, Voltage = 110V

Find Power
Power = 125 x 110 = **13.75 kW**

Convert to Energy
1 kWh = 3.6 MJ
Time to weld = 4.42 hrs

Energy (kWh) = 13.75 x 4.42 = **60.775 kWh**

Energy (J) = 60.775 x 3.6 = **219 MJ**

Energy Saving
Saving 60%

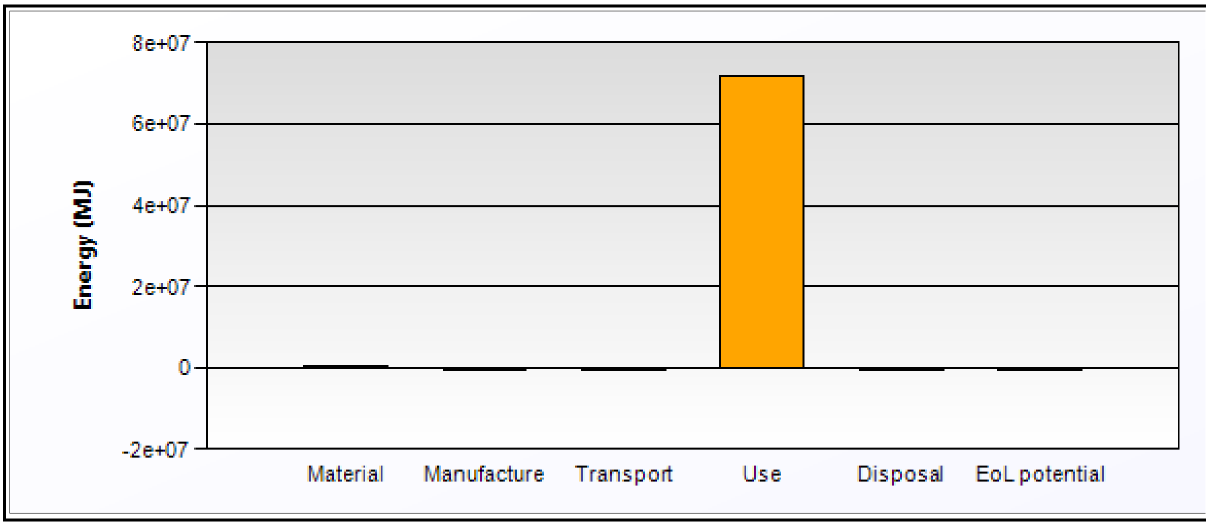
Energy saving = 219 – (219 x 0.6) = **87.726 MJ**

A4.3 Eco-Audit Report for a Rock Drill

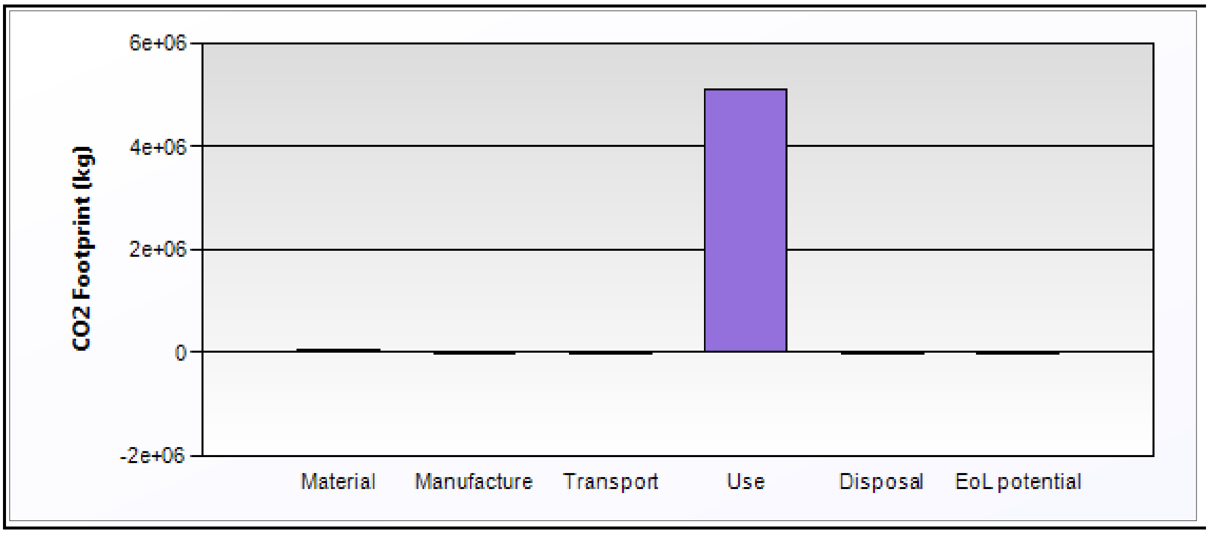
Eco Audit Report

Product Name	Rock Drill
Product Life (years)	5

Energy and CO2 Footprint Summary:



Energy Details...



CO2 Details...

Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	5.26e+05	0.7	3.62e+04	0.7
Manufacture	5.4e+04	0.1	4.06e+03	0.1
Transport	3.1e+04	0.0	2.2e+03	0.0
Use	7.18e+07	99.2	5.1e+06	99.2
Disposal	4e+03	0.0	280	0.0
Total (for first life)	**7.24e+07**	**100**	**5.14e+06**	**100**
End of life potential	-4.66e+05		-3.2e+04	

Eco Audit Report

Energy Analysis

Energy and CO2 Summary

	Energy (MJ)/year
Equivalent annual environmental burden (averaged over 5 year product life):	1.45e+07

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	Energy (MJ)	%
Drill Rig	Low carbon steel	Virgin (0%)	2e+04	1	2e+04	5.3e+05	100.0
Total				**1**	**2e+04**	**5.3e+05**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	Energy (MJ)	%
Drill Rig	Rough rolling, forging	2e+04 kg	5.4e+04	100.0
Total			**5.4e+04**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 2e+04 kg

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Drill Rig	Rail freight	5e+03	3.1e+04	100.0
Total		**5e+03**	**3.1e+04**	**100**

Breakdown by components

Component	Component mass (kg)	Energy (MJ)	%
Drill Rig	2e+04	3.1e+04	100.0
Total	**2e+04**	**3.1e+04**	**100**

Use:

Energy and CO2 Summary

Static mode

Mobile mode

Energy input and output type	Fossil fuel to

	mechanical, internal combustion
Use location	World
Power rating (hp)	8e+02
Usage (hours per day)	10
Usage (days per year)	2e+02
Product life (years)	5

Fuel and mobility type	Diesel - heavy goods vehicle
Use location	World
Product mass (kg)	2e+04
Distance (km per day)	50
Usage (days per year)	50
Product life (years)	5

Relative contribution of static and mobile modes

Mode	**Energy (MJ)**	**%**
Static	7.2e+07	99.7
Mobile	2.3e+05	0.3
Total	**7.2e+07**	**100**

Breakdown of mobile mode by components

Component	**Energy (MJ)**	**%**
Drill Rig	2.3e+05	100.0
Total	**2.3e+05**	**100**

Disposal:

Energy and CO2 Summary

Component	**End of life option**	**Energy (MJ)**	**%**
Drill Rig	Re-manufacture	4e+03	100.0
Total		**4e+03**	**100**

EoL potential:

Component	**End of life option**	**Energy (MJ)**	**%**
Drill Rig	Re-manufacture	-4.7e+05	100.0
Total		**-4.7e+05**	**100**

Notes:

Energy and CO2 Summary

Eco Audit Report

CO2 Footprint Analysis

Energy and CO2 Summary

	CO2 (kg)/year
Equivalent annual environmental burden (averaged over 5 year product life):	1.03e+06

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	CO2 footprint (kg)	%
Drill Rig	Low carbon steel	Virgin (0%)	2e+04	1	2e+04	3.6e+04	100.0
Total				**1**	**2e+04**	**3.6e+04**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Drill Rig	Rough rolling, forging	2e+04 kg	4.1e+03	100.0
Total			**4.1e+03**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 2e+04 kg

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Drill Rig	Rail freight	5e+03	2.2e+03	100.0
Total		**5e+03**	**2.2e+03**	**100**

Breakdown by components

Component	Component mass (kg)	CO2 footprint (kg)	%
Drill Rig	2e+04	2.2e+03	100.0
Total	**2e+04**	**2.2e+03**	**100**

Use:

Energy and CO2 Summary

Static mode **Mobile mode**

Energy input and output type	Fossil fuel to mechanical, internal combustion
Use location	World
Power rating (hp)	8e+02
Usage (hours per day)	10
Usage (days per year)	2e+02
Product life (years)	5

Fuel and mobility type	Diesel - heavy goods vehicle
Use location	World
Product mass (kg)	2e+04
Distance (km per day)	50
Usage (days per year)	50
Product life (years)	5

Relative contribution of static and mobile modes

Mode	**CO2 footprint (kg)**	**%**
Static	5.1e+06	99.7
Mobile	1.6e+04	0.3
Total	**5.1e+06**	**100**

Breakdown of mobile mode by components

Component	**CO2 (kg)**	**%**
Drill Rig	1.6e+04	100.0
Total	**1.6e+04**	**100**

Disposal:

Energy and CO2 Summary

Component	**End of life option**	**CO2 footprint (kg)**	**%**
Drill Rig	Re-manufacture	2.8e+02	100.0
Total		**2.8e+02**	**100**

EoL potential:

Component	**End of life option**	**CO2 footprint (kg)**	**%**
Drill Rig	Re-manufacture	-3.2e+04	100.0
Total		**-3.2e+04**	**100**

Notes:

Energy and CO2 Summary

A4.4 Eco-Audit for a Fabricated Footbridge

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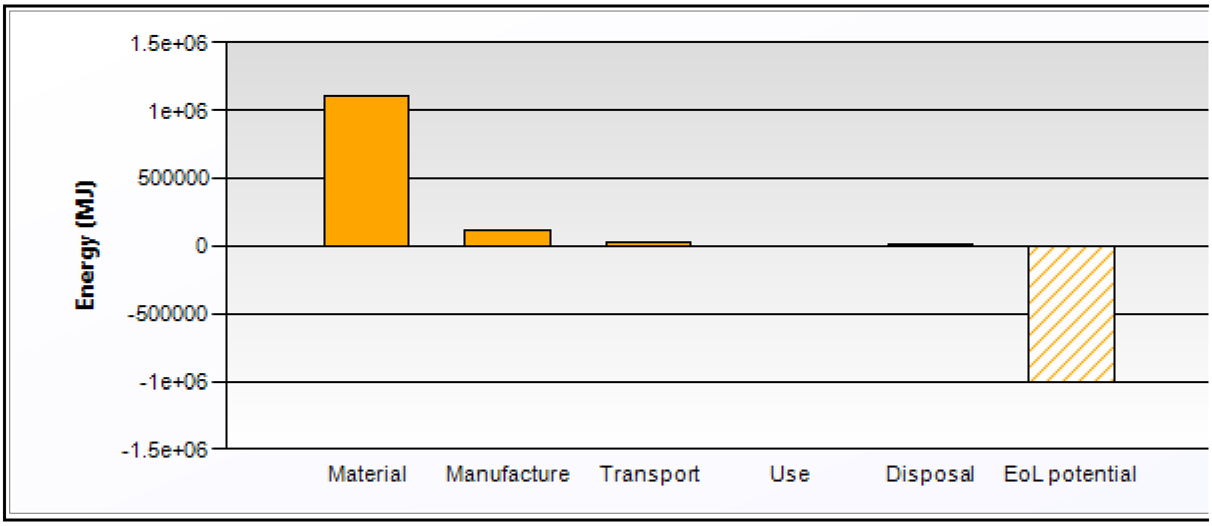
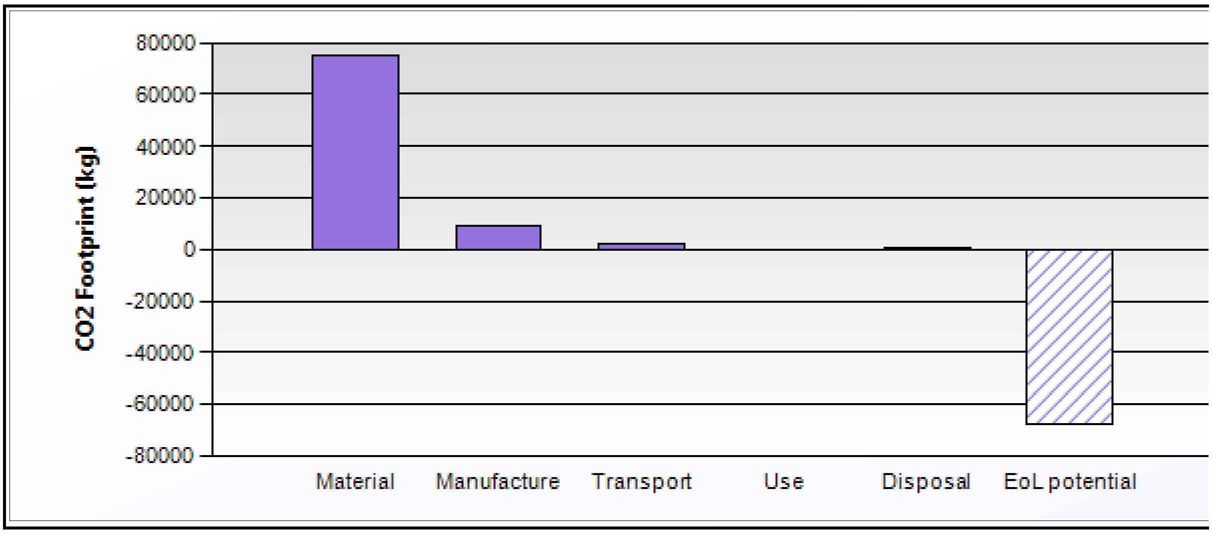
Eco Audit Report

Product Name	Foot Bridge
Product Life (years)	50

Energy and CO2 Footprint Summary:





Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	1.11e+06	88.0	7.54e+04	87.1
Manufacture	1.17e+05	9.3	8.76e+03	10.1
Transport	2.62e+04	2.1	1.86e+03	2.1
Use	0	0.0	0	0.0
Disposal	8e+03	0.6	560	0.6
Total (for first life)	**1.26e+06**	**100**	**8.66e+04**	**100**
End of life potential	-1e+06		-6.8e+04	

Eco Audit Report

Energy Analysis

Energy and CO2 Summary

	Energy (MJ)/year
Equivalent annual environmental burden (averaged over 50 year product life):	2.5e+04

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	Energy (MJ)	%
Foot Bridge	Low alloy steel	Virgin (0%)	3.5e+04	1	3.5e+04	1.1e+06	95.3
Deck	Wood, typical along grain	Virgin (0%)	5e+03	1	5e+03	5.2e+04	4.7
Total				**2**	**4e+04**	**1.1e+06**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	Energy (MJ)	%
Foot Bridge	Rough rolling, forging	3.5e+04 kg	1.2e+05	100.0
Total			**1.2e+05**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage

Total product mass = 4e+04 kg

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Footbridge	32 tonne truck	5e+02	9.2e+03	35.1
Deck	14 tonne truck	5e+02	1.7e+04	64.9
Total		**1e+03**	**2.6e+04**	**100**

Breakdown by components

Component	Component mass (kg)	Energy (MJ)	%
Foot Bridge	3.5e+04	2.3e+04	87.5
Deck	5e+03	3.3e+03	12.5
Total	**4e+04**	**2.6e+04**	**100**

Use:

Energy and CO2 Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Energy and CO2 Summary

Component	End of life option	Energy (MJ)	%
Foot Bridge	Re-manufacture	7e+03	87.5
Deck	Reuse	1e+03	12.5
Total		**8e+03**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Foot Bridge	Re-manufacture	-9.5e+05	94.8
Deck	Reuse	-5.2e+04	5.2
Total		**-1e+06**	**100**

Notes:

Energy and CO2 Summary

Eco Audit Report

CO2 Footprint Analysis

Energy and CO2 Summary

	CO2 (kg)/year
Equivalent annual environmental burden (averaged over 50 year product life):	1.73e+03

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	CO2 footprint (kg)	%
Foot Bridge	Low alloy steel	Virgin (0%)	3.5e+04	1	3.5e+04	7.1e+04	94.1
Deck	Wood, typical along grain	Virgin (0%)	5e+03	1	5e+03	4.4e+03	5.9
Total				**2**	**4e+04**	**7.5e+04**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Foot Bridge	Rough rolling, forging	3.5e+04 kg	8.8e+03	100.0
Total			**8.8e+03**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 4e+04 kg

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Footbridge	32 tonne truck	5e+02	6.5e+02	35.1
Deck	14 tonne truck	5e+02	1.2e+03	64.9
Total		**1e+03**	**1.9e+03**	**100**

Breakdown by components

Component	Component mass (kg)	CO2 footprint (kg)	%
Foot Bridge	3.5e+04	1.6e+03	87.5
Deck	5e+03	2.3e+02	12.5
Total	**4e+04**	**1.9e+03**	**100**

Use:

Energy and CO2 Summary

Relative contribution of static and mobile modes

Mode	**CO2 footprint (kg)**	**%**
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Energy and CO2 Summary

Component	**End of life option**	**CO2 footprint (kg)**	**%**
Foot Bridge	Re-manufacture	4.9e+02	87.5
Deck	Reuse	70	12.5
Total		**5.6e+02**	**100**

EoL potential:

Component	**End of life option**	**CO2 footprint (kg)**	**%**
Foot Bridge	Re-manufacture	-6.4e+04	93.5
Deck	Reuse	-4.4e+03	6.5
Total		**-6.8e+04**	**100**

Notes:

Energy and CO2 Summary

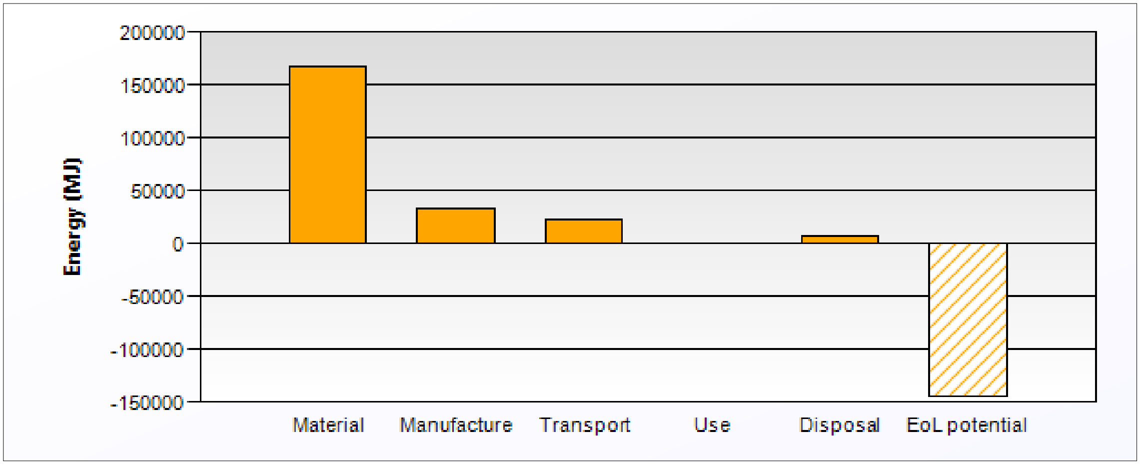
Appendix 5A1 Eco Audit Report Flywheel Rotor

Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)

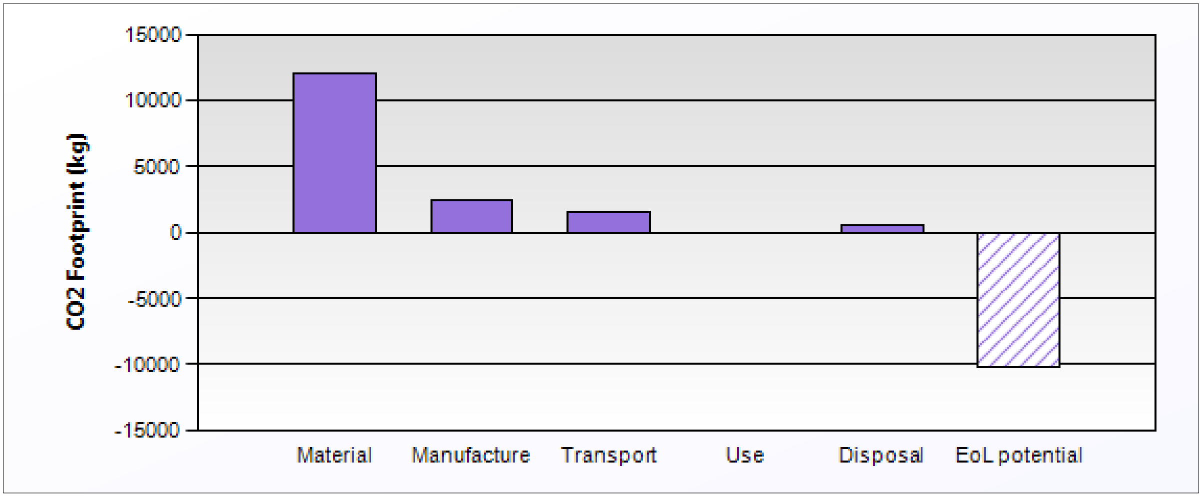
Eco Audit Report

Product Name	Product
Product Life (years)	1

Energy and CO2 Footprint Summary:



Energy Details...



CO2 Details...

Material	1.68e+05	72.4	1.21e+04	72.2
Manufacture	3.28e+04	14.2	2.46e+03	14.7
Transport	2.28e+04	9.8	1.62e+03	9.7
Use	0	0.0	0	0.0
Disposal	8.2e+03	3.5	574	3.4
Total (for first life)	**2.31e+05**	**100**	**1.68e+04**	**100**
End of life potential	-1.44e+05		-1.03e+04	

Eco Audit Report

Energy Analysis

Energy and CO2 Summary

	Energy (MJ)/year
Equivalent annual environmental burden (averaged over 1 year product life):	2.24e+05

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	Energy (MJ)	%
casing	Low carbon steel	Typical %	4.3e+03	1	4.3e+03	7.9e+04	47.2
rotor	High carbon steel	Typical %	1.6e+03	2	3.2e+03	5.9e+04	35.4
base	Concrete	Virgin (0%)	8.5e+03	3	2.6e+04	2.9e+04	17.4
Total				**6**	**3.3e+04**	**1.7e+05**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	Energy (MJ)	%
casing	Rough rolling, forging	4.3e+03 kg	1.2e+04	35.5
rotor	Extrusion, foil rolling	3.2e+03 kg	2.1e+04	64.5
Total			**3.3e+04**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 3.3e+04 kg

Stage name	Transport type	Distance (km)	Energy (MJ)	%
casing	32 tonne truck	5e+02	7.6e+03	33.3
rotor	32 tonne truck	5e+02	7.6e+03	33.3
base	32 tonne truck	5e+02	7.6e+03	33.3
Total		**1.5e+03**	**2.3e+04**	**100**

Breakdown by components

Component	Component mass (kg)	Energy (MJ)	%
casing	4.3e+03	3e+03	13.1
rotor	3.2e+03	2.2e+03	9.7

base	2.6e+04	1.8e+04	77.2
Total	**3.3e+04**	**2.3e+04**	**100**

Use:

Energy and CO2 Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Energy and CO2 Summary

Component	End of life option	Energy (MJ)	%
casing	Reuse	8.6e+02	10.5
rotor	Recycle	2.2e+03	27.3
base	Reuse	5.1e+03	62.2
Total		**8.2e+03**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
casing	Reuse	-7.9e+04	55.0
rotor	Recycle	-3.6e+04	24.8
base	Reuse	-2.9e+04	20.2
Total		**-1.4e+05**	**100**

Notes:

Energy and CO2 Summary

Eco Audit Report

CO2 Footprint Analysis

Energy and CO2 Summary

	CO2 (kg)/year
Equivalent annual environmental burden (averaged over 1 year product life):	1.68e+04

Detailed breakdown of individual life phases

Material:

Energy and CO2 Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass	CO2 footprint (kg)	%
casing	Low carbon steel	Typical %	4.3e+03	1	4.3e+03	5.6e+03	46.0
rotor	High carbon steel	Typical %	1.6e+03	2	3.2e+03	4.1e+03	34.0
base	Concrete	Virgin (0%)	8.5e+03	3	2.6e+04	2.4e+03	20.0
Total				**6**	**3.3e+04**	**1.2e+04**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Energy and CO2 Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
casing	Rough rolling, forging	4.3e+03 kg	8.7e+02	35.5
rotor	Extrusion, foil rolling	3.2e+03 kg	1.6e+03	64.5
Total			**2.5e+03**	**100**

Transport:

Energy and CO2 Summary

Breakdown by transport stage Total product mass = 3.3e+04 kg

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
casing	32 tonne truck	5e+02	5.4e+02	33.3
rotor	32 tonne truck	5e+02	5.4e+02	33.3
base	32 tonne truck	5e+02	5.4e+02	33.3
Total		**1.5e+03**	**1.6e+03**	**100**

Breakdown by components

Component	Component mass (kg)	CO2 footprint (kg)	%
casing	4.3e+03	2.1e+02	13.1

rotor	3.2e+03	1.6e+02	9.7
base	2.6e+04	1.2e+03	77.2
Total	**3.3e+04**	**1.6e+03**	**100**

Use:

Energy and CO2 Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Energy and CO2 Summary

Component	End of life option	CO2 footprint (kg)	%
casing	Reuse	60	10.5
rotor	Recycle	1.6e+02	27.3
base	Reuse	3.6e+02	62.2
Total		**5.7e+02**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
casing	Reuse	-5.6e+03	54.3
rotor	Recycle	-2.3e+03	22.1
base	Reuse	-2.4e+03	23.6
Total		**-1e+04**	**100**

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