The Sustainable Engineering Design Model: Necessity or Luxury

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Abstract

Sustainability in the field of the design of the built environment has been successfully applied for thousands of years, where materials have been reused and recycled. More recently there has been a great emphasis on sustainability in the field of geographic sciences.

Engineering design is a vast subject covering an enormous range of disciplines, but sustainability issues have rarely been applied to engineering design.

This paper outlines the normally accepted general design model and proposes a model for sustainability as applied to mechanical engineering design. Issues such as sustainable sourcing of materials, ecological design approach, sustainable use of new equipment and sustainable decommissioning using the 4r approach are all explored.

Taguchi proposed that the quality of engineering products could be defined at the design stage rather than at the manufacturing stage. The same is true of the application of sustainability where engineering designers should instigate sustainable engineering in new designs. Furthermore, correctly applied sustainable design techniques will reduce costs and improve the Triple Bottom Line.

The model proposes that mechanical engineering designers apply sustainable design techniques (4R's) to new equipment design. The 4R approach is outlined as follows:

Reduce: Designing products that reduce consumption by utilising resources efficiently, both inherently and in terms of energy utilisation is the single easiest way to reduce business costs as well as one of the best means by which to improve ecological credibility.

Reuse: The manufacturing of goods is hugely resource intensive. Designing products that have extended life spans, are upgradable or refurbishable allows for the optimum use of resources.

Sustainability Past and Present

It seems that sustainability can be considered to be a "hot air" subject. There is much written but results seem to be somewhat lacking. There are, however, some individuals as well as organisations that have embraced sustainability for many years and are very successful. There is much work to do to educate and empower the majority of people and organisations into adopting practical mechanical engineering sustainability.

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. Plates 1 and 2 below show the reuse of building materials applied to the Citadel Walls in Ankara, Turkey. This can perhaps be described as an over enthusiastic reuse of building materials.

Pates 1 and 2: Examples of the Reuse of building Materials in the Citadel Walls, Ankara, Turkey

The Geophysical environment has also been active in the application of sustainability projects. Beach groynes are an excellent example of sustainability of coastline. Plate 3 shows beach groynes in place in Bournemouth, UK. 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.

Plate 3: Beach Groynes, Bournmouth UK

There are some excellent examples of sustainability in Mechanical Engineering, however it could be argued that not enough is being done since most of the sustainability focus is applied to recycling.

Classic Engineering Design and Manufacture Model

The classic engineering design model has a natural extension of manufacturing, component use and eventual disposal. This model has been used for thousands of years and though some elements of sustainability have been practiced, the mind set and pressure on many modern engineers is to design the job so that it can be manufactured to a low cost. See Figure 1.

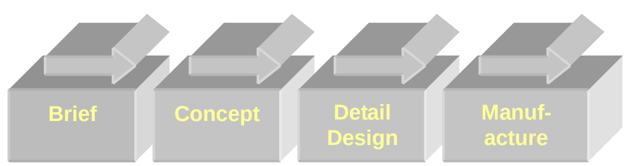


Figure 1: Classic Design and Manufacture Model

Sustainability in Mechanical Engineering has been practiced in some forms for years but it could be argued in a limited sense. Recycling of steel is well practiced as is the recycling of plastics. Steel recycling in the US, figure 2, has reached some dizzying heights reaching recycling rates 103% of output in 2009 [2], though averages are nearer 80%.

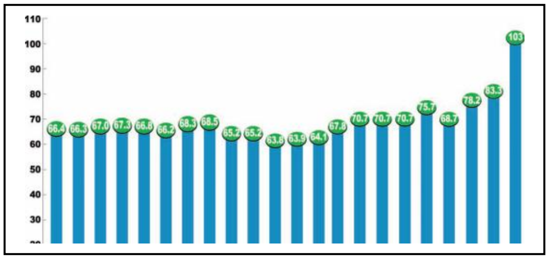


Figure 2: Overall Steel Recycling Rate (Steel Recycling Institute)

Vehicle manufacturers normally aim for 90% recycling of 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 output in 2009, with averages close to 100% [2].

Vehicle manufacturers have also been attempting to design and manufacture the sustainable use of vehicles by optimising new designs to reduce mass, thereby reducing fuel consumption.

Power plants have also been the target of Design Engineers' creativity in the development of leaner internal combustion engines and more specifically the development of hydrogen engines and electrically driven vehicles.

In terms of sustainable mechanical engineering the question has to be asked, "Is this enough?" It is a fact that engineers are still stripping resources from the earth at an alarming rate. Worldwide steel production is around 127.5 million Tonnes [5] with only around 70million tonnes being recycled. Steel however is the world's most recycled commodity. If Design and Manufacture Engineers are to have a conscience the answer must be "We can do more!"

Many global companies have sustainable policies in place but each has its own approach and its own agenda. There is a great need for a cohesive and coherent approach so that all designers can work towards similar goals and have a significant effect.

Taguchi, a manufacturing and statistical engineer whose most significant work was publicised in the 1950's and 1960's expounded theories relating to the quality of manufactured goods. He noticed that the quality of manufactured goods was usually left to the manufacturing craftsmen to achieve. Taguchi suggested that quality could be designed-in before components were manufactured. He also recognised that to achieve designed-in quality the mind set of the designers had to be changed.

Similarly the Smallpiece Trust, set up in the 1960s aimed to change the mind-set of designers to embrace simplicity of design and efficiency of materials usage.

As designers were eventually made more aware of the "new" design method, manufactured goods became more available at a lower cost and higher quality. Engineering designers had created better components by introducing standards, tolerances, machine tools, which lead to high production methods.

The Taguchi analogy can be applied to Sustainable Engineering Design (SED). Sustainability has to begin with the designer who creates the products. It is he who is the key and who must envisage and design components using sustainable techniques, equipment and methods.

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

The Engineering Design Process can no longer be related purely to cost benefits. The Engineering Design process must now accommodate cost and sustainability.

It is proposed to offer a new design and manufacture model that combines the original model with sustainable issues.

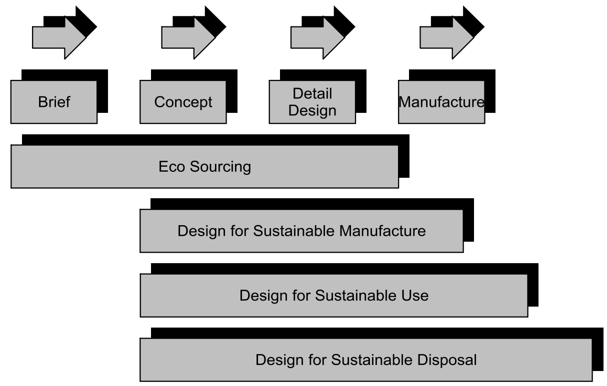


Figure 3: Sustainable Engineering Design Model

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 become sustainability. Within the engineering design environment the emphasis on pollution has now evolved into a fairly detailed approach under the new label of Sustainability. This now encompasses the whole process from sourcing to disposal.

Sustainable Sourcing (Eco Sourcing)

Transportation: It is inevitable that 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. It should be remembered that the environmental impact of producing these goods is roughly similar in the Pacific Rim as it would be in the west. The real impact on the planet's resources is in the burning of fossil fuels used in the energy generated 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.

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 this transport be arranged in a sustainable way?" Sailing ships could be employed or perhaps modern sailing versions that used the natural elements for propulsion. This is no pipe dream. Examples such as the MV Beluga (see fig 4 below) 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* [7] we can reduce energy by 50% on a good day, giving at least 15% annual fuel savings."

Flettner rotors [8], rotating sails, have also been fitted to freighters with some success.

Figure 4: Skysails MV "Beluga"

Courtesy of Skysails

Similarly, Eco Marine Power [9] are already designing solar powered craft from small ferries to freighters. Figure 5 shows Eco Marine Power solar ferry "Medaka". Critics may scoff at using sail or solar power for freight but what would we use if there were no more fossil fuels?

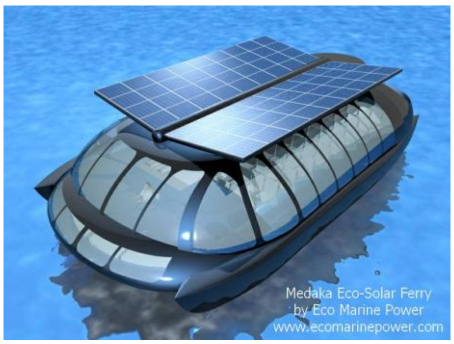


Figure 5: Solar Power Ferry "Medaka"

Courtesy of Eco Marine Power

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

Techniques are now being developed which create 3D components using laser fused metal powders. This technique effectively reduces time to manufacture and reduces transport costs and environmental impact to almost zero since the component can be formed with no waste at the assembly plant.

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 cost of the raw material. This may seem a tall order but the system already exists in the form of managed exotic timber, which carries a certificate of authenticity of sustainable sourcing. With such a system in place designers could select a material according to its sustainable impact.

Material flow systems – open and closed loop: This concept, introduced in the 1990s is now being embraced by, amongst others, the EU. Joke Schauvlike, [11] President of the EU Environmental Council is of the opinion that "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" [12].

Taking the matter further, we can see that the present linear materials flow systems model, figure 6 is not sustainable over the longer term as manufacturers take no account of the issues of raw material extraction and transport discussed above, nor of the end-of-life issues once the product is no longer usable or obsolete.

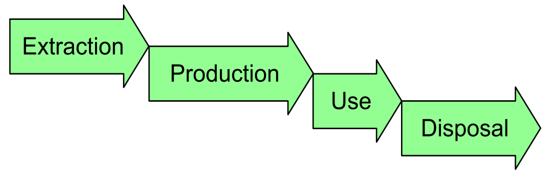


Figure 6: Linear Flow Systems Model

In the closed-loop flow system model, figure 7, 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 techniques.

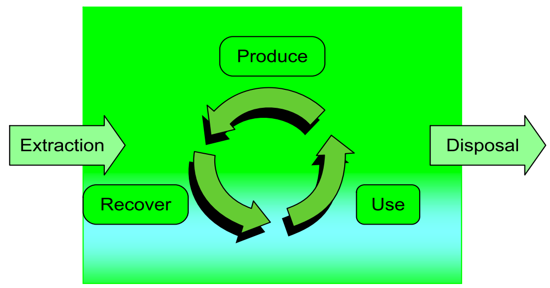


Figure 7: Closed Loop Flow Systems Model

Recycle, refurbish, re-use: Re-used and refurbished products and materials use even less energy in restoration. Designing machinery and equipment such that it can be repaired and refurbished became less common as companies sought to save cost by reducing the labour content and by moving production to cheaper labour sources. In line with the thinking of Stahel of the Product Life Institute in Geneva, It is our contention that legislation, lobby pressure and tax-based initiatives will drive a 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 explores how moving from disposable products to service delivery could lead to restructuring of a post-industrial economy. Energy use would partly be substituted by labour, mainly skilled labour, as re-engineering substitutes for primary material demand. 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 more localisation of economic activity under the maxim "Do not repair what is not broken, do not remanufacture something that can be repaired, do not recycle a product that can be remanufactured"

Reduce: This is perhaps the oldest of the sustainable design techniques. By optimising design, the use of materials and hence the energy associated with transportation etc. can be reduced. This has been seen particularly in packaging improvements, where a revised approach can improve the material usage efficiency without compromising on product life, safety or security

Designers Duty; It is the duty of the designer to source materials from sustainable sources or at least from sources which have a reduced impact on the planets resources. This emphasis would reduce the Sustainable Source Value (SSV)

Design for Sustainable Manufacture

The designer or design team is the entity who selects the manufacturing process. He can chose processes, techniques and materials. The formation of components has for centuries 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 defines the shape with much less waste, but even this process requires a great deal of energy to produce molten material and then machine to final size. Sometimes the energy expensive process cannot be avoided but the designer should fix his gaze on reducing energy and material waste. Focus should also be directed towards the selection of materials that can be processed easily and select processes that are not energy hungry.

Sustainable manufacture may not always be focussed at the component. Factories can improve their energy usage. 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) These achievements were implemented by the Brandix Group in Sri Lanka [10] who converted their thirty year old factory to meet “green” factory standards. Brandix achieved 80% carbon emissions reduction and 46% energy reduction.

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.

Design for Sustainable Use

For certain classes of machinery and equipment, this is arguably the element in a product’s life which has the most impact on sustainability.

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. JCB, 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. At the CEA conference 2011, Ms Hendricks clearly indicated that design for sustainable usage and extended product life cycle was the key challenge facing the industry as it developed new products.

Similarly, Emerging technologies have allowed radical improvements in electric car charging, reducing the use of low-efficiency internal combustion engines at least for short journeys.

Designers have to take responsibility for the impact of their equipment on the environment. The complete non-use of fossil fuel power may not be practically achieved but it may be significantly reduced. This can be done in several ways:

Design Optimisation: One optimised aspect of vehicle design is that of reduced weight. Structures are optimised for strength; buildings are optimised to accommodate earthquake oscillations. Optimisation can also be applied to sustainable use in selecting appropriate power systems and methodology in use that improves the Sustainable Use Value (SUV).

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 (PV panels) on the roof. Vehicles could also be fitted with PV panels and make use of the air they disturb in travelling by incorporating micro wind generators.

Reduce energy usage: There are many options here. A few are listed: Design equipment which is lighter in weight, apply smaller power units, specify leaner power units, use energy from renewable power sources, insulate against heat loss.

Use of natural energy: Power is the driver for any usage process. It makes sense to use naturally generated power and low energy solutions where possible. It is the designer’s role to select the lowest energy option and to design that option in to the 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, whist still in their infancy, have a zero impact on the environment.

Energy Storage: No matter how clever the application it is inevitable that there will always be “take” from the environment. Devices have to be built therefore which have the capacity or 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 in use, though their manufacture and eventual disposal can take a heavy toll on natural resources.

An alternative to chemical storage is the use of of Kinetic Energy Storage Devices. 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 resource. Other systems can be low tech, made to normal engineering principles, which demand fewer resources from the environment for manufacture A version of the low-tech device is currently being developed at the University of Huddersfield in conjunction with ESP Ltd.

Whichever method is adopted the resources used in its manufacture are given back during the use of the device. These storage devices are able to accommodate energy when there is low demand and introduce it back to the grid when there is high demand. This evens out the electricity demand and reduces the necessity to generate electricity on demand, thus reducing resources required for generation.

In a 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, the requirement for power stations would be reduced.

The emerging technology of electrically powered vehicles requires not only infrastructure but also a quick means of recharging. A bank of flywheels in strategic locations would provide that means, perhaps domestically or whilst parked at the 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 life of the device.

Design for Sustainable Disposal

The designer is the creator of the product and has the power to create a sustainably friendly disposal technique. The designers mind set is always to reduce cost and should now refocus slightly into 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:

Recycling and re-use: 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 gleaned from several other sources. Perhaps the most obvious source is from recycled materials.

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 [6] that up to 90% of discarded items and products can be recycled or reused. Materials gleaned from recycling processes are less costly and use less energy than the original source material.

Refurbish / Repair: 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 plastics became the popular use for toys, kitchen implements, garden tools, household devices and many other products. These were normally "snap-together" and were almost impossible to dismantle without breaking the product and hence difficult to repair. It was the beginning of the "throw-away society." The mind set of throw away and buy another has to some extent started to turn towards refurbish and re-use.

Refurbishment means that products are not thrown away but restored so that the product's life can be extended. The current recession has focussed companies into refurbishing components rather than buying new. The civil engineering industry in the UK has been hit hard by the recent recession which means fewer building projects and fewer purchases of new items of plant and ancillary equipment.

A West Yorkshire manufacturer of brick and block crane attachments has found a lucrative market in refurbishing equipment and supplying spares as the new-equipment market has evaporated. Figure 8 shows a typical brick /block crane attachment. This is a product which 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 resources than a new product. This is an excellent example of extended life giving a very low Sustainable Disposal Value (SDV)

Figure 8: Brick/Block Clamp

Courtesy of HE&A Ltd

An excellent example of repair is that of motorcycles used in India and Pakistan. In these countries the favoured individual transport is the 70cc or 100cc motorcycle shown in figure 9.

Figure 9: 70cc Motorcycle

Here the designers have taken the initiative and designed a vehicle with a low resource impact value. These motorcycles are designed to have simple parts, be low cost, easy to repair and have a relatively low impact on resources when manufactured and also in use. They can be refurbished as long as parts are available. This is an excellent example of low SUV.

Give-back

No matter how products are re-used, refurbished or recycled or how clever the usage impact is reduced the plain fact is that the usage of resources is being merely being slowed. There will always have to be some form of "take" from the earth's resources.

Give-Back is a technique where designers actually build devices which give back to the environment or perhaps design give back components in to current products.

Solar power panels on car roofs, 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 give discount to the liquid fuel or the recharging of the vehicle. In another application solar panels could be incorporated on the roof of new buildings.

Imagine the energy generation possibilities that solar panels would make if introduced on the millions of homes in the UK. The power generation would be enormous and reduce the reliance on power stations.

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 is being developed shown in figure 10. These Kinetic Energy Storage Devices 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 low Sustainable Give Back Value (SGBV)

Figure 10: Idealised Flywheel Battery 20KWh Storage

An excellent example of Sustainable Give Back Value (SGBV) is the World Trade Centre Building in Bahrain, figure 11. This building incorporates wind generators. The building rises 240m. The shape of the towers is designed to funnel the wind on to the wind turbines generating 675KW in total which is up to 15% of the total power consumption of the building.

Figure 11: Bahrain World Trade Centre with Wind Turbines

General Overview Tool Requirement.

Carbon dioxide is always painted as the ogre of greenhouse gases, but it is not the largest constituent. The proportions of the main greenhouse gases are as follows [4]:

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

It can be seen that moisture 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 is certainly a large proportion of the whole of greenhouse gases perhaps the question should be asked “why is carbon dioxide used as an environmental yardstick?” The focus on carbon dioxide cannot be considered as wrong since it is a useful tool but it does not really cover the whole picture

When reviewing the sustainable design options it is clear that the conversion of materials into products uses energy. One of the by-products of the energy usage is carbon dioxide however **energy usage** is a much clearer indicator of resource usage and is a much better indicator of the environmental impact.

Energy is used in one form or another to extract raw materials, convert them in to products, drive them during their useful life and dispose of them at the end of their life.

It is therefore proposed that each element of the sourcing-conversion-use-disposal process is given a Sustainable Value. These elements are mentioned above and can now be assembled in to a tool by which designers and environmentalists can judge the sustainable impact of a product. The definitions are listed below:

SSV: Sustainable Source Value

SMV: Sustainable Manufacturing Value

SUV: Sustainable Use Value

SDV: Sustainable Disposal Value

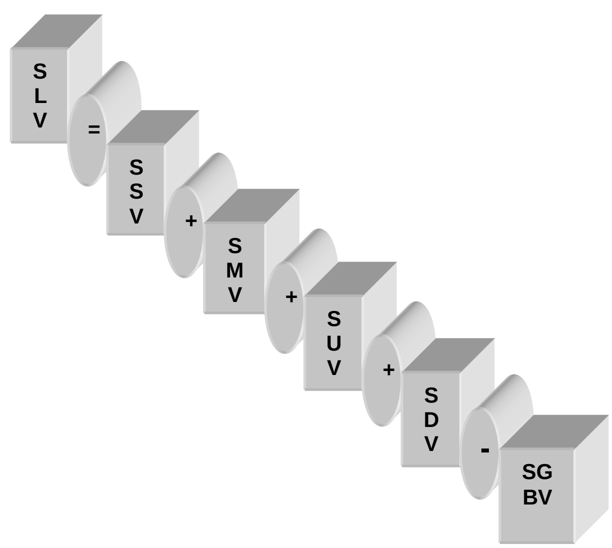
SGBV: Sustainable Give-Back Value

These indicator values should be kept as low as possible since the lower the value, the lower the impact on the earth’s resources.

These values combined below give the overall sustainable impact tool or “Sustainable Life Value” or SLV.

SLV is derived from the addition of SSV, SMV, SUV and SDV and is a measure of the resource impact during the life of a product.

SGBV is a measure of how much resource is returned and can therefore be deducted from the resource impact (sustainable Life Value: SLV) as the model shows in figure 12.



Conclusions

In this world-wide consumer society it is inevitable that products will be produced used and disposed of, but every product reduces the earth's resources. Perhaps this process cannot be prevented, but it can be slowed substantially.

The task falls to our Engineering Designers and Engineering Design teams to instigate a change in attitude and approach towards Sustainable Engineering Design. As in the Taguchi model for quality engineering it can only be the designer who can instigate the shift in attitude and the change in design practice. Design is the key to Sustainable Engineering

The model outlined above reduces transport distances reduces manufacturing resources reuses, recycles and repairs goods. Adopting these elements will lead to a localised economy model reducing financial costs and providing local, specialist employment.

It can also be seen that an element of "Give-Back" will help to reduce the impact of a product by reducing the Sustainable Life Value (SLV) and that the implementation of give-back technologies such as flywheel batteries can greatly offset the impact products may have on earth's resources.

The use of carbon foot printing is useful but is viewed as a commercial tool only and does not embrace the whole life cycle of the product from sourcing to disposal. It is proposed that a much more useful and accurate measurement is energy usage since this is involved at every stage of the products life.

The introduction of a measurement tool, Sustainable Life Value (SLV) is a great step forward in the measurement of resource impact. There is some work yet to accomplish to ensure this measurement tool becomes viable.

Sustainable Engineering Design: Necessity or Luxury

The earth's resources are dwindling at a heavy rate and over the last 30 years in particular there has been much debate and suggestion as to how the use of resources could be reduced. A few lone practitioners began to act, but still the extravagance continued. Recent years has seen increased climate change and a greater thrust towards sustainability. Recently The Institution of Mechanical Engineers has urged its members and partner institutions to adopt a sustainable approach. The initiative has begun to focus the minds of Mechanical Engineers and initiated action. Many Global Companies are developing their own strategy but there is a great need for a cohesive and coherent approach so that all designers can work towards similar goals and have a significant effect. It is the proposal of this paper to propose a complete model from sustainable sourcing to sustainable disposal and further suggest a much needed measurement method, that of Sustainable Life Value.

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