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TOTAL LIFE-CYCLE CONSIDERATIONS IN PRODUCT DESIGN FOR SUSTAINABILITY: A FRAMEWORK FOR COMPREHENSIVE EVALUATION

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ABSTRACT
This paper presents a new framework for comprehensively evaluating the sustainability content of a product through Product Sustainability Index (PSI) in terms of all three components of sustainability (economy, environment and society) over its total life-cycle (pre-manufacturing, manufacturing, use, post-use). This method is useful in comparing various competitive products of the same family. This technique uses a visual representation of PSI to give an overview of the product's inherent and built-in sustainability levels in a simple and effective manner.
Keywords: Product Sustainability Index (PSI), total life-cycle, sustainability evaluation

1. INTRODUCTION
Traditional product design and manufacturing methods are based on a range of product characteristics such as functionality, performance, cost, time-to-market, etc. Product design and manufacture in the 21st century will require a greater integration of life-cycle data, sustainable product/process designs and their implementation in the manufacture of innovative engineered products. This will apply to industrial and consumer products, both in high volumes and small varieties, and in low volumes and large varieties. In particular, the design and manufacturing practices for next-generation of manufactured products need to undergo major changes from traditional approaches to include concerns that span the entirety of the traditional life-cycle, and ultimately from the perspective of multiple life-cycles toward a (near) perpetual product/material life. Novel design methodologies and innovative manufacturing techniques must be developed to simultaneously address traditional characteristics and life-cycle issues including the following major objectives:

- Reduction of manufacturing costs
- Reduction of product development time
- Reduction of material use
- Reduction of energy consumption
- Increased operational safety
- Enhanced societal benefits
- Reduction of industrial waste
- Repair, reuse, recovery and recycling of used products/materials
- Consideration of environmental concerns
- Education and training of workforce
- Increased product and process innovation

This paradigm shift in product design and manufacture necessitates optimized methodologies incorporating environmentally conscious, energy-efficient and lean product design and manufacturing methods for sustainability with product maintenance, disassembly, material recovery, re-use, re-manufacturing and recycling considerations. It promotes a systems thinking in the design of new products and processes and calls for attention to the interests of all stakeholders in our living environment. It requires devising new design methodologies, manufacturing processes, post-use processes, and enterprise resource planning for simultaneously achieving the multiple objectives including company's profitability, bringing new products to market rapidly, conserving natural resources with environmental concerns.

Sustainability studies in general have so far been focused on environmental, societal and economical aspects including public health, welfare and environment over their full commercial cycle, defined as the period from the extraction of raw materials to final disposition [1]. Sustainable products are generally defined as those products providing environmental, societal and economical benefits while protecting public health, welfare and environment over their full commercial cycle, from the extraction of raw materials to final disposition, providing for the needs of future generations. It is also generally known that sustainable products are fully compatible with nature throughout their entire life-cycle [2]. Traditionally, the economic and environmental analyses performed for products impacting the society are almost entirely developed for a single life-cycle of a product. Aspects such as material recovery along with possible multiple reuse opportunities that are themselves associated with economic gains, and societal and environmental benefits are hardly evaluated in current manufacturing practice.

The idea of recycling, reuse and remanufacturing has in recent times emerged with sound, innovative and viable engineered materials, manufacturing processes and systems to provide multiple life-cycle products This is now becoming a reality in a range of application areas of product manufacture. The old concept of "from cradle to grave" is now transforming into "from cradle to cradle" [3], and this is a very powerful and growing concept in the manufacturing world which takes its natural course to mature. Added to this is the awareness and the need for eco-efficiency and the environmental concerns often associated with minimum toxic emissions into the air, soil and water; production of minimum amounts of useless waste; and minimum energy consumption at all levels.

In the past few years, researchers in the area of product and process sustainability have made attempts to develop methodologies to assess/evaluate the level of sustainability in various stages during the life of a product. This kind of assessment helps the manufacturer to identify non-sustainable elements inherently present during any stage of the product life-cycle. Previous research has produced qualitative results on product life-cycle which are mostly, with the exceptions of a few recent efforts [4-5], difficult to measure and quantify. Hence, these analyses are largely non-analytical and less scientific in terms of their perceived value of contributions. Moreover, product sustainability does not just cover a simplistic assessment of the environment as a contributing measure; it involves a comprehensive simultaneous assessment of the environmental, economic, and societal impact categories, which are all interrelated. These three major components of sustainability are interlinked and have some impact on every stage of the life-cycle of a product although the level of impact may vary between different stages.

Legislation is one of the main motivational drivers for sustainable products. Examples of well known legislative drivers include: (i) *Waste Electrical and Electronic Equipment* (WEEE) *Directive* [6], (ii) *Restriction of Hazardous Substances* (RoHS) *Directive* [7], (iii) *End-of-Life Vehicles* (ELVs) *Directive* [8], and (iv) *Energy Using Product* (EuP) *Directive* [9]. These legislative drivers place responsibility of the product's conformance to specified sustainability targets throughout its life-cycle squarely on producers, manufacturers, and importers. The other major motivational drivers for sustainable products are societal expectations and potential economic gains. In a recent work, two specific scenarios, one involving the "economy" as the driver and the other showing the "society" as the driver, both acting through "environment" are illustrated [10].

This keynote paper highlights the significance of product design for sustainability by focusing on the need for creating truly sustainable products to achieve societal, economic and environmental benefits. A new framework for comprehensive evaluation of product sustainability is developed and presented in this paper. This new methodology involves all four product life-cycle stages (pre-manufacturing, manufacturing, use and post-use), and covers all three components of sustainability (economy, environment and society), all integrated into a total ranking system to provide a composite sustainability score for a product.

2. TOTAL LIFE-CYCLE OF MANUFACTURED PRODUCTS – FOUR STAGES

Total life-cycle of a manufactured product consists of four key stages in a closed loop system: pre-manufacturing, manufacturing, use and post-use. These four stages are shown in Figure 1.

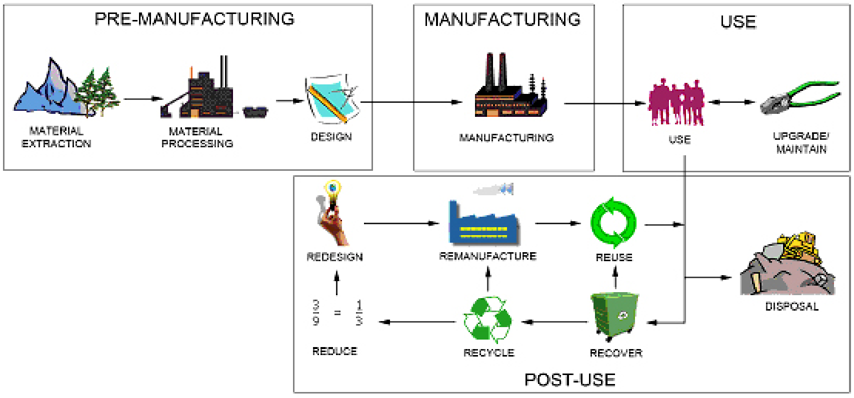

Figure 1. Closed loop product life-cycle system showing the "6Rs" for perpetual material flow.

Pre-manufacturing: The foremost stage in the life-cycle of any product is the extraction of material from their natural reserves. Raw material extraction is the process of excavating valuable virgin material from the layers of the earth's crust. These extracted virgin materials are then processed and consumed in the manufacture of the final product. Pre-manufacturing includes mining metal ores and smelting them into metal alloys, extraction of crude oil and processing it into hydrocarbons, cutting trees and transforming them into usable wood or paper, etc. This stage also involves packaging, storage and transportation of the processed/semi-processed products. Design for environment is also an integral part of this stage since it involves conceptual design, in terms of environment, functionality, use, safety, and various other aspects of the final product.

Manufacturing: Manufacturing is the phase where semi-processed materials are transformed into finished goods for sale. The processing techniques (machining, forming, rapid prototyping, casting, etc.) involved in this phase are quite diverse and are based on desirable performance characteristics needed to be incorporated into the final product. Assembly is an integral part of the manufacturing phase of a product life-cycle where manual or automated processing is used to join or integrate the various parts. Depending on the complexity of product design this phase may vary from a couple to a large number of steps. Product manufacture may involve – shaping metals into parts via molds or cutting tools, assembling components into a product, storing and transportation of final parts, etc. Product packaging and advertising are also generally considered to be a part of the manufacturing phase.

Use: The use phase of the product life-cycle pertains primarily to the amount of time the consumer owns and operates the product. During its use stage, the product needs to be energy-efficient, safe, reliable, easy to operate, maintain, service/repair, etc. The product should be upgradeable to compete with the newer models in order to last longer. The product becomes obsolete when one or several of its desirable features cease to fulfill the consumer needs.

Post-use: After its use, the product reaches its end-of-life, where it can no longer satisfy the consumer. Post-use also termed as end-of-life, is the final processing of a product for disposal, incineration, recycling, remanufacturing, or other end-of-life processing. The concept of '6R' can be effectively used in this stage to prolong the product life-cycle and also to ensure perpetual material flow.

2.1 The "6R" Concept

In considering the material flow in a sustainable product life-cycle, the "*3Rs*" [11], i.e., *Reduce*, *Reuse*, and *Recycle* have often been referred to as end-of-life processing strategies. However, a more comprehensive and complete depiction would include three other "*Rs*". These are *Recover*, *Redesign*, and *Remanufacture*.

Reduce involves activities that seek to simplify the current design of a given product to facilitate future post-use activities. Of all the end-of-life activities in the post-use stage, *Reuse* may potentially be the stage incurring the lowest environmental impact mainly because it usually involves comparatively fewer processes [12]. *Recycle* refers to activities that include shredding, smelting, and separating. *Recover* represents the activity of collecting end-of-life products for subsequent post-use activities. It also refers to the disassembly, and dismantling of specific components from a product at the end of its useful life. *Redesign* works in close conjunction with *Reduce* in that it involves redesigning the product in view of simplifying future post-use processes. *Remanufacture* is similar to manufacturing. However, the difference is that it is not conducted on the virgin material but on an already used product. The introduction of the "6R" concept into a product's life-cycle is aimed at reaching the condition of a *perpetual material flow*, resulting in a minimization of that product's ecological footprint [13, 14].

2.2 Closed Loop vs. Open Loop Life-cycle Systems

Figure 2 shows a closed loop, "cradle to cradle" product life-cycle system. Conversely, in an open loop, "cradle to grave" life-cycle system, products are consumed and disposed of at the end of their useful life. With this scenario, material resource, waste output, energy usage, and other system emissions, etc., are all primarily a function of consumer demand.

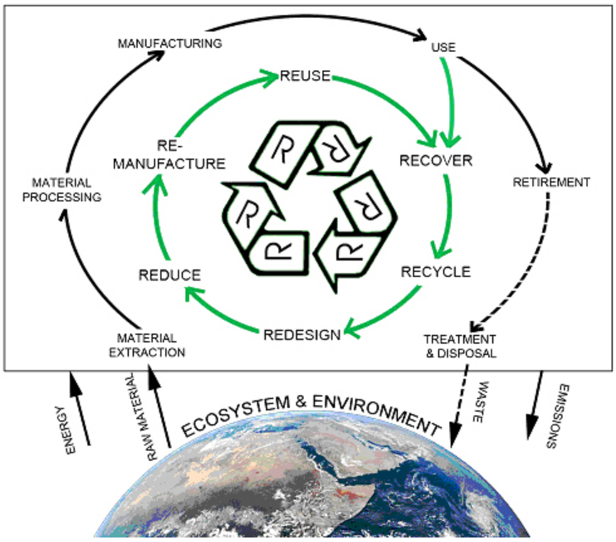

Figure 2. Closed loop product life-cycle system.

To make a shift towards the closed loop system, at least three criteria of sustainable product development must be met. These are: (a) minimization of material and energy resources needed to satisfy the product function and the consumer demand, (b) maximization of expended resources usage, and (c) minimization/elimination of adverse impacts of wastes and emissions. A closed loop product system as typified in Figure 2 must fulfill at least the first two criteria ((a) and (b)) [15]. In this type of product system, the activities of product reuse, remanufacture, and recycle circulates the material within the product system. These activities reduce the requirement for new material extraction to feed into the system, resulting in the reduction of the overall energy input requirement and emissions per unit of the product consumption.

It may be argued that such a closed loop system would not be beneficial, at least from the business standpoint, to product manufacturers. This is especially for the market situation today where discrete product sales is dominant and consumers continually demand new and varied products at the lowest possible cost. With such an approach, the value associated with the reduced energy and raw materials used are taken into account.

A paradigm shift towards "cradle to cradle" product development would persuade manufacturers to invest more in ways to promote efficient material use and reuse. With such an approach, the values, associated with the reduced energy and raw materials, used are taken into account. As a result, the "cradle to cradle" paradigm shift that considers the life-cycle stages of reuse, remanufacture, and recycle not only can work toward manufacturing a more sustainable product, but also would provide realizable economic gains [15].

3. PRODUCT DESIGN FOR SUSTAINABILITY: THE PRODUCT SUSTAINABILITY WHEEL

Six major product sustainability elements, each containing several sub-elements, have been identified. Relative influence of each element on the product sustainability can be established if an appropriate quantification method can be developed. Figure 3 shows the integral role of all six sustainability elements and their sub-elements in generic form with equal weighting placed for each of the six major elements. These interacting elements and sub-elements need to be fully studied for their effects on product sustainability. Other relevant influencing elements and their relevant sub-elements can be identified and added as needed. The educational challenges involved in developing a science-based understanding of product sustainability through structured educational programs are described in a recent paper [16].

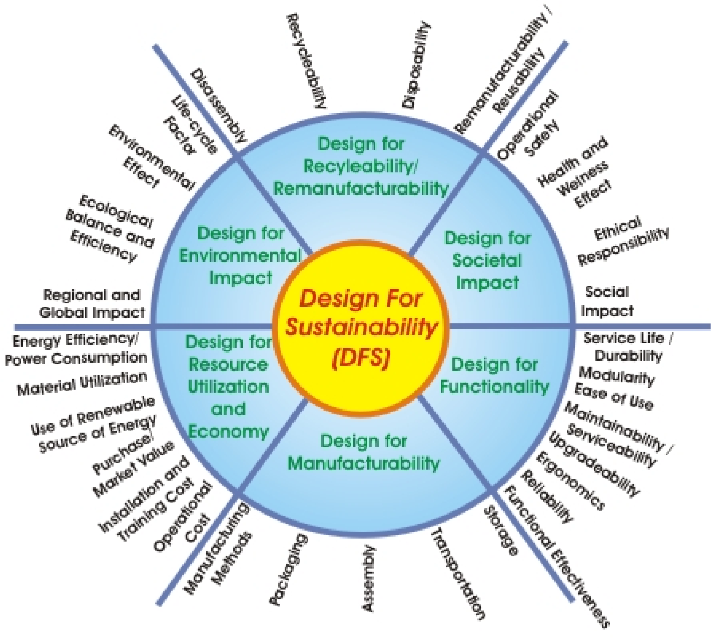

Figure 3. Basic elements and sub-elements of product design for sustainability.

4. ANALYTICAL FOUNDATION OF PRODUCT DESIGN FOR SUSTAINABILITY

This section presents a recently developed new methodology for measuring the product sustainability.

4.1 A New Methodology for the Evaluation of Product Sustainability over the Total Life-cycle

A new comprehensive evaluation methodology to assess the sustainability content of any given manufactured product, in terms of all three components of sustainability (economy, environment and society), over its total life-cycle (pre-manufacturing, manufacturing, use and post-use), is presented in this section. This rating system gives the 'Product Sustainability Index (PSI)' which is versatile enough to be applied to a wide range of products. This system will assist product developers and manufacturers in achieving their sustainability targets. The new procedure for evaluating the PSI is given below:

Step 1: The product developers need to identify potential influencing factors based on national/international regulations, federal and state laws, and also based on what they consider to be important from their own perspective. The product designers should not just focus on the economy component of sustainability, but also look broadly at numerous environmental and societal aspects as well. Similarly, to be effective, they should not just concentrate on the product pre-manufacturing and manufacturing stages, but also consider the product's use and post-use stages. After identifying the potential influencing factors, product developers can form a [3×4] dimensional matrix, with the three horizontal rows representing the components of sustainability – economy, environment and society, and the four vertical columns representing the four product life-cycle stages – pre-manufacturing, manufacturing, use and post-use.

Step 2: Product developers will have to conduct a detailed life-cycle assessment (LCA) of all influencing factors that they have identified in the previous step to obtain the absolute values of these factors to represent the anticipated sustainability levels. Once they have obtained these absolute values for the influencing factors, they can then allocate a score/rating between 0-10 for each factor (typically, with 0 being worst and 10 being best). Weighting can be applied to the influencing factors based on their relative importance and company priorities. Some of these factors can be non-quantifiable in which case the designer should assign a score based on his/her experience and judgment.

Step 3: The template for the PSI matrix is shown in Table 1. The product designers need to record the scores of the influencing factors in each box of the matrix. To evaluate the PSI, go across the matrix and sum up the scores of each influencing factors in each matrix box and calculate the percentage value using the equation (this equation represents the first box of the matrix) given below:

$$PSI_{(en\_pm)} = \{[\sum_{i=1}^{n} IF_{(en\_pm)_i}]/(n*10)\}*100\% \qquad \ldots(1)$$

where,

$PSI_{(en\_pm)}$ = Product Sustainability Index for Environment component of Pre-manufacturing stage

$IF_{(en\_pm)}$ = Influencing Factor rated on a scale of 0-10 for the Environment component of Pre-manufacturing stage

n = Number of influencing factors considered

The PSI values for Society ($PSI_{(so\_pm)}$) and Economy ($PSI_{(ec\_pm)}$) can be calculated similarly. The product sustainability index (PSI), for a single life-cycle stage, for instance pre-manufacturing, can be evaluated by vertically adding the PSI of sustainability components over that particular life-cycle stage, as shown in the equation below:

$$PSI_{pm} = [PSI_{(en\_pm)} + PSI_{(so\_pm)} + PSI_{(ec\_pm)}]/3 \qquad \ldots(2)$$

where,

PSI_{pm} = Product Sustainability Index for Pre-manufacturing stage

$PSI_{(en\_pm)}$ = Product Sustainability Index for Environment component of Pre-manufacturing

$PSI_{(so\_pm)}$ = Product Sustainability Index for Society component of Pre-manufacturing stage

$PSI_{(ec\_pm)}$ = Product Sustainability Index for Economy component of Pre-manufacturing stage

The PSI values for manufacturing (PSI_m), use (PSI_u) and post-use (PSI_{pu}) stages can be obtained similarly. The Product Sustainability Index (PSI) for the Environment component of Sustainability for all four stages of product life-cycle can be calculated by horizontal summation of Product Sustainability Indices of every stage of the product life-cycle as shown below:

$$PSI_{en} = [PSI_{(en\_pm)} + PSI_{(en\_m)} + PSI_{(en\_u)} + PSI_{(en\_pu)}]/4 \qquad \ldots(3)$$

where,

$PSI_{(en\_pm)}$	=	Product Sustainability Index for Environment component of Pre-manufacturing stage
$PSI_{(en\_m)}$	=	Product Sustainability Index for Environment component of Manufacturing stage
$PSI_{(en\_u)}$	=	Product Sustainability Index for Environment component of Use stage
$PSI_{(en\_pu)}$	=	Product Sustainability Index for Environment component of Post-use stage

Similarly, the PSI for Society (PSI_{so}) and Economy (PSI_{ec}) components can be obtained. The overall product sustainability index (PSI_{TLC}) for a product over its total life-cycle can be calculated as:

$$PSI_{TLC} = PSI_{so} + PSI_{en} + PSI_{ec} \quad \ldots(4)$$

The PSI scores can be interpreted as shown in Table 1.

Some of the influencing factors can be subjective and company-specific, in which case, the company can still use the PSI technique for self-assessment of its products to meet its internal sustainability goals. This technique will help the product designers and manufacturers to identify opportunities to improve the performance of their product over its total life-cycle. The visual representation of the influencing factors in terms of economy, environment and society components of sustainability for a generic product is shown in Figure 4. The three concentric circles represent the three components of sustainability (Economy, Environment, and Society). The influencing factors are listed on the periphery of the outer circle. A rating scale for each influencing factor that cuts through all three sustainability component circles with markings of 0-10 indicates the impact of that particular influencing factor for the three sustainability components. It is interesting to note that in this figure, each influencing factor is represented to have possible direct or indirect impact on all three sustainability components. For example, the *hazardous substance* content in an automobile can have a direct influence on the environment, whereas it can have an indirect impact on the society and the economy. Disposal of hazardous substances causes unwanted additional economic burdens on the manufacturer. Seepage of these substances that leads to environmental pollution and contamination also causes unwanted environmental and societal burdens. Decontamination procedures also place unwanted economic burdens on the manufacturer. This example shows an interrelationship between all three components of sustainability caused by a single influencing factor - *hazardous substance* in a product.

5. CONCLUSIONS

The new methodology presented in this paper provides a comprehensive evaluation of product sustainability covering all four stages of product life-cycle and it represents all three components of sustainability. This new technique will significantly assist product developers and manufacturers in evaluating the existing product in its entirety and will help to improve the future upgrades for existing product families in terms of economic, environment and society components of sustainability. This methodology needs a joint effort and commitment from legislators, product developers, manufacturers, researchers, etc. to standardize the scoring system and to subgroup the influencing factors that affect the product sustainability.

Table 1. A framework for a comprehensive total life-cycle evaluation matrix for product sustainability (using fictitious numbers).

Sustainability Components		Influencing Factors in the Product Life-cycle Stages									
		Pre-manufacturing	**Score out of 10**	**Manufacturing**	**Score out of 10**	**Use**	**Score out of 10**	**Post-use**	**Score out of 10**		
Sustainability Components	**Environment**	Material Extraction	7	Production Energy Used	7	Emissions	9	Recyclability	7	(%) PSI_{en} =	77.29
		Design for Environment	8	Hazardous Waste Produced	9	Functionality	8	Remanufacturability	8		
		Material Processing	6	Renewable Energy Used	8	Hazardous Waste Generated	9	Redesign	7		
								Landfill Contribution	7		
		(%) $PSI_{(en\_pm)}$ =	70	(%) $PSI_{(en\_m)}$ =	80	(%) $PSI_{(en\_u)}$ =	86.67	(%) $PSI_{(en\_pu)}$ =	72.5		
	Society	Worker Health	8	Work Ethics	7	Product Pricing	7	Take-back Options	7	(%) PSI_{so} =	73.54
		Work Safety	8	Ergonomics	7	Human Safety	9	Re-use	6		
		Ergonomics	7	Work Safety	8	Upgradeablility	7	Recovery	7		
						Complaints	8				
		(%) $PSI_{(so\_pm)}$ =	76.67	(%) $PSI_{(so\_m)}$ =	73.33	(%) $PSI_{(so\_u)}$ =	77.5	(%) $PSI_{(so\_pu)}$ =	66.67		
	Economy	Raw Material Cost	6	Production Cost	6	Maintenance Cost	7	Recycling Cost	7	(%) PSI_{ec} =	61.25
		Labor Cost	3	Packaging Cost	7	Repair Cost	6	Disassembly Cost	8		
				Energy Cost	8	Consumer Injury Cost	8	Disposal Cost	4		
				Transportation Cost	5	Consumer Warranty Cost	7	Remanufacturing Cost	7		
		(%) $PSI_{(ec\_pm)}$ =	45	(%) $PSI_{(ec\_m)}$ =	65	(%) $PSI_{(ec\_pu)}$ =	70	(%) $PSI_{(ec\_pu)}$ =	65		
		(%) PSI_{pm} =	63.89	**(%) PSI_{m}** =	72.78	**(%) PSI_{u}** =	78.06	**(%) PSI_{pu}** =	68.06	**(%) PSI_{TLC}** =	70.69

Note: The integrated PSI in the last column and row (denoted by PSI_{TLC}) shows the computed total sustainability index with equal weighing for all elements and sub-elements.

Visual representation of the PSI

Symbol				
Score	Excellent 85-90%	Good 70-84%	Average 50-69%	Poor < 50%

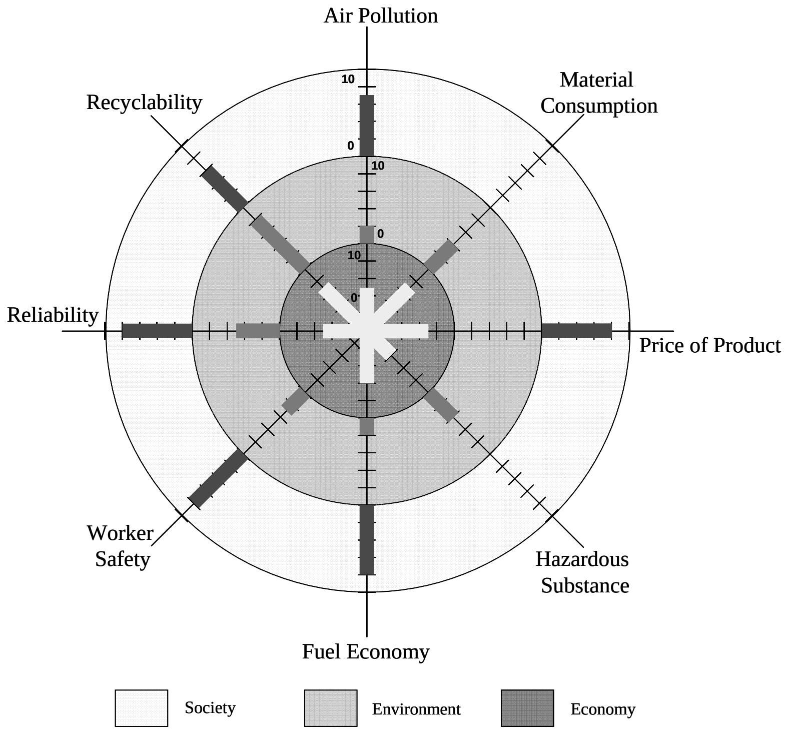

Figure 4. An example of a generic product sustainability score showing the influence of various factors on society, environment and economy and their sustainability ratings.

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