DESIGN FOR SUSTAINABILITY (D4S) IN PRODUCT DEVELOPMENT USING SOLIDWORKS SOFTWARE: A CASE STUDY OF REDESIGN A SUGAR CANE EXTRACTOR MACHINE

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A master project report submitted in
Fulfillment of the requirement for the award of the
Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
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JULY, 2014

ABSTRAK

Design for Sustainability (D4S) adalah kaedah diterima pakai untuk menghasilkan produk mampan yang merangkumi tiga elemen utama iaitu: alam sekitar, ekonomi dan sosial. Walau bagaimanapun, penekanan pada D4S adalah masih asing dikalangan industri di Malaysia. Objektif kajian ini adalah untuk mencadangkan senarai semak penilaian keatas D4S yang mesra pengguna yang berasaskan perisian SolidWorks dan seterusnya melaksanakan satu kajian kes menggunakan senarai semak tersebut. Pelaksanaan kajian ini dilakukan dengan membuat senarai semak D4S terlebih dahulu. Senarai semak ini mengandungi pemetaan antara unsur-unsur utama kemampanan dan perisian SolidWorks. Kajian kes D4S yang dipilih adalah merekabentuk semula Mesin Pemerah Tebu (SCEM) berdasarkan senarai semak yang telah dipetakan dengan perisian Solidworks. Keputusan kajian telah menunjukkan peningkatan di ketiga-tiga elemen utama kemampanan. Pada unsur alam sekitar, SCEM rekabentuk semula telah direka dengan kesan alam sekitar kurang daripada reka bentuk asal seperti yang berikut; *Carbon Footprint* 17.4%, *Total Energy Consumed* 19.0%, *Air Acidification* 16.2% dan *Water Eutrophication* 49.4%. Pada unsur ekonomi, SCEM rekabentuk semula yang telah direka dengan kos bahan mentah and pengeluaran yang lebih rendah berbanding reka bentuk asal berharga USD28.00 dan USD58.50 masing-masing. Pada unsur sosial, SCEM rekabentuk semula yang telah dilengkapi dengan penutup keselamatan tambahan di kawasan yang berisiko dan pemegang ergonomik untuk memudahkan aktiviti menolak, menarik dan mengangkat mesin pemerah tebu tersebut. Kesimpulannya, kajian D4S itu telah dilakukan berjaya dengan mempertimbangkan ke atas semua tiga elemen utama kemampanan.

ABSTRACT

The Design for Sustainability (D4S) is a recognized method to produce sustainable product that embrace three main elements: environment, economic and social. However, the emphasization on the D4S is immature among industries in Malaysia. The objectives of this study are to propose a user friendly D4S assessment checklist base on SolidWorks software features and to implement on a case study. Implementation of this study done by established a D4S assessment checklist. The checklist consists of mapping between the sustainability main elements and SolidWorks software. The D4S case study is redesign a Sugar Cane Extractor Machine based on the proposed assessment checklist using Solidworks software. The results of study have shown improvement on all three main elements of sustainability. On the environment element, the redesign SCEM has been designed with less environmental impact than original design as following; Carbon Footprint 17.4%, Total Energy Consumed 19.0%, Air Acidification 16.2% and Water Eutrophication 49.4%. On the economic element, the redesign SCEM has been designed less material and production cost than original design for USD28.00 and USD58.50 respectively. On the social element, the redesign SCEM has been equipped with extra safety cover at exposed area and ergonomics handles to ease pushing, pulling and lifting operation. In conclusion, the D4S study has been done successful with consideration on all three main sustainability.

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LIST OF SYMBOLS AND ABBREVIATION

PDS	-	Product design specification
PDP	-	Product development process
LCA	-	Life cycle assessment
SCEM	-	Sugarcane extractor machine
E-LCA	-	Environment life cycle assessment
S-LCA	-	Social and socio-economic life cycle assessment
WCED	-	World Commission on Environment and Development
D4S	-	Design for sustainability
TBL	-	Triple bottom line
3P	-	Planet, people and profit
PSS	-	Product-service systems
UNEP	-	United Nations Environment Programme
SETAC	-	Society of Environmental Toxicology and Chemistry
ISO	-	International Organization for Standardization
SME	-	Small medium industry
EPA	-	Environmental Protection Agency, United State
CML	-	Centre of Environmental Science, Leiden University
LCI	-	Life Cycle Inventory
LCIA	-	Life Cycle Impact Assessment
CFC	-	Chlorofluorocarbon
USD	-	US Dollar

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The World Commission on Environment and Development (WCED) issued a report entitled “Our common future”, also known as the “Brundtland Report” defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, and required for a strategy that integrated development and the environment (WCED, 1987).

The Design for Sustainability (D4S), also referred to sustainable product design, is a recognized method for companies to improve their product. D4S focus on development of products needsto embracethree main components:environment, economic and social concerns, also known as triple bottom line (TBL), also known as people, planet and profit (3P).D4S has the potential to improvequality of product, environmental performances, profit margins; market opportunities and social benefits by considering the impact of product throughout its life cycle,from the extraction of raw materials to final disposition. D4S framework approach includes redesign, benchmarking, new innovation product design and radical design.

Product design is one of the most important phase that influencing sustainability. Most of the consumer products are outputs of the product development process (PDP). Design decisions at early stage of PDP can have a very significant impact on sustainability. These decisions not only relate to material and manufacturing selection but also the product’s entire life cycle, including transportation, distribution, and disposal.The main challenges are to translate the theory of sustainability into design practice and to integratetechnical, environmental, economic and social consideration (Azapagic, 2004).

1.2 Problem Statement

ISO 14040 has defined LCA as ‘the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its entire life cycle”. The full life-cycle assessmentprovides clear view into a product's potential impact on the sustainability. But to performing a full LCA requires capable expert from various fields, time-consuming, extensive datagathering and large scope of study. Since the product design phase commonly has frequent design change, lack of information, tight datelines given and higher life cycle cost committed,it isimpractical to perform full LCA at this stage.

Consideration of specification for sustainability at early design stage creates lower cost and the cost will increase significantly for later stages. For example, a product designed for disassemblyeasier to dismantling into recyclable and reusable components than comparable product designed as a single module. So, it is important to not ignore LCA and next to choose and apply feasible approach and method of LCA at this stage to reduce the fixing errorscosts as product mature in their life cycle.LCA-based design assessment tool whichuses secondary LCA data can help to develop a quick, low-cost and robust assessment. One of the available LCA-based design assessment tools for LCA at early PDP is SolidWorks software.

There are three elements of design for sustainability (D4S) and several SolidWorks software features that can cater for D4S study. It makes D4S criteria selection and SolidWork software feature complicated. Without a user friendly assessment checklist, it is difficult to design a sustainable product through the D4S using SolidWorks software. However, there are lacks of user friendly D4S assessment checklist. Available unsuitable option for sustainability checklist for an example, Dow Jones Sustainability Indices, which a business approach that creates long-term shareholder value by embracing opportunities and managing risks deriving from economic, environmental and social developments.Furthermore there are very minimum researches done in this D4S field in Malaysia. So, the user friendly checklist is able to assist the D4S criteria selection process easier and generate the result effectively.

1.3 Objectives

The objectives of this study are:

1. to produce a user friendly design for sustainability (D4S) assessment checklist based on SolidWorks software features.
2. to redesign a Sugar Cane Extractor Machine based on above checklist.

1.4 Scope of Study

The scopes of this study are:

1. Study the sustainability features in Solidworks
2. Generate a sustainability checklist using the Solidworks.
3. Select a SCEMfor referenceof redesign case study.
4. Conduct reverse engineering process, to includedisassembly,inspect measure and sketch all components of reference SCEM, and rebuild it into CAD Model using 3D SolidWorks.
5. Perform a LCA on the components of reference SCEM using SolidWorks Sustainability.
6. Based on LCA information ofthe SCEM components redesign SCEM components using 3D SolidWorks.
7. Perform a LCA on the components of redesign SCEM using SolidWorks Sustainability.

8. Evaluate the LCA results between thecomponents of redesign SCEM against the components of reference SCEM.

1.5 Potential Contribution

The possiblecontribution can be summarized as following:

1. Reference project of introducing sustainability influencing factor consideration at product design stage for related institutes and industries.
2. Reference information for database of SCEM design and developmentfor related institutes and industries.

CHAPTER 2

LITERATURE REVIEW

2.1 Sustainable Development

Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own" (WCED, 1987). It suggests the integration between the human and nature. This integration between human and nature embrace three main components: environment, social and economy as shown in Figure 2.1. Sustainable development represent at the intersection of three main components circles and occurs when all environment, social and economic potential impact have considered, fulfilled and balanced. The other interpretation of this integration between these three main components, represent that an economically viable depends on a socially equitable, both of economically viable and socially equitable rely on an environmentally bearable as shown in Figure 2.2.

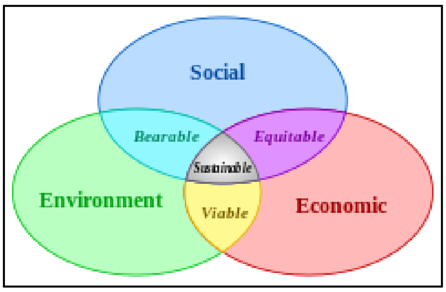

Figure 1.1: Three main components of sustainable development (Adams, 2006).

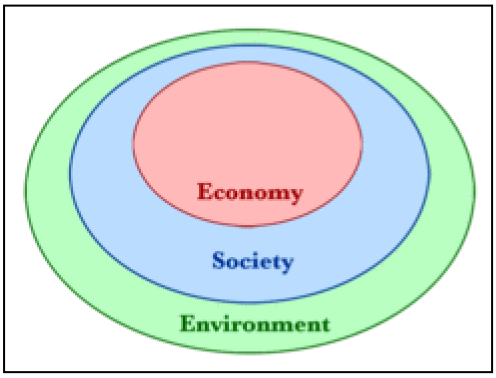

Figure 1.2: Sustainable concepts are constrained by environment limit (Scott, 2009).

Other term related to sustainability is the triple bottom line (TBL) that consists of three Ps: profit, people and planet as shown in Figure 2.3. It aims to measure the financial, social and environmental performance of the company over a period of time. It encourage businesses must consider their environmental and social impact in addition to the traditional bottom line – profit (Elkington, 1997).

Figure 1.3: Triple bottom line is consists of planet, people and profit.

2.1.1 Stakeholders

Motivation to integrate sustainability requirements can come from government, business partners, non-governmental organizations and surround community. Several common stakeholders involved in sustainability issue and their specific interest on three main components of sustainability represent as shown in Table 2.1 (Azapagic et al., 2004).

Table 2.1: The common stakeholders' interest on components of sustainability.

Stakeholders	Environment	Social	Economic
Employees	+	*	*
Customers	+	+	*
Trade unions	-	*	*
Contractors	+/-	+/-	*
Supplier	-	-	*
Shareholders	+	+	*
Creditors	+	+	*
Insurers	*	*	*
Local communities	*	*	*
Local authorities	*	*	*
Governments	*	*	*
NGOs	*	*	-
Strong interest (*), Some interest (+) & No interest (-)			

2.1.2 Drivers

Furthermore, motivation to implement the integration of sustainability requirements or design for sustainability (D4S) in product design can come from two different sources, from inside the business organization itself known as internal drivers or from outside the business organization known as external drivers. It is important to know the most influencing driver because it can provide valuable information on the best types of D4S projects to initiate. The internal and external drivers for D4S represent as shown in Table 2.2. In general, in developing economies, internal drivers are more significant for the initiation of D4S projects than external drivers because external drivers currently are less developed in many developing economies (UNEP, 2006).

Table 2.2: D4S internal and external drivers.

D4S	Internal driver	External driver
Planet	• Green marketing: The design and production of products with environmental value-added elements can boost brand value and reputation. • Environmental awareness: Managers often are aware of the importance of environmental issues and want to act accordingly.	• Legislative requirements on environment will increase in many developing economies and can force a company into a more proactive stance. • Disclosure requirements of environmental information towards suppliers and customers can start an improvement process in the company. • Ecolabeling scheme can be an additional element to a companies' marketing strategy. • Consumer organization requirements such as safety, low toxicity and recyclability of product can be an incentive for D4S. Products failing to get a good score on these aspects may no longer qualify as a good choice in consumer tests. • Pressures from dedicated environmental groups have forced industry to eliminate substances like CFCs from their products. These often highly professional organizations will continue to expose environmental harmful products. • Direct community neighbour pressure is often directed towards environmental and safety risks of the company and can have a large impact on production and products.
People	• Social equity: Can reduce risk on social and labour problems. As a result it can help avoid liability and reputation problems. • Strong social policy: Can increase employee motivation. Employees can gain energy and experience from social projects and programs launched by a company. • Governance and management systems on social aspects: Can make company achievements more visible by shareholders and stakeholders.	• Public opinion: Consumers are increasingly interested in the world that lies behind the product they buy, which is leading companies to take environmental and social issues into account. • NGO Pressure: For years industries have been under fire from NGOs for controversial practices and the related impact on the environment. For example: Irresponsible company practices may lead to boycott campaigns which can cause significant damage to a company reputation.
Profit	• Reach new consumers: Survey demonstrate that consumers are increasingly ready to purchase on ethical ground. • Product quality improvement: Reliability and functionality often go together with a more sustainable product.	• Norms and standards on sustainability aspects of product will continue to become stricter and may force companies to improve products. • Subsidy schemes are available in some countries to improve sustainability aspects of products and production. At the same time, subsidies on energy and raw materials are ending, forcing company improve materials and energy efficiency.

Table 2.2: (Continued).

	• Saving costs: Cost reduction can be made on material use, energy, waste treatment charge, transport and distribution system. • Boost brand value and reputation. • Product innovation: New possibilities from product innovation can find solution to meet customer needs and wants. • Brand differentiation. • New opportunities for value creation.	• Suppliers competition is evolving to enter or remain in supply chain, pushing companies to become more sustainable. • Customer demand for healthier, safer and more environmental and socially responsible products is increasing in specific product categories. Market competition is growing as competition is increases at local and global levels. Industry may look to improved innovative performance, which might include reviewing the sustainability aspects of their products.

2.1.3 Challenges

In addition, D4S also must meet a number of challenges related to people, planet and profit. These challenges are varies over the economies of the world. The differences are large, for example the average American consumes 17 times more than his or her Mexican comparable and hundreds of times more than of the Congolese. The sustainability challenges over developed and developing economies represent as shown in Table 2.3 (UNEP, 2006).

Table 2.3: The sustainability challenges in developed and developing economies.

D4S	Developed economies	Developing economies
Social and equity (people)	• Increase urban and minority employment. • Improve safety and well-being. • Acceptation and integration of minorities. • Reduce income inequity.	• Enhance number of skilled workers. • Reduce income inequity. • Improve working conditions. • Basic health services. • Clean drinking water. • Reduce population growth. • Improve status of women. • Abolish child labour. • Reduce illiteracy. • Abolish large scale dislocation of people.
Ecosystems (planet)	• Reduce fossil energy use (climate change). • Reduce use of toxics. • Clean contaminated sites. • Improve level of prevention, recycling, and reuse.	• Reduce industrial emissions. • Waste water treatment. • Stop overexploitation of renewable resources, water. • Stop deforestation, soil loss, erosion, • ecosystem destruction. • Reduce dung and wood burning.

Table 2.3: (Continued).

Customers and stakeholders (profit)	• Profitability. • Value for company, stakeholder. • Value for customer. • Fair business model.	• Fair share of and linkage to global value chains. • Linkage of SMEs to large and transnational companies. • Industrialization of production, economies of scale. • Fair price for commodities and raw materials. • Ownership and credit opportunities for entrepreneurs.

2.1.4 Impact Influencing Factors

Assessment of influencing factors for environment, social and economic are varies depends on applications, organizations, industries and countries. Azapagic et al. (2004) established influencing factors of three main components of sustainability represent as shown in Table 2.4.

While Jawahir et al. (2007), established similar influencing factors that separate into the four life cycle stages of a product as shown in Table 2.5. The four main stages of a manufactured product are represented as: pre-manufacturing, manufacturing, use, and post-use.

Table 2.4: The influencing factors on three main components of sustainability.

Environment factors	Socials factors	Economics factors
• Energy use. • Water use. • Water discharge. • Solid waste. • Global warming. • Resources reduction. • Ozone reduction. • Acidification. • Summer pollution. • Eutrophication. • Human toxicity. • Eco-toxicity.	• Provision of employment. • Employee health and safety. • Citizens' health and safety. • Customer health and safety. • Nuisance (odour, noise, visual impact, transport). • Public acceptability.	<u>Micro-economic:</u> • Capital costs. • Operating costs. • Profitability. • Decommissioning costs. <u>Macro-economic:</u> • Value added. • Taxed paid, including green taxes. • Investment (e.g. pollution prevention, health and safety, decommissioning) • Potential costs of environmental liability.

Table 2.5: The influencing factors in four stages of entire life cycle.

Environment factors	Social factors	Economic factors
Pre-manufacturing stage		
• Material Extraction. • Design for Environment. • Material Processing.	• Worker Health. • Worker Safety. • Ergonomics.	• Raw Material Cost. • Labor Cost. • Recovery Cost.
Manufacturing stage		
• Production Energy used. • Hazardous waste. • Renewable Energy used.	• Work Ethics. • Ergonomics. • Worker Safety.	• Storage Cost. • Production Cost. • Packaging Cost. • Energy Cost. • Transport Cost.
Use stage		
• Emissions. • Functionality. • Hazardous waste.	• Product Pricing. • Human Safety. • Upgradability. • Complaints. • Quality of Life.	• Maintenance Cost. • Repair Cost. • Consumer Injury Cost. • Consumer Warranty Cost.
Post-use		
• Recyclability. • Remanufacturability. • Redesign. • Landfill Contribution. • Potential for next life. • Modularity.	• Take Back Options. • Reuse. • Recovery.	• Recycling Cost. • Disassembly Cost. • Disposal Cost. • Remanufacturing Cost. • Recycled Material value.

2.1.5 International Bodies

Several international bodies that have concerned with the development and application of LCA such as Society of Environmental Toxicology and Chemistry (SETAC), United Nations Environment Programme (UNEP), International Organization for Standardization (ISO), review of these bodies as following (Jeroen et al., 2001):

1. SETAC was the first international body to act as an umbrella organization for development LCA. It is a scientific organization with its root in academia, industry and government, to offer science based platform for the coherent development LCA as a tool. SETAC's aims are scientific development in specific and application of the results in the field of environmental management. Code of practice LCA has been developed, prototype of activities which are performed under ISO.

2. UNEP is international player in field of LCA. UNEP focus is mainly on the application of LCA, particularly in the developing countries. An important contribution was the publication in 1996 of the UNEP's user friendly and easy to read guide to LCA, entitled Life Cycle Assessment: What it I, and what to do about it. SETAC and UNEP now cooperating in a major new task, concerning the identification of the best practice in the field of life cycle assessment. The task involves identification of the available practice in establishing a database for life cycle inventory phase, and a list of environmental impact categories and accompanying factor to address these impact categories.

3. ISO is a worldwide private organization, including national bodies from both developed and developing countries, which aims to standardize a wide range of products and activities. The 14000 series of ISO standards includes the standard 14001 on Environmental Management Systems, as well as a 14040 series of standards which are relating to LCA. The ISO LCA standards concern the technical as well as organization aspects of an LCA project. The organizational aspects mainly focus on the design of the critical review processes, with special attention to comparative assertion disclose to the public. They also cover matters such as the involvement of stakeholders.

2.2 Life Cycle Assessment (LCA)

Product sustainability is not only relative, it's multidimensional. There is no single, universal indicator of sustainability. The appropriate impact metrics and dimensions on which products are compared can differ significantly, depending on the purpose of the evaluation. Impact measurement creates the key dashboard for sustainable design, so it's important to choose an assessment approach that will generate information consistent with its intended use. The appropriate technique for evaluating the environmental impact of a design depends on a guide as following (SolidWorks):

1. The impacts to be concerned.
2. The scope of the assessment.
3. The types of metrics are appropriate for the purposes of study.

2.2.1 Environmental Impact

There are a wide range of environmental impacts that can be assessed. However, it's not always necessary to cover many of these impacts if you're mainly interested in one impact environmental indicator. So, first step is to determine which impacts should be measured based on the purpose of the assessment and how its data will be used. Several of the common environmental impact categories divided into five major domains represent as shown in Table 2.6 and theirs explanation as following (SolidWorks):

Table 2.6: The common environmental impacts.

Domain	Environmental impact categories
Natural resource depletion	• Water Use • Mineral Extraction • Land Occupation/Use • Non-Renewable Energy
Air impacts	• Air Acidification • Photochemical Oxidation • Ozone Layer Depletion
Terrestrial & aquatic impacts	• Water Eutrophication • Aquatic Ecotoxicity • Terrestrial Ecotoxicity
Climate effects	• Climate Change or Global Warming
Human health	• Human Health • Human Toxicity • Respiratory Inorganics • Ionizing Radiation

1. Natural Resource Depletion. This first domain reflects the many ways human activity uses up the Earth's natural resources. "Depletion" means that those resources are no longer available for further use in their original forms.

   i. Water Use. Water is the only resource that is both renewable and finite. All of the water that was ever on Earth is still on Earth, but the breakdown of its location, physical state (water, vapor or ice), and salinity can limit its usefulness as a resource.

ii. Mineral Extraction. Mineral deposits can't be renewed. Once a mineral deposit (like iron ore) is mined, it doesn't return to the earth as ore, no matter how much it's reused or recycled. There's only a finite amount of each mineral, so any used now will not be available for future generations to mine.

iii. Land Occupation/Use. Land can't be depleted, but since a given acre can only be used for a limited number of purposes, land shortage can be a real issue. Land can also become unusable, or at least less valuable, due to physical changes such as erosion. A decrease in available land can impact a wide variety of systems, including agriculture, civilization, and biodiversity.

iv. Non-Renewable Energy. While there are a variety of non-renewable natural resources used for energy, the ones that usually get the most attention are oil, coal, and natural gas. This non-renewable energy impact includes the energy (electricity or fuels) used during the product's manufacture and use, and can even go one step further to include the upstream energy required to obtain and process the energy consumed in the product's lifecycle. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) can also be factored in. The non-renewable energy demand can also include a measure of the embodied energy of the materials - that is, the energy that would be released if the product were burned.

2. Air Impacts. The Earth is wrapped in a layer of gases mixed in proportions necessary to sustain life on the planet. There are several ways humans affect those proportions, with far-reaching results.

i. Air Acidification. Burning fuels creates sulfur dioxide, nitrous oxides, hydroflouric acid, ammonia, and other acidic air emissions. This causes an increase in the acidity of rainwater, which in turn acidifies lakes and soil. These acids can make the land and water toxic for plants and aquatic life, and can leach life-sustaining minerals from the soil. Acid rain can also slowly dissolve manmade building materials, such as concrete or these statues seen here.

ii. Photochemical Oxidation. Many recognized it as "smog." The emission of air pollutants such as non-methane hydrocarbons can cause decreased visibility, eye irritation, respiratory tract and lung irritation, and vegetation damage.

iii. Ozone Layer Depletion. The holes growing in the ozone layer were the top environmental concern. Caused primarily by the emission of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, and methyl bromide (CH3Br), the thinning of the atmosphere's ozone layer allows increased ultraviolet radiation to reach the earth. This radiation can cause cancer in animals and decreased plant and algae viability.

3. Terrestrial & Aquatic Impacts. Several types of impacts directly affect land and water quality.

i. Water Eutrophication. Eutrophication occurs when an overabundance of plant nutrients are added to a water ecosystem. Nitrogen and phosphorous from wastewater and agricultural fertilizers causes an algal bloom (explosive growth of algae), which then depletes the water of dissolved oxygen, a situation known as hypoxia--resulting in the suffocation of aquatic life.

ii. Aquatic Ecotoxicity. While eutrophication occurs due to an excess of nutrients, ecotoxicity results from the presence of poisons in the water. This is generally caused by chemicals being neglected into lakes and rivers. It results in decreased aquatic plant and insect production and biodiversity, as well as impacting water drinkability.

iii. Terrestrial Ecotoxicity. Toxins present in soil cause decreases in wildlife and plant production and biodiversity. While some of these toxins may be introduced from airborne or aquatic sources, many are the result of direct human application or through leaching from industrial processes or waste accumulations.

4. Climate Effects. The global climate is the result of many interacting systems. In many ways all of the other impacts have some influence over the climate. However, one climate effect in particular has been identified as a key factor in shaping the future of life on Earth. Climate change, sometimes called global warming, is one of the most commonly identified impacts of interest. Carbon dioxide (CO_2), methane (CH_4), and other so-called greenhouse gases resulting from burning fossil fuels accumulate in the atmosphere, trapping solar heat which in turn increases the earth's average temperature. A product's climate change impact is often referred to as its "carbon footprint" because global warming potential is usually measured in units of carbon dioxide equivalent (CO_2e). It is widely understood that global warming is the cause of such problems as loss of glaciers, extinction of species, soil moisture loss, changes in wind and ocean patterns, and more extreme weather, among others.

5. Human Health. While the other impact domains affect humans in many ways, they focus on the Earth's biosphere as a whole. This group of impact categories is human-centric (Jolliet et al., 2003), (EPA, 2006).
   i. Human Toxicity. Toxic chemicals released to the air, water, and soil enter the human body through breathing, ingestion, and through the skin. Whether cancer-causing agents (carcinogens), substances that can cause birth defects (teratogens), or other pathogens, the net result is an increased likelihood of human sickness and other negative health effects.
   ii. Respiratory Inorganics. Many organic causes of respiratory problems are covered by some of the general environmental impacts already covered (e.g., photochemical oxidation). Respiratory inorganics are particulate matter, often resulting from the burning of fossil fuels emitting sulphate and nitrate aerosols. This particulate matter causes breathing difficulties.
   iii. Ionizing Radiation. Ionizing radiation is what most people are thinking of when they talk about radiation exposure. It is radiation that has enough energy to ionize atoms or molecules. Exposure can damage living tissue, resulting in cancer, radiation sickness, mutation, and even death (SolidWork).

2.2.2 Scope of Assessment

The second major consideration in assessing the sustainability of a product is the scope of analysis. For products, the scope is usually described by how much of its lifecycle is included in its impact assessment (SolidWorks). In general, the entire lifecycle of a product can be divided and measured in several important stages as shown in Figure 2.4.

1. Raw material extraction stage includes the energy and other resources used to get the basic materials used in the product, such as through mining ore, harvesting timber, extracting oil, etc.
2. Material processing stage where the raw materials are converted into simple forms used for manufacturing. It includes the processes required to make steel, copper, plastic feedstock, paper, gasoline, and etc.
3. Part manufacturing includes all single part and product component. Common processes include injection molding, metal stamping machining, weaving and milling.
4. Assembly stage where product parts need to be assembled to a complete product includes processes fastening, welding riveting etc.
5. Product use cover energy used, emissions generated, other resources affected directly by the product. This includes waste that occurs in the context of a product's use, such as discarded packaging.
6. End of life stage where the product is no longer used. This stage is usually divided into three resulting streams: whether a product to be sent to landfill, to incineration, and to reuse or recycling.
7. Transportation is occurs between each of the lifecycle. Transportation could be included among the stages. Also, transportation could be separate lifecycle component, especially between Assembly and Product use for consumer products.

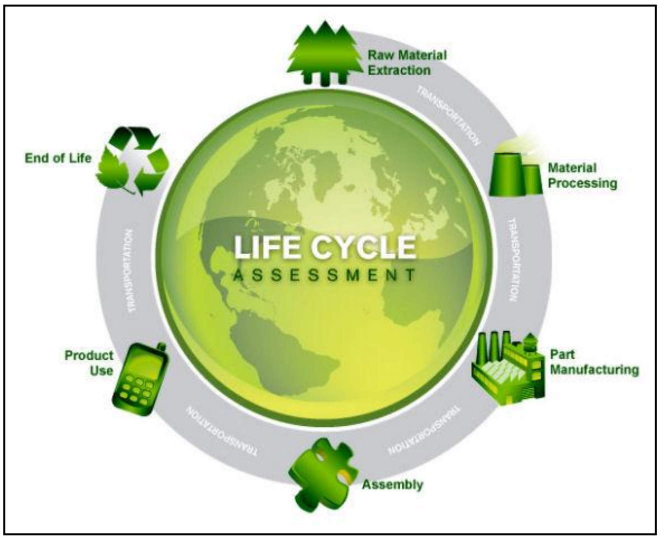

Figure 2.4: General stage of a product throughout their life cycle (SolidWork).

Product lifecycles intersect a great many processes, some more directly linked to the product than others. Since an assessment can't always cover everything, system boundaries clarify what it will include. It's often helpful to draw a process diagram, and then trace a boundary around what will be measured (SolidWorks).

For example, Figure 2.5 shows a possible system boundary chart for an assessment of a polystyrene cup, with a functional unit of one cup.

Some of the standard product lifecycle system boundary scopes include:

1. "Cradle to grave" – Usually denotes all phases from raw materials through disposal.
2. "Cradle to cradle" – Like cradle to grave except that it tracks where the product's elements go after end of use, with special attention to recycling and reuse.
3. "Cradle to gate" – Includes part of the product lifecycle, typically either: all upstream phases, not including the assessing company's own processes; this is used to assess the "environmental burden" of raw materials coming through the door; or all phases through the assessing company's manufacturing and assembly (the factory gate), bound for the customer, since this is the end of most manufacturer's ability to directly influence impact.
4. "Gate to gate" – A narrowly-scoped lifecycle assessment, focused on only one particular stage or set of stages of the product lifecycle.

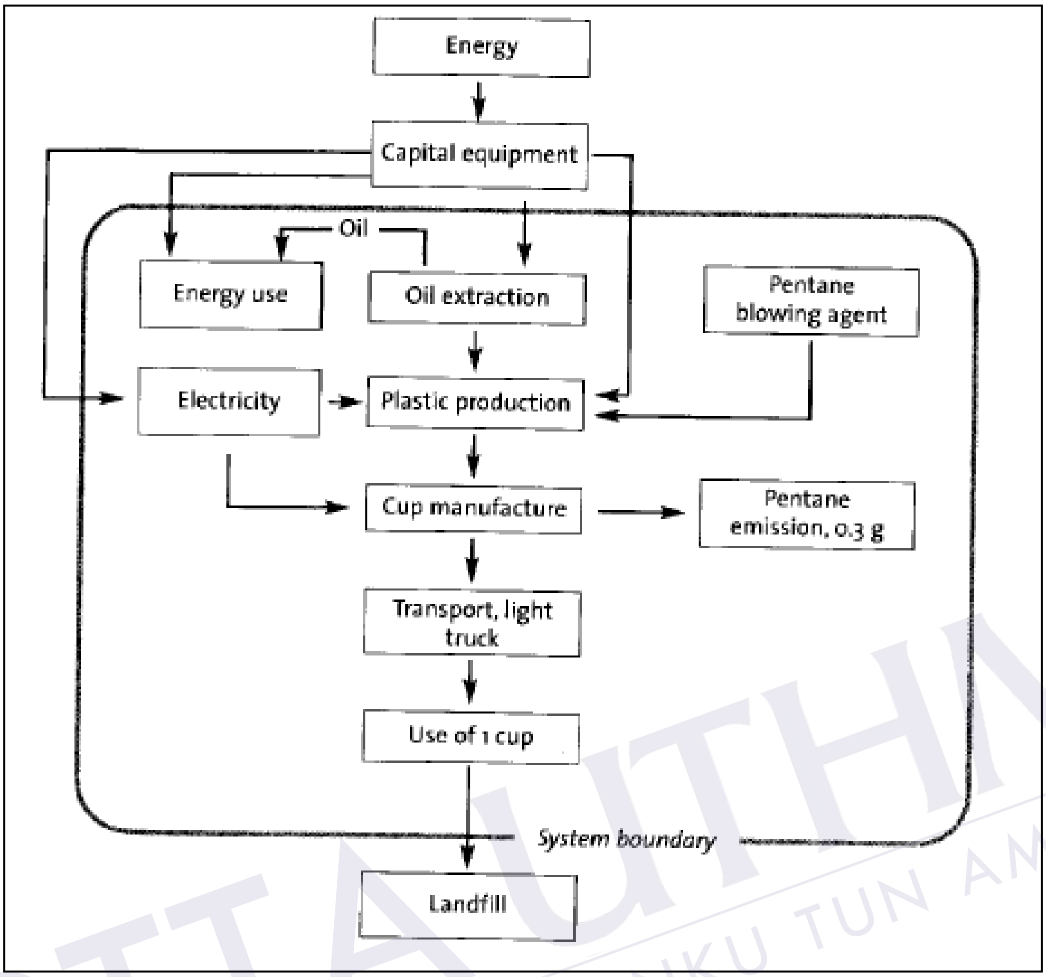

Figure 2.5: Example of system boundary a polystyrene cup (SolidWork).

2.2.3 Metrics

After determined what impacts want to focus on and how far up and down the product's lifecycle want to assess, the final decision is how accurate measurement the selected impacts across chosen lifecycle stages. Once determined choice of the metrics, and then need to identify the types of impact assessment tools and techniques that will be most useful (SolidWorks). Most metrics fall into one of four categories:

1. Comments. The most qualitative, and usually most subjective, way impacts are expressed is through text alone. People can generally describe what they believe an impact will look like, its severity, and so forth at a high level based on their understanding of the product. Comparisons read more like product

reviews than detailed technical analyses. This form might be appropriate for a first-pass assessment or as a basis for narrowing down alternatives to be compared (SolidWorks).

2. Checkmarks. In some cases, evaluations are based on checklists. The assessment will have certain criteria for each of the categories, which are either met, or not. Is mercury present? Does at least 25% of the energy used come from renewable resources? Checklists like this have the advantage of resulting in evaluations that are easy to compare across a wide range of products. They can be used relatively; while the checkmarks don't reflect many details or degrees of difference they may provide enough information to support relevant decisions (SolidWorks).

3. Scores. Whether in the form of grades, number scales, or stars, scoring systems have the advantage of the checklists, while also reflecting a more nuanced evaluation of a product's impact. One of the challenges that comes with nuance however is that someone needs to decide whether something gets an A or a B, 3 stars or 4. In many cases, scoring systems lay out guidelines for what qualifies as an A versus a B so that there is some consistency across evaluators and products. A balanced and transparent evaluation process can produce a helpful assessment of the scale of a product's environmental impacts. Such scoring systems are especially useful when a quick assessment is needed to initiate the first discussion across a multi-stakeholder group (SolidWorks).

4. Measurements. The most precise and objective metrics come in the form of specific numbers representing impact levels. These usually take two forms, one impact-specific and the other a standardized conversion into a single proxy number (SolidWorks).
   i. Impact-Specific. The impact-specific metric is usually expressed in equivalencies of a certain key component of that impact, such as kilograms of CO2 for global warming. In this case, no matter what the source of the impact on global warming, it would be converted into the equivalent kilograms of CO2 (often written as "kg CO2e," "kgeq CO2",

"kg-eq CO2", etc.) using standardized equations (EPA). Other common equivalency units for several environmental indicators are listed in the Table 2.7 (Jolleit).

Table 2.7: Common equivalency units for environmental indicators.

Impact Category	Reference Substance
Human toxicity	kg-eq chloroethylene into air
carcinogens + non-carcinogens	kg-eq PM2.5 (particulate matter < 2.5μm) into air
Respiratory (inorganics)	Bq-eq carbon-14 into air
Ionizing radiations	kg-eq CFC-11 into air
Ozone layer depletion	kg-eq ethylene into air
Photochemical oxidation	kg-eq triethylene glycol into water
Respiratory (organics) for human healt	kg-eq triethylene glycol into water
Aquatic ecotoxicity	kg-eq SO2 into air
Terrestrial ecotoxicity	kg-eq SO2 into air
Terrestrial acidification/nutrification	kg-eq PO43- into water
Aquatic acidification	m2-eq organic arable land•year
Aquatic eutrophication	kg-eq CO2 into air
Land occupation	MJ Total primary non-renewable or kg-eq crude oil (860 kg/m3)
Global warming	MJ additional energy or kg-eq iron (in ore)

There are actually well over a dozen methods for classifying substances (EPA, 2006). Each maps materials to impacts based on scientific research, with many materials having impacts in multiple categories. The assessment is usually facilitated by software that can take component inputs and calculate allocated impacts based on either actual data gathered or standardized data tables. While there are pros and cons to each assessment tool, some have been adopted more broadly than others. A survey of 65 LCA practitioners reported that (Cooper et al. 2006):

a. 58%* used GaBi (PE International)
b. 31%* used SimaPro (PRé Consultants)
c. 11%* used TEAM (Ecobilan)

Other tools cited:

a. BEES (NIST)
b. Umberto (ifu Hamburg)
c. ECO-IT (PRé Consultants)
d. Excel-based spreadsheets
e. Math package (e.g. MATLAB, Mathematica)

ii. Single Proxy. Because it is difficult to compare the impact of 1 kg-eq CO2 and 1 kg-eq chloroethylene, for instance, it can be useful to convert all impacts into a single proxy metric. All of the impact-specific equivalencies can be translated into a universal impact factor, often expressed in terms of "millipoints," sometimes after being normalized based on a national or global reference model. Such single-number impact factors are therefore a weighted measurement showing relative impacts across multiple categories. While there are some standard sets of factors, each represents a specific perspective on what to use as a reference model and how to calculate the conversions. Several of the most widely-used data sets are Eco-Indicator 99 (EI99), EcoInvent, U.S. Life-Cycle Inventory as shown in Figure 2.6, and CML.

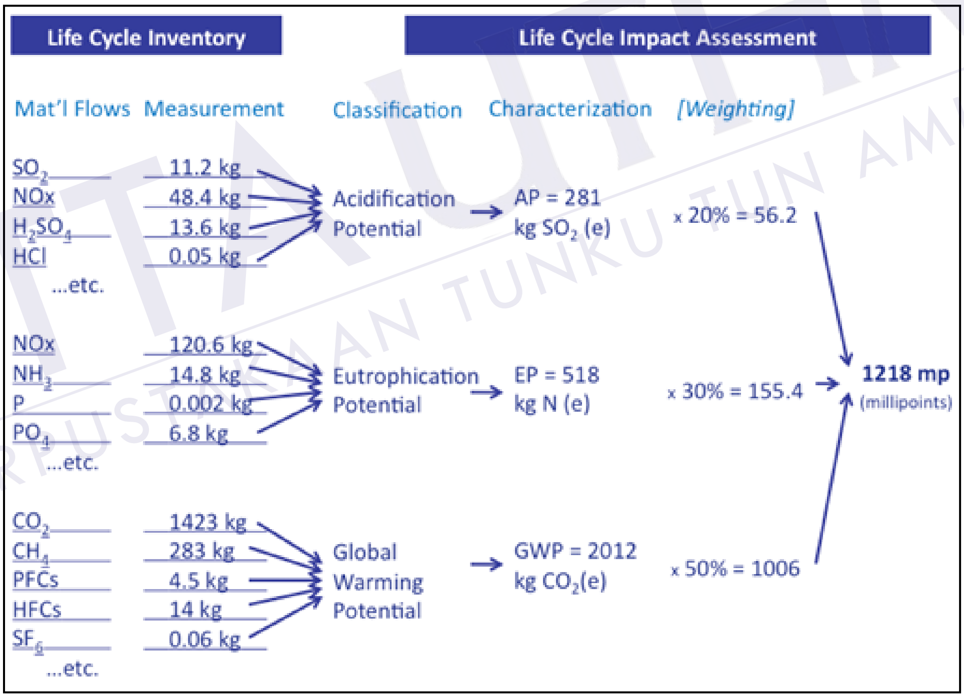

Figure 2.6: Example of impact conversion single proxy metric.

iii. Weighting. Whenever multiple factors are combined and represented by a single number, some sort of weighting takes place. Sometimes all of the inputs are considered of equal value, but in many cases some inputs are given more influence over the final result than others, reflecting a certain prioritization of the importance of each type of impact. Weighting is more of a political (social, cultural) than a scientific process - giving, say, more weight to the global warming indicator than to acidification is a values-based decision. Stakeholders may differ significantly on their views about the importance of impacts, as shown in the Figure 2.7 (Gloria et al., 2007).

Many practitioners choose to leave the impact scores broken out into categories, with no weighting at all. Although this approach creates a more complicated report, it enables impact comparisons between products on a more granular level. The advantage of variable weighting approaches is that they can be customized to fit an organizations goals and values.

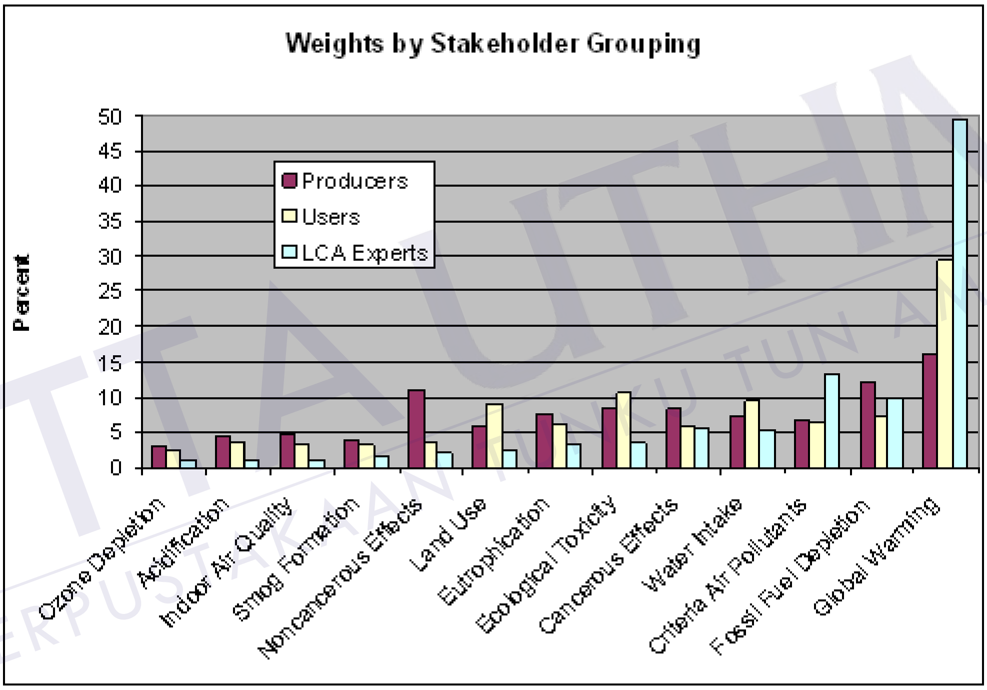

Figure 2.7: The importance of impacts by some of stakeholders.

2.3 Common Tools

While each of the three environmental assessment choices can be made independently to generate an impact assessment, there are several commonly used approaches. These techniques range from relatively quick, cheap, and low accuracy to much more expensive and time-consuming, but with more rigorous and robust results.

Most sustainability assessments, until relatively recently, were qualitative. Data-driven environmental impact measurements have traditionally been too slow or expensive to acquire. Even today, many organizations find that qualitative assessments are good enough for their purposes. Methods vary from “back of the envelope” to more rigorous, as represent in Figure 2.8 (SolidWorks).

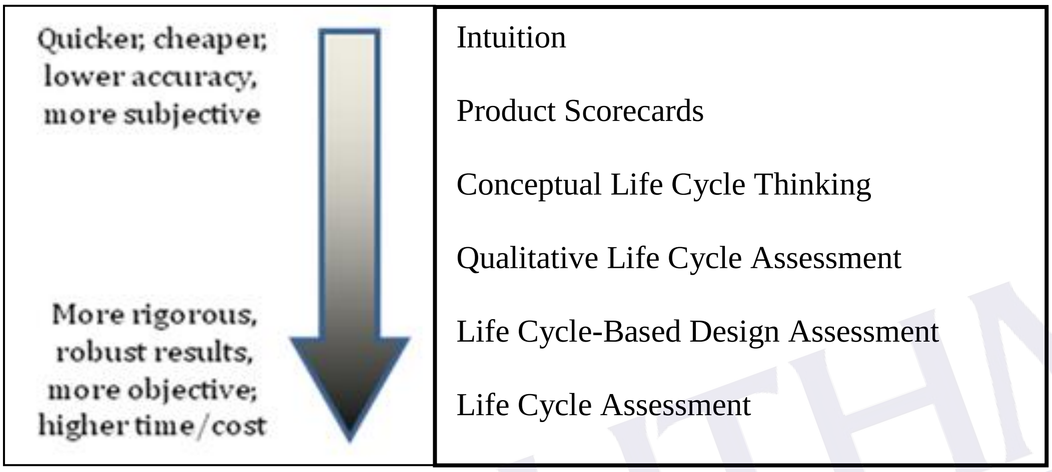

Figure 2.8: Type of assessment and theirs result accuracy.

2.3.1 Intuition

Most people have a broad-brush sense for the relative impacts of major design choices. For instance, intuition alone will tell you that a lighter version of a product would save on transportation costs or that a more energy-efficient product would have less of an environmental impact.

2.3.2 Product Scorecards

Some companies have created scorecards to enable them to evaluate a variety of products with at least some internal consistency. Scorecards of this type are not particularly life cycle-based, but instead focus on the attributes of a product. For example, the design firm Ximedica (formerly Item Group) created what they call

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