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A framework for integration of sustainability issues into traditional product design process.

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A Framework for Integration of Sustainability Issues into Traditional Product Design Process

By

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Abstract

The integration of sustainability requirements into product development is a widely accepted strategy in principle, although not commonly practiced. How we can combine sustainability issues with the traditional design requirements such as cost, function, and quality in product development process still needs investigations. This research is an attempt to provide a systematic easy to follow framework for designers in order to incorporate the sustainable development issues related to their product ideas.

In this research, sustainable product design ideas have the following three features:

- Environmentally benign – design idea or option offers measurable environmental benefits
- Socially equitable – design idea fills the needs of stakeholders involved in the product life-cycle
- Economically viable – design ideas is innovative and competitive in the marketplace such that it drives new revenues by using environmental focus and human-centric approaches to add value to products, reach out to (green) consumers.

Introduced framework promotes innovative solution to meet the functional requirements of customers by incorporating Theory of Inventive Problem Solving (TRIZ) into the idea generation process. One of the special features of this methodology is before detail design stage; a product idea is comparatively evaluated in terms of sustainability criteria. Featured methodology identifies that when a product idea (or option) is evaluated, both subjective and

quantitative criteria have to be considered. Analytical Hierarchical Process (AHP) is used as the basis for product idea evaluation process. The product idea generation with consideration of sustainability factors is considered as a problem situation in which there exist a large number of social and human activity components. The steps of the presented methodology are anchored in Checkland's Soft System Methodology (SSM) steps.

DEDICATION

To my parents

Acknowledgements

I am fortunate to have Dr. Michael Wang as my supervisor. He provided me needed direction, support and encouragement. The best thing he provided me was flexibility. I could not have completed this work without the help of Dr. Wang. During the last seven years at the University of Windsor, there were plenty of occasions when it became very difficult for me even to hope that someday I would be able to complete my Ph.D. His positive words always made me hopeful.

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Nomenclature

Sustainability

Sustainability is a characteristic of a process or a state that can be maintained at a certain level indefinitely. Sustainability focuses on providing the best outcomes for both the human and natural environments now, and into the indefinite future. Sustainability relates to the continuity of economic, social, environmental and institutional aspects of human society, as well as the non-human environment.

Sustainable Development (SD)

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). Sustainable development can be described as the process of using our material resources wisely, so that future generations can also enjoy improved quality of life, a continually increasing standard of living, and a stable environment.

Sustainable Product

Products that are:

Environmentally benign - design idea offers measurable environmental benefits

Socially equitable – design idea fills the needs of stakeholders involved in the product life-cycle

Economically viable – design idea is innovative and competitive in the marketplace

Soft Systems Methodology (SSM)

Peter Checkland first developed the methodology as a seven stage model in 1981 (Checkland, 1981). The objective of SSM is not to solve a problem or to simply implement and create a computer system but instead to analyze and structure a previously unstructured situation and initiate a learning system through which actors have the opportunity to understand and to deal with the 'problem' situation. It is attempting to identify the underlining issues that help in the understanding of the situation and the environment within which the 'problem' lays, hoping that this will achieve a possible solution.

TRIZ

The TRIZ method is an available tool for the designer to handle design conflicts (Stratton and Mann, 2003). TRIZ is a Russian language acronym for Teoriya Resheniya Izobreatatelskikh Zadatch. Translated into English it means "The Theory of Inventive Problem Solving." TRIZ is the product of an exhausted analysis of the world's most creative technological innovations as described in worldwide patent literature. The objective of TRIZ is to discover how inventor's invent.

The Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), developed by Thomas L. Saaty is designed to solve complex multicriteria problems. AHP requires the decision maker to provide judgments about the relative importance of each criterion and then specify a preference for each decision alternative using each criterion (Saaty, 1980). The output of AHP is a prioritized ranking of the decision alternatives based on the overall preferences expressed by the decision maker.

A list of Acronyms

Terms	Short form (Acronym)
Sustainable Development	SD
Soft Systems Methodology	SSM
Analytic Hierarchy Process	AHP
World Council of Environment and Development	WCED
Design for Environment	DFE
Environmental Management System	EMS
The Theory of Inventive Problem Solving	TRIZ
Quality Function Deployment	QFD
Voice of Customer	VoC
World Business Council for Sustainable Development	WBCSD
Global Reporting Initiative	GRI
Human Activity Systems	HAS
New Product Development	NPD

Chapter 1

Introduction

The twenty-first century will be a crucial era in the history of mankind: if we succeed in taking the right decisions, we will be able to create a world in which the inhabitants – all inhabitants – can live on a fairly high standard of living [WCED, 1987].

Sustainable development is finding win/win/win solutions for both the short and long-term effects of design on social responsibility (equity), environmental performance and business results (business profitability) – the triple bottom line (Smith, 2004). The triple bottom line has been, and remains, a useful tool for integrating sustainability into the business agenda. Balancing traditional economic goals with social and environmental concerns has created a new measure of corporate performance (McDonough and Braungart, 2002).

Over the last few years, organizations have been seeking to improve their sustainability performances due to rapid increase in market pressure. This has increased the need for industry to address sustainable development issues in the industrial design/ product design process. To respond to this need, both academics and practitioners have been developing and implementing sustainable development strategies. A growing number of *design for environment (DFE) tools* to assist in developing and implementing these strategies into product design and development processes are now available (Santos-Reyes et al., 2001).

Hence there is still a need for systems approach to design products for sustainable development that will assist designers to find the adequate support under the premise that the time of learning and exercising method procedures and nomenclature is often very short or even nonexistent (Strasser and Wimmer, 2003). A structured approach to design for sustainable development should also support an organizations environmental management system (EMS) (Santos-Reyes et al., 2001).

1.1 Introduction to the Research Problem

Today we are being challenged to rethink the character and design of our technologies and products, the processes applied to make them, the patterns of their marketing, distribution, usage as well as take-back and recycling (Griese et al., 2004). There is a growing belief that investing in industrial design/ product design is beneficial to company performance (Gemser and Leenders, 2001; Chiva-Gomez, 2004; Griese et al., 2004). However, there is no generally accepted agreement as to exactly what activities design management involves.

We opted to define industrial design / product design in a general way, namely as the activity that transforms a set of product requirements into a configuration of materials, elements and components. This activity can have an impact on a product's appearance, user friendliness, ease of manufacture, efficient use of materials, functional performance and more (Gemser and Leenders, 2001). Research shows that besides being innovative with respect to design and design strategy can help to enhance competitiveness regardless of industry evolution (Gemser and Leenders, 2001).

The discipline of industrial design/ product design emerged during the early part of the twentieth century to provide design services for manufacturing industry (Dormer, 1990). Since then, the role and expertise of the industrial designer has evolved with that of manufacturing (Walker, 2002). Today, industrial design is often a key aspect of a company's success in the market (Walker, 2002; Santos-Reyes et al., 2001). The wide range of knowledge and expertise of industrial designers enables them to make significant contributions within our contemporary, globalized systems of product development and manufacturing (Walker, 2002; Gemser and Leenders, 2001).

In this study, product design process is considered from sustainable development point of view. Significant improvement can be achieved integrating environmental and social aspects as optimization parameters in product design together with more traditional values such as production costs, functionality, aesthetics, etc. It is well documented fact that creativity, imagination, and innovation are needed to develop new directions that begin to weave together scales of production, levels of technological sophistication, and diverse cultural needs in ways that are environmentally, socially and economically responsible and desirable (Walker, 2002). This study examines the role played by sustainable development issues during the product design process. The firms which include sustainable development issues in the design process have the opportunity to reduce disposal costs and permit requirements, avoid environmental fines or environmental penalties related to product manufacturing/

disposal etc. (information about Ontario, Canada's environmental fines related to industrial operation can be found on www.ene.gov.on.ca), better utilize raw materials, boost profits, discover new business opportunities, rejuvenate employee morale, and improve the state of environment. In order to develop a more harmonious fit between sustainable ways of living and creations and production of our material needs, it may be necessary to take a somewhat different view of the situation (Walker, 2002). Rather than considering how to integrate the principles of sustainability into an *existing* product development system, it may be useful to approach the problem from the opposite direction, and consider how functional objects might be designed and created in ways that are compatible with the principles of sustainability. This requires a change in our perspective. Sroufe et al. (2000) suggests that amount of waste generated by a product is a direct consequence of decisions made during product design. As has been shown in Sroufe et al. (2000) that product design is relatively responsible for approximately 5-10 percent of the total costs, has significant impact on the actual costs incurred within the system. Fabrycky (1987) estimated that up to 85 percent of life cycle costs are committed by the end of the preliminary design stages. According to Kriwet et al., (1995) that only 10-20% of recycling costs and benefits depend on recycling process optimization and the remainder is already determined at the design stage. In light of increasing pressure to adopt a more sustainable approach to product design and manufacture, research has identified requirement for a framework based on systems view.

1.1.1 Requirements of Sustainable Design Support

Following problems, which researchers find difficult to solve while they consider inclusion of sustainable development principles in engineering design process.

- A designer must treat too much information, and therefore the designer's workload is greatly increased.
- A holistic design methodology that considers the product, its life cycle and the business strategy is not systematized yet.
- A designer may be confused because each design support tool can be used without process management.
- It is difficult to achieve a balance between cost performance and environmental and social targets in a design project, and to attain the targets.
- Many tools are not practical for designers (Kobayashi et al., 1999).

1.2 Motivation of Research: Current Sustainability Trends and Developments

Sustainable development is relatively new concept. The majority of today's businesses have some form of declaration or "mission statement" with respect to how they view the environmental and societal aspects of their businesses. If we visit corporate websites, we see that companies are actively thinking and processing the information of sustainability. For example, a list of companies' websites that contain very detail regarding how they are changing their way of development and distribution of products to show that they care about sustainability is included here.

- ♦ HP http://www.hp.com/hpinfo/globalcitizenship/environment/index.html

- Mitsubishi Corp http://www.mitsubishicorp.com/en/csr/index.html
- Kodak http://www.kodak.com/US/en/corp/HSE/stewardship.jhtml
- Ford http://www.fromonline.org/DOC/BS_FORD_Summary_2005.pdf

This list can go on and on. But often it is not clear whether such corporations are true advocates of sustainable development principles or have simply adapted their business model to include a form of sustainable development consciousness. Nevertheless, it is true that today's consumers and corporations are more acutely aware of sustainable development issues that range from issues surround "sustainable (or eco) product labeling" to the growth in ISO 14000 series certification.

The purpose of this research is to integrate sustainability principles in the earliest stages of product design and development process, in order to minimize negative environmental and societal impacts throughout the product's life cycle. Industry efforts to cost-effectively address the sustainability impacts of products through design can be tied directly to the need to compete in an increasingly global marketplace where regulatory requirements, voluntary initiatives, certification schemes and consumer demands can vary dramatically and have a direct impact on a product development company's ability to business in any given market. The following are a few recent initiatives that show the requirement of research on sustainable product development:

Takeback Laws, Extended Product Responsibility, Waste Electrical and Electronic Equipment (WEEE), and End of Life Vehicles (ELV) Directives: One of the main reasons for needed research in this field is the growing legislation of "product stewardship" and "extended producer responsibility". Under product stewardship, all stakeholders in the product life cycle – designers, suppliers, manufacturers, distributors, retailers, consumers, recyclers and disposers – share responsibility for the sustainability aspects of products. Product stewardship is the principle behind Extended Producer Responsibility policies that require manufacturers of the products and services to take responsibility for the end-of-life management of their products (Northwest, 2007). Extended Producers Responsibility is a strategy that encourages a closed-loop pattern of materials use. This way financial responsibility for managing end-of-life shifted products from government to producers (Northwest, 2007). Such movements are gaining importance because of a growing body of takeback legislation. In Europe, takeback legislation started with Germany in 1991 with the German Packaging Ordinance and today includes most of the European Union countries. As a result of such legislation, companies that do business in Europe may find their profits reduced if their products and packaging are not designed for efficient recovery, and reuse or, at a minimum, recycling. In the countries that have not passed mandatory take-back laws, there is mounting dialogue and debate on the issue of product responsibility is an emerging principle for a new generation of pollution prevention policies that focus on product systems instead of production facilities (http://www.bsr.org/). All participants along the product chain share responsibility for the lifecycle environmental and societal impacts of products, including upstream impacts such as selection of materials and the manufacturing process itself, and downstream impacts such as the use and disposal of the product. The Waste

Electrical and Electronic (WEEE) directive was adopted by the European Union (EU) in 2003. It aims to reduce the amount of WEEE being disposed in landfills by promoting separate collection, treatment and recycling. This directive started in effect in various parts of the UK this past January. The European Union passed a directive on End of Life vehicles (ELV) in 2000, although implementation by member countries laws has been delayed in 2003. The directive has several elements with a common goal of preventing vehicle waste through the re-use, recycling and recovery of materials and components form end-of-life vehicles. One component of the directive requires auto producers to cover the cost of vehicle recovery, while other aspects of it restrict the use of certain materials in vehicle manufacturing. Though producer responsibility-type regulations do not currently exist in the United States, many multinational companies are facing these regulations in Europe and therefore are already being forced to comply with the requirements.

Stricter Upgrades to Existing Regulations Affecting Product Design: Existing environmental regulations that are updated time to time, with the trend generally being towards more respective regulations. For example, the European Union Directive of Packaging and Packaging waste, first passed in 1994 was updated in 2003 to raise recycling targets for packaging waste. Legislation today is developing that will soon cover automobiles and electronic products such as televisions, computers, refrigerators, air conditioners, and washing machines (William et al., 2000).

Voluntary Co-operative Initiatives: Increasingly, government agencies are teaming up with the commercial sector to find cost-effective solution to the challenge of sustainable product design. The U.S.A. Environmental Protection Agency has several such projects within its design for environment program. One example is Garment and Textile Care Partnership program <http://www.epa.gov/dfe/pubs/projects/garment/index.htm>.

Industry and Nongovernmental Organization Collaboration: Companies such as Starbucks and S.C. Johnson have partnered with the environmental defense on its alliance for environmental innovation, which aims to incorporate stakeholder participation in product and packaging design, supplier management, and other design for environment issues. In another example, Philips electronics successfully teamed with the Dutch Institute for energy research to develop a green TV that is manufactured with no toxic chemicals, reduces energy consumption during production and use, and is recyclable (http://www.bsr.org/).

New Systems of Business: Some companies develop completely new business initiatives to facilitate green product design. Instead of selling customers products, these companies sell customer service based on green product design principles. For example, a flooring company called Re:Source Technologies provides a full range of floor covering services to its customers, instead of supplying only carpets and similar products. Instead of replacing a client's entire carpet, this company periodically take back and replace worn carpet tiles for refurbishment or recycling, depending on their condition.

Restricted Material Lists: Driven by increasing materials restrictions in Europe, a growing number of companies are developing restricted materials lists for their own operations and suppliers. The restricted materials lists prohibit and limit the use of certain input materials in the company's products. In the auto industry, companies are working together to develop a common list for suppliers, in effect standardizing the list of restricted materials across major players in the industry. A few example of restricted list of materials:

- Royal Phillips Electronics List of Restricted Substances in Products http://www.philips.com/shared/assets/Downloadablefile/RoyalPhilipsRestrictedSubstances2007-16041.pdf
- Restricted Substances in Apparel Products http://www.bsr.org/CSRResources/Environment/RSLImplementationResources.pdf
- HP Environment: Material Use in Product Design http://h41111.www4.hp.com/globalcitizenship/uk/en/environment/productdesign/materialuse.html
- Restricted on Using Substances in Electrical and Electronic Products in European Union http://eicta.org/uploads/media/ChemicalsList-154448A.pdf

Academic Programs: An increasing number of undergraduate and graduate schools across the globe are introducing green product design curricula into engineering and/or industrial design programs. At the graduate level, many of these schools work in cooperation with industry on innovative design projects.

Eco-Labeling / Environmental Certification: There are many eco-labeling programs across the world, sponsored by the government and nongovernmental organizations. Many of the best-developed programs are in Europe, but other labeling programs exist in the U.S. and other countries. The certification criteria of these labels often provide standards for sustainable product design. For example, energy star (www.energystar.gov), Global Ecolabeling Network (www.gen.gr.jp), Eu Eco-Label (http://ec.europa.eu/environment/ecolabel/index_en.htm), ISO 14000.

1.2.1 Business Importance

Practicing sustainable product design can benefit the bottom-line benefits by reducing material costs and improving the product. This can increase market share, broaden access to global markets, and decrease compliance fees. Less tangible benefits include enhanced corporate image, improved community relations, and increased access to investor capital. Ways in which companies can benefit from green product design include:

Cost Reduction: Designing for recovery, reuse or recycling can benefit a company's bottom-line when products are considered from a lifecycle perspective. Additionally, designing products to eliminate hazardous substances and reusing components can decrease costs and liabilities associated with product storage, shipping, handling, and disposal. Xerox, for example, reuses and recycles parts extensively in its manufacturing operations, and incorporates the concepts of easy disassembly, durability, reuse and recycling into product design. The company estimates that in 2002 is saving several hundred million dollars a year through equipment remanufacturing and parts reuse. Similarly, Dell Computer offers leasing and asset recovery services that eliminate the burden of obsolescence and disposal for the end user. Dell computers are built for serviceability, disassembly and reuse, the company is able to remarket many of these previously leased or owned products, extending the life of the computers and keeping them out of landfills. The design changes that have made recovery and reuse possible have also lowered Dell's manufacturing costs.

Decreased Production Time: When a product is designed for recycling, the designer may designing the product with less number of parts and also with quick release fasteners, in turn, can speed up the manufacturing process increase workers productivity and decrease time-to-market. For example, when Phillips designed a high-end color monitor using green product design techniques, it needed 35 percent less time to manufacture than a conventional monitor due to a 42% reduction of materials and components (http://www.bsr.org/).

Design for Lifetime Customer: Using sustainable design methodologies can help designers improve overall product quality and performance resulting in highly satisfied customers and increased sales. For example, Quantum Corporation developed a global packaging reuse program that reduced the volume of environmental resources consumed in shipping hard disk drives worldwide to Quantum customers. Quantum's customers, including Apple, Dell, IBM and Hewlett-Packard, supported the program, because it contributed to their own environmental initiatives. By providing post purchase services, like take back of used items, companies can develop a relationship with customer that can yield lucrative referrals and repeat business.

Recognition: Companies that integrate sustainability principles into their product design may benefit from recognition by both consumers and financial markets.

Lastly, despite the potential environmental social and economic rewards associated with product design for sustainable development, little research has focused on methodologies to allow product development companies ability to understand and evaluate how sustainability can be integrated into their product design and development processes. New ways of integrating sustainability issues into product design process need to be developed to tackle a new set of regulations, directives (both mandatory and voluntary) relating to product's sustainability issues.

1.3 Research Objective

This research is focused on how product development can be assisted in developing product design concepts (ideas) so that quality, environmental, social and economic benefits are addressed in an early stage for the eventual purpose of maintaining the company's competitive advantage and meeting the current concern of sustainability. To deal with the stated research problem, the following approach is considered.

The main objective of the developed approach is to illustrate a flexible systems framework (a step-by-step procedure) that attempts to integrate sustainable development issues at design stage of product development process. The sub-objectives are to:

(1) to facilitate a design process where necessary well-established systems design and innovation management tools can be applied under a systems framework with ease

(2) to enumerate potential alternatives for improvement to meet the company's strategy and customers requirements for sustainability
(3) to support designers throughout the entire design phase
(4) to prove the practicability of this design process, an example is given

To cope with increasing complexity of product design for sustainable development needs knowledge of *systems engineering approach.* We know that product design is continuously challenged to change their way of dealing with triple bottom line of sustainable development as a response to new opportunities, regulatory requirements, competitive threats, or changed circumstances (as identified in Section 1.2).

1.4 Research Approach

This research recognizes the fact that product design process is an important part of product development process and should be tackled and modeled as a complex system. A framework for the methodology for managing product design process that considers sustainable development criteria at early stages of the process is demonstrated in this research.

Checkland (1985) mentioned that rational intervention in human affairs, if it is to constitute not only action but also research, so that future interventions may be made more effective, needs a well-defined methodological framework. The proposed framework is based on Soft Systems Methodology (SSM) approach and theory. A supporting tool is used within this framework:

- TRIZ, the TRIZ (the Theory of Inventive Problem Solving) method as a *tool* for a designer to handle design contradictions in innovative design problem solving process. The TRIZ method was developed in the former Soviet Union by Altshuller through analysis of over 400,000 patents (Jones and Harrison, 2000).

Within the larger SSM framework, this tool provides a synergy that makes it suitable and valuable for innovation management. This synergy builds on the concurrent and iterative characteristics evident in those application tools, and overlaps many of the phases of SSM. Product design is a creative process that shall not be limited by too strict guidelines (Nielson and Wenzel, 2001). Thus the framework presented in this research shall only be considered as general framework for sustainable development modeling and decision making during the product design process. As soon as the general procedure is recognized, product designers are encouraged to adapt the principles to their own situations.

1.5 Organization of this Document

This dissertation is organized as follows:

Chapter 1 introduces the research problem.

Chapter 2 reviews the relevant literature on sustainable development, industrial design, product development and issues related to product design for sustainable development.

Chapter 3 presents a framework for systematic inclusion of sustainable development principles in product design process.

Chapter 4 discusses an example to demonstrate the methodology developed in Chapter 3.

Chapter 5 presents conclusions and description of the future work to be done.

Chapter 2

Literature Review

Current literature shows that combining sustainable development criteria in product design and development still needs to be further examined (Waage, et al., 2005) because current form of eco-design does not include optimization of social, ethical and economic issues (Maxwell and van der Vorst, 2003). In this respect, our research will shed some light on systematic inclusion of sustainability principles in product idea generation phase of product development process. We argue that the complexity of inclusion of all three categories of sustainability criteria (three bottom line of sustainable development) is the major cause of infancy in structuring this process efficiently. According to Waage et al. (2005),

- There is still a vacuum in developing process to integrate sustainability criteria and characteristics in product design process through combined stakeholder negotiation and academic review.

This research has crucial importance in product design, development and marketing because sustainability performance will increasingly constitute an asset, even a priori requirement for selling products in international markets or qualifying as a supplier. Further, firms that take full responsibility for the environmental and social impacts of their products from cradle to grave experience high levels of organizational learning (Lefebvre et al., 2000). This research focuses on systematic combination of social, environmental, and economic dimensions in technical dimension of product design. The rest of this chapter introduces the concept of sustainable development and its components; how engineering analysis and design can be related to sustainable development; the relationship of product design process and sustainable development; and discussions of Soft Systems Methodology (SSM), and TRIZ (the Theory of Inventive Problem Solving).

2.1 Sustainable Development (SD)

The concept of sustainable development has emerged in the 1970s out of a general concern about the global environment as a result of pollution and an increasing usage of sources of raw materials and energy (Ron, 1998). Sustainable development is the most important and greatest challenge in the 21st century (Griese et al., 2004). Sustainability means the rearrangement of technological, scientific, environmental, economical and social resources in such a way that the resulting heterogeneous system can be maintained in a state of temporal and spatial equilibrium; while sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

Since the Brundtland Commission introduced the concept sustainable development (WCED, 1987), many ins and outs of this concept have been studied (Kruijsen, 1998). Over the past years the basic idea of sustainable development has spread all over the world. It has found a large number of supporters on all levels of society and in each region of the world. Sustainable development can be described as the process of using our material resources wisely, so that future generations can also enjoy improved quality of life, a continually increasing standard of living, and a stable environment. These debates undoubtedly will influence the way we manage our natural resources, safeguard human health and the environment, grow our foods, and design industrial products and processes in this century (Sikdar, 2000).

The concept of sustainability applies to integrated systems comprising humans and the rest of nature; the structures and operation of the human component (society, economy, law, etc.) must be such that they reinforce the persistence of the structures and operation of the natural component (ecosystem trophic linkages, biodiversity, biogeochemical cycles, etc.) and vice versa (Cabezas, et al., 2003).

While it has proven difficult to develop a detailed consensus around the concept of sustainability, there is an increased recognition that the current growth of human activity cannot continue without significantly overwhelming critical ecosystems (Cabezas, et al., 2003; Sroufe et al., 2000; Maxwell and van der Vrost, 2003).

2.2 Systems Perspective of Sustainable Development

There are two fundamental, distinct and broad visions of the concept of sustainability (Morse et al., 2001) are shown in the following table:

Table 2.1. Two Fundamental Visions of the Concept "Sustainable Development"

Visions	Features	Specialties
Sustainability as an approach	A package of 'good' practice	It has clear definition and progress toward sustainability can be monitored by simply noting the implementation of 'good' practices
Sustainability as a system property	The ability of the system to exist in some preferred state and continue to deliver its products over time	This vision poses more problems in terms of definition and measurement than a simple list of 'good' practice, not least being the need to identify the system boundaries and time scale.

Perhaps the most subtle but critically important aspect of sustainability is the fact that it has to be viewed from a systems point of view (Geddies, 1993; Morse et al., 2001). In this research, we consider sustainability from systems point of view. It is important for sustainability that the operation of the elements making up the system sustain each other, in the same way that the organs that make up a body work together to sustain the person. A system cannot be sustainable with a major subsystem (economy, ecology, law, etc.) operating without regard to the rest of the system any more than a person can live with a malfunctioning major organ (Cabezas et al., 2003).

The need to understand the entire system presents a challenge for the scientific investigation of sustainability because it becomes necessary to look for approaches that are applicable across range of disciplines (Cabezas et al., 2003). This is difficult because most of the measurable variables, principles, and criteria commonly used in science are discipline specific, e.g., there is no exact economic equivalent to the second law of thermodynamics (Cabezas et al., 2003). There are some similarities between concepts among different disciplines, but the mapping across disciplines is not sufficiently accurate for it to form the basis of reliable principles. Therefore, principles are needed that are applicable to the entire range of systems and subsystems.

2.3 Sustainable Development and Engineering Analysis and Design

Engineering analysis and design is a huge challenge (Crittenden, 2002). Crittenden (2002) considers three components of engineering analysis to be very important:

- To dig deeper into the sciences and theory and translate them to practice
- To consider the environment in a systems engineering context to promote high quality of life for humans, plants, and animals as well as future generation
- To include social dimension in feasible solutions for engineering problems. It is very important to communicate to the society about the long-term consequences of these solutions. Promoting an engineering solution should promote the theme that no one group is left behind regardless of their ethnicity or national background or beliefs.

It is a well-established fact that developers must be able to incorporate sustainable development ideas at the invention and design phase of product and process development. Tools and models also need to be developed that allow the developers a "holistic" view of their works (Sikdar, 2000). This task is very multidisciplinary (Sikdar, 2000; Geddies, 1993). Geddies (1993) pointed out a few issues that are applicable to many professions including engineering where the practitioners attempt to assess the future direction of markets and economies:

- to learn to forget what has always been done in the hope of discovering new insight
- to know the differences between a fad (short life span-when it is out, it is really out of fashion) and a trend (long life span- makes basic sense and has sustaining value)
- for every trend there is a counter-trend which exists in tandem

- compromise does not work, least common denominator does work (because it reflects the true concerns and commitments of all the players)
- no social trends ever swings back along the same path

2.3.1 Sustainability and Technology

Technology has major role to play in sustainability because it provides the means by which humans take resources from the environment and transform them to meet their needs (Cabezas et al., 2003). Further, the size of the human population practically guarantees that any technology that is widely adopted will use and transform large amounts of resources with consequent impacts on the environment. New technologies are constantly making new resources available or improving access to currently available resources. According to Ulrich and Pearson (1998), technology development is a distinct activity in which the core technologies that might be embodied in future products are refined and proven.

Technology, however, comes with a price: the environmental impact of the processes involved in accessing resources made available through the technology, or both. Moreover, technology is subject to social, political and economic forces that determine the extent of the uses which technology is put and its penetration in the society. Any technology therefore must be judged on its environmental cost as well as potential benefit in social, economic and legal framework within which it resides. Depending on how it is used and marketed, technology can change the way we view nature and the degree to which we rely on its services, and thus out impacts on it (Cabezas et al., 2003).

One driver for technology development is *efficiency*. While efficient processes make it less expensive to manufacture products, efficiency plays a role in sustainability as well by reducing the amount of resources going into a product. With increased awareness of ecological impacts of various activities, technology also often is specifically developed to mitigate such impacts. For example, one may seek to replace older technologies, however, are not a guaranteed route to sustainability since this does not necessarily mean lower or better use of resources. If economic, social and legal systems are not carefully developed to coincide with sustainability goals, resource use and pollution could increase despite the availability of appropriate technologies.

The development and adoption of technology as well as our use of resources is driven by various factors. The "best" technology is not necessarily that which is adopted – market phenomena such as lock-in, social forces and politics can impede the adoption of appropriate technologies even if these are available. Improved efficiency often means products can be offered at lower prices, increasing overall demand. Technology can also make us feel isolated or independent of the environment and thus free to do as we please, when in fact this is not fully known or not necessarily even studied. We must understand not only technologies, but the social, political, legal, and economic systems within which they operate. In view of global, environmental and social challenges such as resources depletion, the regional imbalances of resource allocation, and the disparities in access of new technologies, science and industry have to reconsider the basic objectives in technology development (Griese et al., 2004).

2.4 Product Design Process as a Part of New Product Development (NPD) Process

The design process is one of the major tasks for any firm, responsible for two major types of design activities (Sroufe et al., 2000):

- New product design and development
- Process design and development

Both product and process designs are closely interrelated and greatly influence each other while simultaneously impacting the environment and social sub systems. These design activities, in general, present opportunities for firms to find solutions to environmental and social issues. These two design activities, when combined, shape the scope of the transformation process by determining the types of inputs required and outputs created (Sroufe et al., 2001).

The traditional NPD framework views the process as linear system consisting of seven linked stages (Tsinopoulos and McCarthy, 2002; Sroufe et al., 2000):

- Advanced research
- Product concept
- Product specification
- Product development
- Pilot product/ developing prototype
- Production
- Reincarnation/disposal

This research considers NPD process as a complex system of decisions (Tsinopoulous and McCarthy, 2002). The information required to make decisions is often not adequate, because the problem space is nearly always infinite and subject to nonlinear behavior (Anderson, 1999). In fact, non-linear mechanisms are responsible for the unpredictable dynamics of the innovation process. Therefore adopting a nonlinear approach (complex systems) to NPD would appear to be reasonable and rational step (Tsinopoulous and McCarthy, 2002). In all stages of the NPD process, environmental and social factors must be considered in addition to all other objectives and issues. The end of NPD process creates several important outcomes, such as the design and introduction of the product, the determination of the types and quantities of materials used and various processing characteristics (i.e., equipment needed) (Sroufe et al., 2000).

When taken together, the product design process sets in place the material and capacity requirements, establishes the cost and performance traits of the product, and determines the types and timing of waste streams created and when those waste streams will be created (Sroufe et al., 2000).

The design activities are strongly cross-functional in nature. That is, to be successful from both a corporate and marketing perspective, the product design activities must consider *the perspectives of multiple parties and stakeholders* (O'Connor and Hawkes, 2003; Westerberg and Subrahmanian, 2000). Included are areas such as marketing, product engineering, finance, manufacturing, production and inventory control, accounting, manufacturing engineering, quality assurance, top management, stockholders, suppliers, government, competitors, special interest groups and the customer (Santos-Reyes et al., 2001).

Additionally, within the design process, there are transition points. For example, there is a transition point between product concept and product design (Sroufe et al., 2000). The transition point's role is to ensure that all of the major concerns, objectives and issues present in the preceding stage have been addressed before permitting the process to continue to the next stage. At these transition points, different factors affect resource management such as formal information systems, the presence of a green corporate culture; and the use of different tools, metrics, and options. During these transition points we can study how firms generate new opportunities from environmental and social problems.

2.4.1 Product Design Process

Product design process is an essential factor during the early phase of new product development, which can be considered as a complex set of integrated efforts, including generating ideas, developing concepts, modifying details, and evaluating proper solutions (Hsiao and Chou, 2004). Since the 1960s, some design scholars have successively developed many design processes, taking advantage of definite methodology to eliminate the illusion of "Designer as black boxes" (Hsiao and Chou, 2004). Stevens et al. (1999) found that NPD requires breakthrough creativity because the first ideas for commercialization are almost never commercially viable until they have been substantially revised through a thought process involving branching.

Design is an activity based on problem solving and of a cognitive nature. The purpose behind design is to create or restructure a specific component, product or service in order to fulfill a social, organizational and engineering objective efficiently. Design is a creative process in which products and processes are conceptualized and specified, which plays a role in enabling firms to successfully exploit their innovative research.

Design activity involves the creative visualization of concepts, plans, and ideas, which are represented through the use of sketches, and it is aimed at providing instructions to create something that does not exist, or at least does not do so in that particular shape or way.

Design is broad and complex concept that takes in varied and distinct disciplines. It can be perceived and dealt with in different ways, but it is design as creativity that perhaps stands out most clearly. The act of designing requires a combination of logical and intuitive thought. One of the objectives of design management is to design with an environment that stimulates and fosters creativity (Cooper and Press, 1995).

Product design process is an essential factor during the early phase of new product development, which can be considered a complex set of integrated efforts, including generating ideas, developing concepts, modifying details, and evaluating proper solutions. An inappropriate product design process not only affects product life-cycle phases but also increases the possibility of failure in new product development (Hsiao and Chou, 2004).

Design is considered as being the essence of innovation – the moment in which a new object is thought up, put into material form and shaped into prototype. Thus, design is closely linked with innovation, since the very act of designing itself always introduces something new. Design is crucial to innovation because it represents the creative aspect, where ideas are put into material form, and also because it involves the meeting or union of technical capabilities and consumer demands.

Bruce and Cooper (1997) divide the product design process into four phases:

1. planning – problem formulation and idea generation
2. evaluation – idea refinement and prototype development
3. implementation – transfer of design to production, launch and delivery
4. monitoring – evaluation of outcome against objectives

However, product design can be considered as a more simplified two-phase process (Chiva-Gomez, 2004):

- *The analytical phase* – conceptual phase: The objective of this phase to assess and analyze the socio-economic context and the tendencies within the target market, together with the commercial, strategic, productive, logistic and technological facets of the firm, and aspects dealing with image and communication.
- *The technical phase* – creative phase: This phase involves a formal and creative interpretation of the above mentioned characteristics, as well as the technical resolution required to determine the product.

According to Westerberg and Subrahmanian (2000), there are 5 basic steps involved in product design.

a. **Client statement** (statements of need)

The first activity is to establishing goals for the design – i.e., what it must deliver all the stakeholders involved to be happy about it. Stakeholders include the designers, the manufacturers, the distributors, the customers and the waste processing companies. Goals can be broken down into objectives and constraints, noting that the same goal could be either depending on the effort we may be willing to expand to meet it.

b. **Managing the design process**

Definitions of design management can be either very specific or broad. However, we understand that all of them emphasize the need for certain managerial activities to compromise design or its apparent effects. Product design management is understood in different ways, depending on the aspects or activities highlighted. The main activities included with this concept that mentioned in the literature may be classified into four groups (Chiva-Gomez, 2004):

The first consists of the activities linked to decisions on organizational aspects of design: the existence of an in-house design function, the use of external expertise, etc.

The second activity consists of the transmission of information and knowledge about the company (objectives, priorities, competitors, design strategy, post evaluation measurement and feedback) to the designers.

The third type includes activities associated with the creation of an organizational context that favors the design process, with special emphasis on communication, dialogue, creativity encouragement, participation and management support to raise its importance.

Lastly, the activities that form a part of the operational management of human and other resources within the actual product design process itself: stages, customers' and suppliers' involvement in the process, use of computer-aided design tools, assessment of manufacturability, cost estimation of new products, etc.

c. Establishing design function

In this step, previously defined objectives into an appreciation of all functions the product must deliver. These are often in the form of an action verb and a noun. A list of tools for this activity can be found in Dym and Little (2000).

d. Estimate desired level of performance

For each goal, a limit(s) is to be determined. This step helps to reduce the number of options to examine by establishing the location in the desired space.

e. Develop tests

Tests should be created to pick a design alternative. With tests design efficiency is determined in terms of stated goals (Westerberg and Subramahnian, 2000). Modeling, making prototypes, consulting a panel of experts are a few example of test methodology. Tests often can be very time consuming.

There are many more steps that are parts of product design process. These include establishing the space in which one is willing to look for design alternatives, generating and evaluating alternatives, etc (Westerberg and Subrahmanian, 2000). Decision making regarding manufacturing parts or purchasing parts is a big deal in design process. Serious focus must be given to distribution, servicing, and disposal of the product.

Roy and Riedel (1997) define product design as "the choice and configurations of elements, materials and components that give the product particular attributes of appearance, performance, ease of use, method of manufacture, etc." According to Westerberg and Subrahmanian (2000), product design is a mixture of many talents, including those from business, fine arts, social science, other engineering, as well as the specialist of the particular field where the product will belong to (for example, for chemical product design: experts for chemical and chemical engineering). A valid experience requires much more than the technology to be considered to make a successful product.

In sum, product design is understood to be the process by which a product is developed while taking into account any function, use, manufacture, communication requirements, and end-of-life strategies. This implies not only the creative effort, but also a whole series of technical, strategic and market aspects. These convergences and requirements entail a complexity within the process, which needs certain management activities to support and sustain it. Product design is fascinating and complex. Design teams with diverse backgrounds of people are more efficient.

2.4.2 Product Design - Challenges of Sustainability

Bullinger et al. (2000) once stated that the new millennium has fostered a look towards the future, accompanied by both hopes and fears. In today's highly competitive and uncertain market environment with short product life cycles, product design must not only satisfy the 'quality' and 'speed' of production, but it also ensures that products themselves have included innovative values (Hsiao and Chou, 2004).

Product design and innovation project with 'sustainability' element are still treated with particular caution. Sustainable product innovation is a new field and a business model which integrates economic, environmental, social and ethical issues still to be developed (Charter and Tischner, 2001). Firms have financial resources, technological knowledge and institutional capability; as well as international and long-term vision to include sustainability as a new dimension of operations performance. The recent introduction of systematic innovation methods into sustainable design can reduce the innovation risk (Mann and Jones, 2002).

Table 2.2. The literature exploring the motivating forces in combining environmental and social issues in technological innovation can be grouped into three general areas

Views	Driver of Innovation	Scholar(s)
The public policy view	Regulation is considered as a driver of innovation	Allenby (1999); Delplace and Kabouya (2001); Porter (1991)
A voluntary standard perspective	Corporations adopt environmental performance standards to avoid existing or anticipated (for example, ISO 14000 series)	Nash and Ehrenfeld (1996); Deleplace and Kabouya (2001)
A resource based view/ Included in company's operations strategies	Eco-design / design for environment concept: Ecological considerations are incorporated into strategic management, and efficiency improvements are achieved through pollution prevention and product stewardship	Hart (1997); Barney (1991); Wernerfelt (1984); Jimenez and Lorento,(2001); Sroufe et al. (2000); Blattel-Mink (1998); Chang and Chen (2003); Strasser and Wimmer (2003); Santos-Reyes and Lawlor-Wright (2001); Jones et al. (2001); Partidario and Vergragt (2002); Ritzen and Beskow (2001); Borland and Wallace (2000); Griese et al. (2004)
	Sustainable product development concept: the strategic management should consider triple bottom line (balancing economic, environmental and social aspects) through sustainable product development process.	Maxwell and van der Vorst (2003); Walker (2002); Gao et al. (2003); Roche and Toyne (2004); Bhander et al. (2003); Ljungberg and Edwards (2003)
	Sustainable product development concept: the strategic management should consider triple bottom line (balancing economic, environmental and social aspects) through sustainable product development process.	Maxwell and van der Vorst (2003); Walker (2002); Gao et al. (2003); Roche and Toyne (2004); Bhander et al. (2003); Ljungberg and Edwards (2003)

The discipline of design is also about exploring new ground and charting new territory, and if we are to do this effectively and sustainably, we must be fully aware of the context in which we find ourselves and learn to respond to it in appropriate ways. Product design is part of the broader product development activity, which also includes creation of the product requirements, development of the basic product concept, product testing, and production ramp up (Ulrich and Pearson, 1998).

Product design has received increased attention in the academic and business communities over the past decade. For example, Business Week sponsors an annual design competition and devotes dozens of magazine pages each year to product design. This attention resonates with the widely held belief that product design is important to the success of the manufacturing firm. For the variation to be significant it should contribute to competitively important differences in the profitability of the associated products.

Product profits are determined by both revenues and costs. Design may influence revenue by leading to changes in market share and / or price. This influence may come about because of design's role in defining the features of product, its performance quality, its reliability, and its aesthetic appeal (Ulrich and Pearson, 1998). The WBSCD (World Business Council for Sustainable Development) and Global Reporting Initiative (GRI) have identified a few major elements in designing sustainable products. They are:

- Reduction of mass intensity (total quantity of material used)
- Reduction of energy used
- Reduction of dispersion of any toxic materials (reduction of health and environmental risks)

- Enhancement of recyclability
- Maximize the sustainable use of renewable resources
- Extension of life of product

2.4.3 Product idea generation for sustainable development

Designing products with consideration of all three categories of SD criteria is somewhat different than regular product idea generation process. Next few sections will discuss about what this process is and what makes this process "complex"?

2.4.4. Steps of Idea generation for sustainable development process

Discussion about product idea generation for SD process involves the definition of the process in terms of its input and output, the temporal and causal relations between these, and the relations between these and the organizations (product development company), people and system that execute them. Discussions also involve the assessment of product design process in terms of reliability, efficiency, efficacy, etc. In practice, product design processes are seldom designed from scratch. Typically, existing product design processes are taken as a starting point and adapted to changed requirements.

2.4.5 Complexity

What makes product idea generation for sustainable development processes complex? Complexity concerns the structure of product idea generation for SD processes:

- the variety and "manyness" of elements (heterogeneous) and
- relationships between them and with its surroundings

Besides, the perception of and changes in this structure are important.

With respect to variety of elements, we consider three aspects as the most important.

First, product idea generation for sustainable development typically involves several knowledge domains. A design process needs to consider technical and analytical data. Analytical data is needed to assess and analyze socio-economic context and the tendencies within target market, together with the commercial, strategic, productive, logistic and technological facets of the manufacturing firms, and aspects dealing with image and communication. All these determine the characteristics of the product. On the other hand, technical data needs to formally interpret the above-mentioned characteristics (Chiva-Gomez, 2004).

Second, product idea generation for SD processes operate on vastly different time scales. On the one hand, some information, both analytical and technical, remains same for many years. For example, macro social performance data such as, changes in product value chain, external value of purchases, etc. may remain unchanged for years. On the other hand, data for new knowledge development or new regulations imposed on the products may change frequently. Varying time scales make it difficult to understand product idea generation for SD processes.

Third, product idea generation for SD processes operate at different geographic locations (Shooter et. al., 2000). Traditionally, design was undertaken by a small team of designers operating out of a single location. The team captured design information as notes and sketches in logbooks and as design drawings. As a result, team members could easily exchange the relevant design information. The exchange of design information is not much more difficult given the complexity of modern products and design processes (Shooter et al., 2000). At present, product realization may be a collaborative effort among teams operating at different geographical locations.

Fourth, different members (designers, production engineers, material specialists, environmental regulations specialists, human factor specialists, etc.) of product design teams use heterogeneous systems, in terms of software and hardware, to generate design information (Shooter et al., 2000). Design information now comes in many forms and is generated by a wide variety of computer-based tools. However, currently available information exchange tools are typically used only during the latter stages of design. They store information that is the outcome of design activities with little regard to capturing the information produced through development of the design or by the processes that generated this information. Furthermore, these tools essentially limit exchange to geometry-related information and provide little support for top-down concept ideation. The shortcomings of these tools provide fertile ground for misunderstandings between participants in a product realization effort. It is therefore, necessary to examine the flow of design information and characterize it so that it can be captured, catalogued and delivered in a useful manner.

With respect to the variety of relations, we find that steps of product idea generation for SD seem to be independent, but in fact they exchange information at certain point of time. As the number of elements or relationships increases (manyness), more attention is required to comprehend and classify the sorts of the elements and relationships.

Comprehension, however, is related to mental capabilities of humans. A major reason that product idea generation for SD appears complex is probably the fact that minds are used to reason about three-dimensional world- whereas product idea generation for SD - do not fit in a simple geometric representation. For example, designing a simple product for sustainable development does possible by considering its functions only. Product idea generation for SD practices allow product developers to minimize waste and turn wastes into profitable product(s) in all stages of product's lifecycle. Complexity is partly subjective, i.e., a matter of perception (Biemans et al., 2001). Whether we perceive something as being complex depends on our background. This observation in itself gives rise to another cause of complexity. Many people are involved in product idea development for SD and a common frame of reference among product design engineers, managers, experts in different fields, and the people that are to carry out the product idea generation for SD processes does not exist. They all speak a different language, which impedes a common understanding.

Finally, immensely complicating are the uncontrolled modifications of product design processes to incorporate sustainable development criteria to meet all sorts of demands. In the course of time, different people with different objectives, styles, budgets, and experiences modify the existing product design processes. The result is a myriad of entangled processes that hardly resembles the original design process. It stays complex because it resists the large-scale overhauls and clean-ups necessary to install a modular structure that would allow us to oversee the product idea generation for SD processes. Lack of time is one explanation, another is the natural resistance to change processes that were developed at high costs and still at high costs and still work one way or another.

Compounding this problem is the fact that product idea generation for SD processes can change autonomously. For example, the people that are part of product design process might modify this process to implement an eco(re)design approach whereby they start with an existing product and reduce its environmental impacts which is not sustainable (Maxwell and van der Vorst, 2003).

2.5 Soft Systems Methodology (SSM)

Systems analysis, which emerged from disciplines related to engineering, succeeded in its operating field, dealing with structured situations. This type of analysis extended to managerial decision making, creating an equivocal, because the necessities of these systems have different characteristics from those of the hard core engineering situations. To tackle these kinds of problems Soft Systems Methodology (SSM) was first introduced by Peter Checkland in 1981 in his book: *Systems Thinking, Systems Practice.*

SSM has been grouped among the "soft" operations research tools versus the "hard" mathematical and decision models that have traditionally existed in the operations research field. It is a methodology for analyzing and modeling *hard-to-define and complex systems* that integrate *technology (or hard) systems* and *human (soft) systems*. The latter system is defined by Checkland (1981) as a human activity system (HAS). These systems are different from natural systems or designed systems (which can be either physical or abstract). An HAS is defined as a collection of activities, in which people are purposefully engaged. Two important characteristics of HAS are (Wilson, 1984):

- systems of activities and
- a social system related to activities

Checkland (1981) proposes that the same methods used for engineering technology may not work well for the more unpredictable and complex human side of the system. SSM addresses "fuzzy" problems that occur when objectives are unclear, multiple objectives exist, and where there may be several different perceptions of the problem. SSM recognizes that different individuals will have different perceptions of the situation and different preferable outcomes. It recognizes these differences, and explicitly attempts to take these into account from the outset to ensure that the results of the analysis are acceptable to all parties concerned.

Use of an SSM approach does not attempt to define a single right method of action, but through an *iterative process,* defines an acceptable improved path of action. People who are involved in the methodology include not only actors within the designated system, but also clients and owners of the system. This is a very useful and important consideration, especially when involved and buy-in of all potential customers is desirable. In general, any approach to model this complex system should have a number of characteristics including:

- The capability for understanding and modeling complex problems; capability to incorporate multiple views of the problem; and
- Capability to learn

Checkland (1981) argued against the goal-seeking model of human action found in management sciences theories as well as in traditional organizations theories (Bergvall-Kareborn, 2002). Here, the manager is viewed as a purely rational decision-maker, pursuing organizational goals that often provide the standards against which progress will be judged. Thus, in order to find a complement to contemporary management theories, Checkland (1981) began to investigate whether systems thinking approaches of that time, like Systems Analysis and Systems Engineering, could be used. This was done by studying what happened when these methodologies were applied to 'soft' problems, such as those of policy-makers, administrators and managers. It was especially the methodologies were described by Jenkins (1969) that constituted the starting point for SSM. However, these approaches were also found to be inadequate for managerial real world situations due to their emphases on structured problems, and hence on finding efficient means of achieving known and defined ends. This was an inappropriate focus for management problems, characterized by Checkland (1981) as ill structured, fuzzy and 'soft' and where the real difficulty lies in defining the problem itself. Beside this, these approaches, later referred to as hard systems approaches, also shared management science's view of reality as objective neutral and value-free as well as the goal-seeking model of human behavior. Checkland (1981) reacted against this and instead pointed out that people interpret situations differently, depending on what they find meaningful. What is perceived as meaningful is dependent on an individual's background, pervious knowledge, experience and so on. Therefore, a situation perceived as problematic by one person does not need to be interpreted accordingly by another. Further, depending on the way we interpret a situation, we form intentions; i.e., in the light of our interpretation we decide to do one thing rather than another (Bergvall-Kareborn, 2002). Ferrari et al. (2002) considers that this methodology situates in an intermediate status between a philosophy and a technique as shown in Figure 2.1. *Philosophy* holds wide and nonspecific guides to actions, dealing with the matter "What" of a situation. The *techniques,* which embody specific action programs that will produce standardized results, deal with the matter "How." SSM has both elements, "What" and "How," being neither too vague, thus not being able to provide a direction, nor too specific, almost limiting the application of actions. SSM promotes easy exchange of relationship between systemic view and reality (Figure 2.2).

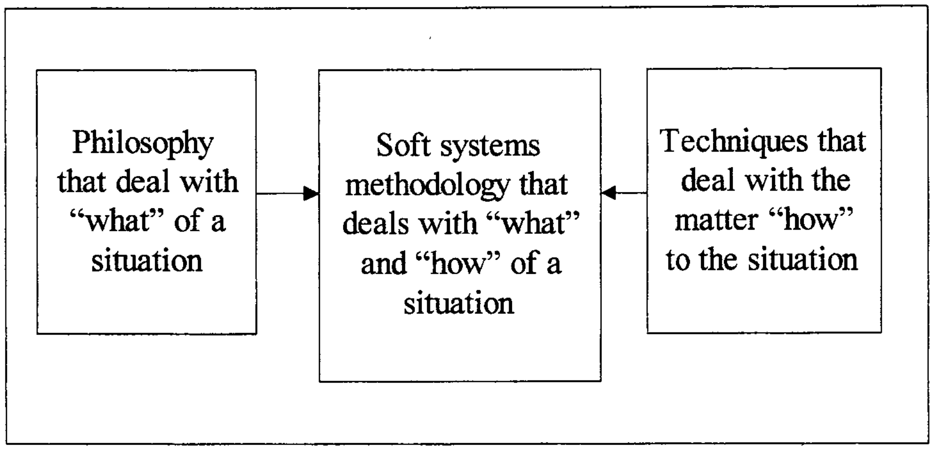

Figure 2.1. SSM's status between philosophy and technique

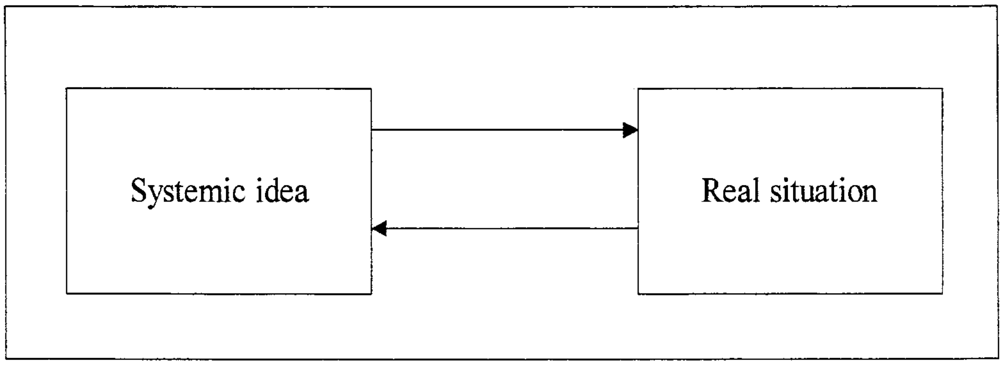

Figure 2.2. Exchanging relationship between systemic view and reality (Ferrari et al., 2002)

There are many other methodologies that can be used to tackle vagueness and imprecision of a decision making process, for example, fuzzy approach. Utilizing the mathematics of fuzzy sets, represents and manipulates imprecision in engineering design. This includes the effects of customer and designer preferences, formal strategies for trade-offs (including ability to record these trade-offs decisions for later examination or modification), iteration in engineering design, and noise (such as uncontrollable manufacturing and material property variations) (Otto and Antonsson, 1994). In this research, we wanted to have a system methodology not a technique, if properly applied, can guarantee a particular kind of result; it leaves room for personal styles and strategies of problem-solving. Unlike other methodologies, in SSM the output is the learning aspect, which leads to actions, knowing that this will lead not to 'the solution', but to a changed situation and new learning. The SSM also allows smooth implementation of any decision tool in any of its stages.

SSM is a seven-stage process (Figure 2.3) in which users, analysts, and designers incrementally define the problem, generate and evaluate alternatives, and choose an acceptable solution. The application of SSM in practical settings has been gaining popularity with scores of applications (Presley et al., 2000).

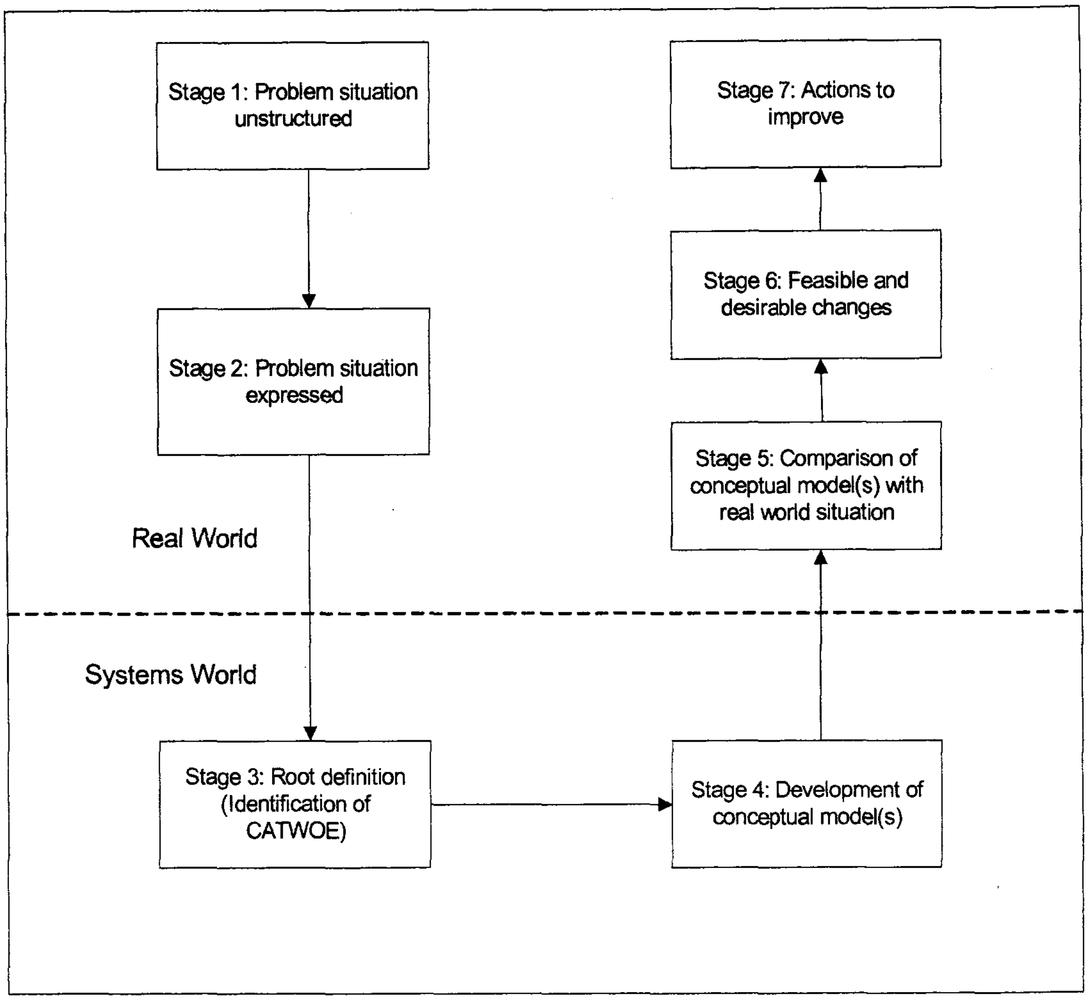

Figure 2.3. Graphical representation of SSM (Checkland, 1981)

2.5.1 Stages 1 and 2 of SSM

These two stages are reported together, because they are part of the phase of explanation, in which we are seeking richest possible "panorama," not of the problem, but of the real situation in which it is found. This expression should be done to minimize the influence of preconceived structures, considering that stages 1 and 2 will be integrated with the "real-world" field. The description of this situation must be done considering structure, process, and the relationship between structure and process.

2.5.2 Stage 3 of SSM

This stage involves the distinction of some systems of the situation described in the previous stages, which might be outstanding to the matter at hand, and the preparation of brief definitions of the character of this system. Ferrari et al., (2002) emphasizes that the distinction of more than one system in this stage can enrich the analysis of SSM.

As we can see in this stage, the methodology moves to the field of systemic thought, applying the concepts of an outstanding system to describe how the system is. The elements of the distinct systems must be as follows:

- The customers: Beneficiaries or victim affected by the activities of these systems
- The actors: Those who perform the main activities of the systems
- The transformation process: The ways in which the inputs of the system turn into outputs
- Weltanschauung: The worldview that permeates these systems
- The owners: Those who have the power of creating the systems and, also ending them
- The restrictions of the environment for these systems

In short, the definitions of the outstanding systems must be described as a group of human activities conceived as a process of transformation. Checkland (1981) points out in one of the so-called SSM laws that these definitions of the human activity must be described by verbs where the actors can perform directly (how to collect information and make plans), and not by verbs that characterize the consequences more than the actions (how to lower costs or raise morale).

2.5.3 Stage 4 of SSM

Stage 4 is in charge creating a conceptual model able to reach the transformation described in Stage 3. Still the systemic field, this stage makes use of systems concepts to describe how the outstanding systems should be for this situation. This description can be done at different levels of detail, making use, though, of the systems hierarchy concept.

After having created the conceptual models, it is necessary to validate them through comparison with a formal system and/or with other systemic conceptions. A formal system has following elements:

- Purpose/assignment
- Performance measurement
- Process of making a decision
- Connected subsystems
- Interaction with the ambient

- Physical and human resources
- Continuity

2.5.4 Stage 5 of SSM

This stage still in the field of systemic focus, involves comparison of the real situation (stage 2) with the conceptual models (stage 4). This comparison can be at the level "What" and/or "How," emphasizing, once again, the application of the systems hierarchy. In this stage, the author points out the importance of the participation of those involved in the problem, having as the objective creating debates about possible changes that might occur to minimize the situation-problem.

2.5.5 Stages 6 and 7 of SSM

Back to the real world, stages 6 and 7 are analyzed together. In these stages, based on the comparisons from stage 5, changes in the processes, structures, and attitudes are proposed. Once desirable and feasible changes are defined, then the new problem situation includes the implementation of changes; how to do that may also be tackled using SSM; its learning cycle can begin again (Checkland, 1985).

2.6 TRIZ

When a designer tries to solve an innovative design problem, it is usually a system incompatibility or conflict design problem (Liu and Chen, 2001). As the designer changes certain parameters of the system in his/her design problem, it might make other parameters bad. Traditionally, the designer makes compromise with this kind of contradiction situations and restricts himself/ herself on performing innovative design tasks. The TRIZ method is an available tool for the designer to handle this conflict conditions during the innovative design problem solving process. TRIZ method was developed in former Soviet Union by Altshuller (Altshuller, 1991). TRIZ is a Russian language acronym for Teoriya Resheniya Izobreatatelskikh Zadatch (Skurpskis and Ungvari, 2001). Translated into English it means "The Theory of Inventive Problem Solving." TRIZ is the product of an exhausted analysis of the world's most creative technological innovations as described in worldwide patent literature. This analysis has been conducted over a fifty-year period with the total number of patents analyzed now totaling approximately three million.

The objective of TRIZ is to discover how inventors invent. Trying to understand the inventive process was aimed specifically at inventions that solved difficult engineering problems in novel ways. The problems considered were difficult because they contained one or several contradictory requirements, e.g., speed vs. precision and a situation where compromise was no longer acceptable solution. For a solution to be labeled "novel" or "inventive," it had to comply with five requirements (Stratton and Mann, 2003):

1. The solution fully resolved the contradictory requirements, e.g., speed with precision

2. The solution preserved all of the advantages of the previous system

3. The solution eliminated the disadvantages of the previous system

4. The solution did not introduce any new disadvantages

5. The solution did not make the system more complex

The field of creative thinking is rich with many different approaches and techniques. The range of techniques spans the spectrum from psychologically based approaches such as brainstorming to knowledge based approaches such as Value Engineering and Morphological Analysis.

Psychological methods such as brainstorming are aimed at tapping into the "creative" subconscious mind to stimulate the process of idea generation. The rules for these types of approaches emphasize quantity over quality and the separation of idea generation from idea evaluation. There is no doubt that brainstorming can be an effective tool for generating ideas. The three critical assumptions in psychologically based techniques such as brainstorming are:

- The best solution to a problem is lurking in the mind of the individuals involved in the exercise.

- In the freeform "creative" atmosphere of the brainstorm, the idea will be articulated.
- The idea will be recognized as the "best idea" and chosen from the myriad of others that had been proposed.

Value Engineering is a systematic method to improve the "Value" of goods and services by using an examination of function. Value, as defined, is the ratio of Function to Cost. Value can therefore be increased by either improving the function or reducing the cost. It is a primary tenet of Value Engineering that quality not be reduced as a consequence of pursuing value improvements. Producing original ideas in VE process is done mainly by brain storming session. It is already mentioned that brainstorming process has some inherent problems related compared to TRIZ. TRIZ and value engineering method can be complementary to each other. VE technique typically can be very useful as a check on the designs finally evolving from the procedures used by TRIZ methodology. TRIZ can come handy during the idea generation step of value engineering.

The Quality Function Deployment (developed in Japanese industry in the 1970s, which is based firmly on an assessment of customer needs (Griffin and Hauser, 1993). QFD can be applied in six steps. These are:

- Identifying the customers and determining customer requirements
- Determining relative importance of the requirements

- Competition benchmark
- Translating customer requirements into measurable engineering requirements
- Setting engineering targets for the design

QFD evolution is customer requirement/ product driven (Pugh, 1991), while TRIZ can be operated in situations where initially there is no product, and hence no 'voice of customer'. TRIZ identifies the "core" problems through the definition of contradictions that are to be solved. TRIZ consists of many sophisticated innovation tools, which is not found in QFD. Thus, it may be said that the operation of designing innovative product by TRIZ may be further refined by the application of QFD.

Concurrent engineering is a business strategy which replaces the traditional product development process with one in which tasks are done in parallel there is an early consideration for every aspect of a product's development process. The problems with product development performance that Concurrent Engineering aims to overcome are those of the traditional serial product development process in which people from different departments work one after the other on successive phases of development. TRIZ and concurrent engineering cannot be interchangeable. TRIZ is used to produce creative ideas but concurrent engineering process itself is a business strategy that addresses important company resources. The major objective this business strategy aims to achieve is improved product development performance. Concurrent Engineering is a long-term strategy, and it should be considered only by organizations willing to make up front investments and then wait several years for long-term benefits. It involves major organizational and cultural change.

Sustainable product design should have creative components in it to gain competitive advantage. Sustainable product is a compromise between three dimensions of sustainable development not necessarily the least expensive product. To motivate customers to buy that product the designer must make sure that product is an innovative product on top of its sustainability quality. TRIZ is selected as design developing tool in this research because of the popularity and acceptance of TRIZ as an innovative idea generation tool at worldwide corporations and organizations, among which are Hitachi, Mitsubishi, NASA, Proctor and Gamble, Philips, Samsung, Siemens, Unilever, just to name a few. TRIZ can effectively and without much costly trial and errors handle contradictions that arise in product design process.

2.6.1 The ideal design with no harmful functions

Finding the ideal solution to a needed effect or function with no additional resources or negative secondary effects is referred to in TRIZ circles as Ideality:

Ideality = (All useful effects or functions) / (All harmful Functions)

One can argue there is little new in this, as a similar emphasis on improving functionality is also evident in widely established approaches such as Value Engineering. However, the difference is that this thinking is central to TRIZ and specialist supporting tools have been developed that specifically concentrate on improving the functionality through innovation rather than traditional cost cutting or sub-optimization focus.

2.6.2 An inventive solution involves eliminating a contradiction

Altshuller's (Altshuller, 1999) early work on patents resulted in classifying inventive solutions into five levels, ranging from trivial to new scientific breakthroughs. Through this work he defined an inventive problem as one containing at least one contradiction and that an inventive solution wholly or partially eliminated the contradiction.

2.6.3. The inventive process can be structured

This early work convinced Altshuller that there was potential to structure the inventive process around trade-off contradictions and it led to several developments (Figure 2.4). In each case empirical data was used to develop Technical Contradiction Solution System. After having identified the significance of contradictions Altshuller went on to classify them into 39 parameters and in a similar way he identified 40 common principles that he found had been repeatedly used in patented solutions. To display the possible technical contradiction combinations he produced a 39 X 39 matrix and identified which of the 40 inventive principles were more commonly associated with specific combinations of contradictions parameters. This matrix is called the Technical Contradiction Matrix. These 40 inventive principles and the Contradiction Matrix have stood the test of time, however, this was only the first of the TRIZ solutions systems.

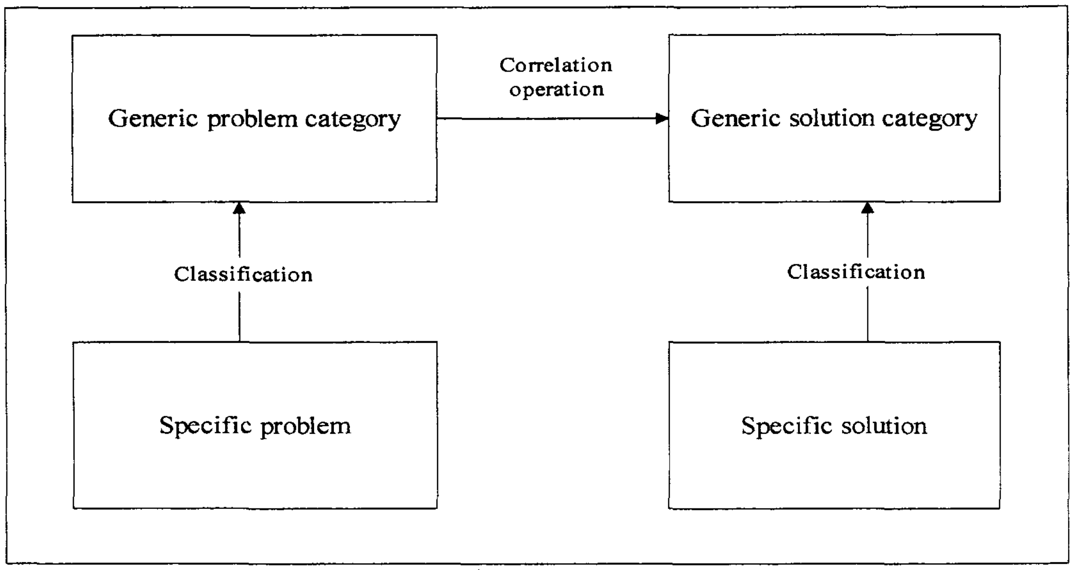

Figure 2.4. The general case for abstracting a solution system (Stratton and Mann, 2003)

2.6.4 Physical Contradiction Solution System

Over a period of time Altshuller and his associates (Altshuller, 1999) identified a further level of abstraction from the technical contradictions. He found that in many cases the technical contradiction could be presented as two extremes of one feature, which he called a physical contradiction. Put more formally: A physical contradiction requires mutually exclusive states as they relate to a function, performance or a component. Typical physical contradictions include: fast vs. porous; movable vs. stationary; hot vs. cold etc.

The relationship between the technical and physical contradictions has been graphically illustrated as shown in Figure 2.5. In the Figure 2.5, a technical contradiction between parameters A and B has been further abstracted to present the contradiction in terms of a common variable parameter C, which represents the physical contradiction. Altshuller found that by defining the contradiction around one parameter with mutually exclusive states the correlation.

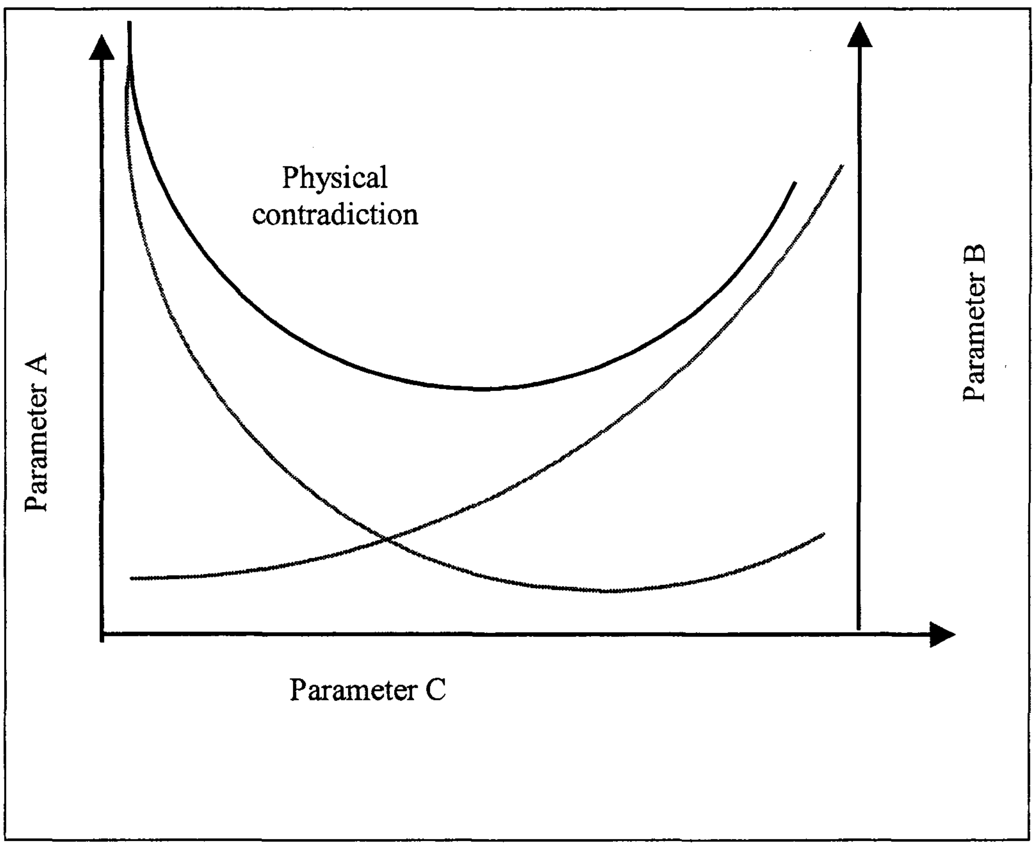

Figure 2.5. A graphical illustration of a physical contradiction (Stratton and Mann, 2003)

operators used to detect a solution could be more generic and there are just four separation principles used to help resolve this type of contradiction.

These separation principles can be summarized as:

1. separation of opposite requirements in space
2. separation of opposite requirements in time
3. separation within a whole and its parts
4. separation upon condition.

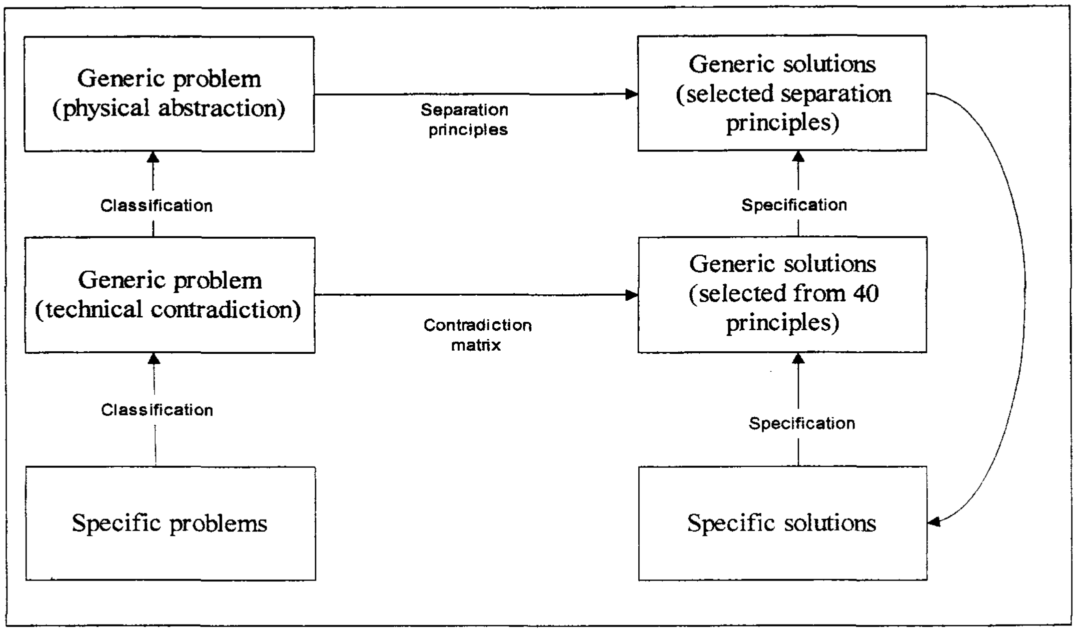

Figure 2.6. The first and second levels of abstraction (Stratton and Mann, 2003)

Figure 2.6 illustrates the relationship between these two levels of abstraction. If one considers the aircraft example, this further level of abstraction would take the original technical contradictions of speed and adaptability and look for another common parameter displaying mutually exclusive states, as displaying in Figure 2.6. Such a parameter in this example might be wing area. For speed a small wing area is required, but for take-off, landing and general maneuverability a larger wing area is required. The four separation principles would then be considered and in this case 'separation in time' naturally leads wing area is required. The four separation principles would then be considered and in this case 'separation in time' naturally leads to the possible option of variable wing geometry.

2.7 Summary

In this chapter, a literature survey demonstrates the need for research in the area of inclusion of sustainable development principles in product design process. In the discussion of product idea generation for sustainable development, little research has been conducted on inclusion of three dimensions of sustainability principle in product design process. Waage et al. (2005) confirms that there lacks systems methodology for inclusion of SD principles in product design process in literature, which could allow a product design & development team to incorporate three dimensions of sustainable development in product design process and also can evaluate their progress at the same time without much complexity.

Chapter 3

Methodology

Competitive industries are required to innovate, design and develop products for sustainable development (SD). Product development companies urgently need to initiate a systematic well-managed yet radical change in product idea generation and innovation to include SD criteria in the early stages of product development. Product design is a unique point of leverage from which to address environmental and societal problems related to the product in all of its life cycle stages.

There is no simple way of how to develop 'sustainable products' (Ljungberg, 2007). The complexity of the situation has already been presented in the last two chapters. According to thermodynamic laws, total sustainable products are not possible to develop in general. This chapter presents a methodology for systematic inclusion of environmental and societal criteria in addition to traditional criteria during the early stages of the product development process. In this research, finance, functionality, aesthetics, overall quality are considered as traditional criteria. Products for sustainable development must retain the level of primary (or traditional) attributes and cost structure that enable them to compete in markets where the rule is survival of the economic fittest (Fuller and Ottman, 2004). This research focuses on the fact that ecological and/ societal attributes in products must not sacrifice product performance or escalate unit costs. Rather, the opposite should occur.

In this research, sustainable product innovation includes activities and decisions started from the idea generation stage to the conceptual design stage. Decisions are made in these stages regarding the types of resources to be used. The decisions taken in the very early stages of product development ultimately determine the characteristics of waste streams.

Inclusion of sustainable development criteria during early stage(s) of product conception phase increases the likelihood of seeing environmental and societal goals of product as economically profitable. This new strategy requires inclusion of sustainable development specialists in the product design team. The rest of this chapter describes:

1. features of the proposed methodology to include sustainability criteria in product development process (Section 3.1)
2. details of the systematic methodology (Section 3.2)

Figure 3.1 shows a systematic diagram of the proposed methodology.

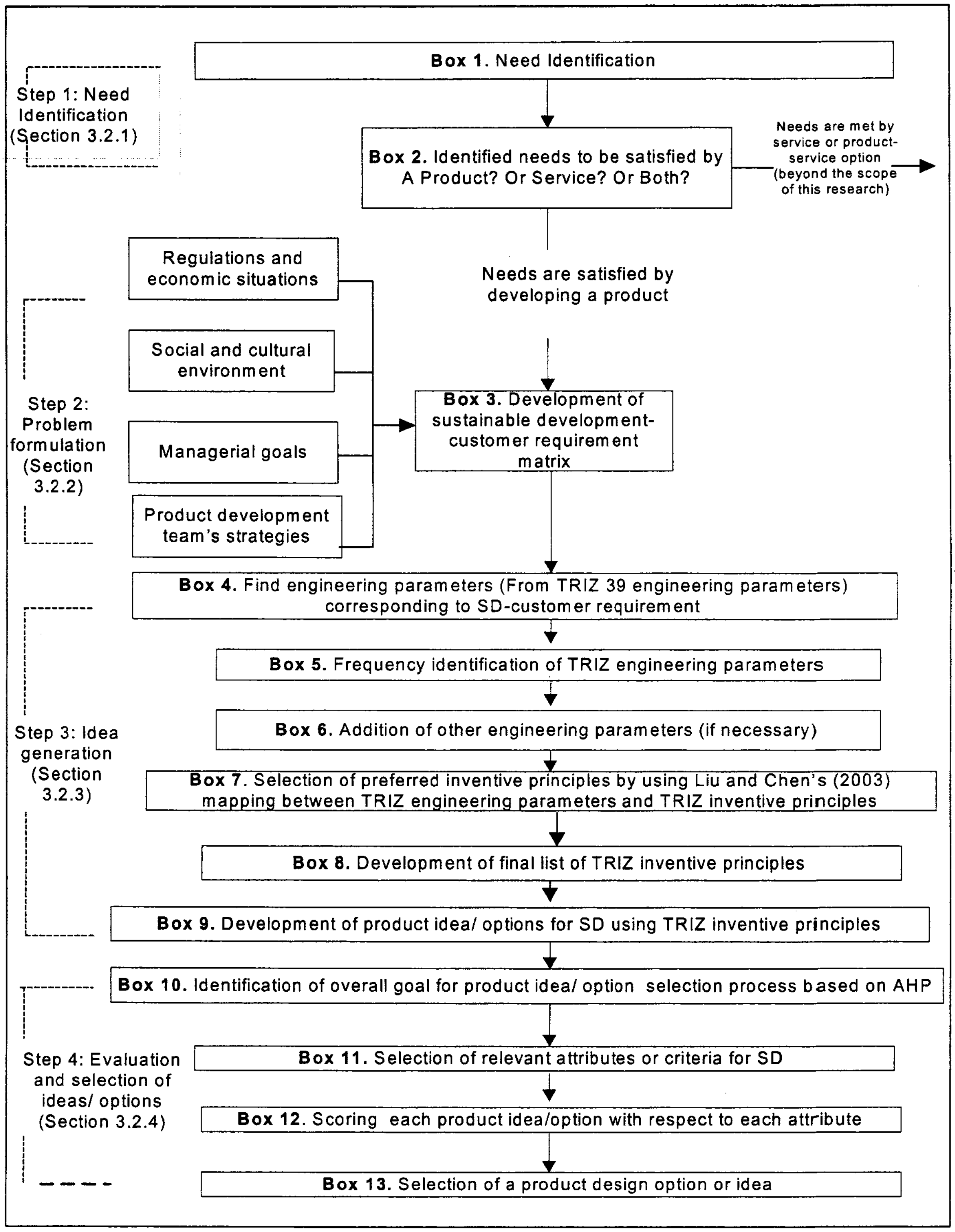

Figure 3.1. Methodology Diagram

3.1 Features of the Methodology

The methodology introduced in this research has the following features as *essential framework conditions* for ensuring effective implementation of sustainable product idea generation process in industry. These features include:

- Use of soft systems methodology (SSM) (Checkland, 1981) approach as philosophical and methodological guidelines for the proposed methodology (Section 3.1.1)
- Active involvement of all stakeholders including owners, customers, problem solvers, and sustainable development specialists (Section 3.1.2)
- Use of strategy level approach, which integrates into existing corporate business, and product development systems (not a stand alone program). This is a simple, flexible, less resource intensive approach that is designed to mesh with the business reality (Section 3.1.3)
- Integration and optimization of environmental, financial and societal criteria with traditional product specifications over the entire product life cycle (Section 3.1.4)
- Assessment of sustainability of developed product idea(s) (Section 3.1.5)

These features are described further in the following sections.

3.1.1 Relevance with Soft Systems Methodology (SSM) Approach

In this research, use of soft systems methodology (SSM) approach for philosophical and methodological guidance is one of the most important features of the methodology that is proposed in this research. SSM has been grouped among the "soft" operations research tools versus the "hard" mathematical and decision models that have traditionally existed in the operations research field (Presley, et al., 2000). It is a methodology for analyzing and modeling hard-to-define and complex systems that integrate technology (or hard) systems and human (soft) systems. The human system is defined by Checkland (Checkland, 1981) as a human activity system (HAS). These systems are different from natural systems or designed systems (which can be either physical or abstract). An HAS is defined as a collection of activities, in which people are purposefully engaged, and the relationships between these activities. Checkland (1981) proposes that the same methods used for engineering technology may not work as well for the more unpredictable and complex human side of the system.

SSM addresses "fuzzy" problems that occur when objectives are unclear, multiple objectives exist, and where there may be several different perceptions of the problem (Checkland, 1981). Product idea generation for sustainable development is still in its infancy. Objectives for the idea generation for sustainable development vary in different companies, even in different projects in the same company. Even objectives change in different steps of a single product idea generation process. SSM recognizes different individuals (parties) will have perceptions of the situation and different preferable outcomes. Use of an SSM approach does not attempt to define a single right method of action, but through an iterative process, defines an acceptable improved path of action. The proposed methodology has provisions to include not only actors with designated system, but also clients and owners of the system. This is a very useful and important consideration, especially when involvement and buy-in of all potential customers is desirable.

The steps of the proposed methodology are based on the seven stages of SSM. This methodology includes users, analysts, designers, sustainable development specialists

- to incrementally define the problem,
- to generate and evaluate alternatives, and
- to choose as acceptable solution

SSM contributes a set of techniques to description of the product idea generation for SD situation as a socioecological system. Particularly obvious influences can be seen in adaptations of "rich picture" and CATWOE (Checkland, 1981) techniques. (For detail description, please refer to Chapter 2 of this dissertation)

There are three identified general phases in early models of SSM:

1. building a "rich picture" of the problem situation
2. developing models of relevant human activity systems, and
3. using those models to simulate thinking about organizational change

These three phases capture the purpose of various activities in the methodology. The first phase deals with

- identification of a problematic situation and
- unstructured (nonsystems) expression of the problem

Soft systems methodology (SSM) thinks the term 'the problem' as inappropriate because it might narrow the view of the situation. Soft systems methodology believes that 'the problem situation or the problematic situation' is more appropriate since there might be many problems, which are perceived need to be solved (Couprie et al., 1997). Here, product idea generation for sustainability is considered as a problematic situation.

The second stage consists of activities

- to draw important themes out of the expression of the situation and to model them as systems.

The third phase involves

- Exercises to stimulate debate about desirable and feasible change in the situation.

Activities within these phases do not necessarily occur in sequence in modern applications of SSM. However, the three-phase description is heuristically useful. More important than the tools described in the SSM literature is the influence of SSM in *adopting a soft systems mode of thinking*. In this mode, explicit design of new systems was avoided. Instead, the research was approached as the operation of a system of learning, which informs action to improve the situation. Rather than developing visions of the future as blueprints (fixing goals and targets to be attained), which would require a system to be engineered out of the "mess" of the real world situation, this work uses SSM techniques and systems concepts to construct conceptual models that are insightful narratives about a particular perspective on the situation. The process of constructing these models and their exploration in the context of product idea generation for SD problem situation led to ideas for the future of the situation that is fundamentally different from previous product idea generation efforts.

SSM can be used in a variety of ways to explore problematic situations (Bunch, 2003). Mature applications use SSM to organize observations and understanding about it, in the sense of "doing work using SSM" rather than "using SSM to do a study." Current research is undertaken as in which the emphasis of the approach is *as a set of guiding principles within which tools and techniques are suggested.*

Rather than go into detail about the stages of methodology at this point, we will present them as we discuss our methodology for developing product ideas for sustainable development. The proposed methodology is presented within the context of the seven stages of the soft systems methodology. The stages of SSM are shown in Figure 3.2:

1. Problem situation unstructured
2. Problem situation expressed
3. Root definitions of relevant systems
4. Conceptual models
5. Comparison of conceptual models with the real world
6. Feasible, desirable changes

7. Action to improve

3.1.1.1 Relevance of Step 1 of the methodology with stages of SSM

Stages 1 and 2 of the SSM are often combined in *descriptions of the methodology*. Objective of the stages are to define the problem at a high level, preferably without imposing a particular structure. In this stage, the problem situation is identified and represented in general terms, with a diagram, showing communication links. A market survey, a competition analysis, a list of complains can be used to describe problem situation. In original SSM (Saaty, 1980), this way of representation is called as "rich picture." A rich picture is a representation of the problem situation, typically presented in the form of an abstract drawing, which describes the structure, processes, and issues of the system that are relevant to the problem definition (Coupre et al., 1997). It attempts to provide a complete picture of actual activities rather than reducing problems to their component parts.

3.1.1.2 Relevance of Step 2 of the methodology with the third stage of SSM

In the "root definition" stage (the third stage of SSM) refines and completes the identification of the elements of the system. Identification of transformations required in the system is done in the context of the actors, customers, and owners. Objective of this stage is to capture a particular view of a system, which might address the problem situation. The system is defined in the context of the organization and the viewpoints of the affected individuals. In this stage, to address customer requirements, and to make overall design procedure successful, CATWOE analysis (Customer (C); Actor (A); Transformation (T); Weltanschauung or worldview (W); Owner (O); and Environment (E)) for the particular system is done very carefully. In this research, the root definition is developed for the principles of sustainability. The relationship between customer requirements and desirable sustainability criteria is determined.

3.1.1.3 Relevance of Step 3 of the proposed methodology and the fourth stage of SSM

At the stage 4 of SSM (Checkland, 1981), a formal model of the system including transformation activities and their interactions is developed. Necessary flow of information and decisions that compromise the system are identified. The conceptual model should focus on what is done, not how it is done. This research proposes a problem formulation stage, which is based on the philosophy of the fourth stage of SSM. Relationship between TRIZ 39 engineering parameters (Jones and Harrison, 2000) and desired sustainability criteria of the product-to-be developed.

3.1.1.4 Relevance of Step 4 of the proposed methodology and the last three stages of SSM

In the stage 5 of SSM, the conceptual model is compared with the real world system to highlight possible areas where changes are necessary. This conceptual model will identify where problems / deficiencies exist between what is happening (the "rich" picture) and what is desirable (the "root definition) as defined by the models.

In stage 6, changes to address the "disconnects" or gaps between the conceptual model and the real world that were identified in the Stage 5 are introduced and evaluated for feasibility.

In stage 7 of the SSM, recommendations for change are implemented. These changes result in a modification of the problem situation. This new situation may lead to a new cycle of the methodology.

The last step of the methodology presented in this research is equivalent to the last three stages of SSM are performed in the methodology:

- With TRIZ inventive principles, one or more product idea can be generated. Assessments of these ideas are done using an SD assessment list of criteria.
- Find risk related to proposed idea(s) in terms of SD issues, and find ways to change those. Implementation of the changes to the design idea(s) and final design idea is chosen.

If there are more than one feasible options are determined, AHP (Saaty, 1978) procedure can be a good choice for selecting the desirable design solution.

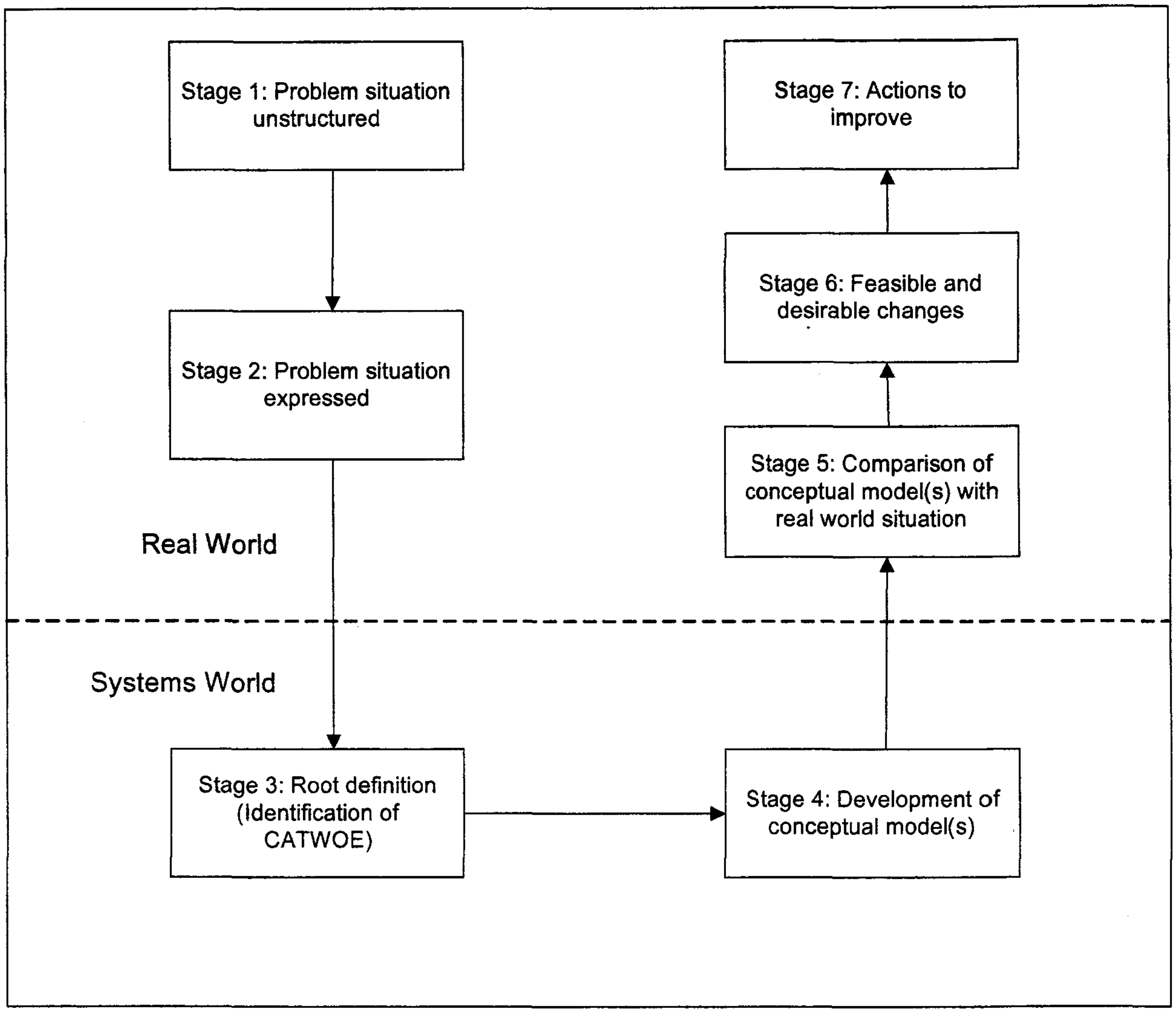

Figure 3.2. Graphical representation of soft systems methodology (SSM) (Checkland, 1981)

3.1.2 Involvement of all stakeholders

The proposed methodology includes systematic learning of customers' needs, and fulfilling those needs by developing product ideas that incorporate sustainable development principle. It is extremely important for product design team to recognize the views, roles, influence and concerns of the people involved with the product. Figure 3.3 illustrates a typical range of interested parties or 'stakeholders' in sustainable product development.

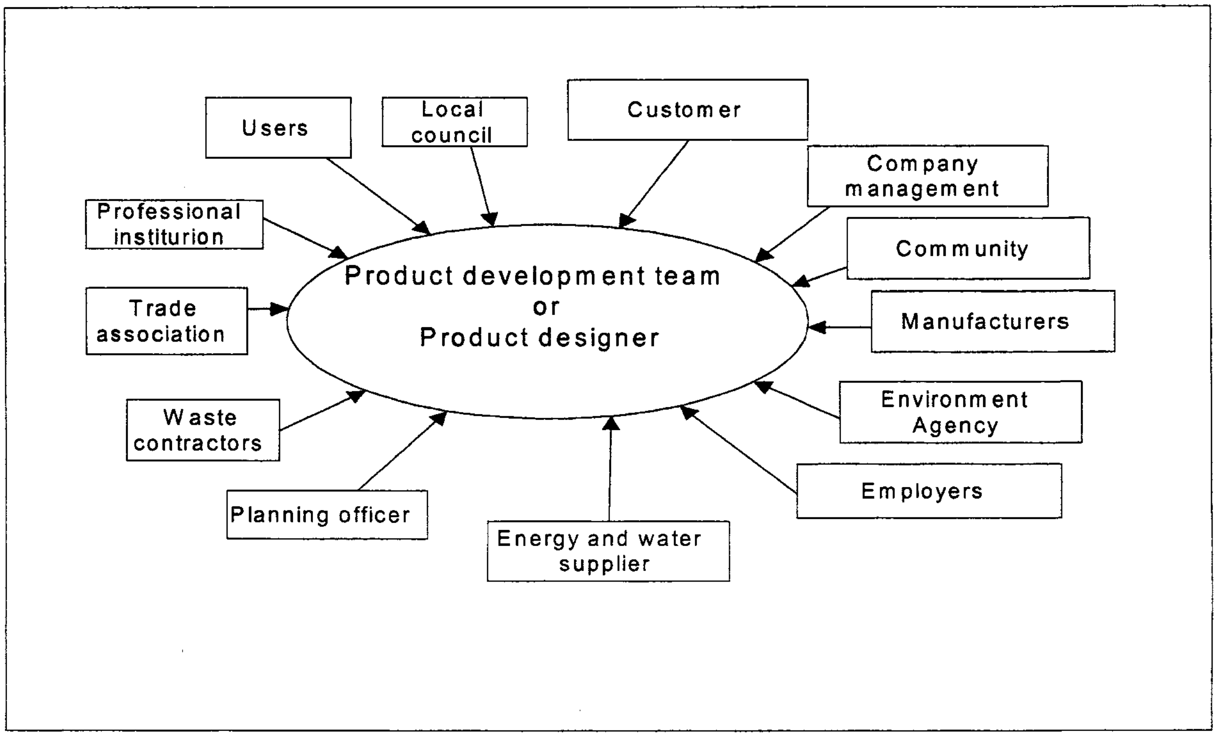

Figure 3.3. Typical range of stakeholders (Howarth and Hadfield, 2006)

The systematic consideration of involved parties in product development process fits well within the six CATWOE elements under the soft systems methodology (SSM) (Checkland, 1981) for defining and analyzing the problem situation. The SSM places special emphasis on individual human beings, whether a problem owner, customer, or problem solver (including product designers, sustainable development specialists). Successful inclusion of SD principle in product incubation stage involves:

- Identifying needs of users or customers (C) for developing a product.

- Developing the internal management and staff researchers as capable of responsive actors (A), problem solvers, or solution providers, who carry out the main product conception generation tasks.
- Characterizing the need transformation (T) process by which the current and future requirements of customers are being converted into a new product concept
- Establishing product development process culture, shared value, relevant world-view or weltanschauung (W), which makes the activities of product development meaningful and purposeful to the various stakeholders. The product development team leadership is thus required to simultaneously appreciate this multitude of perspectives of interacting, sometimes conflicting, interests and needs. The appreciation and handling of the multi-stakeholders' needs should be at the core of a product conception for sustainable development initiative.
- Determining product development team's accountability to the company as problem owner (O) who has the authority to initiate, alter and terminate the core activities of the product development process.
- Forecasting and anticipating intensifies regional and international competition, relative of the domestic economy, the current environmental and social policies, and the available state-of-the-art technologies as the prevailing and changing macro environment (E) and constraints.

A root definition is a carefully phrased statement of intent expressed in terms of the six CATWOE elements. Through the CATWOE analysis and resulting root definition, the major needs of the customers can be addressed sensibly. In the event that world-views of the stakeholders are incompatible, it is necessary for the stakeholders to arrive at a consensus or an 'accommodation' among themselves before a firm root definition is attempted. After reaching a consensus, the leadership must issue a definitive root definition. It is very daunting task to try to bring to the design concept all very complex and often conflicting issues and concerns, plus trying to understand the views of particular stakeholders and finally to change customer behavior. One way is to identify the risks and benefits / opportunities during the early stages of product idea generation process. The reason for choosing SSM as the basis for the proposed methodology is that SSM can capture stakeholders' needs and viewpoints in a systematic manner. This methodology proposes that many risks and benefits can be identified even before building a prototype of a product just by following systematic planning of activities.

3.1.3 Integrated and pragmatic Approach

There is a growing view in the sustainable development (SD) as well as sustainable product development fields that building in sustainability at a strategic level within industry will result in greater improvements in sustainability performance. However, at present most eco-design methods focus at the operational rather than strategic levels (Maxwell and van der Vorst, 2003). Further, many existing eco-design approaches are not integrated into product development (new product development), let alone into company strategies and standard business functions.

This research has found that incorporating sustainable product idea generation process into existing business strategy is necessary for corporate commitment and is more effective for cascading sustainable product idea generation process throughout the company's activities. The requirement to produce sustainable products as relevant is integrated as one element of the existing corporate strategy. In this research we consider that it is core business criterion that can be incorporated into all other business functions for overall sustainability performance improvement. In particular, inclusion of SD principles in product idea generation process should be incorporated within the product development (this includes design) approaches used by the company. Other functions that traditionally feed into product development, e.g., quality, finance, purchasing, etc. will then be incorporated more easily with the sustainability criteria. Further, where a company operates a system to manage their environmental and social performances, e.g. EMS, this process should be imbedded within it. Some manufacturers that have implemented eco-design, have integrated it into their company's existing systems for managing their environmental performance. For example, Nike and Ikea have integrated their eco-design into their TNS (The Natural Step) approach (Maxwell and van der Vorst, 2003). Overall, by integrating sustainability in the corporate strategy it is set up as a core element necessary for improving business performance rather than a stand alone programme.

In addition to embedding the method for inclusion of SD principles in product idea generation process into the corporate strategy and integrating it with the company's existing business functions, this research proposes that the process for inclusion of SD principle in product idea generation only be effective if is simple, pragmatic, flexible and is in line with business realities. Research articles on Motorola, recommended such as approach on the eco design front. This is even more important for the more holistic method that is proposed in this research. Further, it should not be overly resource intensive in terms of time, cost or personnel especially in light of typically short time span from product concept to market. There is a growing recognition that eco-design can be complex, highly quantitative and resource intensive in terms of the expertise, personnel, time and costs incurred for implementation. Incorporating this view the proposed methodology uses mainly qualitative information. This approach easily can be customized to the companies' existing business and product strategies which is supported, where relevant, by suitable quantitative tools, e.g. abridged LCA (Santos-Reyes and Lawlor-Wright, 1999). This flexibility in approach can be very advantageous to companies incorporating and maintaining sustainability criteria in their product and service development processes.

3.1.4. Optimization of Equity, Economy and Ecology

In the 21st century, it is well documented that marketing strategies facilitate consumption, which includes processes such as product development, distribution, and consumer use, which involve conversions of natural capital/ resources, and all conversions generate waste - the antecedent to pollution. Conversions of natural capital / resources also bring change in equity. These outcomes are designated as unintended consequences of product development processes because the decision making processes that underlie product development strategy formulation generally fail to recognize environmental and social impacts as standard decision influences. The optimization of social, ethical and economic issues is not included even in eco-design in its present form. If sustainability is the aim, just reducing the environmental impact of a product using as eco-design approach is not enough. In order to effectively integrate sustainability in product idea development and innovation process, the proposed method demonstrated how sustainable product idea generation and innovation process could counter ecosystems degradation and social disequilibrium. This methodology integrates sustainability with traditional product criteria.

3.1.5. Sustainability Assessment

For sustainability analysis, there is consensus among different scientific disciplines and development sectors on the need to include environmental and social indicators and criteria as long-term oriented economic and ergonomic indicators in the analysis. The experience has shown that long lists of indicators are impractical. In this research, we omit the approach of showing progress towards sustainability by a single numeric value because a single numeric value offers little or no guidelines for further design of alternatives. Methodological frameworks are urgently needed that can assist in the selection of appropriate indicators and in the integration and transformation of the information to set the basis for the design of more sustainable alternatives.

The framework for assessing the sustainability of product idea(s) is an attempt to translate the general principles of sustainability into indicators in the context of product idea development process. This research identifies that the evaluation of sustainability in product development process is a participatory process requiring an evaluation team with an interdisciplinary perspective. Keeping this requirement in mind, this research proposes development of product idea generation team with an interdisciplinary perspective.

This research identifies that sustainable product development assessment will need to include:

- A generic list of issues/ concerns – topics.
- Ability to add additional specific issues/ concerns.
- More detail on these issues to check and revise the level of understanding.
- Level of importance of these topics/ issues.
- The sustainable development aspects – environmental or social or economic or a combination.
- Are these impacts high, medium or low?
- Are these impacts a risk or a benefit?

Analysis of the above mentioned assessment in various ways is needed. The key decision is identified based on the balance between risk and benefits. The key risks and benefits need to be identified, tabulated or graphed so it is possible to compare the environmental, social and economic impacts separately or together as sustainable development. This can be completed for the product idea(s) developed in this process. Finally, having seen these tables and graphs there must be the ability to go back into the assessment and change the detail on the score, impact aspect and level of importance etc.

3.2. Steps of the Methodology

This section presents the detailed procedure for the proposed methodology. Figure 3.1 represents the basic diagram of the steps proposed in this research. The proposed methodology is a four-step cycle.

3.2.1 Step 1: Need Identification (Box 1 & 2 in Figure 3.1)

This step of the methodology makes the product development team aware of the problematic situation that might be resolved by introducing a sustainable product. Some of the key factors that generate successful innovative ideas include the followings:

- Emphasizing user-needs
- Building customer linkages
- Involving users in the development process
- Building a strong market orientation

Proposed methodology is based on the fact that consumers' needs should bring sustainable development enhancement. Therefore, extraction of sustainable development aspects from conventional customer requirements (needs) matrix can be one of the solutions to initiate development of sustainable products. It also can be effective for sustainable development marketing for increasing consumer's recognition and market share. In this methodology, we encourage that customers are initially listened to, and a list of customer needs and expectations is created systematically.

The customer requirements are normally qualitative and tend to be imprecise and ambiguous due to their linguistic origins. A sustainable product development team should put considerable efforts in capturing the genuine or 'real' needs of the customers, rather than too much focus on the technological issues during early stage of product development. One of the systematic approaches to capture, analyze, understand and project customer requirements, called Voice of the Customer (VoC), has received a significant amount of interests in recent years (Jiao and Zhang, 2005). Traditionally, taking qualitative approach and focus group technique are implemented to provide a reality check on the usefulness of a new product design (LaChance-Porter, 1993). Similar techniques include one-on-one interviews and similarity-dissimilarity attribute rankings (Griffin and Hauser, 1993). While these types of methods are helpful for discovering the customer needs, it is still difficult to obtain design requirement information because marketing folks do not know what engineers need to know. It is difficult to apply the VoC alone to achieve a synergy of marketing and engineering concerns in developing product specifications. Many methods and tools in the field of knowledge acquisition such as observation, self-reporting, interview, protocol, ethnographic methods, and sorting techniques have some applicability in requirement elicitation for product development.

In this section, we present a method for capturing user (customers) requirements to generate sustainable product idea. The objective of this step of the proposed methodology is to initiate systematic process of identifying conventional voice of customer. This objective is achieved by performing a series of activities:

1. Extraction of customer requirements

2. Verification of need to develop a sustainable product

Getting customer requirements for developing a product can be gathered from consumer interviews, complaints, brainstorming, etc. (Presley, et al., 2000). This engages two teams:

- "customer" team and
- "development" team

The customer team consists of those individuals who will be system operator or product users or the most affected individuals by developed product. Selection of the customer team members is a critical aspect of the success of the methodology, as they will define the problem domain and the requirements of development of a product to address their need (problem situation). The development team may consist of experts from broad background, as well as facilitators who adept at extracting information from potential users.

Development team elicits and categorizes customer requirements from the customer team. Consensus relative importance ratings are then developed for the requirements. This is shown in a matrix format. This is a matrix of influence coefficients that prioritizes the needs and/ requirements based on criteria for competitiveness. Usually, a list vector in the matrix (say a column) consists of one or more of the following:

a. Marketing information ratings, which identify the relative importance of each of the needs

b. Ratings showing how important the different customer groups perceive each of the needs. These are often referred to as customer importance ratings (CIRs).

c. Ratings showing how well a competitor's product is perceived as meeting each of the needs.

d. Ratings showing where the product ranks or is perceived relative to the competition (better or worse)

e. Factors that a company would like to consider in its (a product) specification set to be a "world-class quality producer."

The above criteria provide a set of possible options for identifying the stated importance ratings and factoring – in how a product is perceived relative to competitors. Most importantly, the above criteria can be used to determine a weighted average of needs as a single performance index.

The goal of this step is to elicit the requirements of customers / users. In the most consumer goods production companies, identification of customer needs is considered as representation of market requirement (Prasad, 1998). Some typical customer needs and/ expectations ("what") might be:

- "pleasing to the eyes"
- "looks well built"
- "opens and closes easily"

The Kano model shows that customer satisfaction for each need and/ expectation can further be categorized into primary (must have), secondary (may be), and tertiary (like-to-have) categories (Prasad, 1998). Weighting factors on the identified needs might be

- a vector list of "overall importance" or
- a vector list of "importance to the world purchaser" or
- a set of "world-class achievable performance of product"

In this research, we present development of a matrix with three columns (Table 3.1). The first column lists the identified needs. The next column has the information of relative importance of each need (verbal expression). The last column gives numerical values to represent verbal importance of each need (customer requirement) for a new product. The relationships of strong, medium, and weak are shown in numeric values of 9, 6, and 3, respectively. Scaling techniques we adopt ratings on linear interval scales (Franceschini and Rupil, 1999). Let us consider, for instance, a variable defined on three levels: 'low", "medium" and "high". Let us define as m(low), m(medium), m(high) the corresponding numbers assigned to each level:

- If the judgment "high" implies it is greater than "medium" by the same amount as that existing between "medium" and "low", then the assigned numbers satisfy the following relationships (linear interval scale):

  m(high) – m(medium) = m(medium) - m(low)

Table 3.1. An example of a matrix of customers' needs (requirements) and their relative importance

Conventional customer requirement for a general hair dryer	Verbal representation of importance of customer requirement	Numerical representation of importance of customer requirement
1. "safe to use"	Strong importance	9
2. "looks well built"	Medium importance	6
3. "low noise"	Weak importance	3

By producing customer requirement matrix, the development team has the basic idea of customer's needs and wants. The next stage of the process involves questioning the necessity of developing a product to fulfill customer's needs. Sustainability principle promotes the fact that it is more sustainable to replace physical product by service to meet customer's needs. In practice, complete replacement of a product by a service is difficult to achieve. There is always possibility to have some combination of product and service (Maxwell and van der Vorst, 2003). This methodology considers preparation of answers to a list of questions (Table 3.2) by analyzing the traditional customer requirements to identify requirements of developing a product. The list of questions can be elaborated depending on specific circumstances.

Step 1 of the proposed methodology is based on the basic idea of the first stage of soft systems methodology, which is about how to define the problem situation in not-so-structured manner.

Table 3.2. Common questions for identifying the necessity of product development

Questions
What is the primary need of customers that need to be met?
Could this need be fulfilled by a service?
Is it essential to have a product?
Is there any option for product and service combination?
Additional questions can be added as necessity arises

3.2.2 Step 2: Problem Formulation (Box 3 in Figure 3.1)

This step refines and completes the identification of the elements of the problem situation on the basis of information learned from the need assessment (Step 1 of the methodology: Section 3.2.1). This is done in three stages:

1. Identification of involved stakeholders who are the primary members of sustainable product development project and their worldview (Section 3.2.2.1)
2. Redefining the problem situation (Section 3.2.2.2)
3. Development of sustainable development-customer requirement matrix (Section 3.2.2.3)

3.2.2.1 Idea generation team

In SSM, CATWOE is used to guide the development of the elements of the root definition of the problem situation. Root definition (RD) is part of the terminology of soft systems methodology (SSM). A root definition is a statement that concisely describes a system of interest. It is usually a single sentence starting 'A system to…' and it should include all the key elements of the system. It usually takes several iterations before a complete definition is agreed. As mentioned earlier, a root definition is a carefully phrased statement of intent expressed in terms of the six CATWOE elements.

- Customer/ client (C): people who are going to use the developed product
- Actor (A): people performing activities to develop the product
- Transformation (T): what specified elements are changed by the system (i.e. how are inputs transformed into outputs)?

  The main function that carried out by the developed product
- The Weltanschauung / worldview (W): different individuals will perceive the same event in varying ways, according to their view of the world.

  What is the thought that justifies the transformation?
- Owners (O): the person(s) with the authority to decide how the product will be developed / idea for a product will be generated
- Environment (E): The larger system within which the developed product has to perform, for example, where the product will be actually made and/or used, special regulations or laws associated with making or using the product.

What constraints will hinder the activities of the system?

These differing individual views must be appreciated and incorporated where possible. The CATWOE procedure is used to check that all necessary elements are included in the root definition before proceeding to a conceptual modeling phase.

In our methodology, by CATWOE analysis, a group is designated to work together to find out sustainable solution to meet customer's needs. In this stage of product development, possible communication channels are determined between group members. Recommended special feature of sustainable product idea generation team is compulsory involvement of sustainable development consultant(s). A sustainable development consultant has special knowledge and training about sustainable development issues and how this can be achieved. A company always has an option of hiring a consultant from outside of the company, if training someone is not cost effective. It is also crucial that any member of the product development team can easily communicate with the sustainable development consultant with ease.

The product idea generation team in developing sustainable product idea must promote cross-functional coordination. The focus on coordination and communication linkages as an integral part of the sustainable product development team fosters a global view-point and reduces the chances of functional sub-optimization that plagues traditional product idea generation processes. In this research, we promote innovative product idea generation as sustainable solution. So, we look at a few issues that could be easily implemented during formation of team in sustainable product idea generation process. The most consistent recommendations in the innovation literature are regarding the structures of product development teams to facilitate innovation. The organic structures characterized by diversity of pooled skills, informal communication, and broad multi-disciplinary skills facilitate innovative behavior in a team.

3.2.2.2 Redefining the problem situation

Observation and opinion of the design team members (selected stakeholders outside of the design team also can be consulted, if necessary) are considered in redefining the whole problem situation. Redefining the whole system is done by identification of the following:

(a) What is the purpose of development or improvement of product or what the stakeholders' perspective of the need for designing and developing that product with focusing on three dimensions of SD in addition to all traditional technical aspects?

(b) What are the desirable functions the particular product has to perform (start with a rough description and underline the key words and phrases)?

(c) If it is redesigning an existing product, is the problematic situation can be isolated from the other parts of system? (in terms of redesigning a product, here we consider the part which has the most negative effects in terms of one or more dimensions of sustainable development; an example can be found in Nielson and Wenzel, 2001).

(d) How long the need for a new product has been existed? (This part will answer when new legislation will be implemented or when the competitors market their new or improved product, etc.; this answer helps to determine the availability of time to introduce a product to the market).

(e) Really now, what is the product that might fulfill all or the most of the stakeholders needs?

(f) What would happen if nothing is done to solve the problem? (loss of market share for a new product, loss of financial resource to pay fine for not changing old design, etc.)

(g) Formal representation of required product

One of the objectives of this exercise is to capture the variation in perception of the problem situation in the design and/or product development team. Extreme range of responses of the questions, even in simple identification of problem or particular properties of the products, demonstrates how ill-defined and complicated the situation is. However, when asked to reconsider the problem ("really now, what are the functions or needs to be fulfilled by designing the product?") participant responses not only reinforced several of the problem categories, but practically defined the category of "technological, material, social and environmental aspects" of the situation, which was considerably augmented with new input.

3.2.2.3 Development of SD-customer requirement matrix

Sustainable development criteria are in fact sustainable design guidelines. A default sustainable development checklist supports designers to select related sustainable development criteria for particular problem situation. This research shows a way to develop sustainable development-customer requirement matrix.

A list of common sustainable development criteria is presented in Table 3.3. Defining strategies for environmental performance improvement is not only concerned with raw material and energy consumption, and waste reduction, but also with the reduction of human health and safety risk and ecological degradation. Sustainable development profile strategies can be defined for the eventual elimination or reduction of hazardous contents of a product and toxic releases, as well as emissions that can affect workers, employees, users and the communities in which the company operates. The set of sustainable development principles can be used to define the sustainable development profile strategies for improving the product sustainability performance. In Table 3.3, eighteen sustainable product design guidelines are listed. This list can be modified according to specific situation. The last three columns of Table 3.3 show apparent influence of individual guideline toward three dimensions of sustainable development.

The task of defining sustainable development strategies or goals in a particular product development scenario does not end there. Prioritization of sustainability guidelines is next. In this methodology, we show how to interpret relationships between customer requirements, which are identified in Step 1 (Section 3.2.1) of the methodology and SD guidelines that are presented in Table 3.3. We consider, the relationships of strong, medium, and weak are shown in numeric values of 9, 6, 3, respectively. When there is no relationship, it is expressed as a vacant cell with a value of 0.

Table 3.3. A list of common sustainable product design guidelines

Sustainable product design guidelines	Societal factor (Equity factor)	Economic factor	Environmental factor
#1 Less material		X	X
#2 Less energy		X	X
#3 Easy transportation and storage		X	X
#4 Easy disassembly		X	X
#5 Low emissions		X	X
#6 Durability	X	X	X
#7 Less hazardous substance		X	X
#8 Reduce packages	X		X
#9 Cleaner and renewable energy	X		X
#10 Trading agreements		X	X
#11 Ergonomically safe	X		X
#12 Easy to operate	X		
#13 Recyclable and reusable materials	X	X	X
#14 Modular design			X
#15 Local community benefit	X		
#16 Cost effectiveness	X	X	X
#17 Consideration of environmental cost	X	X	X
#18 Easy to process and assembly	X	X	X

For example, customers identify that "safe to use" is an important property of a product. Table 3.4 shows an example of relationships between a customer's requirement ("safe to use") and SD factors. The omitted SD criteria are considered as not related to "safe to use" criteria.

Table 3.4. An example of relationship between a customer's requirement – "safe to use" and SD factors

Specific customer requirement	**Sustainable development criteria (from Table 3.3)**	**Strength of relations**	**Quantitative interpretation of relations**
Safe to use	3. Easy to transport and storage	Strong relation	9
	6. Reduce susceptibility to damage/ high durability	Medium relation	6
	7. Reduce hazardous substance	Strong relation	9
	5. Less emissions	Strong relation	9
	1. Consume less materials	Weak relation	3
	9. Use cleaner energy	Weak relation	3
	11. Ergonomically safe	Strong relation	9
	12. Easy to operate	Strong relation	9

Overall score of both customer requirements and sustainable development criteria is calculated and shown in table format (Table 3.5). The relationships between sustainable development requirements and customer requirements are converted into numeric matrix in order to select the most important sustainable development requirements. This matrix is used as designer's aid to find out which sustainable development criteria are relevant to a specific product. Table 3.5 shows an example of customer requirements and SD criteria relational matrix. To demonstrate how to develop relational matrix between customer requirements (from the Step 1 of the methodology) and SD criteria (From Table 3.3), we only consider three customer requirements and three SD criteria. For this example, three customer requirements (From Table 3.1) are:

1. Safe to use (highly important according to customer's preference: equivalent quantitative importance level is 9)
2. Looks well built (moderately important according to customer's preference: equivalent importance level is 6)
3. Low noise (weak importance given by customers: equivalent importance level is 3)

Three SD criteria are randomly chosen from the Table 3.3. These are:

- SD Criteria #7. Reduce hazardous material
- SD Criteria #12. Easy to operate
- SD Criteria #6. High product durability

Now, each of the customer requirements is evaluated against each SD criteria to find relationships. For example, customer requirement "safe to use" is strongly related to reduction of hazardous materials. This relationship can be interpreted numerically as 9. The relationship between customer requirement and SD criteria need product development team's knowledge and judgment. These values are not fixed, and can vary depending on the team members. In the Table 3.5, the level of importance of the SD criteria (the second last right hand side column) means how many importance relations the SD criteria have with traditional customer requirements.

Level of importance of a SD criteria = $\sum$ (relationships of conventional or traditional customer requirement with that particular SD criteria)

For example, relations of "easy to operate" to all conventional customer requirements presented in Table 3.5 is calculated as:

Level of importance of "easy to operate" = relationship of "safe to use" with "easy to operate" + relationship of "low noise" with "easy to operate" = 9 + 9 = 18

The importance of SD criteria weighted to customer requirements means the importance of SD criteria when we consider not only the relations but also the importance of conventional customer requirements as shown in Table 3.1 (An example of a matrix of customers' needs (requirements) and their relative importance).

Levels of importance of SD criteria according to customer requirements = $\sum$ (relationships of conventional/ traditional customer requirement with that particular SD criteria X customer preference level of the traditional customer requirement)

In Table 3.5, the example level of importance of SD criterion "easy to operate" is 108, which is calculated as:

Summation of (customer preference level of "safe to use": 9 is multiplied by the relative importance of "easy to operate", i.e., 9) and (customer preference level of "low noise": 3 is multiplied by the relative importance of "easy to operate", i.e., 9). Level of importance of SD criteria according to customer requirements is calculated as follows:

Relative level of importance of a SD criteria according to customer requirements (%)

$$= \frac{\text{Level of importance of that SD criteria according to customer requirements}}{\sum(\text{Level of importance of SD criteria according to customer requirements})} \text{ X } 100$$

For example, relative level of importance of SD criterion "easy to operate"

$$= \frac{\text{Level of importance of that SD criteria according to customer requirements is 108}}{\sum(\text{Level of importance of SD criteria according to customer requirements}) \text{ is 234}} \text{ X 100}$$

= 46%

From the last column of the Table 3.5, we see that "easy to operate" and "reduction of hazardous material" have the highest weighted importance. This means those are the most consumer favorable SD criteria, which are effective for the sustainable design.

Table 3.5. An example of customer requirement and SD criteria relational matrix (3: weak relationship, 6: medium relationship, and 9: strong relationship)

SD criteria	**Customer requirements (Quantitative importance levels for each requirement)**			**Level of importance of the SD criteria**	**Level of importance of SD criteria according to customer requirements**	**Relative level of importance of SD criteria according to customer requirements in percentage**
	Safe to use (9)	Looks well built (6)	Low noise (3)			
7. Reduction of hazardous materials	9	0	0	9	81	34%
12. Easy to operate	9	0	9	18	108	46%
6. High product durability	3	3	0	6	45	20%

The sustainable development criteria, which have greater importance level in the Table 3.5 are listed together with conventional customer requirements (from table 3.1) in Table 3.6. Some of these criteria from both lists might be similar or same. The designer has the freedom to choose the final criteria from each group of criteria.

Table 3.6a. Conventional/ traditional customer requirements and related sustainable development criteria

No.	Conventional customer requirements	Level of Importance
1.	Safe to use	9
2.	Looks well built	6
3.	Low noise	3

+

Table 3.6b. Sustainable development criteria related to traditional customer requirements

No.	SD Criteria	Level of Importance
#12	Easy to operate	46%
#7	Reduction of hazardous materials	34%
#6	High product durability	20%

3.2.3 Step 3: Idea Generation (Box 4 – Box 9 in Figure 3.1)

One of the main purposes of the methodology is to provide the best chances to develop innovative product idea to meet both traditional design criteria and sustainable development criteria. In sustainable product development process, design engineers encounter two common problems:

- System incompatibility
- Design conflict

Changes of certain parameters of the system often negatively affect other parameters. Traditionally, the design engineer's ability to generate innovative design is challenged by design contradictions. Conventional approaches, such as brainstorming, often hinder the search for breakthrough concepts because they are not very effective at defining and solving concepts. Instead, they tend to rely on trade-offs. For instance, if a desired improvement of a product's parameter caused an unacceptable deterioration of another parameter, *the conventional approach would accept this trade-off rather than seek a solution that would satisfy both conflicting parameters.* At the end of Step 2 of the methodology, a list of elements of sustainable design is derived. This list is input for the product idea generation stage (Step 3) of the methodology. In this research, we choose the TRIZ (the Theory of inventive Problem Solving) method as a *tool* for a designer to handle design contradictions in innovative design problem solving process. The TRIZ method was developed in the former Soviet Union by Altshuller through analysis of over 400,000 patents (Jones and Harrison, 2000). TRIZ researchers have identified the fact that the world's strongest inventions have emerged from situations in which the inventor has successfully sought to avoid the conventional trade-offs that most designers take for granted (Chang and Chen, 2003). TRIZ offers a system of solving technological problems and improving decision making that replaces trial and error with a methodological approach. For an engineer, this means being able to solve difficult technical problems more quickly and more inventively - to approach a problem from an angle not previously imagined. According to Chang and Chen (2003), the basic constituents of TRIZ are:

- the contradictions
- 40 inventive principles (Table 3.7)

- the matrix
- the law of evolution
- the substance field analysis modeling
- ideal final result
- substance field resources
- scientific effects
- ARIZ (the Russian acronym for the 'algorithm of inventive problem solving')

The core TRIZ consists of

1. contradiction means that a worsening engineering parameter and an improving one exist simultaneously,
2. 40 principles (Table 3.7)
3. the matrix is a 39X39 matrix, which contains the zero to four most likely principles for solving design problems involving the 1482 most common contradiction types

When using the TRIZ method in developing innovative design, the designers have to go through following five steps:

1. Convert the design problem statement into one of a conflict between two performance considerations.
2. Match these two performance considerations to any two of the 39 engineering parameters.
3. Look up solutions to the conflict of these two parameters using the TRIZ table. (The two engineering parameters have numbers associated with them.

4. Look at the corresponding row and cell for the column number, which will in turn give several numbers. These numbers correspond to solution principles.)
5. Look up these solution principles on the master list of solution principles.

Convert the general solution principles into possible working solutions for your design problem.

Table 3.7. The 40 inventive principles in TRIZ (Chang and Chen, 2004)

No.	Principles	No.	Principles
1	Segmentation	21	Skipping
2	Taking out	22	Blessing in disguise
3	Local quality	23	Feed back
4	Asymmetry	24	Intermediary
5	Merging	25	Self service
6	Universality	26	Copying
7	Nested doll	27	Cheap short living object
8	Anti-weight	28	Mechanics substitution
9	Preliminary anti-action	29	Pneumatics and hydraulics
10	Preliminary action	30	Flexible shells and thin films
11	Beforehand cushioning	31	Porous materials
12	Equipotentiality	32	Color changes
13	The other way round	33	Homogeneity
14	Spheroidality - Curvature	34	Discarding and recovering
15	Dynamics	35	Parameter changes
16	Partial or excessive actions	36	Phase transitions
17	Another dimension	37	Thermal Expansion
18	Mechanical vibration	38	Strong oxidants
19	Periodic action	39	Inert atmosphere
20	Continuity of useful action	40	Composite materials

Table 3.8. The 39 engineering parameters in TRIZ (Chang and Chen, 2004)

No.	Engineering Parameters	No.	Engineering Parameters
1	Weight of moving object	21	Power
2	Weight of non-moving object	22	Waste of energy
3	Length of moving object	23	Waste of substance
4	Length of non-moving object	24	Loss of information
5	Area of moving object	25	Waste of time
6	Area of non-moving object	26	Amount of substance
7	Volume of moving object	27	Reliability
8	Volume of non-moving object	28	Accuracy of measurement
9	Speed	29	Accuracy of manufacture
10	Force	30	Harmful factors acting on object
11	Tension/ pressure	31	Harmful side effects
12	Shape	32	Manufacturability
13	Stability of object	33	Convenience of use
14	Strength	34	Repair ability
15	Durability of moving object	35	Adaptability
16	Durability of non-moving object	36	Complexity of device
17	Temperature	37	Complexity of control
18	Brightness	38	Level of automation
19	Energy spent by moving object	39	Productivity
20	Energy spent by non-moving object		

However, sometimes designer only knows how to improve one parameter of this system. Furthermore, for some contradiction conditions, TRIZ contradiction table does not recommend any inventive principle. Therefore, the contradiction table is useless in helping the designer finding suitable inventive principles and solving his /her innovative design problem.

There are several techniques in TRIZ that do not require a definition of a contradiction, such as,

- the System Operator,
- the Ideal Final Result, and
- the 76 Standard solutions

All these techniques work without explicit definition of a contradiction. In this research, the proposed methodology is an effort in developing innovative sustainable product design by solving engineering innovative design problem without contradiction information through the 40 inventive principles (Table 3.7). This inventive design problem solving method was first proposed by Liu and Chen (2003). Liu and Chen (2003) are able to utilize the 40 inventive principles of the TRIZ method for design problem solving without the information of system contradiction. The flow chart of the Liu and Chen method is described in Figure 3.4.

A sustainable innovating design method based on guidelines of sustainable development (please see the sustainable innovation design elements in Table 3.6), 39 engineering parameters of TRIZ (please follow Table 3.8) and 40 inventive principles of TRIZ (please see Table 3.7) is followed in this research. The design processes of sustainable innovation design method are shown in Figure 3.5.

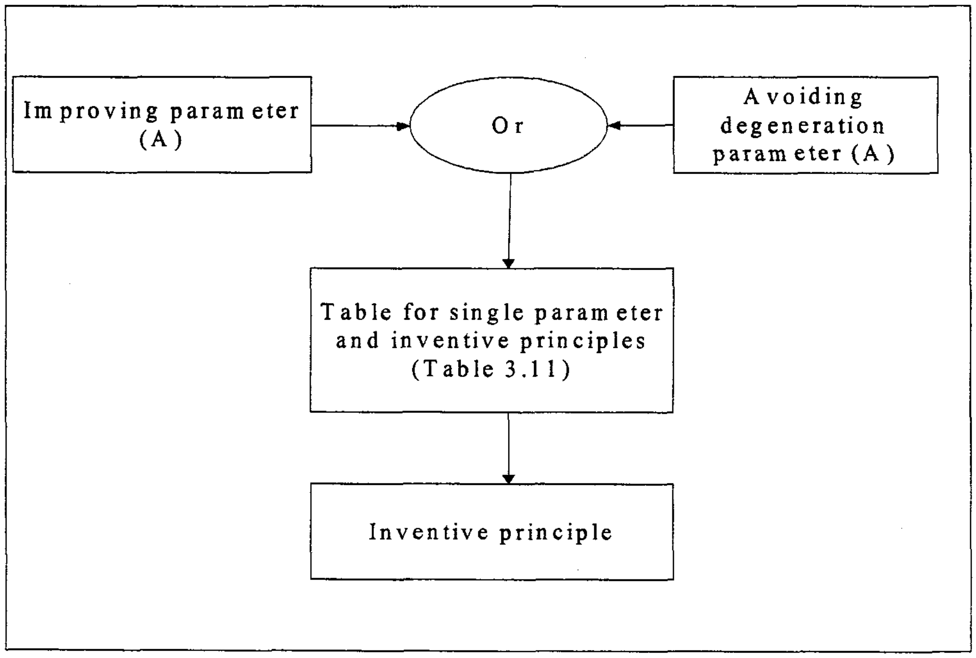

Figure 3.4. The model of TRIZ problem solving without requiring contradiction analysis (Chang and Chen, 2004)

First, the designer gathers the essential elements that are desirable in a particular sustainable product (From table 3.6) by following steps 1 and 2 of the proposed methodology. The designer's duty is now to find out relationship of elements of sustainable product (from table 3.6) and 39 TRIZ engineering parameters (Table 3.8). This can be shown in table format similar to the Table 3.9. Table 3.9 shows relationship between an element that is essential in a sustainable product design and all 39 engineering parameters. For example, reduction in product's "material intensity" can be achieved by changing product's properties, such as weight, dimensions, shape or the amount of material used, etc. This process requires the designer's familiarity with TRIZ engineering parameter table (Table 3.8). A cross in a cell in the Table 3.9 shows that there exists a relationship between that particular design element and the engineering parameter. Similar to Table 3.10, the designer has to form a table with the following information:

- one column states the preferable criteria for a sustainable product (Table 3.6)
- the next column states corresponding engineering parameters (Table 3.8) that need to considered to get a sustainable innovative design

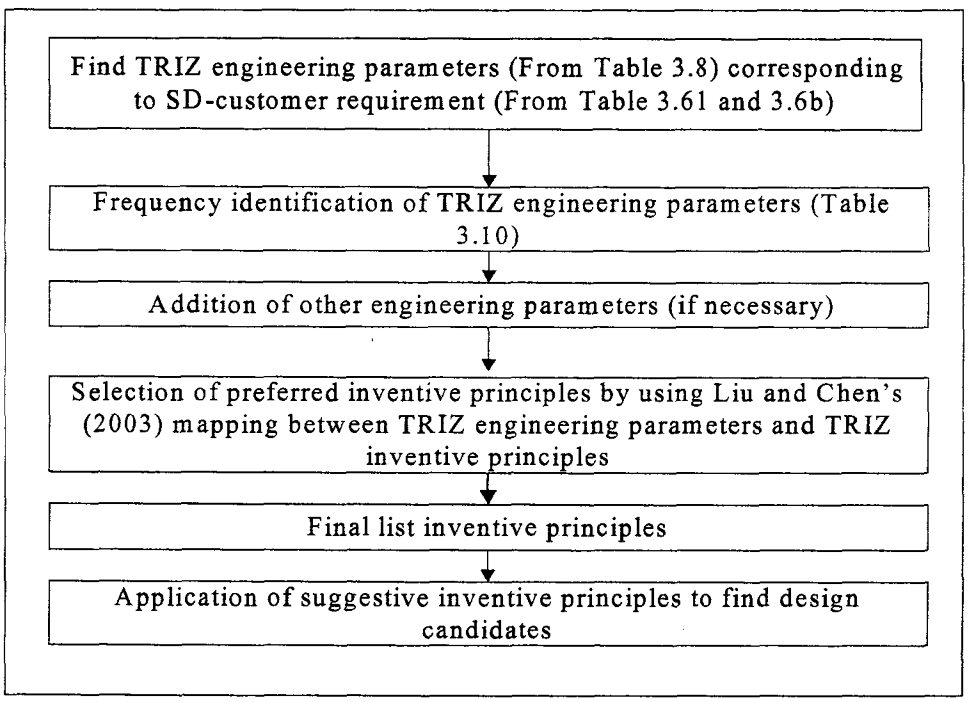

Figure 3.5. Development of sustainable product idea/option

Table 3.9. Relationship of 39 engineering parameters and sustainability elements

Elements for sustainability	Engineering parameters related to the corresponding element of sustainability
Safe to use	27, 31
Looks well built	12, 18
Easy to operate	33, 36
Reduction of hazardous materials	30, 31
High product durability	15, 16, 27, 34,

(Numbers in right hand side column represent identification numbers of 39 TRIZ engineering parameters shown in Table 3.8)

From the Table 3.9, we can extract two sets of information:

1. Which engineering parameters are related to the desired elements for sustainability for a particular product
2. The frequency of appearance of each parameter in the Table 3.9

Table 3.10 has three columns. The first two columns have information regarding the engineering parameters and the last column shows the frequency of appearance of a particular engineering parameter.

Table 3.10. Frequency identification of TRIZ engineering parameters in Table 3.9

No.	Engineering parameter	Frequency of appearance in Table 3.9
9	Speed	1
12	Shape	2
13	Stability of object	1
14	Strength	1
15	Durability of moving object	1
16	Durability of non moving object	1
17	Temperature	2
18	Brightness	1
27	Reliability	2
30	Harmful factors acting on object	1
31	Harmful side effects	3
33	Convenience of use	1
34	Repairability	1
36	Complexity of device	1
37	Complexity of control	1

(Numbers in left hand side column represent identification numbers of 39 TRIZ engineering parameters shown in Table 3.8)

Table 3.10 shows that a few engineering parameters appear frequently. For example, here, both engineering parameters, #17: Temperature and #27: Reliability appear two times. Engineering parameter #31: harmful side effects, which appears the most, i.e., 3 times. The next part of the method is finding inventive principles corresponding to the engineering parameters that appear most frequently in the Table 3.10. In this research, we follow the path of solving design problem without getting into contradiction analysis. The Liu and Chen method (2003) examines all corresponding inventive principles associated with each "improving parameter" in the TRIZ in the contradiction table. Particular principles were seen a number of times. This situation can be explained as that the inventive principles will make improvements to a certain "improving parameter" in the system, possibly corresponding with other "avoiding degeneration parameter" types. Hence, for certain inventive principles appeared more often, indicating that is a good one to try in solving innovative design problem.

Next, the same procedures were applied to each "avoiding degeneration parameter" in another dimension of the TRIZ contradiction table (Liu and Chen, 2003). The corresponding inventive principles were examined and accounted for their number of appearances. The use of those principles by the designer means that it can improving a system's parameters and can avoid the deterioration of certain "parameters" simultaneously. As before, certain inventive principles appeared many times show that using those principles will give the designer a good try to solve innovative design problems.

Finally, combination of both parts together and summing up the number of appearances of all of the principles constructs a table for single engineering parameters and inventive principles, as shown in Table 3.11. The vertical axis is the TRIZ 39 parameters that the designer wanted to improve. The horizontal axis shows the frequency of appearances of each parameter's corresponding engineering principles. In this research we have done this exercise hand but it also can be done using available TRIZ software.

Here are two websites that contain TRIZ software:

- http://www.triz40.com/
- TRIZWorks http://www.ciri.org.nz/trizworks/software.html

The Table 3.11 classifies inventive principles into different ranks according to the number of appearances in the contradiction table for each parameter (Liu and Chen, 2001), such as:

- Engineering parameter that appeared more than 19 times is designated as A,
- Engineering parameter that appeared between 16-18 times is designated as B,
- Engineering parameter that appeared between 13-15 times is designated as C,
- Engineering parameter that appeared between 10-12 times is designated as D,
- Engineering parameter that appeared between 7-9 times is designated as E,
- Engineering parameter that appeared between 4-6 times is designated as F, and
- Engineering parameter that appeared between 1-3 times is designated as G.

Those engineering principles appearances most frequently (ranked at A, B, C, etc. in Table 3.11) will have better chance at success in solving inventive design problem. Therefore, the designer can solve engineering innovative design problem without contradiction information choosing suitable TRIZ principles based on information in Table 3.11. This table is very useful for the designer in situations where it is unknown whether there is a contradiction and some parameters need to be improved. For example, if the designer has to change the weight of moving object, then Principle #35 from Table 3.7 has to be considered first because Liu and Chen (2003) identified that weight of moving object can be achieved by changing its parameter.

Table 3.11. Single engineering parameter and inventive principles (Liu and Chen, 2001)

TRIZ engineering parameters		Level						
		A (more than 19 times)	B (16-18 times)	C (13-15 times)	D (10-12 times)	E (7-9 times)	F (4-6 times)	G (1-3 times)
1	Wt. of moving object	35		28	26,18,02,10, 08,15,40,29,31	27,34,01,36, 19,06,37,38	03,32,22,24, 39,05,13,11	12,21,20,17,04, 30,16,14,25,23
2	Wt. of non moving object	35	28,10,19, 01,26	26	27,13,02,18	06,15,22,29	39,32,09,14, 40,05,08,03	17,25,30,20,16, 11,36,37,24
3	Length of moving object	01,29	15	35,04,17	10,28,08,14	19,24,13,26	16,02,34,09,07	37,39,18,32,36,05 12,22,25,23,40,06 38
4	length of non moving object			35	28,14,26,01,10	07.15	03,02,29,18 30,24,32,16	17,40,08,13,27,09, 37,38,39,06,25,23, 19,31,12,11,05
5	Area of moving object		15	17,26,13,02	10,29,30,04	01,14,19,32, 34,28,03	18,39,16,35	07,05,25,36,33,22, 40,11,06,31,38,23, 19,31,06
6	Area of non moving object			18,35	39,30,17,04, 36	39,30,17,04, 36	32,15,07,01, 38	28,26,37,22,09,29 03,14,13,13,27,25, 23,19,31,06
7	Volume of moving object		35	02,10,29	01,15,34,04, 06,07	13,40	16,28,14,39,17, 18,26,22,30,25, 37,36	24,38,11,12,32,19, 09,23,27,20,21,05, 03
8	Volume of non-moving object	35		02		18,14,34	10,04,39,19,31, 37,30,06,01,16	25,17,07,24,15,26, 27,03,09,32,38,40, 08,28,22,36,05
9	Speed	28.35	13	34	10,38,15	08,02,18,19	32,03,29,14,04, 26,01,30	16,21,36,24,27,06, 11,12,05,33,23,25, 09,20,22,07,40
10	Force	35.10.36	37,18	28,19	15,01,02	03,21,13,40	14,26,16,17,08	12,11,34,29,09,24, 20,05,23,27,30,32, 28,39,04,06,25
11	Tension/pressure	35.10	36,37		02,14	19,03,18,40, 01	06,15,13,24,27, 25	33,04,16,32,22,28, 21,29,39,11,09,23, 38,12,08,34
12	Shape	01	10,14,15,35	29.34	32,13,40,04	02,28,22	30,05,26,18,07, 17,03	16,06,08,25,37,27, 39,19,36,09,12,11
13	Stability of object	35	39,02	01	40,13,18,32, 30	27,15,03,22,28	19,10,14,17,11, 04,23,34,33	24,21,26,37,31,16, 06,29,08,05,09,38
14	Strength	3.35.10.28	40,15	14,27		26,09,18,02, 32,01,29	08,11,13,17,19, 30	34,22,06,07,37,31, 25,16,05
15	Durability of moving object	35.19	03,10	27	28	02,06,18	13,04,29,15,25, 39,01,22,40	31,09,33,14,16,26, 11,38,34,20,17,30, 21,12,08,32
16	Durability of non moving object			16	35,10	01,40	38,27,06,34,19, 18,03,02,20	25,24,39,23,22,28, 31,17,33,36,26,21, 30
17	Temperature	35.19	02		03,10,39,18 22	21,32,27,17,16, 28,36,26,38	24,30,04,14,15, 06,40	31,13,09,34,33,25, 01,29,20,07

Table 3.11. Single engineering parameter and inventive principles (Liu and Chen, 2001), Continued

TRIZ engineering parameter		Level						
		A (more than 19 times)	B (16-18 times)	C (13-15 times)	D (10-12 times)	E (7-9 times)	F (4-6 times)	G (1-3 times)
18	Brightness	19,32,0132	13		15,35,02,26	06	17,16,03,10,24	28,27,11,25,30,39, 21,08,04,22
19	Energy Spent by moving object	35.19			18,28,02,06	15,24,01,13, 27,32	16,12,38,17,29, 14,34,10,03	10,16,28,02,23,29, 03,32,06,09,30
20	Energy spent by non-moving obj.					01,35,19	18,27,04,37,36, 31,22	10,16,28,02,23,29, 03,32,06,09,15,12, 25
21	Power	35,19,10,2			32,06,38,18	34,31,26,28,17	27,16,20,01,15, 22,30,37,14	12,25,36,08,29,03, 13,04,24,21,11,40
22	Waste of energy	35	02	19,07	15,10	18,06,38,32	13,28,22,26,14,17, 01,21,26,23,25,30	16,27,39,03,29,11, 36,05,12,37,24,31, 20.09.34
23	Waste of substance	10.35.28	18	31,24	02,27,39,03	34,40,29,05,13	38,01,36,06,30, 14,15,33,23,16	22,32,37,21,25,08, 19,12,04
24	Loss of information	10			35	24,26,22	28,32,19,30,01	02,27,33,13,15,16, 23,21,29,18,04,06, 05
25	Waste of time	10.35.28.18		04,32	34,20,26	29,24,05	01,30,16,37,17, 06,15,36,19,02	14.22.03.38.39.21. 27.25.09.07
26	Amount of substance	35.3.29	18	10		14,27,40,31,28, 15,02	13,06,24,25,34, 30,01,39,16,19, 32,36	33,26,17,38,04,07, 23,22,21,20,12,08
27	Reliability	35.10.11				13.24.08.02.32. 29	19.21.04.14.16. 23	17.39.26.15.36,06, 34,31,09,30,38,25, 05,18
28	Accuracy of measurement	32.28.26		03,10	24,06,34,01,13	35,02	16,25,27,11,23	05,33,18,15,31,19, 04,12,39,17.22,36
29	Accuracy of manufacture	32	28,10	18	02,26,35	03	01,25,29,30,36, 24,27,23,40	34,37,17,04,11,13, 16,19,31,33,39,09, 38
30	Harmful factors acting on object	22.35.2	01	33,28	18,19,24,27, 40	39,10,37	31,29,21,13,34, 17,15,26	23,30,06,03,32,11, 25,16,36,04
31	Harmful side effects	35.22.2.39		01,18	.40	21,24,17,19	15,03,10,27,33, 34,04,26	31,16,06,28,29,30, 32,23,13,36
32	Manufacturability	1,35	28	27,13	26	24,15,16,29	02,11,10,04,32, 18,34,12,17,19, 40	08,05,36,09,03,33, 37,06,23,25,30,31
33	Convenience of use	1	13	02,28,35,32	12,15,34,25	16,26,17,27	04,03,10,24,40, 19,39,29	22,30,05,18,23,06, 08,09,31,07,11
34	Repair ability	1.10.2	11	35,13	32,15,16,27	25,28	34,04	09,03,12,07,26,19, 17,29,18,31
35	Adaptability	35.15.1		29	16,0213		19,28,10,37,08, 34,03,30,27,06, 17	32,31,14,04,18,07, 26,11,20,22,24,05, 25
36	Complexity of device	1	26,28,10,13	35	02,29,19,24	34,27,15,17	06,36,37,36, 34,06,17	12,04,32,40,14,20, 03,31,39,25,23,05, 11,07
37	Complexity of control	35			02,19,29,15, 16,01,03	18,24,13,32,39, 10	25,40,22,37,39, 10	11,21,30,04,05,38, 31,33,23,12,08,09
38	Level of automation	35		02,28,26	01,13,10,34	18,24	23,27,32,15,17, 08,12,16,19	03,33,14,30,05,25, 06,11,04,21,09,07
39	Productivity	35.10.28		01		18,02,37,26,3, 14,15,38,29,17	24,03,32,13,12, 23,22,39,06,17	16,20,27,30,04,40, 05M25,21,31,36

Inventive principle corresponding to the engineering parameters 17, 27 and 31 are documented in Table 3.12.

Table 3.12. Inventive principle corresponding to the engineering parameters 17, 27 and 31

Engineering parameter	**Inventive principles (according to Table 3.11)**
17	35, 19, 02
27	35, 10, 11, 40
31	35, 22, 02, 39

With the information presented in Table 3.12, the high frequency appearance inventive principles in Table 3.12 are inventive principle #35, and #02. By applying these inventive principles design engineer can find innovative ideas to develop sustainable product.

3.2.4 Selection of Product Ideas (options/ concepts) for Sustainable Development (Box 10 to Box 13 in Figure 3.1)

Traditionally the focus of engineering product development has primarily been in achieving superior products from technical and economic perspectives (Yang and Song, 2006). However, the worldwide recognized need for sustainable development is putting additional challenges to product design and development.

The sustainable view of product development is based on the need for product development companies to fully accept the natural and social system; this fact has two dramatic implications for product development:

- acceptance of scarcity of natural resources and
- the notion of business and the society's co-responsibility related to the use and development of social resources

This decision problem has multiple dimensions, where intuitive judgments are difficult, where many different attributes are present (requiring both quantitative and qualitative inputs), and where there is limited substitutability among the attributes (or criteria). The problem of systematic selection of a product concept based on sustainable development principles from a pool of product concepts is considered as a multi-attribute decision problem.

A *five-step* decision making process to select a product concept as a detail design candidate based on sustainable development principle is shown in Figure 3.7. This methodology is developed based on the Analytic Hierarchy Process (AHP), which is shown in Figure 3.6 (Saaty, 1980).

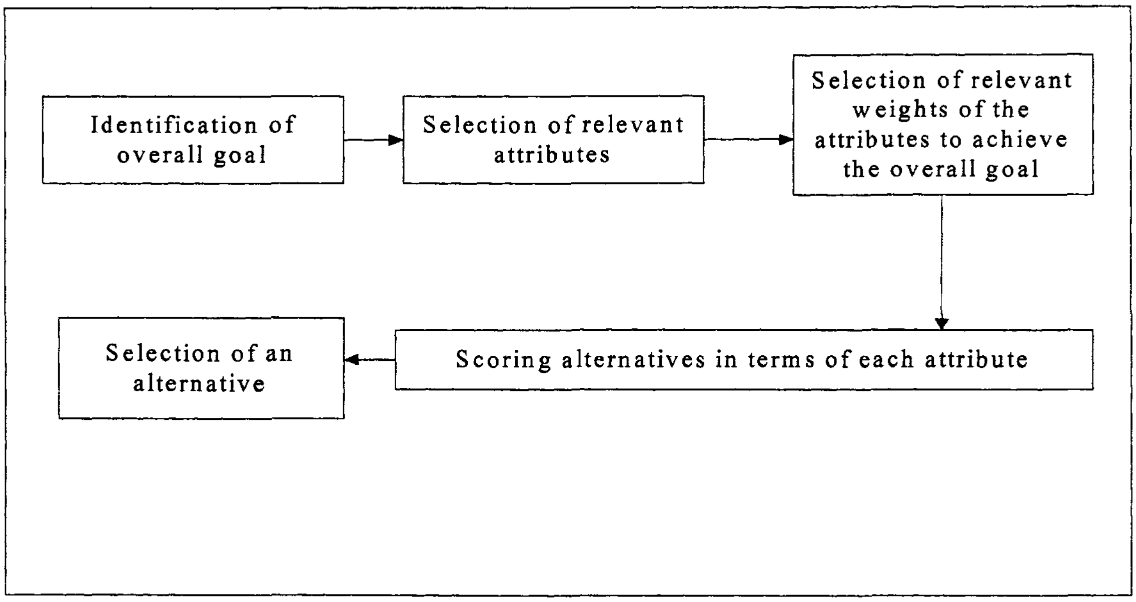

Figure 3.6. Five-step of AHP (Saaty, 1980)

Multi attribute modeling consists of the following steps (Herkert et al., 1996).

- Selection of the overall goal for solving a problem (what is the desired outcome of the decision-making process),
- Selection of relevant attributes (or criteria),
- Weighting relative contribution of criteria to the overall goal (the choice problem), and
- Scoring possible outcomes in terms of each attribute (the measurement problem)

Formal models of choice are then applied to re-aggregate the single-attribute evaluations. Multi-attribute decision framework can be represented by a decision hierarchy like the one presented in Figure 3.8.

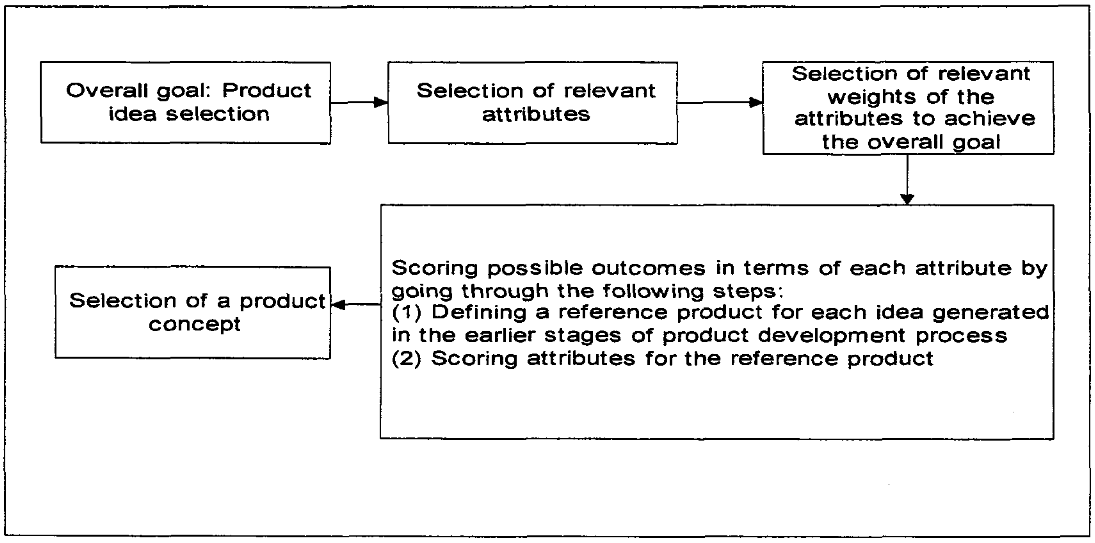

Figure 3.7. Five-step product idea selection process based on AHP

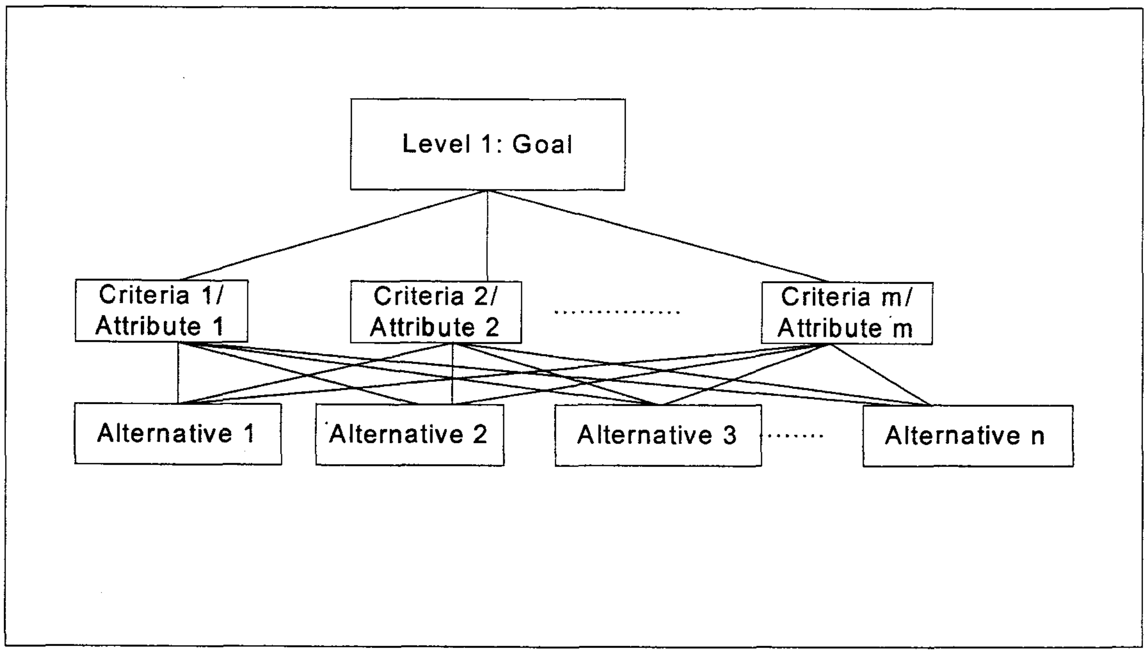

Figure 3.8. Hierarchy structure of multi-attribute decision framework

As mentioned earlier, the overall goal of the decision problem is decomposed into attributes / criteria (sometimes it can be several levels of attributes). The attributes are weighted in comparison to one another with respect to importance in achieving the overall goal of sustainability. This part of the problem is defined as *choice problem.* The attributes selected for this research are similar to the idea of sustainability indicators, which is an important area of both academic research and practical application. Several techniques for determining these weights exist, of which the Analytic Hierarchy Process (AHP) is one. The AHP is a decision-aiding method first developed by Saaty in the 1970s (Saaty, 1980). The Analytic Hierarchy Process is a mathematical approach to the decision-making process. This method aims at quantifying relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision maker. This method stresses the importance of the intuitive judgments of a decision-maker as well as the consistency of the comparison of alternatives in the decision-making process. The strength of this approach is that it organizes tangible and intangible factors in a systematic way, and provides a structured yet relatively simple solution to the decision-making problems. Technically, the AHP uses eigenvector reduction to covert pair-wise comparisons into individual weights. In addition to determining the weights, scores that measure the performance of each alternative in terms of each attribute must be created – this is the *measurement problem*. Together the weights and scores create a weighted additive function by which each alternative is evaluated in terms of the goal.

The proposed decision making model is primarily based on the Analytical Hierarchy Process (AHP). The proposed methodology structures the hierarchy from the top (the objectives from a decision-maker's viewpoint) through the intermediate levels (criteria / attributes on which subsequent levels depend) though the lowest level usually containing the list of alternatives.

3.2.4.1 Decision-Making Scenario

Although the concept "sustainable development" is very rich, it does not provide a robust and practical (i.e., operational) knowledge tool to give insight into complex problems. Indeed, the ambiguity in the concept has caused some analysts to abandon sustainable development as a framework for decision-making. An operational definition is one that is "ready to use", which usually means that it is associated with measurable quantities and can be applied to specific problems (Herkert et al., 1996). A decision maker (DM), such as a product design selection team representative, is considering how to compare more than one detail design candidates (for example, A, B, and C). The alternatives are evaluated against a set of objectives. The decision is complicated by the need to balance profitability, environmental impact, and societal impacts. This example, however, is illustrative only.

3.2.4.2 The Decision Model

The hierarchy structure of sustainability assessment of product concepts is shown in Figure 3.9. Following the Figure 3.9, description of every step of the decision model is presented.

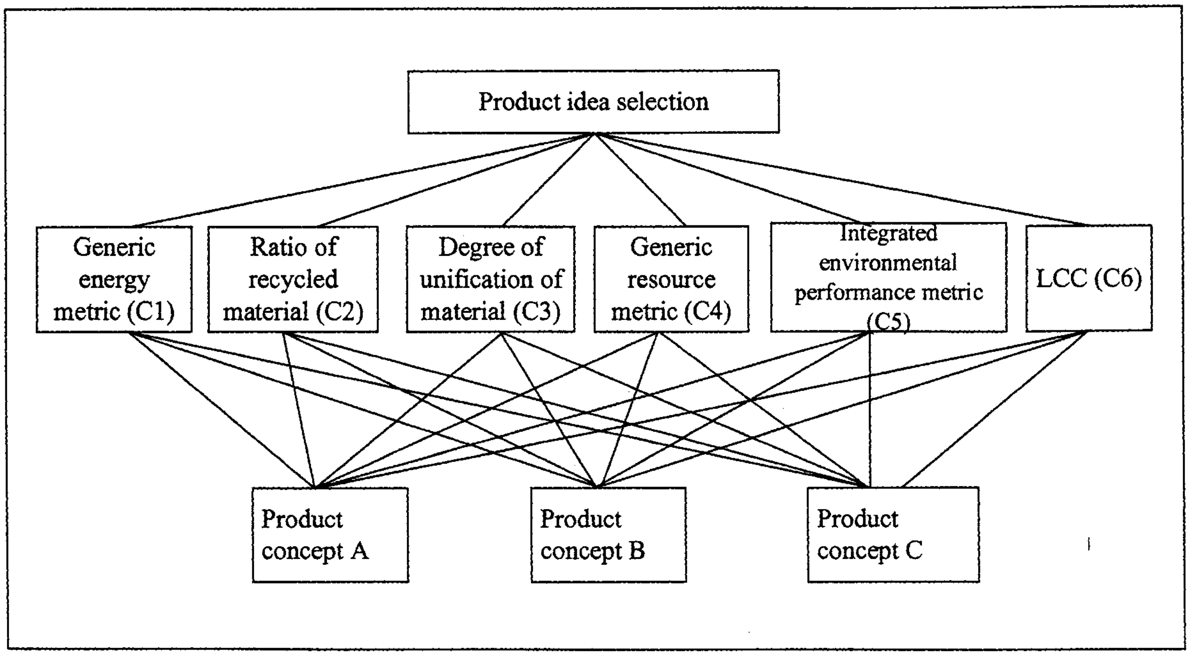

Figure 3.9. The hierarchy structure of sustainability assessment of product concept

A. Step 1 of the decision model. *Setting the overall goal*

In the last few years, sustainable development focus in the product development industry has shifted from manufacturing processes to the products themselves, as these are accountable for all the environmental and societal impacts in all life cycle phases. The sustainable development properties of a product are determined in the product development stage, it is necessary to supply the product development function with methods/tools to assess the environmental, health and safety, societal consequences in product life-cycle and to support selection of sustainable solutions. So, overall goal for this decision analysis is selection of a sustainable product (design) idea.

B. Step 2 of the decision model. *Selection of relevant attributes*

Multi-attribute model developed in this research includes a set of attributes, which we believe are both directly related to the problem of selecting a product idea and necessary to consider in light of the goal of sustainable development. In other way, we could say that the overall goal of the decision problem is decomposed into attributes, each of which is assigned a weight indicating how important the attribute is to the achievement of the overall goal. The attributes chosen for this application include economic (life-cycle cost of material), social (local control), and ecological (integrated environmental performance metric) attributes, as well as attributes (resource use and End-of-Life metric) that arguably span all three categories of sustainable development principle. In this chapter, we present a list of attributes that are useful to measure sustainability of a product idea or concept. In practical situation, we encourage to choose any or all of these attributes to measure sustainability. The design team has freedom to choose many more attributes, if necessary. The model presented for evaluation of a product concept can handle both subjective and quantitative criteria efficiently. Following are a few to discuss:

Attribute #1. Life cycle costs of material used – (cents per unit of product)

Life cycle costing (LCC) can be defined as "the economic assessment of all money flows that are caused by the existence of a product" (Yong and Song, 2006). LCC economic analysis assesses the cumulative cost over the lifecycle of a product or a portion of the lifecycle at early design stages. The efficient allocation of goods and services are important aspects of sustainable development and is part of nearly every sustainability indicator set (Farrell, 1994). The main two reasons for having life cycle cost data as an attribute in this analysis are

- to improve product profitability
- to aid in the design of more environmentally desirable products

Preliminary design choices that ignore economics are neither sustainable nor sensible. This analysis provides critical inputs for decision making on design alternatives to reduce total lifecycle costs and to find the better way of use of resources (e.g., materials and energy). For example, different designs may satisfy the same required performance level, but have different investment, operation or maintenance costs. LCC helps the evaluation of product design options and economic viability of products. Life cycle cost data could be given based on empirical data or projections.

Attribute #2. Energy use

The basic idea of sustainable development promotes less use of nonrenewable energy and use of renewable energy. Energy use is a key concern in ecological economic theory, which suggests that nonrenewable resources should be consumed efficiently and that renewable energy be developed as ready substitutes when the nonrenewable resources are depleted or otherwise unavailable (Farrell, 1994).

Attribute #3. Integrated environmental performance metric

This metric integrates the influences of the following environmental attributes on product's environmental performance, including degree of materials mixing, hazardous substance, water consumption, emission, maintenance level, and so on (Yang and Song, 2006). Under each attribute, sub-factors are identified to illustrate more detailed performance measures and ratings. For example, the hazardous substance attribute contains the sub-factors for health effect, environmental effect, number of undesired substances, and classification of substances. The formula of environmental performance metric, M (performance), is defined by:

$$\text{M(performance)} = \frac{1}{m}\sum_{i=1}^{m} \frac{\sum_{j=1}^{m} w_i r_{ij}}{\sum_{j=1}^{n} w_i Max\,(r_{ij})}$$

Where $i = 1,2,\ldots,m$; m denotes the number of n environmental attributes considered in the metric: $j = 1,2,\ldots n$; n denotes the number of sub-factors under one environmental attribute: r_{ij} is the rating of the j^{th} sub-factor under the i^{th} environmental attribute: w_i is the importance weight of the i^{th} attribute: $Max(r_{ij})$ represents the full rating of the j^{th} subfactor under the i^{th} environmental attribute.

Attribute #4. Ratio of recyclable material

The recyclable material ratio R_1 is measured by the formula introduced by Kobayashi et al. (1999).

$$R_1 = \frac{\sum_{k=1}^{n} w_k}{w}$$

where w: total weight of the product

w_k: k^{th} recyclable material's weight

The product recyclability is desirable. If the value of R_1 is high, the product recyclability is high.

Attribute #5. Degree of unification of the kind of material included in a product.

A measure S_1 (Kobayashi et al., 1999) is used to show the number of kinds of material existence in the product.

$$S_1 = \sum_{i=1}^{l} \frac{w_i}{w} \log \frac{w_i}{w}$$

where, $w = \sum_{i=1}^{l} w_i$, w: total weight

and w_i: i^{th} material's weight ($i = 1, 2, \ldots, l$).

The value of S_1 decreases as the number of kinds of material decreases or the material existence ratio becomes unity.

Attribute #6. End-of-Life (EoL) metrics

To evaluate the EoL performance of a product, relevant EoL metrics are developed. These include:

- Percentage of materials recovered
- Percentage of resources recovered
- Recycled content by weight
- EoL value
- Time for disassembly, etc.

Attribute #7. Local control in decision-making

Influence of local institutions and individuals on product development choice decisions. Virtually every sustainability indicator set reflects the notion that participatory decision making is critical to sustainability.

Attribute #8. Durability

When sustainability is concern, product durability is desirable. Definition of sustainable development presents the idea that if a product can be used longer period of time, it could save production of another product, which in turn saves energy, material, etc.

Attribute #9. Versatility

Sustainable product has to be sufficiently successful to get enough attention in the market. One of the three pillars of sustainability is economical feasibility. If a product does have more features can be called as a better option. For example, if vacuum cleaner has an option to convert in into a hand vac to clean upholstery can be seen as a better product.

Attribute #10. Distance between manufacturing area and primary market

Sustainability encourages cutting down transportation of goods mainly because of the effects of transportation.

C. Step 3 of the decision model. *Selection of relevant weights of the attributes to achieve the overall goal*

This step involves developing a graphical representation of the problem in terms of the overall goal, the criteria to be used, and the decision alternatives. Such a graph depicts the hierarchy for the problem. Figure 3.9 shows the hierarchy for the product idea selection for sustainable development problem. Note that the first level of the hierarchy shows the overall goal is to select a product concept that is the most sustainable between the proposed three ideas. At the second level, a set of criteria each contribute to the achievement of the overall goal. Finally, at the third level, each decision alternative – A, B, and C (arbitrary named) – contributes to each criterion in a unique way.

Using AHP, the decision maker specifies judgments about the relative importance of each of the criteria in terms of its contribution to the achievement of the overall goal. At the next level, the decision maker indicates a preference for each decision alternative based on each criterion. A mathematical process is used to synthesize the information on the relative importance of the criteria and the preferences for the decision alternatives to provide an overall priority ranking of the decision alternatives. In this research, AHP will use the researcher's preferences based on the literature review to provide a priority ranking of the three alternative detail design candidates in terms of how well each design idea meets the overall goal of being the preferable detail design candidate in terms of sustainable development principle.

Now how AHP uses pair-wise comparisons expressed by the decision maker to establish priorities for the criteria and priorities for the decision alternatives based on each criterion is shown. Analyzing the problem at hand, we show how AHP determines priorities for the following:

Pair-wise comparisons form the fundamental building blocks of AHP. In establishing the priorities for the seven criteria, AHP will require the decision maker to state how important each criterion is relative to each other criterion when the criteria are compared two at a time (pair-wise). In this research attribute and criteria are used as synonyms. In each comparison, the decision maker must select the more important criterion and then express a judgment of how much more important the selected criterion is. Table 3.13 shows how the decision maker's verbal description of the relative importance between the two criteria is converted into numerical rating. From Table 3.13, we see "strongly more important" receives a numerical rating of 5, while "very strongly more important" receives a numerical rating of 7.

Intermediate judgments such as "strongly to very strongly more important" are possible and would receive a numerical rating of 6.

Table 3.13. Conversion of the decision maker's verbal description of the relative importance between the two criteria converted into numerical rating (Anderson, et. al., 2005)

Decision Maker's Verbal Expressions	Numerical Ratings
Extremely more important	9
Very strongly more important	7
Strongly more important	5
Moderately more important	3
Equally important	1

For example, three attributes are selected to measure sustainability of three product concepts A, B, and C. These attributes are:

1. Resources use
2. Life cycle costs
3. Ratio of recyclable materials

To illustrate the procedure, preferences of three criteria with respect to each other are as shown in Table 3.14.

Table 3.14. Complete pair-wise comparison matrix for three sustainability evaluation criteria

	Resource use	Life cycle cost	Ratio of recyclable materials
Resource use	1	5	7
Life cycle cost	1/5	1	3
Ratio of recyclable mat.	1/7	1/3	1

Using the pair-wise comparison matrix, we cannot calculate the priority of each criterion in terms of its contribution to the overall goal of selecting the best alternative product idea. This aspect of AHP is referred to as synthesization. The exact mathematical procedure required to perform synthesization is beyond the scope of this research. However, the following three-step procedure provides a good approximation of the synthesization results (Anderson et al., 2005).

1. Sum the values in each column of the pair-wise comparison matrix
2. Divide each element in the pair-wise comparison matrix by its column total; the resulting matrix is referred to as the normalized pair-wise comparison matrix.
3. Compute the average of the elements in each row of the normalized pair-wise comparison matrix; these averages provide the priorities for the criteria.

To show how the synthesization process works, we carry out this three-step procedure for the criteria pair-wise comparison matrix.

Table 3.15. Sum the values in each column

	Resource use	Life cycle cost	Ratio of recyclable materials
Resource use	1	5	7
Life cycle cost	1/5	1	3
Ratio of recyclable materials	1/7	1/3	1
Sum	1.34	6.33	11

Table 3.16. Divide each element of the matrix by its column total

	Resource use	Life cycle cost	Ratio of recyclable materials
Resource use	0.746	0.789	0.636
Life cycle cost	0.149	0.158	0.272
Ratio of recyclable materials	0.106	0.052	0.09

Table 3.17. Average the elements in each row determine the priority of each criterion

	Resource use	Life cycle cost	Ratio of recyclable materials	Priority
Resource use	0.746	0.789	0.636	0.723
Life cycle cost	0.149	0.158	0.272	0.193
Ratio of recyclable materials	0.106	0.052	0.09	0.082

The AHP synthesization procedure provides the priority of each criterion in terms of its contribution to the overall goal of selecting the best product idea. AHP determines that all three criteria has the same priority in the decision making process.

A key step in AHP is the ranking of several pair-wise comparisons as previously described. An important consideration in this process is the consistency of the pair-wise judgments provided by the decision maker. For example, if criterion A compared to criterion B has a numerical rating of 3 and if criterion B compared to criterion C has a numerical rating of 2, perfect consistency of criterion A compared to criterion C would have a numerical rating of 3 X 2 = 6. If the A to C numerical rating assigned by the decision maker was 4 or 5, some inconsistency would exist among the pair-wise comparison (Anderson et al., 2005).

With numerous pair-wise comparisons, perfect consistency is difficult to achieve. In fact, some degree of inconsistency can be expected to exist in almost any set of pair-wise comparisons. To handle the consistency issue, AHP provides a method for measuring the degree of consistency among the pair-wise comparisons provided by the decision maker. If the degree of consistency is unacceptable, the decision maker should review and revise the pair-wise comparisons before proceeding with the AHP analysis.

AHP provides a measure of the consistency for the pair-wise comparisons by computing a consistency ratio. This ratio is designed in such a way that a value greater than 0.1 indicates an inconsistency in the pair-wise judgments. Thus, if the consistency ratio is 0.1 or less, the consistency of the pair-wise comparisons is considered reasonable, the AHP process can continue with the synthesization computations (Anderson, et al., 2005).

Although the exact mathematical computation of the consistency ratio is beyond the scope of this research, an approximation of the ratio can be obtained with little difficulty. The step-by-step procedure for estimating the consistency ratio for the criteria can be found in Anderson et al., (2005).

D. Step 4 of the decision model. *Scoring possible outcomes in terms of each attribute*

The first step of scoring outcomes in terms of each attribute is defining a reference product for each product concept proposed in the earlier stages of product development process is the first task of this step. A reference product can serve as a representative for the new product in the initial phases of the product development (Nielson and Wenzel, 2002). An existing product can serve as the reference product if it is believed that the new product is going to be a modification hereof. For completely new products, this is, of course, not possible and a fictive product must serve as the reference product. Since new products are usually based on existing technologies in new compositions, it is in most cases possible to compose a useful reference product by putting existing units and technologies together. Data gathering procedure can be quite resource demanding for complex products. However, materials and processes, which from an initial judgment are found unimportant from sustainability point of view can be left out of considerations to keep the work in appropriate proportion. According to Nelson and Wenzel (2002), at the conceptual level, a rough model of the reference product is fully sufficient. The second of scoring is done by analyzing the values (both quantitative and qualitative) of selected attributes in the reference products.

E. Step 5 of the decision model. *Selection of a product idea*

Continuing with the AHP analysis of the selection of product idea in terms of SD criteria, we need to use pair-wise comparison procedure to determine the priorities for the three product concepts using each of the selected criteria. Determining these priorities requires pair-wise comparison preferences for the product options using each sustainability criterion one at a time. For example, using resource criterion, we have to make the following pair-wise comparisons:

Option A compared to Option B

Option A compared to Option C

Option B compared to Option C

In each comparison, we must select the more preferred option and then express a judgment of how much more preferred the selected option is.

For example, using resource use as the basis for comparison, assume that we consider the Option A and Option B comparison and indicate that the less resource consuming Option B is preferred. Table 3.14 shows how AHP uses description of preference between Option A and Option B to determine a numerical rating of the preference. For example, suppose that according to resource use data collected from reference products of the respective options, Option B is “moderately more preferred” to Option A. Thus, using resource use data, a numerical rating of 3 is assigned to the Option B row and Option A column of the pairwise comparison matrix. Table 3.18 shows the summary of the product idea pair-wise comparisons. Using this table and referring to selected pair-wise comparisons entries, we see that resource use data shows that the Option C is strongly preferred than the Option A.

Table 3.18. Pair-wise comparison matrixes showing preferences for the product options using resource use criterion

	Option A	Option B	Option C
Option A	1	1/3	1/4
Option B	3	1	1/3
Option C	5	3	1

Using the pair-wise comparison matrixes in Table 3.18, many other insights may be gained about preferences. However, At this point, AHP continues by synthesizing the pair-wise comparison matrix in order to determine the priority of each option using resource use criterion. A synthesization is conducted for each pair-wise comparison using the three step procedure described previously for the criteria (attribute) pair-wise comparison matrix. For all relevant criteria synthesizations are done accordingly. For example, if the priority for each option is computed as shown in Table 3.18, using these priorities and the priorities shown in Table 3.17, we can develop an overall priority ranking for the three options.

Table 3.19. Priorities for each option using each criterion

	Criterion #1	Criterion #2	Criterion #3
Option #1	0.123	0.087	0.593
Option #2	0.32	0.274	0.341
Option #3	0.557	0.639	0.065

The procedure used to compute the overall priority is to weight each option's priority shown in Table 3.19 by corresponding criterion.

Overall priority of the Option 1

0.723 (0.123) + 0.193(0.320) + 0.082(0.557) = 0.196

Similarly priorities for the other two options can be easily determined. Ranking these priorities, we have the AHP ranking of the decision alternatives. These results provide basis for product design team to make a decision regarding the selection of product option alternative for further analysis. As long as the design team believes that their judgments regarding the importance of the criteria and their preferences for the options using each criterion are valid, the AHP result for selection of an option has validity. An important consideration in this process is the consistency of the pairwise judgments provided by the decision makers. With numerous pairwise comparisons, perfect consistency is difficult to achieve, In fact, some degree of inconsistency can be expected to exist in almost any set of pairwise comparisons. To handle the consistency issue, AHP provides a method for measuring the degree of consistency among the pairwise comparisons provided by the decision maker. If the degree of consistency is unacceptable, the decision maker should review and revise the pairwise comparisons before proceeding with the AHP analysis. AHP provides a measure of the consistency for the pairwise comparisons by computing consistency ratio (CR). Although the exact mathematical computation of the CR is not included in this document to reduce computational task. The step-by-step procedure for estimating the consistency ratio for the criteria is available in Anderson and Sweeny (2005). The whole calculation including consistency ratio calculation for unbiased solution can be done by commercial software like ExpertChoice < www.ExpertChoice.com>.

3.3 Conclusions

This chapter begins with the discussion of special features of the methodology to develop more sustainable products. Development of new product idea/ option is usually concerned with novelty and economic usefulness. Here we consider that developing a new product ideas/ options, it is illustrative to move between the three corners Ecology, Equity and Economy in order to obtain a suitable balance so that each category can be fulfilled in the best way. Product idea development for sustainable development is considered as an ill-defined problem because there are many different needs to meet. In this chapter, a novel product idea generation process has been presented. The method is based on the basic idea of soft systems methodology. This method is specifically designed to incorporate other tools to facilitate generation of innovative product solutions. Chapter 4 will demonstrate an application of the developed methodology presented in this chapter.

Chapter 4

Application and Example

In this chapter, an application of the methodology presented in the Chapter 3, is demonstrated. Over the past 10 to 20 years, organizations have been seeking to improve their sustainability performance as a result of rapidly increasing market share. Government regulations on product end-of-life and production processes have emphasized the need to address sustainable development concerns during the product design process to ensure compliance with related regulations. The emergence of standards for environmental management, such as the ISO 14000 series, also encourages manufacturers to develop policies that promote environmentally sound products and processes. To respond to these ongoing pressures, both academics and practitioners have been developing and implementing strategies. A growing number of design for environment (DFE) tools to assist in developing and implementing these strategies is now available. Many of these emergent tools focus on a single issue of the product life cycle, such as disassembly or recycling. They may not, however, attempt to address simultaneously all the relevant product life cycle factors that must be taken into consideration. Only inclusion of environmental perspective of sustainable development into traditional product development process does not make it complete. So, there is still a need for a structured approach to product development that will comprehensively address all three dimensions of sustainable development principle arising from all stages of the product life cycle. A structured approach to include sustainable development principle in product idea generation stage also supports an organization's environmental management system (EMS). This approach is intended to provide an organized process that may help designers to identify and understand sustainable development needs, to determine how best to satisfy the needs and how improvement options can be measured in the design process. Section 4.1 of this chapter presents an application of the methodology.

4.1 Example (Hairdryer)

To apply the described method, a case study is implemented. Reference product is a hair dryer. Hair dryer belongs to the electrical products category and relatively simple.

4.1.1 Step 1. Need Identification

To gather customer needs for the hair dryer, actual market survey done by Yim and Herrman (2003) is reviewed. This survey was done in a group of 30 people. It is relatively very small number of sample compare to actual market survey of industries, however it enhances the reality of the case study. List of customer needs can be generated from two sources:

- consumers' evaluation of provided questions
- consumers complaints

First of all, the result from consumers' evaluation is as shown in Table 4.1. Table 4.1 consists of general importance level of different desired properties of a hair dryer. For a hair dryer, less energy, quick drying, and safe to use are the most desired properties.

Table 4.1. Customer needs for a general **hair dryer**

Conventional customer requirement	**Verbal representation of importance of customer requirement**	**Numerical representation of importance of customer requirement**
Easy to grip	Weak importance	3
Less bulky	Weak importance	3
Quick drying	Weak importance	3
Safe to use	Medium importance	6
Low noise	Weak importance	3
Easy to operate	Weak importance	3

Consumers' complaints can also be gathered from a questionnaire, not from the pre-set questions but from the free-formed comment. Then it has to be translated into positive customer requirement statements. The frequency distribution is performed as to the complaints in order to identify the most frequently raised complaints.

The next stage of the process involves questioning the necessity of developing a product to fulfill customer's needs. Sustainability principle promotes that it is more sustainable to replace physical product by service to meet customer's needs. In practice, complete replacement of a product by a service is difficult to achieve. There is always possibility to have some combination of product and service (Maxwell and van der Vorst, 2003). This methodology considers preparation of answers to a list of questions (Table 3.2) by analyzing the traditional customer requirements to identify requirements of developing a product. The list of questions can be elaborated depending on specific circumstances. For this particular case study, the answers of the questions given in table 3.2 are listed in Table 4.2.

Table 4.2. Question the necessity of product development

Questions	Answers
What is the primary need of customers that need to be met?	Drying wet hair
Could this need be fulfilled by a service?	No
Is it essential to have a product?	Yes
Is there any option for product and service combination?	No

4.1.2 Step 2: Problem Formulation

Formation of design team can be done as it is described in Chapter 3 (Section 3.2.2.1). In this chapter, we only focus on how problem is formulated considering sustainable development perspective. With the preset sustainable product design guidelines from Table 3.3, the sustainable development-customer requirement matrix is extracted and presented in Table 4.3a to 4.3h for the case of developing a hair dryer. In these tables we show that sustainable development product design guidelines have different strength of relationships with each of the customer requirements presented in Table 4.3a to 4.3h. To quantify strength of relationships of customer requirements and sustainable development criteria, we use 9, 6 and 3 for strong medium and weak relationships, respectively. For identification numbers of sustainable development criteria in Table 4.31 to 4.3h, please refer to Table 3.3.

Table 4.3a. Relationship between customer's requirement – "easy to grip" and SD criteria

Specific customer requirement	**Sustainable development criteria**	**Strength of relations**	**Rationale**	**Quantitative interpretation of relations**
Easy to grip	1 Consume less materials	Weak	less bulky and fewer controls	3
	4 Easy to disassembly and part sorting	Medium	Simple design has simpler and few connection points	6
	18 Easy to process and assembly	Medium	Simple design has simpler and few connection points	6
	3 Easy to transport and storage	Weak	Less bulky, durable product	3
	11 Ergonomically safe	Strong	Simple design and simple controlling mechanism	9
	12 Easy to operate	Strong	Simple design and simple controlling mechanism	9

Table 4.3 b. Relationship between customer's requirement – "Less material usage" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Less material usage	#1 Consume less materials	Strong	Simple and light design	9
	#3 Easy to transport and storage	Strong	Lighter unit weight	9
	#7 Use materials causing low environmental impacts	Weak	Total less material means very little chance of having hazardous mat.	3
	#8 Reduce packaging	Strong	Less material means less bulky and lighter product	9

Table 4.3 b (Continued). Relationship between customer's requirement – "Less material usage" and SD

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Less material usage	#18 Easy of processing and assembly	Medium	Simpler design, simpler joints, less chance to have different types of materials, fewer parts	6
	#4 Easy to disassemble and part sorting	Weak	Simpler design, simpler joints, less chance to have different type of materials, fewer parts	3
	#10 Trading arrangements for used raw materials are equitable	Medium	Less materials provide less chance of extracting materials from questionable sources	6

Table 4.3 b (Continued). Relationship between customer's requirement – "Less material usage" and SD

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Less material usage	#12 Easy to operate	Medium	Light weight, simple design	6
	#16 Product is more cost effective	High	Less raw material cost, less transportation cost, less energy required for processing, simple transportation, etc.	9
	#17 Environmental externality cost is less	Medium	Simple design, easy to make, less chance to violate regulations	6

Table 4.3 c. Relationship between customer's requirement – "quick drying" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Quick drying	#2 Reduce energy consumption	Strong	Quick drying mechanism cuts time to dry	9
	#11 Ergonomically safe	Medium	Less time to dry means less chance to have scalp burn or susceptible to electromagnetic radiation	6
	#5 Low emissions	Medium	Less time to dry means les chance to body get into electro magnetic radiation	6
	#6 High product durability	Low	Less time in use, increases longevity	3
	#16 Cost effectiveness	Medium	Less energy consumption means less money usage	6

Table 4.3d. Relationship between customer's requirement – "safe to use" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Safe to use	#3 Easy to transport and usage	Weak	Less prone to break, less hazardous substances, less radiation	3
	#6 Reduce susceptibility to damage/ high durability	Medium	Less prone to break	6
	#8 Reduce hazardous substance	Strong	Only be safe when less hazardous substances are used	9
	#5 Less emissions	Strong	Without conforming less emissions, cannot be declared as safe to use	9
	#1 Consume less materials	Weak	Simpler design, simpler joints, fewer parts	3
	#11 Ergonomically safe	Strong	Ergonomically safe and safe to use go hand in hand	9
	#12 Easy to operate	Strong	Easy to use and safe to use go hand in hand	9

Table 4.3e. Relationship between customer's requirement – "low noise" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Low noise	#2 Reduce energy consumption	Medium	Lighter efficient motor-fan produces less and energy and it takes less energy to run	6
	#1 Consume less material	Weak	Lighter efficient motor fan creates low noise	3
	#11 Ergonomically safe	Medium	Less noise pollution is a criteria for making a product ergonomically safe	6
	#12 Easy to operate	Strong	Less noise actually makes the unit easy to operate without getting annoyed	9

Table 4.3f. Relationship between customer's requirement – "easy operation" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Easy operation	#2 Reduce energy consumption	Weak	Efficient motor-fan makes the drying process less time consuming and it also makes the drying easier and reduces total energy consumption	3
	#6 High durability	Strong	Less susceptible to break makes operation easier	9
	#1 Material reduction	Medium	Easy to use related to less bulky material, means less material needed to produce	6
	#5 Low emissions	Medium	Efficient motor-fan means less emissions and also it makes the unit easy to operate	6
	#11 Ergonomically safe	Strong	Easy operation and ergonomically safe go hand in hand	9
	#12 Easy to operate	Strong	Same	9

Table 4.3 g. Relationship between customer's requirement – "extendable functionality" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative nterpretation of relations
Extendable functionality	#6 High durability	Strong	Extendable functionality and durability goes hand in hand	9
	#3 Easy to transport and storage	Weak	Modular design makes a product easy to transport	3
	#14 Modular design for maximum upgrade possibility	Strong	Parts can be replaced and operation remains same	9

Table 4.3h. Relationship between customer's requirement – "less energy" and SD criteria

Specific customer requirement	Sustainable development criteria	Strength of relations	Rationale	Quantitative interpretation of relations
Less Energy	#2 Reduce energy consumption	Strong	Same	9
	#3 Easy to transport and storage	Weak	Total energy efficiency includes energy usage during transportation	3
	#8 Reduce packaging	Weak	Less packaging means lower energy consumption during production of packaging, and also transportation	3
	#16 Overall cost effective	Strong	Lower energy consumption in all life cycle of product means less overall cost	9

In this part of the methodology, based on the Table 4.3a-h, the relationships between sustainable development criteria (requirements) and customer requirements are converted into numeric matrix in order to select the most important sustainable development requirements. The relations of strong, medium and weak are converted into 9, 6, 3, respectively. When there is no relation, it is expressed as vacant cell or with the value of 0. The results are shown in Table 4.4. In table 4.4, for convenience we use A, B, C, D, E, F, G, H for easy to grip, less material used, quick drying, safe to use, low noise, easy to operate, extendable, and less energy, respectively. The calculation for the last column of Table 4.4, levels of importance of SD criteria according to customer requirements, is done through the following procedure:

Each of the customer requirements is evaluated against each SD criteria to find relationships. The relationship between customer requirement and SD criteria need product development team's knowledge and judgment. These values are not fixed, and can vary depending on the team members. In Table 4.4, the level of importance of the SD criteria (the second last right hand side column) means how many importance relations the SD criteria have with traditional customer requirements. Calculations are done following the sequence presented in Section 3.2.2.3.

For demonstration, calculated level of importance of "low emissions" = relationship of "low emissions" with "quick drying" + relationship of "low emissions" with "safe to use" + relationship of "low emissions" with "easy operation" = 6 + 9 + 6 = 21

In Table 4.4, the example level of importance of SD criterion "low emissions" is 90, i.e., (relationship of "quick drying" with the SD criteria, "low emissions" X customer preference level of the traditional customer requirement, "quick drying") + (relationship of "safe to use" with the SD criteria, "low emissions" X customer preference level of the traditional customer requirement, "safe to use") + (relationship of "easy operation" with the SD criteria, "low emissions" X customer preference level of the traditional customer requirement, "easy operation") $= (6 \text{ X } 3) + (9 \text{ X } 6) + (6 \text{ X } 3) = 90$.

For demonstration purposes, we can show that relative level of importance of SD criterion "low emissions"

$$= \frac{\text{Level of importance of that SD criteria according to customer requirements is 90}}{\sum(\text{Level of importance of SD criteria according to customer requirements}) \text{ is 1800}} \text{ X } 100$$

$= 5\%$

From the last column of the Table 4.4, we see that "low energy" and "low emissions" have the highest weighted importance. This means those are the most consumer favorable SD criteria, which are effective for the sustainable design.

Table 4.4. Customer requirement and SD criteria relational matrix for Hair Dryer

(3: weak, 6: medium, and 9: strong)

SD Criteria	Customer requirements (Quantitative importance levels for each requirement shown in Table 4.1)									Levels of importance of SD criteria according to customer requirements (%)
	A (3)	B (3)	C (3)	D (6)	E (3)	F (3)	G (3)	H (9)	Levels of importance of the SD criteria	
#1 Less material	3	9		3	3	6			24	81 (4.5%)
#2 Less energy			9		6	3		9	27	135 (7.55%)
#3 Easy transportation and storage	3	9		3			3	3	21	90 (5.0%)
#4 Easy disassembly	6	3							9	27 (1.5%)
#5 Low emissions			6	9		6			21	90 (5.0%)
#6 Durability			3	6		9	9		27	99 (5.03%)
#7 Less hazardous substance		3							12	63 (3.52%)
#8 Reduce packages		3					3	3	9	45 (2.5%)
#9 Cleaner and renewable energy								6	6	54 (3.02%)
#10 Trading agreements										
#11 Ergonomically safe	9		6	9	6	9			39	144 (8.05%)
#12 Easy to operate	9	6		9	9	9			42	153 (8.55%)
#13 Recyclable and reusable materials										
#14 Modular design							9		9	27 (1.5%)
#15 Local community benefit										
#16 Cost effectiveness		9	6					9	24	126 (7.04%)
#17 Environmental externality cost less		6							6	18 (1.0%)
#18 Easy to process and assembly	6	6							12	36 (2.0%)

The sustainable development criteria, which have greater importance level in the Table 4.4 are listed together with conventional customer requirements from Table 4.1 in Table 4.5. Some of these criteria from both lists are similar or same. The designer has the freedom to choose the final criteria from each group of criteria. Table 4.5 shows an example of such list.

Table 4.5. Elements of sustainable design (traditional customer requirements + required SD criteria)

Traditional/ conventional customer requirements		
No.	**Conventional customer requirements**	**Level of Importance**
A	Easy to grip	3
B	Less bulky	3
C	Quick drying	3
D	Safe to use	6
E	Low noise	3
F	Easy to operate	3
G	Extendable	3
H	Less energy	9
+		
SD Criteria related to traditional customer requirements		
No.	**SD Criteria**	**Level of Importance**
12	Easy to operate	8.55%
11	Ergonomically safe	8.05%
2	Less energy	7.55%
16	Cost effectiveness	7.04%
6	Durability	5.03%
5	Low emissions	5.0%

4.1.3 Step 3: Idea Generation

In this stage of the proposed methodology, we establish link between each element of sustainable design and 39 engineering parameters of the TRIZ (Table 3.8). The aim of this step is to transfer the problem of product idea development for sustainable development to a TRIZ problem. For example, reducing a product's 'material usage,' that can be obtained by changing its properties, such as weight, dimensions, shape or the amount of material used. Sometimes some of the requirements given by the customers are exactly same as the proposed sustainable development requirements. These requirements are considered once for finding relationship with TRIZ engineering parameters. The developed product idea is ideal if it satisfies all elements of sustainable design. However, the real design task usually does not need to satisfy all elements, it only needs to obtain some specific ones (Chang and Chen, 2004). This process requires the designer's familiarity with TRIZ methodology. The designer forms a table (Table 4.6) with the following information:

- one column states the preferable elements for a sustainable product (Table 4.5)
- the next column states corresponding engineering parameters (from Table 3.8) that need to be considered to get a sustainable innovative design

Table 4.6. Relationship of 39 engineering parameters and sustainability elements

Elements for sustainable design (traditional requirements + required SD criteria)	**Engineering parameters related to the corresponding element of sustainable design (Table 3.8)**
Easy to grip	12, 17, 33
Less bulky	1, 2, 7, 8, 26, 33
Quick drying	17, 33
Safe to use	27, 31
Low noise	33
Easy to operate	33, 36, 31
Extendable	15, 16, 34, 35
Less energy	19, 20
Low emission	31
Durability	15, 16, 27, 34
Ergonomically safe	12, 33
Cost effectiveness	22, 23

From the Table 4.6, we can extract two sets of information:

1. Which engineering parameters are related to the desired elements for sustainability for a particular product
2. The frequency of appearance of each parameter in the table

Table 4.7 has three columns. The first two columns have information regarding the engineering parameters and the last column shows the frequency of appearance of a particular engineering parameter.

Table 4.7. Engineering parameters and their frequencies from Table 4.6

No.	Engineering parameter	Frequency of appearance in Table 4.6
1	Weight of moving object	1
2	Weight of non moving object	1
7	Volume of moving object	1
8	Volume of nonmoving object	1
12	Shape	2
15	Durability of moving object	2
16	Durability of non moving object	2
17	Temperature	2
19	Energy spent by moving object	1
20	Energy spent by non moving object	1
22	Waste of energy	1
26	Amount of substance	1
27	Reliability	2
31	Harmful side effects	**3**
33	Convenience of use	**6**
34	Repairability	2
35	Adaptability	1
36	Complexity of control	1

Table 4.7 shows that a few engineering parameters appear frequently. For example, here, both engineering parameters, #31: Harmful side effects and #33: Convenience of use appear the most, i.e., 3 and 6 times, respectively. The next highest frequency is 3 in the Table 4.7. The next part of the method is finding inventive principles corresponding to the engineering parameters that appear most frequently in the Table 4.7.

In this research, we follow the path of solving design problem without getting into contradiction analysis. The Liu and Chen method (2003) developed a method showing that the designer can solve engineering innovative design problem without contradiction information choosing suitable TRIZ principles based on information in Table 3.11. This table is very useful for the designer in situations where it is unknown whether there is a contradiction and some parameters need to be improved.

By following the method established by Liu and Chen (2003), we can show that engineering parameter 31 can be best achieved by using inventive principles 35, 22, 02, and 39. Similarly, engineering parameter 33, i.e., convenience of use can be achieved by utilizing inventive principles 01 and 13.

Table 4.8. Inventive principle corresponding to the engineering parameters 17, 27 and 31

Engineering parameter	**Designation number of inventive principles (please refer to Table 3.11)**	**Description of inventive principle (Please refer to Table 3.7)**
31: Harmful side effects	35	Parameter changes
	22	Blessing in disguise
	02	Taking out
	39	Inert atmosphere
33: Convenience of use	01	Segmentation
	13	The other way around

By applying six inventive principles presented in the Table 4.8, design engineer first look for innovative ideas for a hair dryer that is functional and also sustainable. Innovative idea for a sustainable hair dryer must have some inherent benefits to get recognition in the mature market. For example:

- Traditional hairdryer boils water out of hair. But if we can ensure a better way of changing water particle's physical state (TRIZ inventive principle #35: Changing parameter), then it will be much easier to dry hair in faster way (http://www.ecohairproducts.com.au/professional_products/chi_pro_rocket.shtml)
- Hand-held hair dryer can generate more than 400mG electro magnetic radiation, while staying far enough away from the motor to reduce electromagnetic exposure to acceptable levels. TRIZ inventive principle #02, taking out, can show the direction for innovative design where motor remains far from the head while hair dryer is used.
- Heat comes from metallic (mainly copper) coil in regular hairdryer. Heat from metallic coil does not ensure even transmission of heat. Uneven heat makes hair dry and freezy. TRIZ inventive principle #2: taking out and inventive principle #39: inert atmosphere are both can be used for finding solution to this problem.
- Use of a traditional hair dryer can take moisture out from hair to serve the purpose of drying hair. But TRIZ inventive principle #13: the other way around can be a way to go in finding alternative solution by infusing moisture into the hair shaft.

Even after using TRIZ inventive principles for having better innovative technology developed to solve the problem, the product design team still can generate sustainably correct product ideas by choosing

- environmentally friendly materials to build the product
- suppliers for materials and parts, who believe and practice sustainable development principles in their everyday practices
- local suppliers

Hair dryer market is already a mature market. To penetrate in this market product developers need revolutionary technology. After thorough consideration of the above mentioned points, the following options have been selected to achieve sustainable hair dryer:

Option 1: Replacing hair dryer copper coil with coil that can produce high heat with relatively in same temperature

Option 2: Keeping hair dryer motor away from user's head by using extra long hose

Option 3: Hair dryer with special technology to produce more even heat and moisture lock-in technology

These options may have the elements of sustainable hair dryer (both traditional customer requirements and SD criteria presented in Table 4.5). In real life, we see that product idea generation team also consider combination of options (or ideas). In this research, for ease of demonstration we avoid consideration of combination of ideas.

As different actors involved in the product idea generation and selection process, ranking needs to be done to select an idea that will be used for detail design. Next step of the presented methodology shows a decision making technique to identify an idea that is more sustainable than other two ideas.

4.1.4 Selection of Ideas (concepts) of Hair Dryer for Sustainable Development

The proposed decision making model is primarily based on the Analytical Hierarchy Process (AHP). The proposed methodology structures the hierarchy from the top (the objectives from a decision-maker's viewpoint) through the intermediate levels (criteria / attributes on which subsequent levels depend) though the lowest level usually containing the list of alternatives.

4.1.4.1 Decision-Making Scenario

A decision maker (DM), such as a product design selection team (or their representative), is considering how to compare more than one detail design candidates (for example, Option 1, Option 2 and Option 3 mentioned in Section 4.1.3). The alternatives are evaluated against a set of objectives. The decision is complicated by the need to balance profitability, environmental impact, and societal impacts. This example, however, is used for illustrative purposed only.

4.1.4.2 The Decision Model

The five step method presented in Section 3.4 is followed for making decision regarding selection of hair dryer design idea for sustainable development.

A. Step 1 of the decision model. *Setting the overall goal*

The sustainable development properties of a product are determined in the product development stage, it is necessary to supply the product development function with methods/tools to assess the environmental, health and safety, societal consequences in product life-cycle and to support selection of sustainable solutions. So, overall goal for this decision analysis is selection of a sustainable design idea of a hair dryer.

B. Step 2 of the decision model. *Selection of relevant attributes*

The overall goal of the decision problem is decomposed into attributes, each of which is assigned a weight indicating how important the attribute is to the achievement of the overall goal. The attributes chosen for this application include economic (cost or preferably life cycle cost, if possible), social (local control), and ecological (integrated environmental performance metric, energy used) attributes, as well as attributes (End-of-Life metric, technological availability) that arguably span all three categories of sustainable development principle.

In the previous chapter (Please see Section 3.4.1.2), we have suggested a few common attributes to evaluate product ideas for sustainable development. Product idea generation team always has freedom to use their judgment to select a list of attributes to evaluate a product idea based on the following issues:

- Product type
- Where the product is manufactured
- Where the product is used
- Where the product will be disposed
- What is the span of useful life of the product

Criteria selected for this problem: Criteria constitute the first level of the hierarchy and the elements at this level include:

Criteria #1. Energy

Criteria #2. Cost

Criteria #3. Versatility

C. Step 3 of the decision model. Selection of relevant weights of the attributes to achieve the overall goal

This step involves developing a graphical representation of the problem in terms of the overall goal, the criteria to be used, and the decision alternatives (similar to the Figure 3.9). Each one of the criteria needs essentially a separate methodology for their subsequent prioritization. In this research, we consider each criterion has "equal importance" to select a product idea.

Table 4.9. Pair-wise comparison scale for the preference of decision alternatives using AHP (Anderson et. al., 2005)

Decision Maker's Verbal Expressions (How much more important)	**Numerical Ratings**
Extremely more important	9
Very strongly more important	7
Strongly more important	5
Moderately more important	3
Equally important	1

Table 4.10. Pair-wise comparison of criteria

	Energy	Cost	Versatility
Energy	1	1	1
Cost	1	1	1
Versatility	1	1	1

Table 4.11. Sum value for each column

	Energy	Cost	Versatility
Energy	1	1	1
Cost	1	1	1
Versatility	1	1	1
Sum	3	3	3

Table 4.12. Divide each element of the matrix by its column total

	Option 1	Option 2	Option 3
Option 1	0.333	0.333	0.333
Option 2	0.333	0.333	0.333
Option 3	0.333	0.333	0.333

Table 4.13. Average the elements in each row determine the priority of each criterion

	Option 1	Option 2	Option 3	Priority
Option 1	0.333	0.333	0.333	0.333
Option 2	0.333	0.333	0.333	0.333
Option 3	0.333	0.333	0.333	0.333

D. Step 4 of the decision model. *Scoring possible outcomes in terms of each attribute*

The aim of having a decision model to select one of the three product ideas presented in the step three of featured methodology. For purposes of supporting decisions in sustainable product development, it is advantageous if various impacts are comparable and expressed on a common scale. The sustainable profile of a product idea cannot be generated without selecting an existing product as reference.

Defining a reference product for each of the option

Defining a reference product for each product concept proposed in the earlier stages of product development process is the first task of this step. A reference product can serve as a representative for the new product in the initial phases of the product development (Neilson and Wenzel, 2002). Since new products are usually based on existing technologies in new compositions, it is in most cases possible to compose a useful reference product by putting existing units and technologies together. In this research, we consider that at conceptual level, a rough model of the reference product is fully sufficient.

After thorough analysis of hair dryers that are sold in the market currently, we select reference products for **three** sustainable product options.

- For Option #1, reference product is Ping Digital Dryer (http://www.folica.com/CHI_Ceramic_Ion_d1206.html)
- For Option #2, reference product is Low EMF hairdryer (http://www.lessemf.com/emf-appl.html)
- For Option #3, reference product is HAI Elite Ionic 1875 Watts Tourmaline Turbo Hair Dryer (http://www.hairproducts.com/view_product_BLO-HAI104.htm)

E. Step 5 of the decision model. *Selection of a product idea*

The decision model we employed requires that attributes be weighted in comparison to one another with respect to importance in achieving the overall goal of sustainability. In addition, it requires that each alternative product idea option be scored with respect to each attribute listed here, The AHP is a method for handling both types of judgments (quantitative and qualitative) by way of ratio comparisons. In this exercise, we consider all attributes have equal importance in achieving overall goal of sustainability. In addition to weighting the attributes, it is necessary to assess how well each alternative (hair dryer design options) meets the objective described by each attribute. In Table 4.9, the product idea scores for these attributes in relation to the overall goal of sustainability.

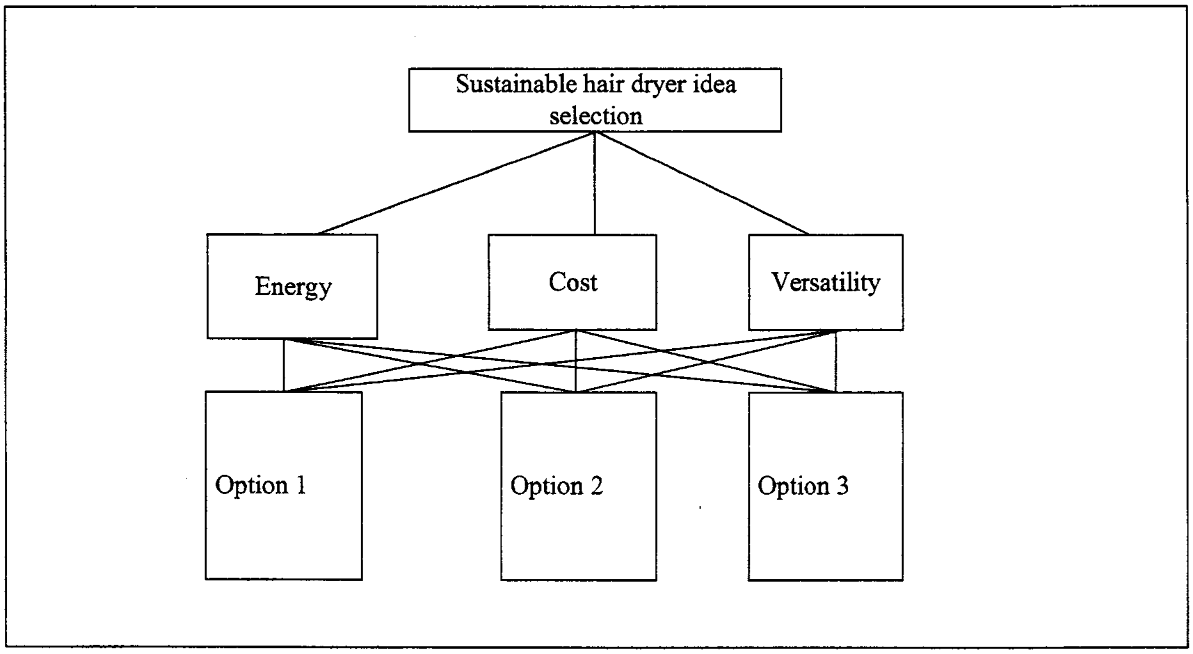

Figure 4.1. The hierarchy structure of sustainability assessment of hair dryer concepts

Energy

Hair dryer uses substantially large sum of energy during its use phase (http://www-mmd.eng.cam.ac.uk/sustainability/seminar/documents/051019ashby.pdf). In this analysis, we only consider energy used by hair dryer during the use phase. Energy used in the use phase is calculated as the following equation:

Average watt hours per week = Watts per hour X average hours of use/ week (1 hour, approximately)

For option 1, Energy used = 1300 watts per hour X 1 hour of use per week = 1300 watts

For Option 2, Energy used = 1200 watts per hour X 1 hour of use per week = 1200 watts

For Option 3, Energy used = 1875 watts per hour X 1 hour of use per week = 1875 watts

According to the definition of sustainable development, less energy consumption is better. Less energy consumption can be translated as less production of CO_2.The value of 1200 watts per week is chosen as the upper end of the scale (most sustainable end point). The lower end of the scale (least sustainable endpoint) is set as 1875 watts per week. Option 2 is moderately more preferable compared to Option 1. Option 2 is extremely preferable compared to Option 3. This is shown in a matrix form in Table 4.14.

Table 4.14. Comparison matrix for three options in terms of energy consumption

	Option 1	Option 2	Option 3
Option 1	1	1/3	7
Option 2	3	1	9
Option 3	1/7	1/9	1

Using pair-wise comparison matrix, we can calculate the preference of each alternative in terms of its energy consumption. The mathematical details are shown in the Chapter 3. Table 4.15, Table 4.16, and Table 4.17 show the details of finding the preferred option when energy use is concerned.

Table 4.15. Sum of the values in each column

	Option 1	Option 2	Option3
Option 1	1	1/3	7
Option 2	3	1	9
Option 3	1/7	1/9	1
Sum	4.14	1.44	17

Table 4.16. Divide each element of the matrix by its column total

	Option1	Option2	Option3
Option1	0.241	0.231	0.411
Option 2	0.724	0.69	0.529
Option 3	0.034	0.077	0.058

Table 4.17. Average the elements in each row to determine the priority for each option with respect to energy consumption

	Option1	Option 2	Option 3	Priority
Option 1	0.241	0.231	0.411	0.294
Option 2	0.724	0.69	0.529	0.647
Option 3	0.034	0.077	0.058	0.056

Cost Analysis

Cost analysis is done by having the retail price of the product and also the energy cost of the use life of the product. Currently, there is no charge involved in disposing of hairdryers.

Option 1:

Initial cost:

Purchase price: 138.95

Energy cost:

1300w x 1hr per 7 days x 365 days per year = 67785.714wh or 67.78kWh/yr

x $5.3 cents per kWh = $3.6/yr (Electric rate information is available at http://www.ontariotenants.ca/electricity/ontario-hydro.phtml)

Life expectancy of this option is 1200 hours = 0.137 years

0.137 years x $3.6/yr = $0.5/yr

Disposal cost:

Disposal cost of a hairdryer is unavailable at the current stage.

Total life-cycle cost is calculated by adding initial cost and energy cost = $139.44

Option 2:

Initial cost: $159.95

Energy cost:

1200w x 1hr per 7 days x 365 days per year = 62571.428wh or 62.57kWh/yr

x $5.3 cents per kWh = $3.316/yr (Electric rate information is available at http://www.ontariotenants.ca/electricity/ontario-hydro.phtml)

Life expectancy of this option is 1 year

Total energy cost for the whole life cycle of this option is $3.316

Disposal cost:

Disposal cost is considered $0.

Total life cycle cost = $163.266

Option 3

Initial cost: $ 109.95

Energy cost:

1875w x 1hr per 7 days x 365 days per year = 97767.857wh or 97.76kWh/yr

x $5.3 cents per kWh = $5.18/yr (Electric rate information is available at http://www.ontariotenants.ca/electricity/ontario-hydro.phtml)

Life expectancy of this option is 1 year

Total energy cost for the whole life cycle of this option is $5.18

Disposal cost:

Disposal cost is considered $0.

Total life cycle cost = $115.13

Table 4.18. Comparison matrix for three options in terms of life cycle cost

	Option 1	Option 2	Option 3
Option 1	1	5	1/5
Option 2	1/5	1	1/9
Option 3	5	9	1

Using pair-wise comparison matrix, we can calculate the preference of each alternative in terms of its life cycle cost. Table 4.14, Table 4.15, and Table 4.16 show the details of finding the preferred option when life cycle cost is concerned. Lowest life cycle cost is considered as the best sustainable option.

Table 4.19. Sum of the values in each column

	Option 1	Option 2	Option3
Option 1	1	5	1/5
Option 2	1/5	1	1/9
Option 3	5	9	1
Sum	6.2	15	1.311

Table 4.20. Divide each element of the matrix by its column total

	Option1	Option2	Option3
Option1	0.161	0.33	0.262
Option 2	0.032	0.066	0.084
Option 3	0.806	0.6	0.762

Table 4.21. Average the elements in each row to determine the priority for each option with respect to energy consumption

	Option1	Option 2	Option 3	Priority
Option 1	0.161	0.33	0.262	0.251
Option 2	0.032	0.066	0.084	0.0606
Option 3	0.806	0.6	0.762	0.722

Versatility:

In this example, we consider versatility as a feature that attracts customers, which ultimately earn revenue, which is economically sustainable. Number of heat settings is considered as a measurable criterion for versatility.

- Option 1 has single heat setting
- Option 2 has single heat setting
- Option 3 has two heat settings

Table 4.22. Comparison matrix for three options in terms of versatility

	Option 1	Option 2	Option 3
Option 1	1	1/2	1
Option 2	2	1	2
Option 3	1	1/2	1

Using pair-wise comparison matrix, we can calculate the preference of each alternative in terms of its life cycle cost. Table 4.17, Table 4.18, and Table 4.19 show the details of finding the preferred option when versatility is concerned. If number of features is greater the product is considered as more versatile and sustainable in the long run to meet customer's requirement.

Table 4.23. Sum of the values in each column

	Option 1	Option 2	Option3
Option 1	1	1/2	1
Option 2	2	1	2
Option 3	1	1/2	1
Sum	4	2	4

Table 4.24. Divide each element of the matrix by its column total

	Option1	Option2	Option3
Option1	0.25	0.25	0.25
Option 2	0.5	0.5	0.5
Option 3	0.25	0.25	0.25

Table 4.25. Average the elements in each row to determine the priority for each option with respect to versatility

	Option1	Option 2	Option 3	Priority
Option 1	0.25	0.25	0.25	0.25
Option 2	0.5	0.5	0.5	0.5
Option 3	0.25	0.25	0.25	0.25

E. Step 5 of the decision model. *Selection of a product idea*

Using pair-wise comparison matrixes many other insights may be gained about the preferences. This section shows how to combine the priorities for the criteria and the priorities for each option using each criterion to develop an overall priority ranking for the three alternative options.

The procedure used to compute the overall priority is to weight each option's priority by corresponding criterion priority. The calculation is as follows:

Overall priority of the Option 1:

0.333 (0.294) + 0.333 (0.251) + 0.333 (0.25) = 0.264

Overall priority of the Option 2:

0.333 (0.647) + 0.333 (0.0606) + 0.333 (0.5) = 0.402

Overall priority of the Option 3:

0.333 (0.056) + 0.333 (0.722) + 0.333 (0.25) = 0.342

Most preferable option is Option 2. These results provide a basis for product design team to make decision regarding selection of a product concept for further investigation and development. As long as decision makers believe that their judgments regarding the importance of the criteria and their preferences for the idea alternatives using each criterion are valid and backed up with thorough investigation, the AHP priorities show that the Option 2 is preferred. The AHP analysis helps us to gain a better understanding of the trade-offs in the decision-making process and a clearer understanding of why the Option 2 is the AHP recommended option.

4.2 Summary

In this chapter, an application of the methodology is demonstrated. We use example of development steps of a hair dryer concept. This chapter began with showing customer's requirements for a hair dryer. Then we convert these requirements into sustainable criteria. A list of product specific criteria is generated. TRIZ is used to convert sustainability requirements into TRIZ principles that can make the product innovative. When more than one concept is presented, there is definitely a need for comparison. In this process, we compare product ideas in terms of sustainability issues. In this process, we omitted life cycle assessment of reference products just to avoid lengthy calculation stage. In the original methodology presented in the Chapter 3 suggests many attributes to compare sustainability of different options using AHP method. But, we only use three attributes to demonstrate the usability of AHP method for comparing three product concepts in terms of sustainability criteria.

Chapter 5

Conclusions

This dissertation demonstrates a research initiative with the aim of developing, disseminating and implementing operational support methods & tools for sustainable product innovation. It promotes a methodology for systematic inclusion of three aspects of sustainable development (SD) (environmental, social and financial) in product idea generation process. This methodology shows prioritizing customer or user needs in terms of sustainability, developing a product specification, generating innovative product ideas (options), and interacting with the customer/community during product development. The importance of this methodology is paramount given that still there is a need for systems methodology to build bridge between three aspects of sustainability and customer's requirements in developing innovative product idea. The rising need for this kind of methodology is topped by the growing body of legislation world-wide focusing on product stewardship practices. This methodology provides the following unique contributions to this area of research:

1. Provides a systematic methodology for developing product idea that is not ignoring what customer really wants. This methodology builds on the idea that a good sustainable product must give as much satisfaction as possible for the user. If not, it will be unsuccessful on the market and failing economic aspect of SD. The first step of the methodology confirms that customer requirements are systematically

evaluated. Mapping of SD requirements and traditional customer requirements is done in the second step of the methodology.

2. Incorporates economic, ecological (environmental), and social (equity, health and safety, etc.) factors of sustainable development by adding a generic list SD factors in Step 2 of this methodology.

3. Helps designers to invent "novelty, usefulness, no environmental and social burden" new product idea (option) by incorporating TRIZ inventive principles.

4. Minimizes the complexity of implementing TRIZ inventive principle to create sustainable product option by choosing TRIZ principles without contradiction information.

5. Stimulates chances for having innovative sustainable product options, not just the redesign.

6. Provides a technique to selection of sustainable product option from a pool of ideas with ease. The selection process demonstrates potential of tackling both qualitative and quantitative evaluation criteria.

5.1 Limitations of the Methodology

This methodology provides only compromise solution to product design process. Results on systematic inclusion of all three dimensions of sustainable development in early stage of product development process are not many in real world. Therefore, general conclusions on the effects of the presented methodology cannot be drawn. Based on presented example, it is known that implementation of presented methodology driven and supported by, for example, consultants may be fruitful. However, it is not known to what extent companies 'spontaneously', i.e., without participation in a particular project, implement the presented methodology. This research does not show how much organizational change might be necessary to implement this framework into a company's regular product development process. This methodology requires substantial amount of experience of product design team related to sustainable development principles and how it is connected to particular product life cycle. So, new sustainability expert should be included in the traditional product design team. Other option could be providing special training related to sustainability to design team member(s). Both of these options involve some initial cost. This research shows an example of implementation of this methodology into a very small and simple product design process. For utilizing this framework for designing a complex product like a computer or a car might not produce sustainable results. Subjective information used in this methodology can impose challenge to the final outcome.

5.2 Future Work

Future work in the area of sustainable product innovation (or idea generation) process is needed. This area of research is considered to slowly evolving with the growth of changing legislation related with product end-of-life legislation. The following topics are considered to be valuable areas of future work:

- **Integrating the featured methodology into an EMS:** An environmental management system (EMS) is a continual cycle of planning, implementing, reviewing, and improving the actions that a company takes to achieve its environmental objectives. The methodology can be used to support the establishment and maintenance of an EMS.

- **Development of gap assessment and benchmarking tool:** This methodology can be translated into a gap assessment and benchmarking tool that provides product development companies with an understanding of how their practices, policies, programs, and systems - related to their products innovation management activities - measure up to their competitors and industry peers.

- **Development of a software tool:** The methodology developed in this dissertation can be translated into an easy to manipulate decision support system.

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