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Lifecycle Design Analysis and Evaluation of Mechanical Elements and System

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Lifecycle Design Analysis and Evaluation of Mechanical Elements and System" submitted by Blake Lu in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract:

Environmental requirements call for sustainable design. Thus, the new design methodology must systematically deal with not only the function, but also the environment and the economy. Most traditional design methodologies can only look after the functional issue. This research explored in the area of the lifecycle design and evaluation. The thesis summarized three dimensions – FEE (functional, environmental, and economic) toward the sustainable design. Based on FEE, a systematic lifecycle design process model was proposed, which consists of FEE requirements, two design objects in terms of the physical structure and the lifecycle structure, and FEE evaluation streams in terms of LCQ, LCA and LCC. From the perspective of lifecycle, a new concept – PBA (Process-Based Analysis) was defined, which founded the base for FEE evaluations. Three evaluation streams are mainly discussed as a major part of the design process.

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I would like to dedicate this thesis to my parents, Kaixiang Lu and Yuqin Gao.

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Acronyms

ABC	Activity-Based Costing
DFE	Design for Environment
DfX	Design for X (X represents individual lifecycle process, i.e. manufacturing, service, recycling,...)
ECDM	Environmentally Conscious Design and Manufacturing
EOL	End of Life
FEE	Functional, Environmental, and Economic
GQFD	Green Quality Function Deployment
LCA	Lifecycle Assessment
LCC	Lifecycle Costing
LCQ	Lifecycle (Functional) Quality
PBA	Process-Based Analysis
QFD	Quality Function Deployment
SD	Sustainable Design
TRIZ	a Russian acronym for the Theory of Inventive Problem Solving

CHAPTER 1

INTRODUCTION

Products impact the environment in various aspects within their lifecycles. Once product designs are completed for production, the environmental attributes of products have largely been determined. Most traditional product design requirements focus mainly on product functionality, quality and cost in order to meet customer requirements.

From the viewpoint of sustainable development, such traditional design requirements should be extended to include environmental concerns. Sustainable development requires good performance in three dimensions – social, environmental, and economic. Thus, a suitable design methodology is needed, which must systematically view the entire product lifecycle for functional, environmental, and economic performance. This thesis will explore this direction. It will focus on the design framework, analysis approach, and evaluation method. This chapter introduces the objectives of the study and summarizes the research problems.

1.1 Problem Summary

Research related to engineering design may be classified generally into the following four categories:

- Systematic design methodology
- Axiomatic design
- Decision-based design
- Knowledge-based design, concurrent design, and design information systems

Systematic design methodologies prescribe step-by-step procedures from function representation, decomposition, solution search, to conceptual, embodiment and detailed design [Pahl and Beitz, 1988, Hubka and Eder, 1988]. Design for X (X = assembly, manufacturing, service and so on) is considered systematic design methodology [Dixon and Poli, 1995]. These procedure-based approaches aim to improve design by providing guidelines for engineers to follow, an example of which is the Adaptable Design Methodology described in this paper. Quality Function Deployment (QFD) can also be considered as a methodology to ensure quality throughout the design and manufacturing processes. House of Quality (HOQ) is a technique developed to capture the "voice of customer", analyze design specifications, and compare design solutions with benchmark products [Clausing, 1994]. There are other design methodologies, such as robust design.

Theory-based and axiomatic design aim to establish design science as a foundation for engineering design. An important attempt is Suh's work in axiomatic design [Suh, 1990, 2001]. If the systematic design process is considered one-dimensional procedure, design axioms are two-dimensional. At each step of the design process – mapping from customer domain to functional domain, then to design parameters domain, and finally to process domain, two axioms have been established: independent axiom and information axiom. The independent axiom suggests maintaining functional independence. The information axiom is used to select the design candidate with the least uncertainty among design alternatives. A design with the highest probability of, and the lowest complexity, in meeting functional requirements has minimal information content. These two axioms are used to assist designers in zigzag design processes from one domain to another. Other design axioms also appear in literature. In addition to the current application in design analysis, substantial effort is required to make axiomatic design systems work as useful design tools.

Decision-based design (DBD) views design as a decision-making process. It is considered as a framework for engineering design. Design starts with customer requirements, and the establishment of engineering specifications; concepts are generated, evaluated and then the best is selected for the detailed design. Except for the generation of design space and design candidates, the main steps in the design process involve either selection decisions or compromise (trade-off) decisions [Allen and Mistree, 1997 and Jin et al, 2002]. Decision theory and utilities can be used by designers in decision-making. Design decision support systems have also been developed to assist engineers in making better decisions.

Knowledge-based design seems appropriate, as design activities are experience- and heuristic-based activities. Design knowledge can be modeled as rules, procedures, models and cases. The early stage of knowledge-based systems' application in engineering included design systems such as digital computer configuration design and design expert system (Dominic). In the conceptual design stage, rule-based domain-specific expert systems and case-based design systems are appropriate for assisting engineers in design concept generation and evaluation. As the design process proceeds, more information becomes available and more quantitative methods can be used in decision-making. Many publications are available in this field [Hashemian and Gu, 1996, 1997].

Concurrent engineering (CE) as a philosophy or strategy brings together a team of experts to design and/or develop products. This has proven effective in many industrial applications. CE requires an effective project management process and an information system to support the team-based design approach. In fact, in any product design as engineers spend considerable time and effort in searching for information such as design catalogues and standards, efficient information search and retrieval would improve the design process. Therefore, design databases and their management are essential for supporting concurrent design processes. Other methodologies, such as Altshuller's TRIZ [Apte, 2000], can also be effectively used in design process to improve product design.

Lifecycle engineering techniques explore effective ways for eco-design. This can be represented by the application of the lifecycle assessment (LCA) and lifecycle costing (LCC). LCA is essential for achieving sustainable lifestyles and products. One of the most important applications of LCA is new product development.

Sustainable design aims to achieve minimal or zero environmental impact, while satisfying the traditional design criteria such as product functionality, quality, features, costs and time to market, ensuring that it satisfies social needs. Therefore, environmental evaluations must be incorporated into the design stage, which adds new design and evaluation activities into the design process. In fact, it should be a systematic methodology, in which functional requirements, environmental impacts, and economic needs should be addressed simultaneously. The design evaluation result would affect further iterative steps during the design process. In principle, in order to deal with functionality, the design must take advantage of traditional design theories; to reflect the environmental aspect, it must adopt modern LCA techniques; to achieve better economic performance, it is necessary to utilize lifecycle costing analysis. However, it can be expected that several challenging problems may arise due to these considerations. The combination of existing design methodologies, the integration of the three different parts (functionality, environmental impact and economic performance) into one design process, and the development of a new design framework will be addressed in this research.

1.2 Objectives

Sustainable design intends to resolve the environmental impact of products early in the design process of the product lifecycle, which is considered the most effective stage for improving environmental performance. Targeting sustainable product design, this research will construct a new design process model based on lifecycle objectives. It will consist of three design requirements, two design objects, and three streams of evaluations. The three design requirements include a functional requirement derived from customer needs, an environmental requirement that reflects society's needs for protecting natural resources and the environment, and the economic requirement that ensures the company's basic business goals. Accordingly, two objects are simultaneously carried out: the physical structure and the lifecycle structure. They are represented by two groups of design parameters: physical parameters and lifecycle parameters. In the comprehensive evaluation phase of product design, the three analysis streams are the lifecycle quality (LCQ) analysis, lifecycle assessment (LCA), and lifecycle cost (LCC) assessment, which are conducted with respect to the functional, environmental, and economic evaluations.

In order to conduct the design analysis and evaluation, more attention needs to be given to the lifecycle structure. As the physical structure may be evaluated through the entire lifecycle, the lifecycle structure will determine the evaluation boundary. A process-based analysis (PBA) concept will be proposed for the analyses of all three dimensions of LCQ, LCA, and LCC. This establishes the basic model for the evaluations based on lifecycle in this methodology.

Based on traditional design theories, a unique robust design and analysis approach will be developed to realize LCQ – the functional evaluation, which will be the first effort to integrate the analyses of independence and robustness. It may benefit future design practices as well.

Generally speaking, LCA could be used in the design process to determine the most environment friendly product design among available design alternatives. It can also provide insight into the main causes of the environmental impact of a product. Thus, design priorities and product design guidelines can be established based on the LCA data. Most other research efforts have been made on detailed LCA. However, in practice, few detailed LCAs published are usable for practical application in the design process. Two other levels of LCA, the conceptual LCA and the simplified LCA, are more capable of being used in design applications. In this thesis, a simplified LCA methodology will be formed and used for LCA stream – the environmental evaluation, which explores the way of LCA application in the early design stage. Detailed assessment techniques will also be developed for effective design evaluations.

The remaining chapters of the thesis are organized as follows. Chapter 2 will review and discuss the current design theories and methodologies. In Chapter 3, a new design procedure will be introduced. It will discuss the three design requirements, two design objects, and three evaluation streams in detail. Based on the proposed design process model, Chapters 4 and 5 will focus on the design evaluation and analysis in terms of LCQ and LCA. Chapter 4 will discuss two classic design methodologies – Axiomatic Design and the Taguchi method. Based on the independence axiom and robust engineering techniques, a new robust design and analysis framework will be derived. Detailed mathematic manipulations and applications will also be provided. The new simplified LCA approach will be presented in Chapter 5. Chapter 6 will be a case study, in which the design and analysis approaches will be applied to a piping system design. Major conclusions and future direction will be given in Chapter 7.

CHAPTER 2

LIFE CYCLE DESIGN AND LITERATURE REVIEW

Sustainable development requires that products have good social, environmental and economic performance. To preserve the environment, the industry has begun to reduce the environmental impact of their operations. The wide diffusion of consumer goods and shortening of product lifecycles have caused an increasing quantity of used products being discarded. This impacts the environment by dwindling the resources of landfill space and raw materials, becoming a significant environmental problem. The environmental impact of a product may occur in every stage of its lifecycle. These effects result from interrelated decisions made at various stages of a product's life. Once a product moves from design to production, its sustainable attributes have largely been determined. Sustainable Design (SD) aims to solve the social, environmental and economic problems early in the design phase. While traditional product design focuses on product function in order to meet the customers' requirements, SD looks after the whole product lifecycle and takes care of the product's functional behaviour, economical result and environmental impact to meet these three kinds of requirements all together.

Research has been conducted into different design methodologies.

2.1 Function-Based Design

Design research and theories are often function-based, including Axiomatic Design, QFD (Quality Function Deployment), Taguchi, and TRIZ.

Suh has been developing Axiomatic Design at the Massachusetts Institute of Technology in the U.S. for about 20 years [Suh, 2001] with his first paper published in 1978 [Kim, 2000]. Axiomatic Design is a decomposition process from customer needs to functional requirements (FRs), to design parameters (DPs), and then to process variables (PVs), thereby crossing the four domains of the design world: customer, functional, physical, and process. There are two axioms: the independence axiom and the information axiom. Based on these two axioms, the best design can be determined.

Quality Function Deployment (QFD) is a system for translating consumer requirements into appropriate company requirements at each stage from product development, engineering and manufacturing, through to marketing and distribution. QFD is accomplished through a series of matrices. The phases of QFD include product planning, part deployment, process planning and production planning. Through these phases' matrices, the voice of the customer is systematically cascaded into the design, process (manufacturing) and production of the product [Guinta, 1993]. The concept of QFD was first introduced by Japanese in 1967 [Prasad, 1998].

The Taguchi method, also known as robust design, divides the design process into three stages: system design, parameter design, and tolerance design.

This method focuses on functional requirements: the most stable quality or high robustness. Since its introduction to U.S. industry in 1980 [Taguchi, 2000], Taguchi's approach to quality engineering and robust design has received significant interest from designers, manufacturers, statisticians, and quality professionals.

TRIZ is a Russian acronym for the Theory of Inventive Problem Solving, which is a little-known algorithmic system for solving engineering problems. It was developed by Altshuller and colleagues over 50 years ago, in the former Soviet Union (he started his work on an algorithm for the solution of inventive problems in 1946) [Kim, 2000]. The heart of TRIZ approach is the adaptation of existing solutions, in the form of analyses extracted from 400,000 inventive descriptions spanning different fields of engineering. The source of this data is the study of patents filed worldwide over many years. The comprehensive database typically supplies a multitude of possible solutions from which to choose [Kim, 2000].

The above design theories and methodologies have been widely used. There is a rich literature on these topics.

2.2 Sustainable Design

Most research in this area deals mainly with environmental issues and are called Environmentally Conscious Design, Green Design, or Eco-Design. (This thesis uses the term eco-design to represent this kind of design methodology.) They were developed for the following reasons [Zhang et al, 1997]:

(1) Environmental legislation;

(2) Corporate image and public reception;

(3) Consumers' demand; and

(4) Rising waste disposal costs.

The research issues in this field include: the integration of product and process design with material selection systems; the development of models for assessing the integration of consumer demand and product use, disposal or recycling; the improvement in methods, tools and procedures for evaluation of the risks associated with environmental hazards and the cost or benefit; the substitution of materials with lower environmental impact in processing or in the final product; the advancement in techniques for forecasting the effects of specific governmental regulations over the complete product lifecycle and for new or improved manufacturing processes; and, the development of new bulk materials and coatings with increased life spans that can be manufactured with decreased environmental impact. The most contributions come from lifecycle engineering techniques.

2.2.1 Lifecycle Engineering and Fundamental Development

The lifecycle viewpoint is the cornerstone of eco-design. Lifecycle Assessment (LCA) and Lifecycle Costing (LCC) are the major techniques to deal with environmental impact assessment and cost. They have become part of the ISO 14000 standard. Several practical tools and methods have been developed and available to industry, such as Eco-Indicator, Eco-Point, EPS and End-of-Life Design Advisor (ELDA).

2.2.1.1 Lifecycle Assessment

Eco-design aims to reduce natural resource (including energy and material) consumption, emissions and wastes. An assessment method is necessary to evaluate design. Simplified methods already exist for some industries. For instance, in the transport industry, energy requirement is a good indicator of overall environmental impact. By looking at the overall energy needs of a vehicle's lifecycle, it provides an indicator on how to direct the design effort [Holloway et al, 1997]. However, in most industries, this has not occurred. Generally, a more systematic method is needed, which is called lifecycle assessment (LCA).

Lifecycle assessment is divided into three stages – inventory analysis, impact analysis, and improvement analysis – described as follows:

- Inventory analysis: using quantitative data to establish the levels and types of energy and material inputs to a system, and releasing that result.
- Impact analysis: relating the outputs of a system to their impacts on the external world.
- Improvement analysis: explicitly describing the needs and opportunities for reducing environmental effects [Zhang et al, 1997].

Duda et al [1997] divided LCA into several steps. The initial step consists of laying out the scope of the study and defining its goals. In this first stage, the boundaries of the study should expressed explicitly.

The next phase is to produce the inventory. In this step, energy and raw material requirements and environmental emissions of the products, processes or activities are quantified. Totals are presented for all stages of production, from raw materials acquisition to waste management.

The third stage is impact assessment, which attempts to translate the inventory data into effects on human and ecological health, and on resource depletion. This is done by classifying the inventory items into "stressor" groups, or "sets of conditions that may lead to an impact". An inventory listing for sulphur dioxide releases, for example, will be classified during the impact phase as a "stressor" contributing to acid rain. Stressors are then prioritized according to the perceived severity of their effects.

The final step is improvement analysis, in which recommendations are made based on the results of the inventory and impact stages. These recommendations may include modifying a production process, using different raw materials, or choosing one product over another.

In principle, LCA could be used in the design process to determine which of several designs may leave a smaller "footprint on the environment". Also, the study of a reference or benchmark LCA provides insight into the main causes of the environmental impact of a certain kind of product. Design priorities and product design guidelines can be established based on the LCA data.

The major disadvantage of quantitative LCA is the complexity and effort required. Also, designers and engineers find it extremely difficult, if not impossible, to work practically with LCA because of:

- The consistent lack of solid data about all aspects of a product's life cycle;
- The nearly infinite amount of data to deal with and decisions to make;
- The lack of standardization resulting in numerous conversions and interpretations;
- The lack of a standard evaluation scheme caused by and resulting in different views on what is environmentally correct;
- The approach is currently only suitable for design analysis and evaluation rather than design synthesis. LCAs are "static" and only deal with a snapshot of material and energy inputs and outputs in a dynamic system.

Below are some commercial tools that are currently used in the practice.

Eco-Indicator

Dutch Eco-Indicator has developed and already issued two versions of a widely used tool – Eco-Indicator 95 and Eco-Indicator 99. The new Eco-Indicator 99 method includes many more aspects and is therefore more complex than the Eco-Indicator 95 version but both Eco-Indicators are user-friendly units [Suurland, 2000]. The weighing system between the different environmental aspects (the core of the Eco-Indicator method) has also been changed. Eco-Indicator 95 used the so-called "distance-to-target" approach. This method was criticized because there was no clear-cut objective way to define sustainable target levels. Eco-Indicator 99 avoids this problem by introducing a damage function approach. The damage function presents the relationship between the impact and the damage to human health or to the ecosystem. Eco-Indicator 99 reflects state-of-the-art LCA methodology and application. This does not mean that all problems are solved. Further developments in environmental science, material technology and LCA methodology will take place and should result in future improvements of the Eco-Indicator. However, we are convinced that the Eco-Indicator 99 methodology is sufficiently robust to play an important role in eco-design.

Eco-Points

The Eco-Points evaluation method has been accepted as a useful instrument, even though objections can be raised against using politically established target levels. The lack of a classification step is also regarded as a disadvantage; and, only a very limited number of impacts can be evaluated. Eco-Points are widely used in Switzerland and Germany. It is also used in Norway, the United Kingdom and The Netherlands. Since 1993, it has been included in SimaPro software [Breedvel, 2001].

EPS

The EPS system was used first by Volvo in Sweden. It is not based on any governmental policy, but on the estimated financial consequences of environmental problems. It attempts to translate environmental impact into a sort of social expenditure.

The first step is to establish the damage caused to a number of “safeguard objects” – objects that a community considers valuable. The next step is to identify how much the community is prepared to pay for these things, i.e. the social costs of the safeguard objects are established. The resulting costs are added up to a single figure. The EPS system includes neither classification nor normalization.

2.2.1.2 Lifecycle Costing

One of the key elements of each product development process is the economic evaluation of the design concepts. Environmental impact occurs over the span of an entire product lifecycle. Hence, the economic implications of Environmentally Conscious Design and Manufacturing (ECDM) and Design for Environment (DFE) should also be assessed over the entire product lifecycle. The term used for this assessment is Lifecycle Costing (LCC).

The four most common methods for lifecycle economic assessment are:

- Total Cost Accounting
- Life-Cycle Costing
- Full Cost Accounting
- Environmental Life-Cycle Cost

LCC basically follows the same four steps as in LCA, except that the outcome is a single numerical monetary value. Many favour Activity-Based Costing (ABC) as a basis for Lifecycle Costing and accounting of environmental costs. Bras and Emblemsvag proposed an ABC system to perform the different lifecycle processes of products [Zhang et al, 1997]. Traditional cost systems assume that each unit of a given product consumes resources, while ABC systems assume that products or services do not directly use up resources but instead consume activities. Costs are traced from activities to products based on each product's consumption of such activities. For ABC systems, the cost of all activities must be considered [Zhang et al, 1997].

ABC breaks out the environmental cost drivers from, and identifies them with, the activity that drives them. By determining the root of environmental costs and their magnitudes, firms can make better decisions. This technique can highlight long-range environmental costs that are useful for strategic decision-making. This form of "green" accounting creates a more efficient system of identifying environmental and other costs to different departments or groups within a company and can also be used for conducting performance appraisals for persons or groups responsible.

2.2.1.3 Other Supporting Tools

End-of-Life Design Advisor (ELDA) is a web-based tool for evaluating and improving product end-of-life strategies. The backbone of ELDA relies on the statistical analysis of case studies, product characteristics and end-of-life strategies. The technique used is Classification and Regression Trees (CART), which is an example of a cluster analysis tool.

The definition of end-of-life that is used throughout this thesis is "the point in time when the product no longer satisfies the initial purchaser or the first user". This allows for reuse and service in addition to recycling as possible end-of-life strategies [Rose at al, 2001].

2.2.2 Design for Environment Techniques

Eco-design needs to consider products' end of life and several kinds of processes, like recycling, reusing, remanufacturing, servicing, and so on. Design for X (X=manufacturing, assembly, service, and environmental impact), in general, represents design techniques in respect to those processes. The three main goals of Design for Environment (DFE) include:

- Minimizing the use of nonrenewable resources,
- Effectively managing renewable resources, and
- Minimizing toxic release to the environment.

Methods used in DFE include qualitative analysis, lifecycle assessment, impact analysis, and environmental accounting methods [Zhang et al, 1997].

Lee et al. [2001] discussed a multi-objective methodology for determining appropriate end-of-life options for products, including the evaluation of the disassembly sequence and the optimal stage of disassembly. Two end-of-life disassembly charts have been introduced, which can assist engineers in product redesign and end-of-life product retirement.

Manufacturers are dealing with environmental problems by adopting strategies such as Design for Disassembly, Design for Recycling and the use of engine technologies, which improve fuel consumption, heat efficiency and reduce emissions. Many car manufacturers use recycled plastic body parts to make components requiring lesser mechanical and aesthetic properties. Thus, bumpers can be converted to wheel arch liners, which help prevent body corrosion. Similarly, used high-grade tires are converted to low-grade crash barriers.

DFE aims to reduce environmental impact by closing the lifecycle loops. Figure 2-1 shows a traditional lifecycle. By applying DFE, the lifecycle will become the one shown in Figure 2-2.

Design for X (reuse/service/remanufacturing/disassembly) aims to prolong the lifetime of products in order to control the purchase of new products and reduce material consumption and waste.

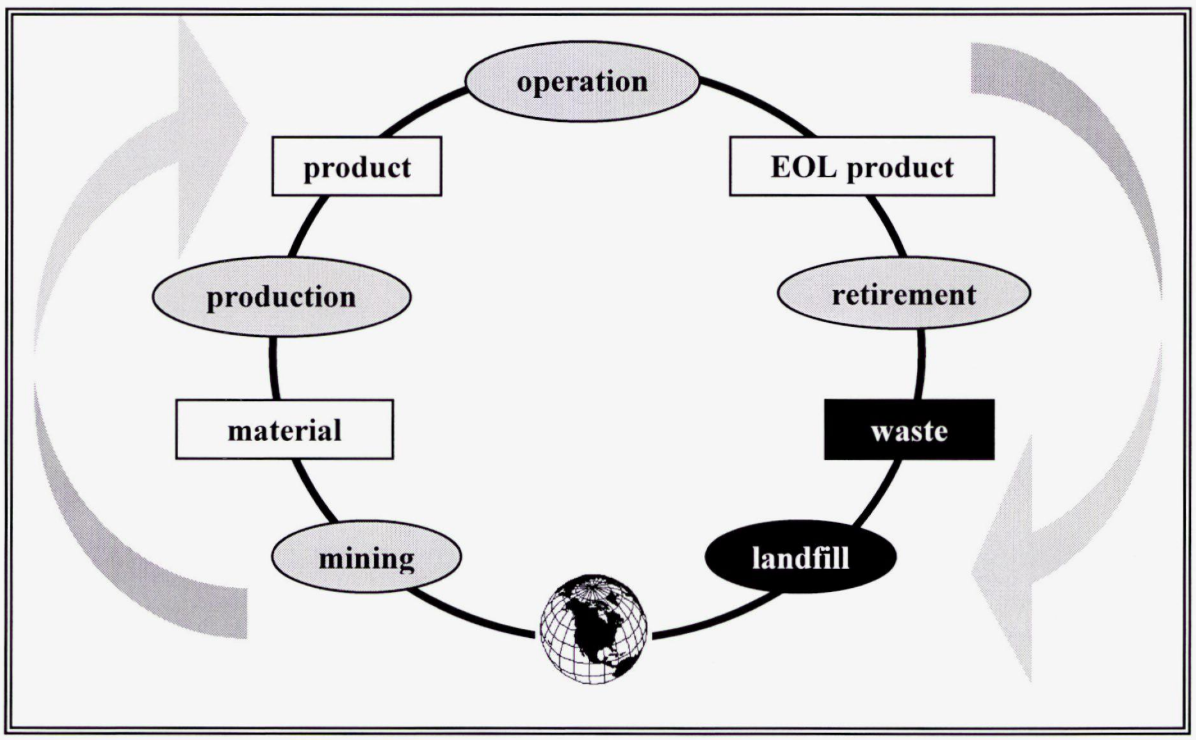


Figure 2-1. Lifecycle Model

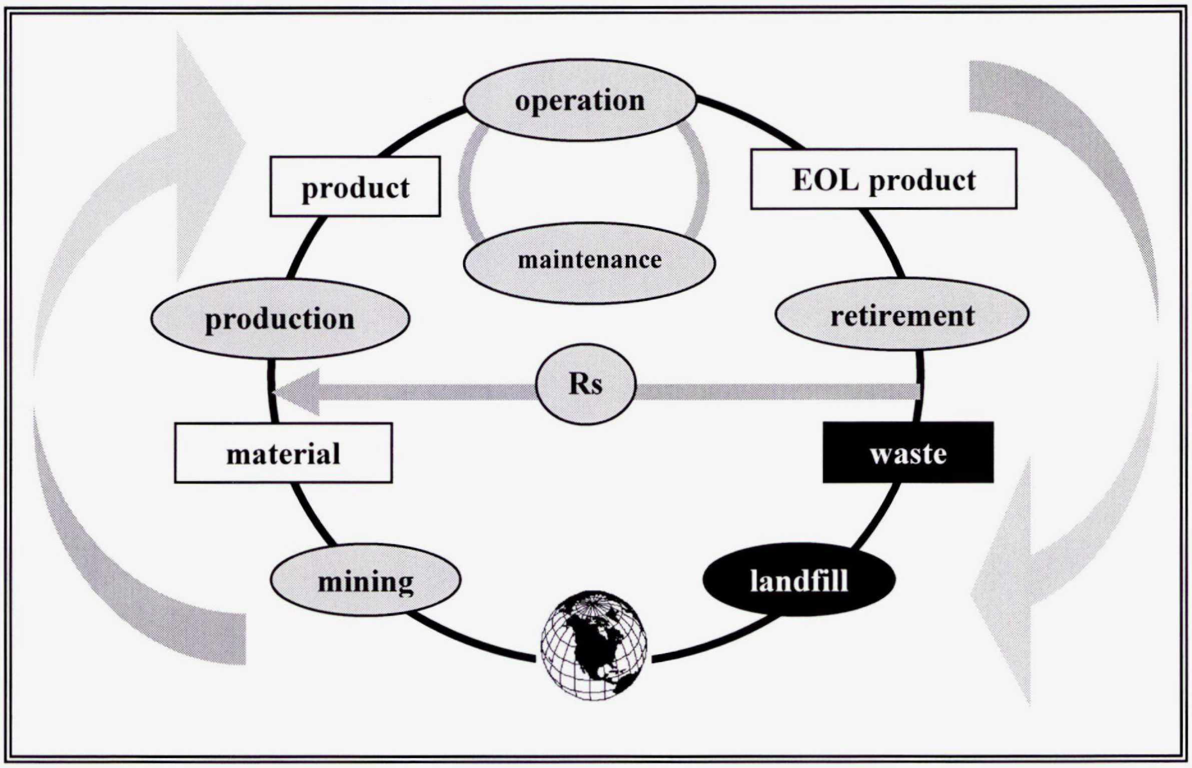


Figure 2-2. Revised Lifecycle Model

Design for Recycling aims for the recovery of materials and energies from the products that used to be dumped in landfills. It may not always be possible or economical to recycle a product completely; therefore, the aim of recycling is to maximize the resources to be recycled and to minimize the pollution potential and mass of the remaining materials. Holloway et al. [1997] suggested that decreasing the use of plastics could be a simple way to recycle, especially in the automobile industry.

Modularization is very important to DFE techniques. Modular design can create benefits for many aspects in a product's lifecycle such as design, assembly, service and recycling [Gu et al., 1999]. Their research also proposed a system called HOME. Information from various aspects of the product design, including functional requirements, product architecture and lifecycle requirements, is incorporated in the method to help ensure that a modularized product would achieve its objectives [Sand et al., 2001].

Otto et al. [1998 to 2001] conducted research aiming to solving modular design problems. They propose the following technique to develop product architectures for a family of products:

- Analyze customer needs and product uses,
- Compile product uses into a family function structure,
- Cluster functions according to function heuristics,
- Cluster functions according to variety heuristics,
- Select physical modules,
- Compare and select architectures.

Fumihiko et al. [2001] proposed that modularization across a family of products and successive generations of products should be made based on product functionality, product commonality and lifecycle similarity.

Product modularity can provide designers with easily detachable subassemblies and components that facilitate remanufacturing, reuse, material recycling and disposal [Rose et al., 2001].

Modularity in product design impacts every stage of the product lifecycle and its importance has been increasingly recognized. It has been found that modularity can reduce the amount of waste and consumption of energy and natural resources; however, few precise methodologies of modular design (for example considering both the structures and functions of modules) are found in the literature [Takefumi, 1999].

According to publications, nearly all works in the area of modular design have either implied or stated that most modular products have lower lifecycle costs and fewer components and/or process tasks. Zhang's research shows that while increasing RRM (relative retirement modules) may not always decrease retirement costs, it will rarely (one in fifteen) increase cost and even then, the change in cost is minimal [Zhang et al, 2001].

2.2.3 Green Quality Function Deployment

A good practice of eco-design is Green Quality Function Deployment (GQFD). It was developed by Cristofari et al. in 1996 [Zhang et al., 1999]. They used Quality Function Deployment (QFD) and lifecycle assessment (LCA) to document the technical requirements. The different product alternatives were assessed based on these requirements so that the best product alternative could be selected. In 1996, Keoleian developed a lifecycle design framework [Zhang et al., 1999]. This method used design checklists to establish product requirements but there was no explicit mechanism to prioritize the requirements by their importance and deploy them into QFD, LCA and LCC separately for environmentally sound product development. It didn't create a systematic methodology that could integrate QFD, LCA and LCC into one efficient tool. QFD was only used for documenting technical requirements from customer wants. In 1995, Stornebel and Tammler incorporated environmental requirements into traditional QFD matrices. Akao described various applications of QFD techniques in product development in 1990. In 1996, Gradel and Allenby developed an environmentally responsible product assessment matrix, which uses checklists to simplify the process of LCA.

Zhang et al. [1999] introduced GQFD-II research. They claimed that it integrated LCA, LCC and QFD into one efficient tool and deployed customer, environmental and cost requirements throughout the entire product development process.

2.2.4 Lifecycle Simulation

Takefumi et al. [1997, 2001] proposed a lifecycle simulation method as a design decision-supporting tool. Their researches focused on inverse manufacturing for global sustainability aiming for:

- A closed loop of material/product flow by maintenance/reuse/recycle; and,
- Reduction of the amount of circulating material/product without reducing levels of service.

Inverse manufacturing brings the following effects [Tomoyuki et al., 1997 ~ 2001]:

- Effective use of natural resources; and,
- Supply of better service to customer by strict control of product quality.

2.3 Summary

To summarize, function-based design methodologies have made significant improvement; however, they have not yet been involved in any practice of sustainable design. In eco-design, several LCA supporting tools have been developed. Some research, such as GQFD and the lifecycle simulation method, has developed effective tools, establishing a solid research base. However, these improvements focus exclusively on the redesign of existing products with the improvements relying mainly on designer perceptions. While the objective is to seamlessly integrate environmental concerns, applications depend on the experience and knowledge of designers for critical input values relating to end-of-life strategies.

Other efforts may not address product end-of-life issues until most of the design parameters are set. Most DFE tools often rely heavily on information that designers may not know at the early stages of design, forcing them to make assumptions about an end-of-life strategy. This may result in ineffective use of design for end-of-life tools [Rose et al., 2001].

If the three dimensions (functional, environmental and economic requirements) are treated individually during the design stage, it could even worse affect the product's existing or lifetime. If a product creates commercial profit but has some problems with environmental impact, the product would be unacceptable. If a product is environment-friendly but the economic assessment is not acceptable, it may never reach the market.

A good practice of eco-design is GQFD, especially the later version GQFD-II. It introduced a new approach to integrate LCA, LCC and QFD into one efficient tool and deployed customer, environmental and cost requirements throughout the entire product development process.

As a summary of the design practices, Table 2-1 depicts the present status in this field.

Table 2-1. Summary of Design Methodologies

<table>
<tr><th colspan="3">Product Design</th></tr>
<tr><th>Functional</th><th>Environmental</th><th>Economic</th></tr>
<tr><td>• Meet consumers' needs</td><td>Reduce:
• Natural resource consumption
• Waste</td><td>• Low cost
• Good revenue</td></tr>
<tr><td>• Axiomatic Design,
• Robust Design
• TRIZ
• QFD
• ...</td><td>• LCA
• DFE</td><td>• LCC</td></tr>
<tr><td colspan="2">GQFD (integrated QFD & LCA)</td><td></td></tr>
<tr><td colspan="3">GQFD-II (integrated QFD, LCA & LCC)</td></tr>
<tr><td colspan="3">New Concepts: Eco-Design / Sustainable Design</td></tr>
</table>

CHAPTER 3

LIFECYCLE DESIGN AND GENERAL PROCESS

The objective of this research is to find a suitable way to systematically solve the functional, environmental, and economic problems during the design stage. The fundamental idea is the construction of a new general design process model and the development of evaluation approaches that are based on this model.

3.1 Design Objects

From the lifecycle point of view, one way to achieve sustainability is to close lifecycle loops by selecting suitable processes for each lifecycle stage. This means that designers must design not only the product's physical structure but also its lifecycle structure. In general, there are four main stages in a product lifecycle structure: the extraction, the production, the operation and the retirement. Each stage may have one or more processes. For example, the operation stage may consist of use, maintenance, and repair; the retirement stage may include reuse, remanufacturing, recycling and/or deposit in landfills. Inputs and outputs of every process may impact the product in terms of the functional performance, environmental effect, and economic result.

The functional performance will determine customer satisfaction. Its inputs and output for each process are just the physical structure itself, including its parts. The environmental impact relates to natural resource depletion and environmental pollution. Inputs include materials and energy; outputs include gaseous, liquid and solid residues, which cause pollution. The economic impact determines cost efficiency. The input is the cost and the output is the value obtained after the process. Therefore, it is the basic requirement of sustainable design that functional, environmental, and economic evaluations are applied to the lifecycle processes to suggest design changes. Based on this thinking, it can be reasonably considered as a lifecycle design. The proposed lifecycle design deals with two design objects – the physical structure and the lifecycle structure. This is a concept different from other methodologies that only deal with physical structure design.

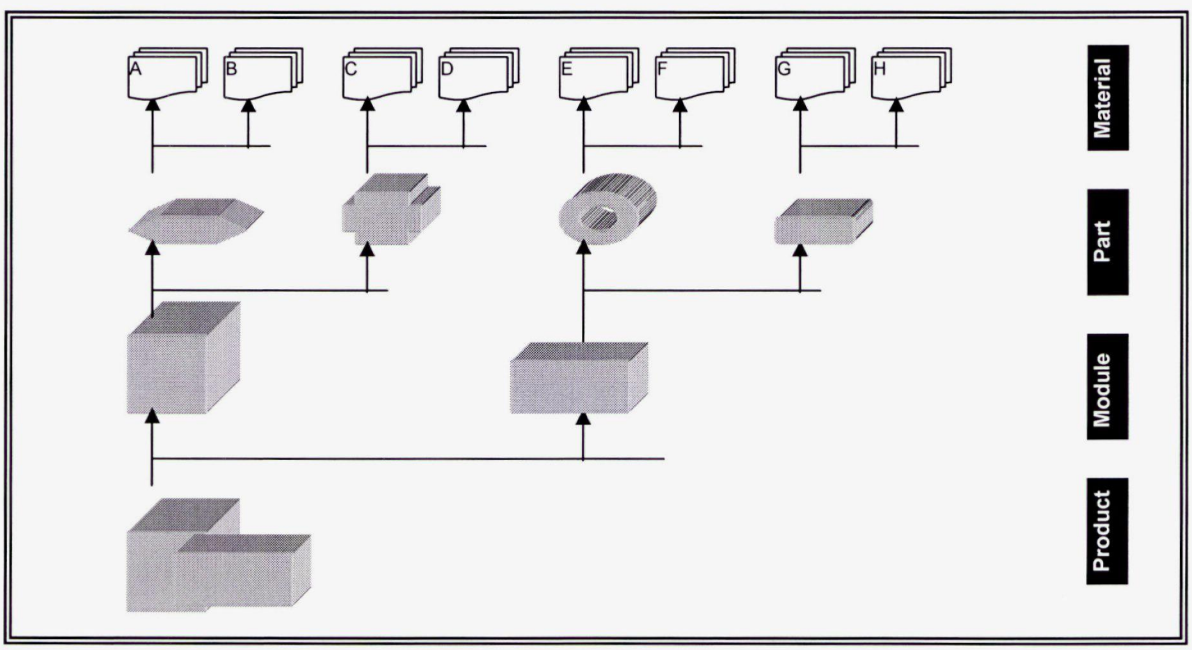


Figure 3-1. Product Physical Structure

To create a sustainable product, the product's physical and lifecycle structures should be designed concurrently to obtain desired functionality, low natural resource consumption and environmental impact, and good economy. Figure 3-1 can be used to express the product's physical structure.

Figure 3-2 depicts a typical product lifecycle structure. In the extraction stage, materials and energy are obtained from natural resources. In the production stage, the materials are manufactured into product components and then assembled into products. In the operation stage, the products are used and their lifespan may be improved by services (maintenance and repair). In the retirement stage, the products may be directed to reuse, recycling or the landfill. The objective of the systematic lifecycle design is to create closed loops for sustainable product lifecycle that can minimize material and energy consumption, and waste and emission generation from the perspective of the whole lifecycle.

The product's lifecycle and physical structures may affect each other. The physical structure may decide characteristics that the lifecycle structure should have. A certain lifecycle structure may require that the product change its physical structure. For instance, a type of copier, which is equipped with a very expensive drum, may suggest that the lifecycle structure adopt a remanufacturing process; and, a lifecycle structure that follows the government's "take back" legislation and has reuse processes will require product structure with modular architecture. The design is an iterative process. Through iterations, the product parameters and lifecycle parameters are optimized to meet all design requirements.

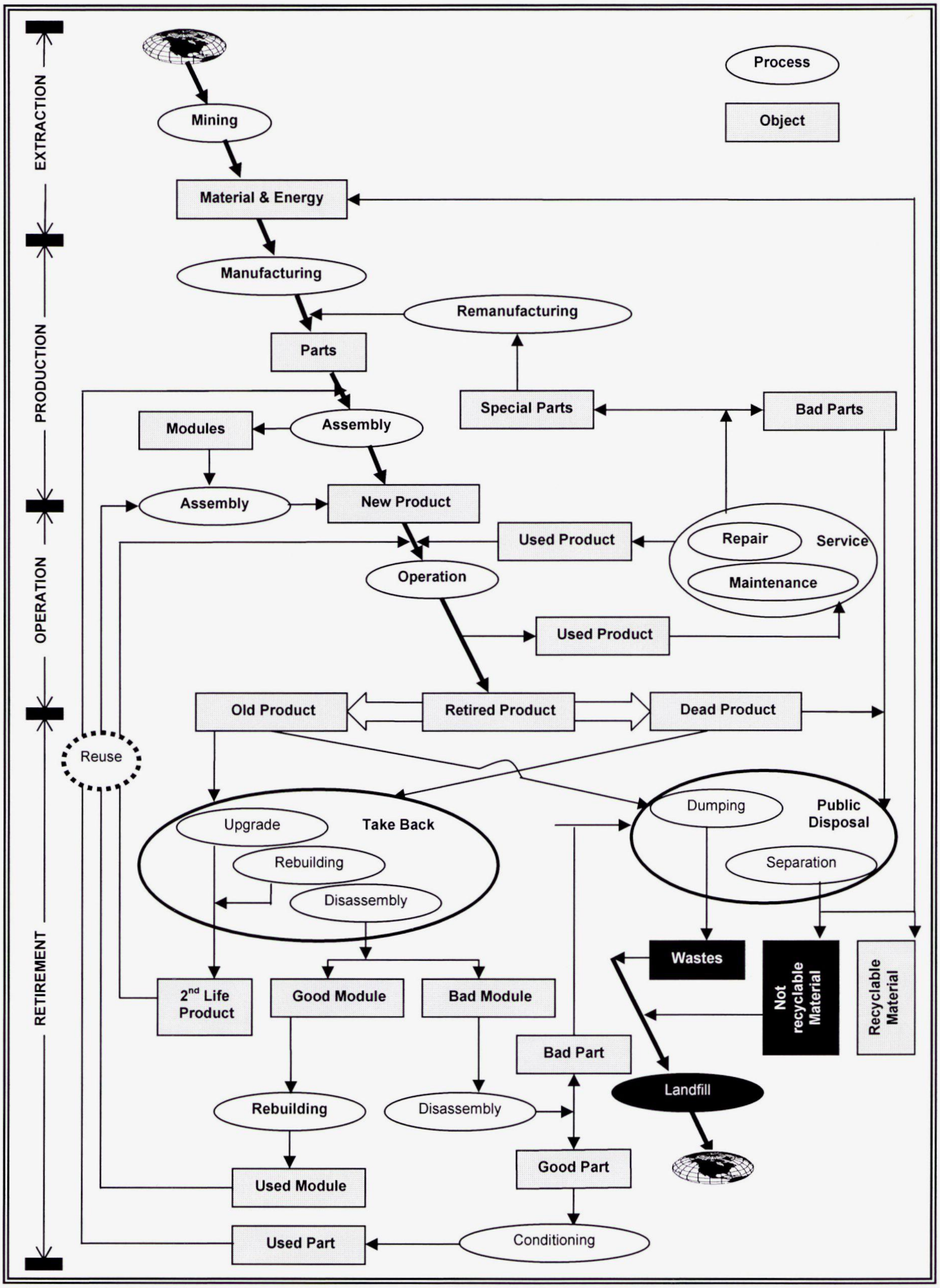


Figure 3-2. Product Lifecycle

3.2 Design Process

Based on the above discussion, a systematic lifecycle design process model is proposed in order to achieve the goal of designing the product with an optimal lifecycle (see Figure 3-3).

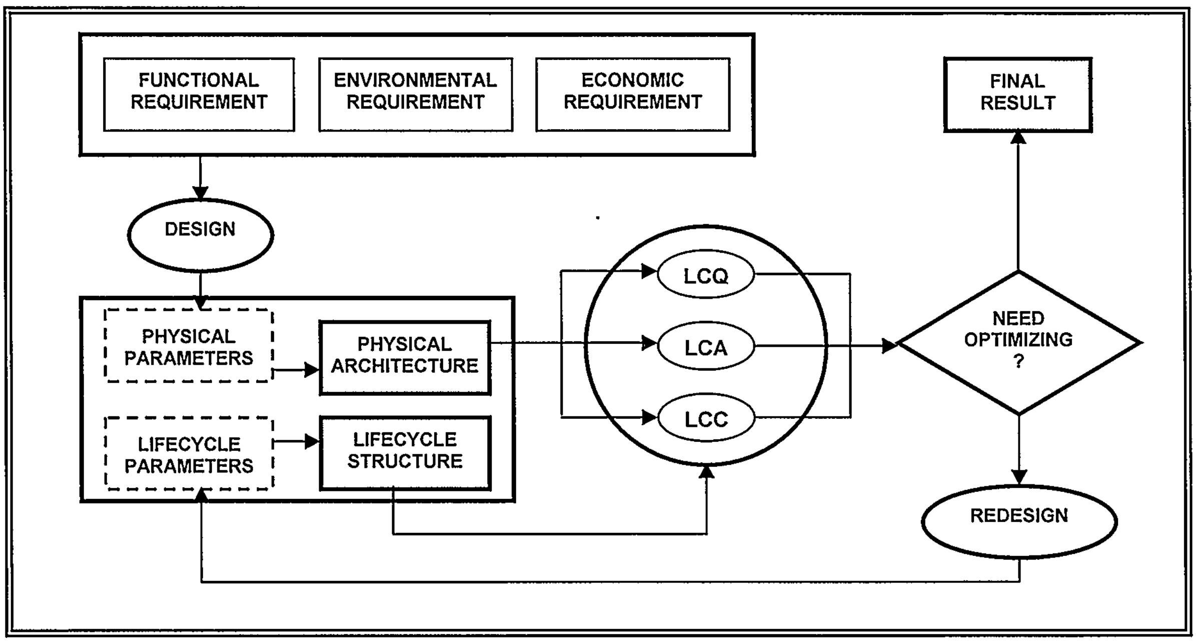


Figure 3-3. Design Process Model

This approach consists of three major components – the three design requirements, the two design objects and the three streams of design evaluations. Three types of requirements may be defined for the design:

- Functional requirements (R_{fu}): deriving from customer needs to reflect the product's main purpose;
- Environmental requirements (R_{en}): reflecting society's need to protect its natural resources and the environment; and,

- Economic requirements ($\mathbf{R_{ec}}$): the basic business motivation to produce the product.

The design action maps from those three requirements to the two groups of design parameters, which determine the two design objects – the physical structure ($\mathbf{DR_1}$) and lifecycle structure ($\mathbf{DR_2}$). Therefore, they have relationships with each other:

$$\mathbf{R_{fu}} = F(\mathbf{DR_1}, \mathbf{DR_2});$$

$$\mathbf{R_{en}} = \Phi(\mathbf{DR_1}, \mathbf{DR_2});$$

$$\mathbf{R_{ec}} = \Psi(\mathbf{DR_1}, \mathbf{DR_2});$$

where $\mathbf{DR_1}$ and $\mathbf{DR_2}$ are relative to each other.

F, Φ and Ψ depict certain relationships. With those relationships, the next step is the design evaluation. The evaluation is equipped with three assessment streams in regard to the functional, environmental, and economic dimensions. These three streams have been created to conduct the functional lifecycle quality analysis (LCQ), environmental lifecycle assessment (LCA), and lifecycle cost evaluation (LCC). While the lifecycle structure forms the evaluation boundary, the physical structure is evaluated along each stream. Depending on the evaluation results, the process goes to redesign or to the next phase of the design process.

The lifecycle structure is detailed to the stages and then to each process. All designed processes determine the boundary within which the object should be evaluated. The evaluation results of each process contribute to the assessment of the stage to which it belongs. The lifecycle assessment is formed from the assessments of all four stages (extraction, production, operation, retirement) together. Thus, process-based analysis (PBA) is proposed for application in all three streams of LCQ, LCA and LCC evaluations. This paper, however, mainly focuses on LCQ and LCA.

From the lifecycle model diagrams (Figures 2-1 and 2-2), it can be seen that every two objects are connected by one process. The process is characterized with inputs and outputs correspondingly along each stream. Figure 3-4 shows the three assessment streams.

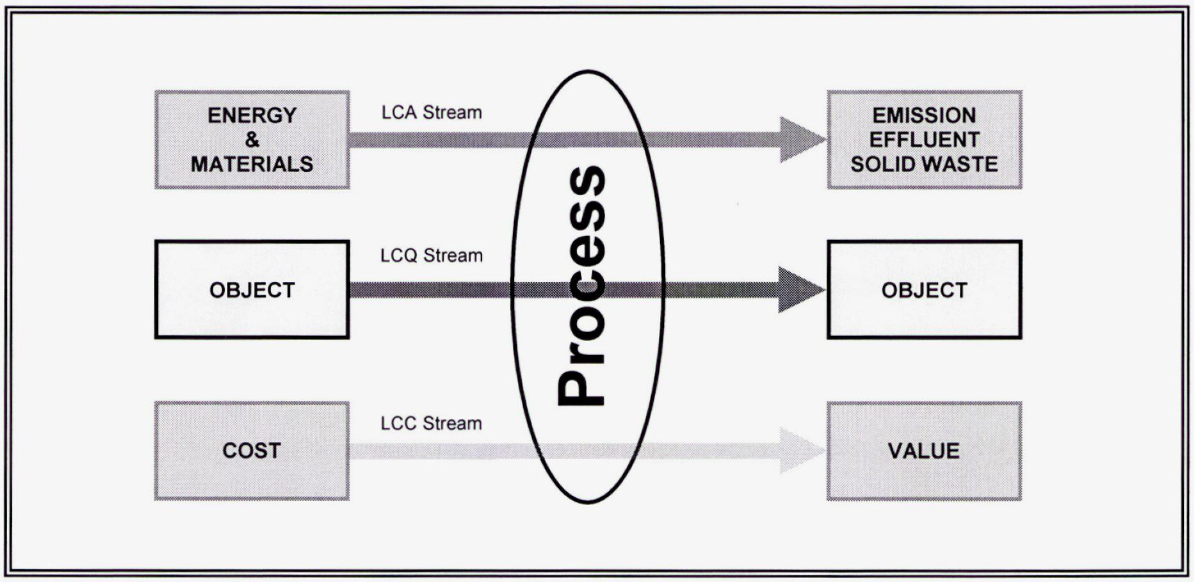


Figure 3-4. Process-Based Analysis

To assist in the focus on the evaluation and analysis techniques needed by the proposed design process model, the following chapters will provide more detailed discussions on the new LCQ and LCA approaches.

CHAPTER 4

LIFECYCLE QUALITY ANALYSIS – ROBUST DESIGN AND FUNCTIONAL EVALUATION

4.1 Introduction

Some mechanical system designs are found to be better or more robust than the others. One of the research efforts is to find a way to achieve “good” or optimal designs. Suh [2001] proposed the Axiomatic Design theory, which consists of two axioms: the independence axiom and the information axiom. This theory defines ideal designs that obey the independence axiom. However in reality, not all designs can be functionally independent but can still serve the purpose.

On the other hand, it is always desirable that product performance is not affected or minimally affected by the operation environment, which is termed robustness. Designers pursue robust design all the time. A robust design is a design that satisfies requirements while minimizing the effects of environmental variability on product performance [Dunsmore et al., 1997]. Environmental variations may come from raw materials, manufacturing processes, and/or operational environments that cause deviations of product performance and functions. This thesis will verify that the independence axiom can always lead to a robust design, while robust designs do not necessarily require independence. Thus, designs may be divided into three categories: feasible designs, robust designs, and ideal designs. It is understandable that, sometimes, it is not always possible for designers to achieve the ideal goals. A possible approach is first to generate a feasible design, then seek to acquire robustness, and then achieve the possibility of the independence.

Currently, it is difficult for engineers to analyze their designs' robustness and independence in a single framework. The functional evaluation scientifically analyzes the physical structure to achieve best design results. While the Taguchi method provides a system that can lead to a robust design, Axiomatic Design assists engineers in achieving an ideal design. Because Axiomatic Design targets the ideal design, it does not support any design that does not obey the independence axiom. Axiomatic Design is a foregoing design theory. The Taguchi method is an experimental system-based traditional robust engineering technique that is not directly related to the independence concept. These different techniques and concepts are difficult to integrate. However, a unified framework would benefit the design and analysis processes and may help to reach the best design goal – to be ideal or, at least, robust. This thesis suggests such a framework that deals with both the independence and robustness of a design. It introduces the integration of the independent analysis, which is based on Suh's Axiomatic Design, and robust analysis, which is based on the traditional robust technique. It can help the designer to seek an ideal design or a robust design in respect to the specific design conditions. Some designs may be neither ideal nor robust. Then the designers need to decide to keep the designs or to make some changes to achieve the ideal or robust design.

4.2 Robust Design Discussion

A robust design means the designed performance is hardly affected by environmental variations. Products face environmental variability in respect to raw materials, manufacturing processes and operational environment, which can cause deviations of the design performance and functions. The product's ability to fulfill the function is then considered robust or insensitive to changes in those uncontrollable noise parameters of the environment.

As previously discussed, Axiomatic Design can lead to an ideal design only if the independence axiom is verified, which means it must be a uncoupled design. In some cases, decoupled designs are also acceptable because they may become independent under specific conditions. However, a decoupled design may not be robust to potential environmental variations.

According to Suh's theory, the design process can be considered a procedure mapping from the functional domain to the physical domain [Suh, 2001]. If **Fr** denotes the functional requirement and **Dp,** the design parameter, then the performance function can be expressed as:

$$\mathbf{Fr} = f\,(\mathbf{Dp}) \qquad (4-1)$$

or

$$\mathbf{Fr} = [\,\mathbf{D}\,] \bullet \mathbf{Dp} \qquad (4-2)$$

where $\mathbf{Fr} = [Fr_1, Fr_2, Fr_3, \ldots, Fr_n]^T$

$\mathbf{Dp} = [Dp_1, Dp_2, Dp_3, \ldots, Dp_m]^T$

[D] is called design matrix. $D_{ij} = \partial Fr_i / \partial Dp_j$

When n > m, it is a coupled design; and, when n < m, a redundant design. Only when n = m, does it has a chance to be an ideal design [Suh, 2001]. Although n = m, it can be a coupled design (which does not obey the independence axiom) or a decoupled design (which may conditionally become independent). In this case, $D_{ij} = 0$ (when $i \neq j$) means uncoupled design; $D_{ij} = 0$ (only when $i < j$) means decoupled design; otherwise, D_{ij} means coupled design. An uncoupled design is preferred.

$$\begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \qquad \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{bmatrix} \qquad \begin{bmatrix} X & X & X & X \\ X & X & 0 & X \\ X & X & X & X \\ X & X & X & X \end{bmatrix}$$

Uncoupled **Decoupled** **Coupled**

Figure 4-1. Design Matrices

In reality, design parameters in the physical domain may have variations **(ΔDp)** caused by changes in the environment, including manufacturing, usage, and other environmental factors. Although these variations cannot be controlled by designers, the performance function may not be sensitive to those changes. The design is still robust.

The sensitivity of **Fr** to changes in the input **Dp** can be measured by S, which is the ratio of the relative errors in the output and the input.

$$S = \left| \frac{\Delta Fr / Fr}{\Delta Dp / Dp} \right| = \left| \frac{\Delta Fr / \Delta Dp}{Fr / Dp} \right| \approx \left| \frac{\partial Fr / \partial Dp}{Fr / Dp} \right| \qquad (4-3)$$

Sensitivity S is also known as the condition number.

Both **∂Fr / ∂Dp** and **Fr / Dp** are performance matrix **[D]** related terms. Therefore, the significant item is the matrix **[D].** It can be concluded that both the functional independence and sensitivity of the design are able to be measured by studying **[D]**.

The functional deviation caused by the environmental variation can be expressed as,

$$\Delta Fr = f(Dp + \Delta Dp) - f(Dp), \qquad (4-4)$$

or

$$\Delta\mathbf{Fr} = [\,\mathbf{D}\,] \bullet \Delta\mathbf{Dp} \qquad (4-5)$$

where **ΔDp** denotes the design deviation caused by environmental variations.

Mathematically, the covariance and variance-covariance are often used to measure a certain kind of dependence between variables. Suppose that **ΔFr** and **ΔDp** are real-valued random variables with means (also called expected values) $E(\Delta\mathbf{Fr})$ and $E(\Delta\mathbf{Dp})$, the means, variance and variance-covariance are defined as:

Means:

$$E(\Delta\mathbf{Fr}) = [E(\Delta Fr_1), E(\Delta Fr_2), \ldots, E(\Delta Fr_n)]^T$$

$$E(\Delta\mathbf{Dp}) = [E(\Delta Dp_1), E(\Delta Dp_2), \ldots, E(\Delta Dp_n)]^T$$

Variance:

$$Var(\Delta\mathbf{Fr}) = E\{[\,\Delta\mathbf{Fr} - E(\Delta\mathbf{Fr})\,]^2\} \text{ and}$$

$$Var(\Delta\mathbf{Dp}) = E\{\,[\Delta\mathbf{Dp} - E(\Delta\mathbf{Dp})\,]^2\}$$

Variance-Covariance:

$$VC(\Delta\mathbf{Fr}) = Cov\,(\Delta\mathbf{Fr}, \Delta\mathbf{Fr})$$

$$= E\{\,[\Delta\mathbf{Fr} - E(\Delta\mathbf{Fr})]\,[\Delta\mathbf{Fr} - E(\Delta\mathbf{Fr})]^T\}$$

$$VC(\Delta\mathbf{Dp}) = Cov\,(\Delta\mathbf{Dp}, \Delta\mathbf{Dp})$$

$$= E\{\,[\Delta\mathbf{Dp} - E(\Delta\mathbf{Dp})]\,[\Delta\mathbf{Dp} - E(\Delta\mathbf{Dp})]^T\}$$

Thus,

$$VC(\Delta\mathbf{Fr}) = VC\,(\,[\,\mathbf{D}\,] \bullet \Delta\mathbf{Dp}\,)$$

$$= E\,[([\,\mathbf{D}\,] \bullet \Delta\mathbf{Dp})([\,\mathbf{D}\,] \bullet \Delta\mathbf{Dp})^{T}]$$

$$= E\,([\,\mathbf{D}\,] \bullet \Delta\mathbf{Dp} \bullet \Delta\mathbf{Dp}^{T} \bullet [\,\mathbf{D}\,]^{T})$$

$$= [\,\mathbf{D}\,] \bullet E\,(\Delta\mathbf{Dp} \bullet \Delta\mathbf{Dp}^{T}) \bullet [\,\mathbf{D}\,]^{T}$$

$$= [\,\mathbf{D}\,] \bullet VC(\Delta\mathbf{Dp}) \bullet [\,\mathbf{D}\,]^{T} \qquad (4-6)$$

For research purposes, we assume variations of both design parameters and functions have normal distributions:

$E(\Delta\mathbf{Fr}) = \mathbf{0}$ and $E(\Delta\mathbf{Dp}) = \mathbf{0}$

The standard variances have uniform values, σ_F and σ_D; their variance-covariance are simply considered to be isotropic:

$VC(\Delta\mathbf{Fr}) = \sigma_F^2[\,\mathbf{I}\,]$, $VC(\Delta\mathbf{Dp}) = = \sigma_D^2[\,\mathbf{I}\,]$.

Then we have,

$$\sigma_F^2[\,\mathbf{I}\,] = [\,\mathbf{D}\,] \bullet \sigma_D^2[\,\mathbf{I}\,] \bullet [\,\mathbf{D}\,]^{T}$$

$$\sigma_F^2[\,\mathbf{I}\,] = \sigma_D^2\,[\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^{T}$$

$$(\sigma_F / \sigma_D)^2\,[\,\mathbf{I}\,] = [\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^{T} \qquad (4-7)$$

It has been mentioned that sensitivity S reflects the ratio of the relative errors in the output and the input.

$$S = \left| \frac{\partial \mathbf{Fr} / \partial \mathbf{Dp}}{\mathbf{Fr} / \mathbf{Dp}} \right| \qquad (4-8)$$

Here **Dp** is the input and **Fr** is the output.

In Equation $(\sigma_F / \sigma_D)^2$ **[I] = [D] • [D]** ^{T} , notice that σ_F represents the variance of output and σ_D represents the variance of output respectively. Their ratio (σ_F / σ_D) can definitely be considered as the sensitivity as well. Let's call it $S_{V.}$

$$S_{V.} = \sigma_F / \sigma_D \qquad (4-9)$$

$$S_V^2 [\,\mathbf{I}\,] = [\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^T \qquad (4-10)$$

And assign

$$[\,\mathbf{S_V}\,] = S_V^2 [\,\mathbf{I}\,] = [\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^T, \qquad (4-11)$$

We call this matrix **[S_V]** the sensitive matrix.

According to the sensitive matrix expression, it can be derived that **[S_V]** has to be a diagonal matrix and all its elements on the main diagonal are identical. It is interesting to note that the result derived from this sensitive matrix equation is the same as the one obtained from calculating the regular norm and condition number. But the present formulation is more reasonable and straightforward. However, only the isotropic matrix is discussed here in the context of the independence. Below is the discussion about the condition number.

For the square matrices that can be obtained from the design satisfying functional independence, the sensitivity can be measured by using the notion of the condition number of matrix D. Because ~~of~~

$$VC(\Delta\mathbf{Fr}) = \sigma_D^2 \, [\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^T$$

And, it is believed that the term $[\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^T$ determines whether the functional performance is sensitive to environmental variation or not. It is also known as the major part of the standard Frobenius norm's expression.

$$\|\,[\,\mathbf{D}\,]\,\|_F = \{\,\mathrm{tr}([\,\mathbf{D}\,] \bullet [\,\mathbf{D}\,]^T)/n\}^{1/2} \qquad (4-12)$$

If one uses it to calculate the norm, then it is easy to obtain the condition number, since we know that the condition number of a matrix is commonly defined as the product of the norm of the matrix and the norm of the matrix-inverse.

$$K = \|\,[\,\mathbf{D}\,]\,\| \;\; \|\,[\,\mathbf{D}\,]^{-1}\| \qquad (4-13)$$

The same result was also reached and demonstrated in a totally different way by another researcher [Angeles, 2002].

If the condition number is large, **[D]** is said to be ill-conditioned. If the condition number is near one, **[D]** is said to be well-conditioned. If the condition number is one, **[D]** is said to be perfectly conditioned.

Thus, when the design brings out vector **Fr** (functional requirements) and **Dp** (design parameters ~ physical parameters), as well as their performance matrix **[D]**, it can be determined whether the design is independent and robust.

Derived sensitive matrix **[S_V]** or the condition number K can definitely be used in the product design. According to **[S_V]** expression, it can be derived that:

1. **[S_V]** has to be a diagonal matrix, and
2. All its elements on the main diagonal are identical.

If a design is uncoupled, its sensitive matrix will always have the first feature. However, it may or may not satisfy the second requirement. Further adjustments may be needed. Based on these points, an ideal design can be reached by obeying the independence axiom and satisfying the robust requirements.

4.3 Design and Analysis

Obviously, Axiomatic Design, especially its independence axiom, provides the most important conceptual guides to the design process. It may also be helpful to take advantages of other techniques. An independence-based robust design may be required to follow the steps listed below:

1. Define the product's functional requirements
    - Gather customer requirements
    - Map to product's functional requirements

2. Correspond the design alternatives
   - Apply the independence axiom to perform functional decomposition
   - Map from functions to design parameters

3. Analyze independence and robustness
   - Summarize performance function equations derived from the 2nd step
   - Maintain the independence - If it is a coupled design, decouple it
   - Based on the derived robust condition, change the design.

4. Go back to the 2nd step or continue

Step 1 - Define the Product's Functional Requirements

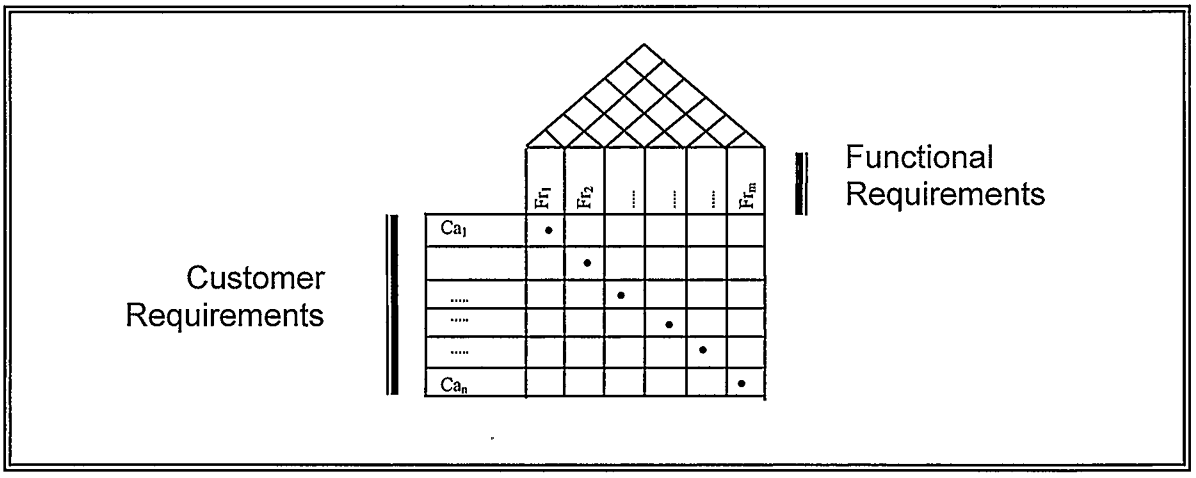


Figure 4-2. Design Requirements

Functional requirements (**Fr**) can be derived from customer requirements (**Ca**, defined as Customer Attributions in Axiomatic Design). Figure 4-2 is a table, based on the Quality Function Deployment (QFD) technique, that is used to gather **Ca**, define **Fr**, show the relations between **Ca** and **Fr**, and analyze correlations among **Fr**.

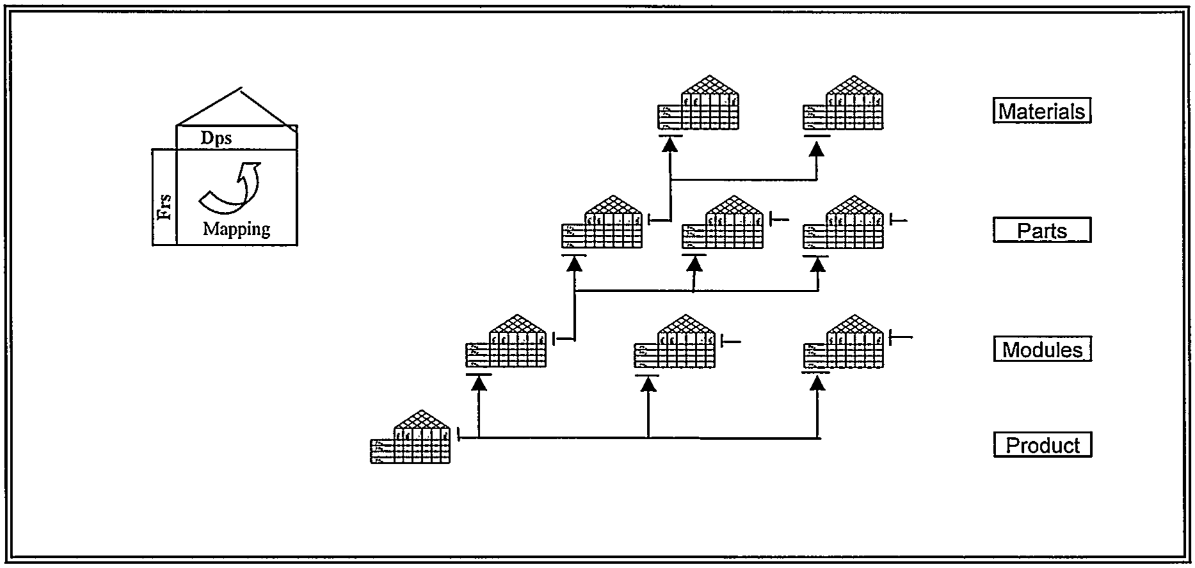


Figure 4-3. Decomposition Process

Step 2 - Correspond the Design Alternatives

The decomposition process starts at the product level and goes down to the material level. At each level, QFD tables are also used to conduct individual mapping processes. As shown in Figure 4-3, the product's functional requirements (listed in the left column) map to design parameters (listed in the top row of the table) in each QFD table. Those design parameters may denote necessary functional modules. Thus, each module's functional requirements can be generated. They fill in the next level's tables and map out the modules' design parameters. Then, the functional requirements of the part level are derived and go to the part tables, which can map to parts' design parameters as well. The part level provides requirements to the material level. Materials for individual parts can be determined at this final level.

A good functional decomposition process will make sure that the design has n = m, an isotropic $[\mathbf{D}]_{nxn}$.

Step 3 – Analyze Independence and Robustness

Through the decomposition process, performance functions can be derived.

$$\mathbf{Fr} = [\mathbf{D}] \cdot \mathbf{Dp}$$

If the design model violates the independence axiom, decoupling may be needed. This can be realized by adjusting the design parameters in a particular order [Suh, 1999].

Calculate and analyze the sensitive matrix:

$$[\mathbf{S_v}] = S_v^2 [\mathbf{I}] = [\mathbf{D}] \cdot [\mathbf{D}]^T$$

$$S_v = \sigma_F / \sigma_D$$

or the condition number

$$\| [\mathbf{D}] \|_F = \{ tr([\mathbf{D}] \cdot [\mathbf{D}]^T)/n \}^{½}$$

$$K = \| [D] \| \; \| [D]^{-1} \|$$

The result indicates whether the design can meet the independence requirement and the robust condition. It may suggest some changes to design parameters.

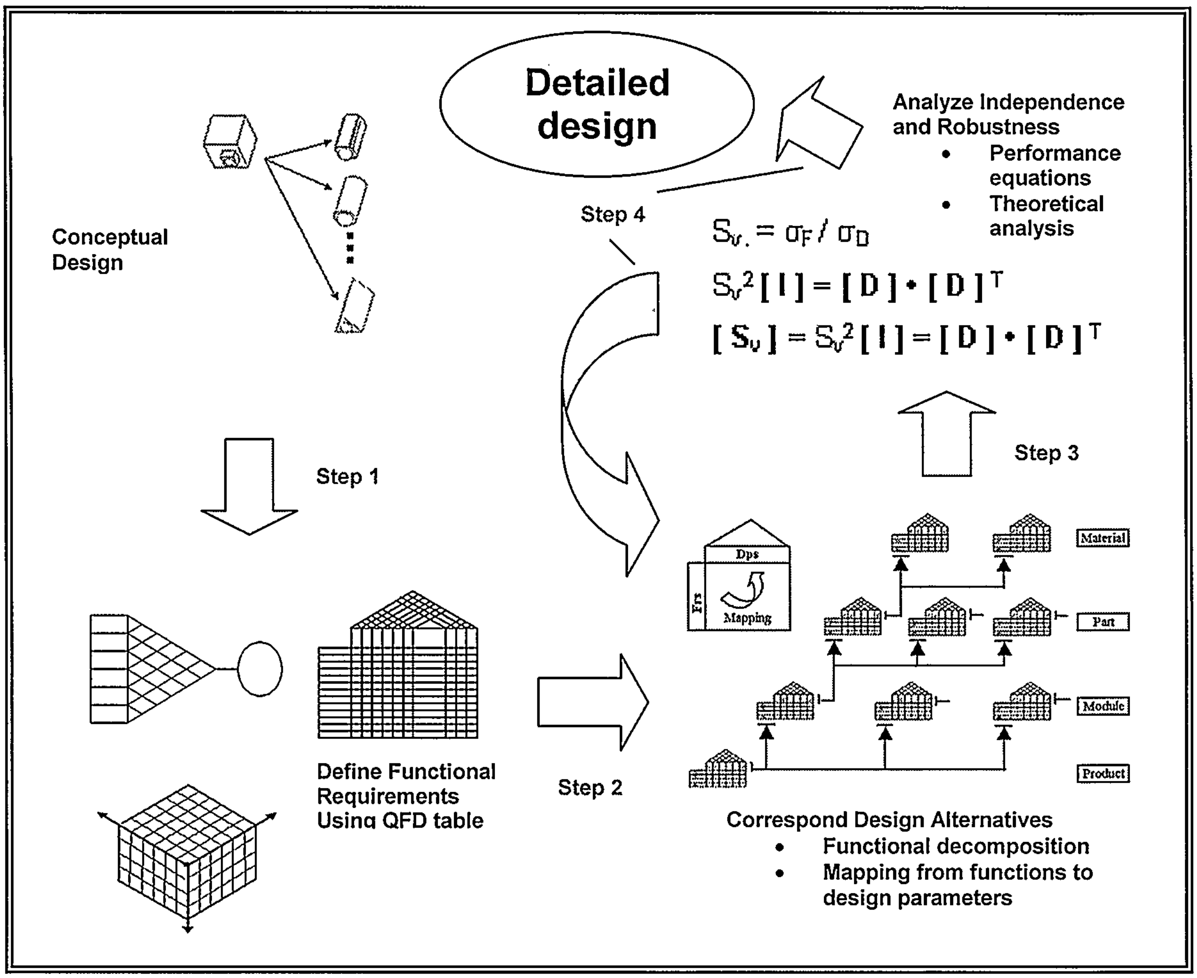


Figure 4-4. Functional Design and Analysis Process

Step 4 - Go Back to the 2nd Step or Continue

According to the robust analysis, it may be necessary to return to the 2nd step, executing the design changes. If the design is demonstrated to be functionally independent and robust, the detailed design can continue.

4.4 Examples

The following three examples are used to explain this approach and its applications. As they are existing physical structures, the main discussions will relate to their analyses instead of design procedures.

Example 1

In industrial practice, serial linkage mechanisms are often used. Each axis of a serial structure supports the other one, which may include the actuator and the joint. From the perspective of Axiomatic Design, the linkage mechanisms could be designed with functional independence, such as with some types of inkjet plotters. However, such structures may not meet high stiffness requirements if heavy moving parts are involved. Thus, more applications go to the parallel principle. Parallel manipulators, in comparison with serial structures, may have better productivity and economy [Zirn et al., 2003].

A manipulator with two degrees of freedom is discussed here, starting at the product level. Two separate driving units are expected to generate two inputs, respectively. This will provide the next level with sub-functional requirements in regard to different links with joints and actuators. Reasonably, one may consider a serial manipulator. It has two perpendicular axes with prismatic joints. Two inputs (actuators) are separately responsible for two dimension motions. Therefore, independence can be obeyed.

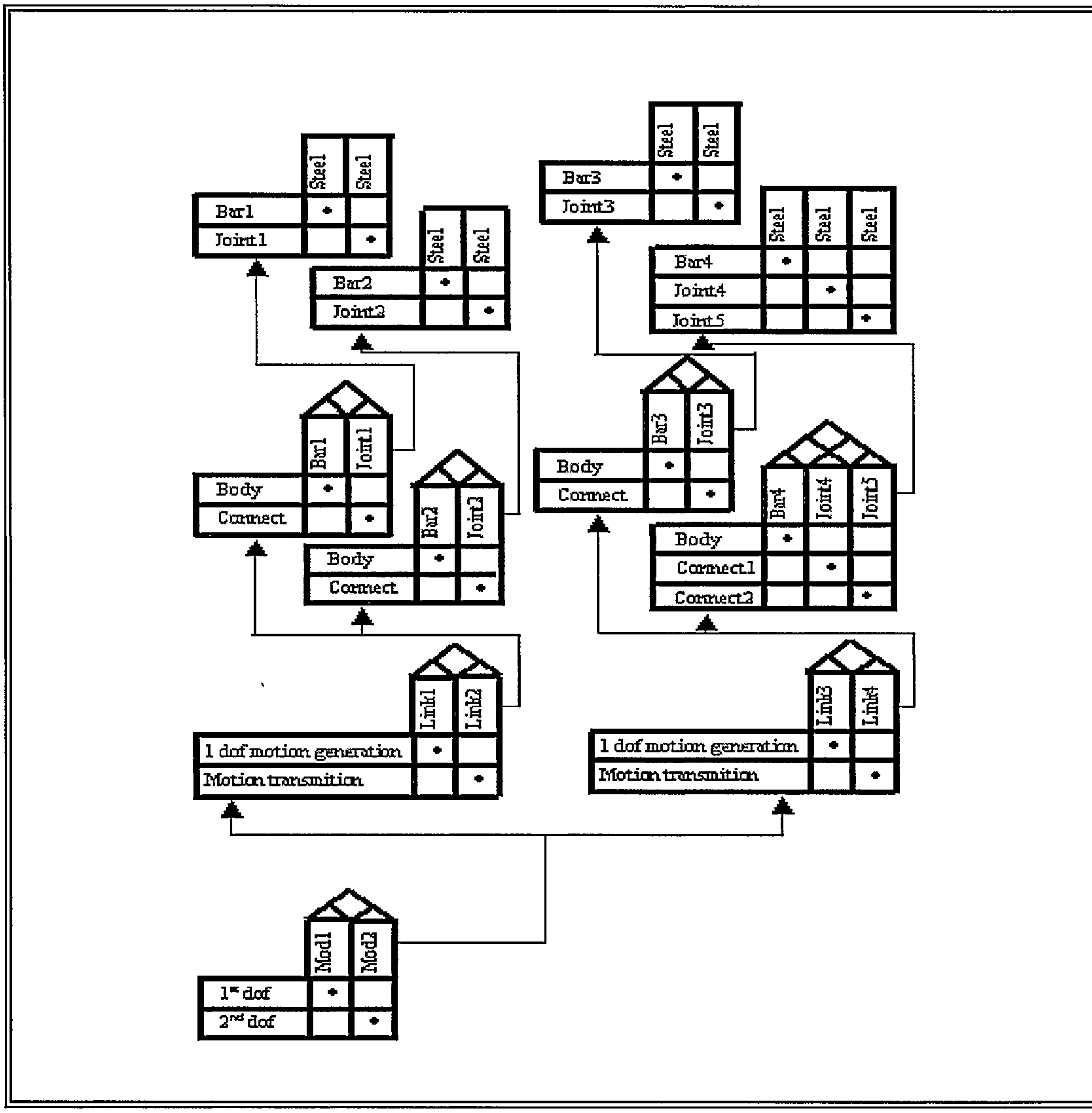


Figure 4-5. Decomposition

In some situations, the design may not obey the independence axiom but still be robust. For a parallel mechanism, to express them in houses, Figure 4-5 depicts its decomposition process. Based on the decomposition and mapping process, the parallel mechanism concept is generated as shown in Figure 4-6. The point at joint 5 is the position of the end effector. It is designed to have horizontal motion V_x and vertical motion V_y. Prismatic joints 1 and 3 allow two horizontal inputs along X direction. They are represented by V_2 at joint 2 and V_4 at joint 4.

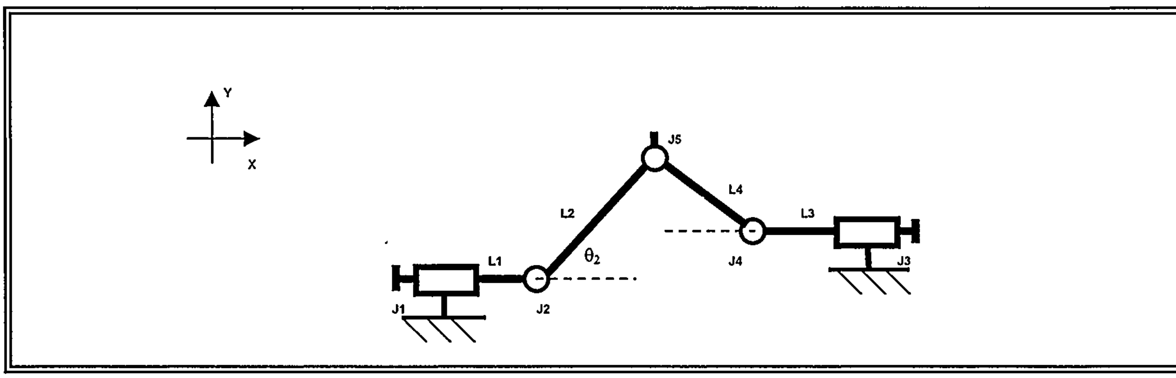


Figure 4-6. Parallel Manipulator Model

The positions of the three major points are:

Point 5 - (X, Y), motions V_x and V_y

Point 2 - (X_2, Y_2), motion V_2

Point 4 - (X_4, Y_4), motions V_4

In this case, V_2 and V_4 are coupled together to generate V_x and V_y; and, an inversed analysis, V_x and V_y are considered as inputs to test the system motion actuators. Thus, V_x and V_y are the design parameters; while V_2 and V_4 are functional requirements.

$$\mathbf{Fr} = [V_2 , V_4]^T$$

$$\mathbf{Dp} = [V_x , V_y]^T$$

$$\begin{bmatrix} V_2 \\ V_4 \end{bmatrix} = [J_b] \bullet \begin{bmatrix} V_x \\ V_y \end{bmatrix}$$

where J_b is Jacobian matrix in relation with two slide bases at Points 2 and 4.

$$[J_b] = \begin{bmatrix} \partial X_2 / \partial X & \partial X_4 / \partial X \\ \partial Y_2 / \partial Y & \partial Y_4 / \partial Y \end{bmatrix}$$

Between Point 5 and the bases, there is the transformation.

$$(X - X_2)^2 + (Y - Y_2)^2 = L_2^2$$

$$(X - X_4)^2 + (Y - Y_4)^2 = L_4^2$$

Thus,

$$X_2 = X - [L_2^2 - (Y - Y_2)^2]^{½}$$

$$\partial X_2 / \partial X = 1$$

$$\partial X_2 / \partial Y = - (Y-Y_2)/[L_2^2 - (Y-Y_2)^2]^{½} = - \text{tg}\ \theta_2$$

$$X_4 = X + [L_4^2 - (Y-Y_4)^2]^{½}$$

$$\partial X_4 / \partial X = 1$$

$$\partial X_4 / \partial Y = (Y-Y_4)/[L_4^2 - (Y-Y_4)^2]^{½} = \text{tg}\ \theta_4$$

Thus, the performance matrix, in relation to the Jacobian matrix, is simply as follows:

$$[D] = [J_b] = \begin{bmatrix} 1 & 1 \\ -\text{tg}\ \theta_2 & \text{tg}\ \theta_4 \end{bmatrix}$$

Its transformed matrix is:

$$[D]^T = \begin{bmatrix} 1 & -\text{tg}\ \theta_2 \\ 1 & \text{tg}\ \theta_4 \end{bmatrix}$$

According to the sensitive matrix defined in this thesis, it can be derived,

$$[D] \bullet [D]^T = \begin{bmatrix} 2 & \text{tg}\ \theta_4 - \text{tg}\ \theta_2 \\ \text{tg}\ \theta_4 - \text{tg}\ \theta_2 & \text{tg}^2\ \theta_4 + \text{tg}^2\ \theta_2 \end{bmatrix}$$

Because of $[S_V] = S_V^2 [I] = [D] \bullet [D]^T$, the elements of this matrix will have the following relationships:

$S_{v12} = S_{v21} = 0$

$tg\ \theta_4 - tg\ \theta_2 = 0$

$tg\ \theta_2 = tg\ \theta_4$

$\theta_2 = \theta_4 = \theta$

$S_{v11} = S_{v22}$

$tg^2\ \theta_4 + tg^2\ \theta_2 = 2$

$2\ tg^2\ \theta = 2$

$tg\ \theta = 1$

$\theta = 45\ ^{o}$

At this point, several explanations can be made in regard to the design. At $\theta_1 = \theta_2 = 45\ ^{o}$, the mechanism achieves the most robustness in respect to the kinematic position. Usually when two slide bases are designed at the same level,

$Y_2 = Y_4$

Then, links 2 and 4 will have the equal lengths.

$L_2 = L_4 = L$

This means,

$Y = L\ Sin\ 45\ ^{o} = L / 2^{1/2}$

These results support other calculations and analyses made from different approaches [See Zirn et al., 2003].

Example 2

In practice, some designs can be made to obey the independence axiom as well as obtaining robustness, while others find it difficult to satisfy the independence axiom. It depends on the designers' choices and certain circumstances.

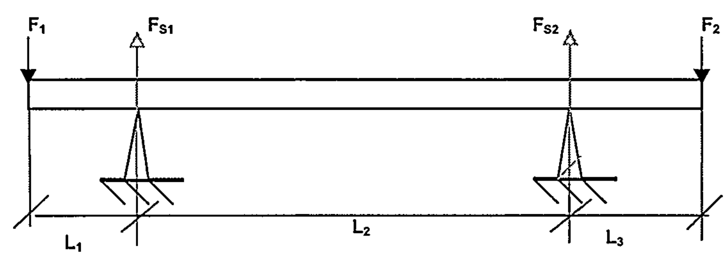


Figure 4-7. Design Concept for Beam Supports [Suh, 2001]

Here is a simple design concept, which is used to demonstrate the proposed approach. Figure 4-7 shows a beam with two supports. Mechanically, the forces have the following relations:

$$F_1 (L_1 + L_2 + L_3) = F_{S1}(L_2 + L_3) + F_{S2} L_3$$

$$F_2 (L_1 + L_2 + L_3) = F_{S1} L_1 + F_{S2}(L_1 + L_2)$$

$$L = L_1 + L_2 + L_3$$

Thus,

$$\mathbf{Fr} = [F_1 , F_2]^T$$

$$\mathbf{Dp} = [F_{S1} , F_{S2}]^T$$

$$\mathbf{Fr} = [\,\mathbf{D}\,] \bullet \mathbf{Dp}$$

Where

$$[\,\mathbf{D}\,] = \begin{bmatrix} \partial F_1 / \partial F_{S1} & \partial F_1 / \partial F_{S2} \\ \partial F_2 / \partial F_{S1} & \partial F_2 / \partial F_{S2} \end{bmatrix}$$

Here, three situations can be considered as starting points – the uncoupled design, the decoupled design, or the coupled design.

Uncoupled Design:

Assuming the original design is perfectly uncoupled, then the terms $\partial F_1 / \partial F_{S2}$ and $\partial F_2 / \partial F_{S1}$ in the performance matrix must be set at zero.

$$\partial F_1 / \partial F_{S2} = L_3 / L = 0$$

$$\partial F_2 / \partial F_{S1} = L_1 / L = 0$$

Thus,

$$L_1 = L_3 = 0,\ L = L_2$$

Then,

$$[D] = \frac{1}{L_2}\begin{bmatrix} L_2 & 0 \\ 0 & L_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$[D] \bullet [D]^T = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

In this case, this means when it is an uncoupled design, it is also a robust design.

Decoupled Design:

If it is originally a decoupled design, the terms of $\partial F_1 / \partial F_{S2}$ in the performance matrix will be zero.

$$\partial F_1 / \partial F_{S2} = L_3 / L = 0$$

Thus,

$$L_3 = 0, L = L_1 + L_2$$

Then,

$$[D] = \frac{1}{L}\begin{bmatrix} L_2 & 0 \\ L_1 & L_1 + L_2 \end{bmatrix}$$

$$[D] \bullet [D]^T = \frac{1}{L^2}\begin{bmatrix} L_2^2 & L_1 L_2 \\ L_1 L_2 & L_1^2 + (L_1 + L_2)^2 \end{bmatrix}$$

Thus,

$L_1 L_2 = 0$

$L_2^2 = L_1^2 + (L_1 + L_2)^2$

Then,

$L_1 = L_3 = 0, L = L_2$

In this case, the result indicates that the original decoupled design has to become an uncoupled design in order to satisfy the robustness requirement.

Coupled Design:

If the original design existed in a coupled status, each term of the performance matrix could be any figure. It goes to:

$$[D] = \frac{1}{L} \begin{bmatrix} L_2 + L_3 & L_3 \\ L_1 & L_1 + L_2 \end{bmatrix}$$

$$[D] \bullet [D]^T = \frac{1}{L^2} \begin{bmatrix} L_3^2 + (L_2 + L_3)^2 & L_1(L_2 + L_3) + L_3(L_1 + L_2) \\ L_1(L_2 + L_3) + L_3(L_1 + L_2) & L_1^2 + (L_1 + L_2)^2 \end{bmatrix}$$

$L_3^2 + (L_2 + L_3)^2 = L_1^2 + (L_1 + L_2)^2$

Then,

$L_1 = L_3$

Because $L_1(L_2 + L_3) + L_3(L_1 + L_2) = 0$, thus,

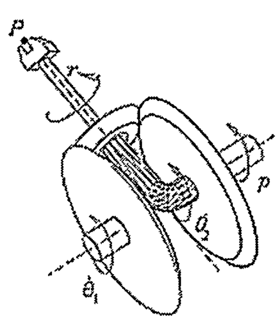
$L_1 = L_3 = 0,\ L = L_2$

Obviously, it becomes an uncoupled design again after applying the robust condition.

In this case, robustness can be achieved while the design satisfies the independence axiom. To verify independence, each support will only serve an individual load. However, this is only a concept. Real structures are not like this.

Example 3

This is an example of a differential gear train between the actuators and the pitch and roll axis.



θ_1 and θ_2 represent the two actuators;
p and r represent the pitch and roll axis.

Figure 4-8. Indirectly-Driven Pitch-Roll Wrist [Angeles, 2002**]**

According to Angeles [2002], the design's Fr, Dp, and Jacobian matrix are expressed as below. This Jacobian matrix **[J_b]** is considered the performance matrix **[D]**.

Fr = $[\theta_1, \theta_2]^T$, **Dp** = $[p, r]^T$,

[D] – Jacobian Matrix [J_b]

$$[J_b] = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ i & -i \end{bmatrix}$$

Here i is the gear number ratio of the sun and the planet. In order to obtain the condition number, Angeles used the following equations, calculating the norms.

$$\| [D] \|_F = \{ tr([D] \cdot [D]^T)/n \}^{½}$$

$$\| [D]^{-1} \|_F = \{ tr([D] \cdot [D]^T)/n \}^{½}$$

The complicated calculation will not be copied here; however, the results are:

$$\| [D] \|_F = \{ (1 + i^2) / 4 \}^{½}$$

$$\| [D]^{-1} \|_F = \{ (1 + i^2) / i^2 \}^{½}$$

Thus, the condition number is:

$$K = \| [D] \|_F \cdot \| [D]^{-1} \|_F = (1 + i^2) / 2i$$

According to the rule, when

$K = 1$

The sensitive matrix can be obtained, then

$i = 1$

Now, the following part will use the proposed approach to verify the same result.

$$[D] \bullet [D]^T = \begin{bmatrix} 2 & 0 \\ 0 & 2i^2 \end{bmatrix}$$

As a defined sensitive matrix feature, it has the following equation:

$$2i^2 = 2$$

Thus,

$$i = 1$$

This manipulation is. easier and faster than the condition number's calculation. Both have the same result $i = 1$. This means the sun gear and planet gear must have the same gear numbers in order to be robust. The result can be verified through the condition number's manipulation, which is much more complicated than that of the sensitive matrix. However in this case, it is impossible to obey the independence axiom.

4.5 Summary

As a general approach, the robust design and analysis can achieve design goals by analyzing the design matrix of the performance function, which indicates if the independence axiom and/or robust requirement are obeyed. The uncoupled design is an ideal design if it also meets the robust requirement at the same time. The decoupled design is acceptable because it can be conditionally uncoupled, but it may or may not be a robust design. When it is uncoupled and robust, it becomes an ideal design. The coupled design will never be an ideal design; however, it still has a chance to become a robust design. To make the design matrix isotropic is a priority. The derived sensitive matrix shows how to reach the least sensitivity to environmental variations. Some cases may violate the independence axiom due to specific reasons. Thus, robust analysis plays an important role in improving design. In regard to the design process, an effective method of decoupling the coupled design needs further exploration as a design practice.

CHAPTER 5

LIFECYCLE ASSESSMENT – ENVIRONMENTAL EVALUATION

As one of the most important parts of the design evaluation, environmental analysis adopts the lifecycle assessment (LCA) technique, which has been verified as the most effective way to deal with environmental problems. However, the application of LCA during the design stage is still a major issue. This chapter provides a simplified LCA approach with a detailed analysis method and evaluation tables. The approach, together with the PBA (process-based analysis) concept proposed in Chapter 3, can be applied to each of the four stages and to every process within each stage of the product lifecycle analysis.

5.1 Lifecycle Assessment

The developer of a product must work toward achieving or satisfying multiple business goals. Environmental performance is only one of these goals and may or may not be weighted equally with other priorities, such as regulatory compliance, product performance, consumer acceptability, and costs. In this study, the focus is on the reduction of environmental impact. Functional and economical issues are not discussed.

The proposed methodology was developed to cover all four stages of the lifecycle – extraction, production, operation, and retirement. However, gathering reliable data on environmental impact can be challenging, particularly for those aspects that are outside of the control of the final manufacturer, e.g. the raw material mining stage. For this reason, individual assessments may focus on those aspects that are under the control of the company performing the analysis. Boundary conditions may be decided respectively by streamlining.

The conceptual LCA describes its assessment results using qualitative statements or simple scoring systems, pointing out sources of environmental impact. Some lifecycle phases may be omitted based on decision-makers' limited choices. The number of examined items may also be limited for the same reason. The simplified LCA is a comprehensive screening assessment, covering the whole lifecycle but simplified by using generic data (qualitative and/or quantitative). It focuses on the most important environmental aspects and/or potential environmental impact, stages of the lifecycle, phases of LCA, and a thorough assessment of the reliability of the results [Christiansen et al., 1997]. Usually quantitative analysis is not necessary to new product development. But instead, the recognition of the relative advantages, disadvantages and uncertainties of an existing or new product is important [Hirschhorn, 1993].

Most simplified LCA techniques are used for internal purposes without formal requirements for reporting. To avoid misinterpretation of the results, the users of the approach should be explicitly aware of the limitations of the study. Therefore, to explain all simplified methods adopted in the approach is necessary [Christiansen et al., 1997]. Prospective users generally are not interested in detailed quantities, but rather in the relative difference among the possible design alternatives. On the other hand, some of the data contents of lifecycle impact are unusable because of the impossibility of applying them in design procedures.

For detailed LCA, the collection of reliable quantitative data is needed. Many manufacturing facilities have more than one product line. It may be difficult to assign energy consumption or waste generation values to separate products with reasonable accuracy. Although activity-based costing (ABC) may provide a solution for this, it may take substantially more effort than companies could afford or are willing to make. Some companies consider the data needed for LCA to be proprietary and are reluctant to divulge this information to outside researchers.

Thus, simplified LCA is the more desirable choice to address environmental concerns in the design stage. The proposed approach will make use of simplified LCA. Qualitative information will be utilized, as the quantitative data may not be available in the design phase. Potential environmental issues will be evaluated from processes, to stages, and to the whole lifecycle.

5.2 Simplified LCA Approach

Based on the lifecycle model, each process in a lifecycle stage has inputs and outputs. As discussed earlier, along the LCA stream, inputs include materials and energy while outputs can be airborne emissions, waterborne effluents and solid wastes. Through the process-based analysis, each process can carry out its own environmental impact evaluation in respects to resources (materials and energy) and potential gaseous, liquid and solid pollutants. In turn, each stage can conduct its environmental evaluation by combining the results of its sub-processes. The integration of all stages can derive the general environmental impact of the lifecycle. The purpose is to obtain the assessment from the product's every material and process. Materials determine the product's physical structure while processes make up the product's lifecycle. If the assessment result indicates that improvement is needed related to the physical structure or lifecycle design, the design change can be made to the specific material or the process. This makes it possible to apply LCA dynamically into design iterations. As mentioned above, the approach will follow simplified LCA, mainly using qualitative analysis techniques.

Table 5.1 is designed to collect information for each individual process in order to conduct a process-based analysis. The six most important impact sections are listed in the table – material, energy, air emission, water effluent, solid waste and eco-toxicant. Each section will detail all items that may cause any impact. Every item will obtain a rating value according to specific criteria. Combining all the items' rating values, with regards to their weighting within their section, will give an assessment value for that section. The values from all six sections make up an array for that process, called PA (process assessment array). The eco-toxicant section is equipped to express any overwhelming items that may be involved in the process. If this occurs, the other section items' ratings become meaningless.

As an example of a rating system, AT&T has adopted a rating of 0~4, in respect to its own assessment approach. They use 0 to depict the highest impact, while 4 denotes the lowest [Todd et al., 1999] and [Graedel et al., 1995]. Most processes can be rated from 0 to 5. One may prefer setting 0 as least impact and 5 as most impact.

We applied the matrix analysis to the proposed PBA. The criteria can be set up according to individual companies' experiences on materials they used. Table 5.2 is used to gather all the process arrays (PA) that a stage may have. A stage assessment array (SA) will be derived by integrating all PAs together. Table 5.3 shows a lifecycle assessment matrix (LM). This matrix reflects the whole lifecycle assessment result.

Table 5-1. Process Assessment Table:

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
												X
												X
												X
												X
												X
PA_n	100%		100%		100%		100%		100%		100%	X

Table 5-2. Stage Assessment Table:

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)						X
Process 2 (PA_2)						X
Process 3 (PA_3)						X
...						X
Process n (PA_n)						X
Stage Array (SA_m)						X

Table 5-3. Lifecycle Assessment Table: (LM_{ij})

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	EcoToxicant
Stage 1 (SA_1)	LM_{11}	LM_{12}	LM_{13}	...	...	LM_{16}
Stage 2 (SA_2)	LM_{21}	...	...	...	...	...
Stage 3 (SA_3)	...	...	...	...	...	LM_{36}
Stage 4 (SA_4)	LM_{41}	...	...	...	LM_{45}	LM_{46}
Subtotal						
Sum						

In this qualitative streamlined lifecycle analysis, functional units and allocation methods are not explicitly considered. However, the use of virgin materials is penalized because credit is given for using recycled materials. Users of the matrix are required to allocate numeric values, by material type, for sustainable and environmental attributes for each product being evaluated. The ideal score is zero. This approach reflects the philosophy that less is better and the least is best. Thus, the approach is intended to reward product developers for creating resource efficient products. The numeric values are subjective and company specific. The values used should be consistent with each company's internal business, social and environmental ethics and goals.

Each cell in the lifecycle matrix may have an integer value (0 - 5), which is derived from the lifecycle process analysis. Once an evaluation is done using the matrix approach, an overall environmentally responsible product rating can be computed as the sum of the matrix elements:

$$I_{Sum} = \sum \sum LM_{ij}.$$

where I_{Sum} is the whole rating. The less it is, the better the design is in term of its environmental impact. There are 24 cells in the matrix. The matrices provide a useful overall assessment of a product design.

5.3 LCA's Effect on Design Optimization

A product consists of functional modules that are made of components with detailed design parameters. At the beginning of any design, a set of initial values may be needed to start the work. The functional, environmental and economic (FEE) requirements can provide enough information. With present CAD/CAM systems, more detailed information can be obtained. On the other hand, the lifecycle can start from a traditional lifecycle structure. As the lifecycle is selected, processes are determined accordingly and process-based calculations become possible. Based on the impact values, it can be seen which stage, process or material of a product causes the greatest impact. If, in the mean time, the functional and economic evaluations have positive results, the design will lead to a new iteration to obtain a new set of physical and lifecycle structure design parameters. Otherwise, trade-offs among the functional, environmental, and economic optimizations may be necessary.

5.4 Evaluation Procedure

This section will conduct and explain a simplified LCA evaluation procedure through the example of an oil filter cartridge.

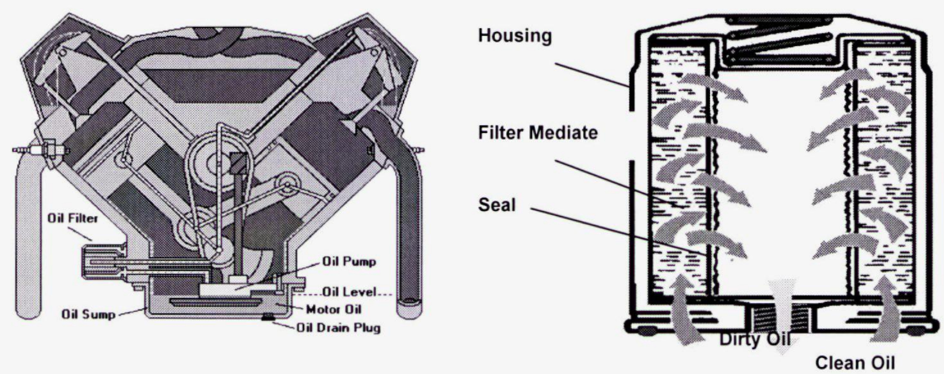


Figure 5-1. Oil Filter Cartridge

Current spin-on oil filters are made up of metal housing and paper filtration medias. They are usually crushed and discarded at their end of life (around 5000 kilometres). The redesign of these components was selected as a case study using LCA. The initial physical and lifecycle structures are given as follows.

Its physical structure has:

- Housing – metal A
- Filtration media – paper
- Seal - rubber

Regarding its lifecycle structure in this case, boundary conditions were set up ~~as~~ from the production stage, through the operation stage, to the retirement stage. The extraction stage was excluded for unachievable data reasons. Thus, there were three main stages that would be involved in the lifecycle evaluation. They are Stage 2, 3, and 4 (without Stage 1).

So, the lifecycle structure has:

- Production stage – manufacturing processes
- Operation stage – a single process of use
- Retirement stage – the landfill process

Production Stage:

Table 5-4. Process Assessment Table: (Manufacturing)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Manuf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
	Metal A	4	Ele	1					Metal A	2		X
	Paper	3							Paper	1		X
	Rubber	2							Rubber	1		X
PA_1	100%	4	100%	1	100%	0	100%	0	100%	2	100%	X

Table 5-5. Stage Assessment Table: (Production)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	4	1	0	0	2	X
Stage Array (SA_2)	4	1	0	0	2	X

Operation Stage:

Table 5-6. Process Assessment Table: (Use)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Use	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
												X
PA_n	100%	0	100%	0	100%	0	100%	0	100%	0	100%	X

Table 5-7. Stage Assessment Table: (Operation)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)						X
Stage Array (SA_3)	0	0	0	0	0	X

Retirement Stage:

Table 5-8. Process Assessment Table: (Landfill)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Landf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
									Metal A	5		X
									Paper	2		X
									Rubber	1		X
PA_1	100%	0	100%	0	100%	0	100%	0	100%	5	100%	X

Table 5-9. Stage Assessment Table: (Retirement)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	0	0	0	0	5	X
Stage Array (SA_4)	0	0	0	0	5	X

Table 5-10. Life Cycle Assessment Table: (LM)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	EcoToxicant
Stage 1 (SA_1)	X	X	X	X	X	X
Stage 2 (SA_2)	4	1	0	0	2	0
Stage 3 (SA_3)	0	1	0	0	0	0
Stage 4 (SA_4)	0	0	0	0	5	0
Subtotal	4	1	0	0	7	0
Sum	12					

According to Aguilar [2002], U.S. businesses alone discard over 400 million used oil filters every year. Those throwaway filters contain at least 3 million gallons of contaminated oil. Based on the above assessment, the oil filter's impact is mainly concentrated on its solid wastes and material consumptions. The product has to make use of certain materials so the material consumption cannot be eliminated. However, lifecycle changes can definitely reduce its contribution to the impact. This suggests that the lifecycle structure adopt a reuse process to increase the product's lifespan and eliminate discards. Accordingly, the physical structure may need to change to use a reusable filtration media in order to meet the reuse requirement; and a simple conditioning process is needed at its end of life. Thus, the new physical structure will have:

- Housing – metal A
- Filtration media – metal B
- Seal – rubber

The lifecycle structure will change to:

- Production stage – manufacturing processes
- Operation stage – process of use
- Retirement stage – conditioning and reuse processes

With this change, the production stage and retirement assessment arrays need to be updated. Because all major parts are reused thereby reducing requirements for new materials and manufacturing, the inputs and outputs of the manufacturing processes would change accordingly.

Assuming the other two design evaluations – functional and economic – are acceptable (however, this may not happen in real practice, trade-off techniques may be needed), the design system would lead to another iteration based on this environmental evaluation.

Production Stage:

Table 5-11. Process Assessment Table: (Manufacturing)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Manuf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
	Metal A	1	Ele	1					Metal A	1		X
	Metal B	1							Metal B	1		X
	Rubber	1							Rubber	1		X
PA_1	100%	1	100%	1	100%	0	100%	0	100%	1	100%	X

Table 5-12. Stage Assessment Table: (Production)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	1	1	0	0	1	X
Stage Array (SA_2)	1	1	0	0	1	X

Operation Stage:

Table 5-13. Process Assessment Table: (Use)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Use	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
												X
PA_1	100%	0	100%	0	100%	0	100%	0	100%	0	100%	X

Table 5-14. Stage Assessment Table: (Operation)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)						X
Stage Array (SA_3)	0	0	0	0	0	X

Retirement Stage:

Table 5-15. Process Assessment Table: (Conditioning)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Reuse	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
	Water	1					Water	1	Rubber	1		X
	CH	1										X
	Rubber	1										X
PA_1	100%	1	100%	0	100%	0	100%	1	100%	1	100%	X

Table 5-16. Process Assessment Table: (Reuse)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Landf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
												X
PA_2	100%	0	100%	0	100%	0	100%	0	100%	0	100%	X

Table 5-17. Stage Assessment Table: (Retirement)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	1	0	0	1	1	X
Process 2 (PA_2)	0	0	0	0	0	X
Stage Array (SA_4)	1	0	0	1	1	X

Table 5-18. Life Cycle Assessment Table: (LM)

Contributors	Impact Rating					
	Inputs		Outputs			
	1. Material	2. Energy	3. Air Emission	4. Water Effluent	5. Solid Waste	6. EcoToxicant
Stage 1 (SA_1)	X	X	X	X	X	X
Stage 2 (SA_2)	1	1	0	0	1	0
Stage 3 (SA_3)	0	0	0	0	0	0
Stage 4 (SA_4)	1	0	0	1	1	0
Subtotal	2	1	0	1	2	0
Sum	6					

Obviously, the new lifecycle structure with conditioning and reuse processes significantly reduces the total impact.

$I_{Sum} = 12$ (the 1st design)

$I_{Sum} = 6$ (the 2nd design)

Because of the adoption of metal filtration media and the processes of conditioning and reuse, the 2nd design, with changes in its physical and lifecycle structures, has significantly decreased the environmental impact from the 1st design. It can be imagined that adding a recycling process to its retirement stage would also benefit the environment and, therefore, improve the design.

However, any practical situation of product design requires simultaneously considering any design problems based on environmental, economical and product functionality evaluations, or when adding a new process to any stage would potentially bring an extra lifecycle cost. This means that conflicts may occur among functional, environmental and economical evaluation criteria when the real design concurrently conducts these three evaluations. This is the future work of this lifecycle design engineering research program.

5.5 Summary

To incorporate environmental evaluations in the design stage, full lifecycle assessment (LCA) may not be suitable to be used as a design assistant tool because of the quantitative requirement. Simplified LCA based on a lifecycle engineering approach provides a qualitative alternative for designers. The LCA approach should be able to dynamically analyze impact because the product's physical and lifecycle structures are changing during design iterations. Because each of the four lifecycle stages has one or more processes, a process-based analysis was proposed to deal with the assessment issues. Within each stage, process assessment arrays were formed to generate a stage assessment array. Four stage arrays together formed the lifecycle assessment matrix. This matrix can reflect the impact of the whole lifecycle with respect to natural resource depletion (material, energy) and environmental pollution (air emission, water effluent, solid waste, and eco-toxicant). The matrix could suggest where to improve the physical structure and/or lifecycle structure. In the design process, evaluations should be done for each design iteration in order to achieve the sustainable product design.

CHAPTER 6

CASE STUDY – PIPING DESIGN AND ANALYSIS

Government agencies and many NGOs (non-government organization) always keep an eye on chemical plants that have a potential for environmental impact. When starting such a plant project, engineering companies are required to design a sustainable plant. They must look after the engineered system in terms of functional performance, environmental impact, and economic effect. This chapter conducts a case study about a plant's piping system.

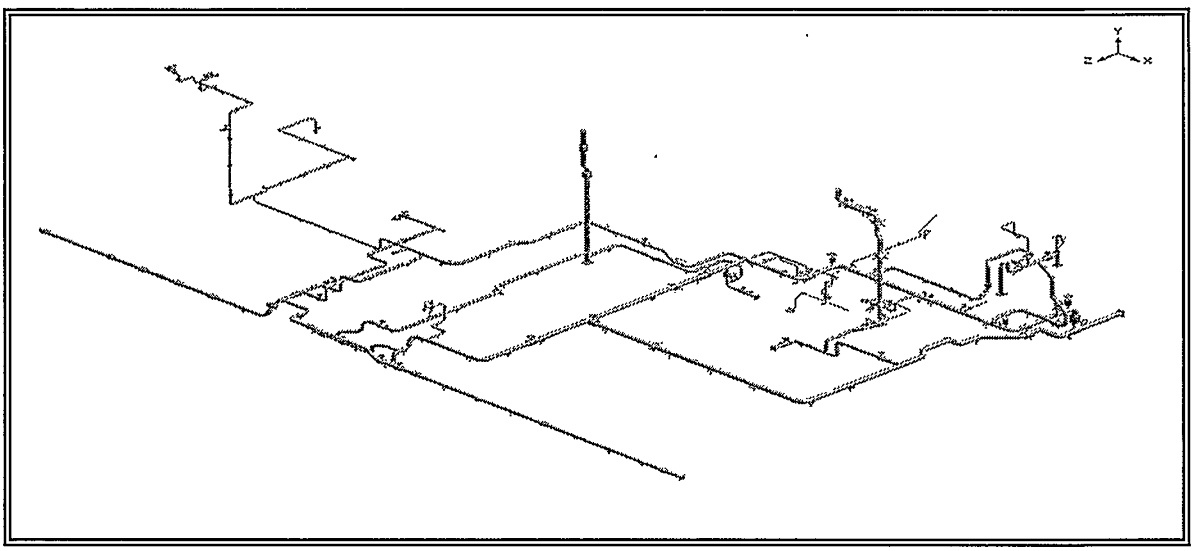


Figure 6-1. Piping Layout

Figure 6-1 shows a piping system. In this thesis, only a part of the system – a "Z" section (shown in Figure 6-2) – has been selected to be designed and analyzed. To test the approaches proposed in former chapters, the study will focus on lifecycle quality (LCQ) and lifecycle assessment (LCA) analyses.

6.1 LCQ Stream – Physical Structure Design and Analysis

6.1.1 The Problem

In piping design, many efforts have been made to reduce the cycle time between the proposed piping layout and the stress analysis. The problem arises due to the current workflow – normally the piping designer generates the layout design, then the analyst conducts the stress analysis. If there are stress problems, the feedback will be given to the designer who redesigns the layout of the pipes and again submits the plan to the analyst. This iterative process keeps going until the design is approved. The designer usually has little knowledge of stress analysis, while the analyst is seldom responsible for designing piping layout.

6.1.2 Current Practices

For such a problem, many design handbooks (i.e. *Process Plant Layout and Piping Design* – a popular one that is widely used by the industry) would recommend a set of tables, diagrams and suggested spans to assist the designer in designing the supports. Analysis on a pipe support design aims to optimize the design among those pre-designed supports, eliminating some supports if possible [Houston et al, 1989]. A software tool available on the market is called PSO (Pipe

Support Optimizer) [www.asdglobal.com/docs/pso_datasheet.pdf, 2004-03-25]. It identifies pipe support locations according to practical distances from supportable structures. Only feasible support locations (most are edited manually) are considered for pipe support location optimization. The optimization actually is the stress analysis process, which is now done by an analyst.

6.1.3 Approach and Application

The above practices have one thing in common, which is first designing all potential supports with the layout based on previous design experience, and then optimizing them. In reality, they are not real optimizations. It's a technique to test and see which of those pre-designed supports are "better" than the others. From the viewpoint of robust design, the problem can be summarized as:

1. A piping system's reliability depends highly upon the stresses and displacements.

2. The stresses and displacements may be caused by the system's static loadings, dynamic loadings, and thermal effects.

3. If the system can be designed so that its stresses and displacements are the least sensitive to changes in those loadings and thermal effects, then its design is robust.

4. Theoretically, robust design can have two levels of application in regard to piping design – static application only and all purpose application (covering static and dynamic). The second level of application may involve every

aspect of the piping design and analysis process, which may lead to a systematic approach to piping systems. However, that is not our purpose in this discussion. Our goal is to eliminate the unnecessary iteration time for the current design procedure – not to change the procedure.

5. Thus, the goal can be achieved by applying robust analysis techniques during the piping design stage. According to present industrial practice, we only need to consider static loadings and thermal effects during this stage.

6. In the traditional design method, most feedback from the analyst suggests that designers change supports' positions or occasionally change the layout. That is because designers arrange those supports based mainly on previous industrial experience.

This case study deals with the piping supports design problem. The proposed robust design and analysis approach will be applied for the purpose of eliminating unnecessary cycle time.

6.1.4 Mechanical Relationship

The piping structure is considered a statically indeterminate system. It can be separated into elements. Each element's stresses can be calculated in terms of its static loadings and temperature changes. In this thesis, the "Z" section was selected as it is the most likely to have a negative reaction force with the most stress, if the support's location is not chosen correctly. As shown in Figure 6-2, an 8" pipe comes from Point A and goes along X direction. From Point B, it goes to C along Z direction, and then continues to go along X direction to D.

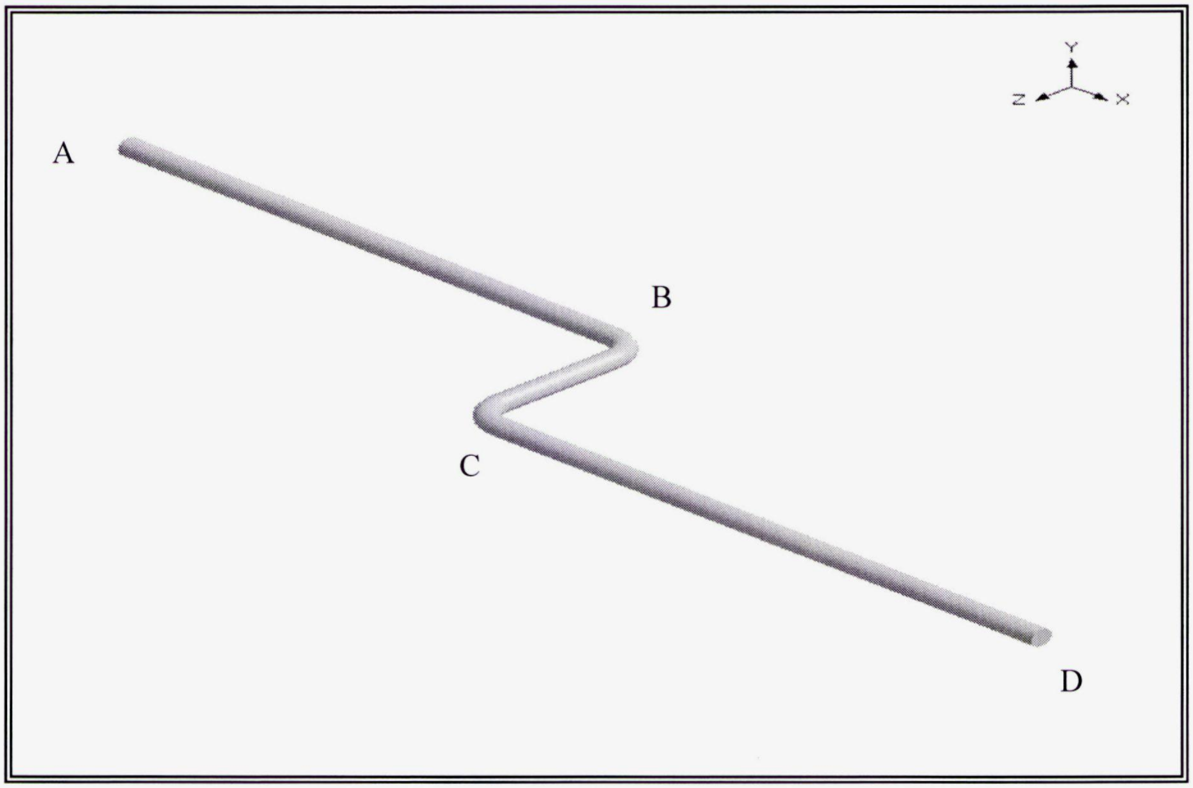


Figure 6-2. "Z" Section

Following the current design method, the designer would normally arrange a group of supports with a span of 15 feet between each pair in regard to A53 steel shown in Figure 6-3.

Is this arrangement a robust design? Mechanically, the design can be simply modeled as a "Z" structure with three supports as indicated in Figure 6-4. In other words, the pipe section between supports 3 and 5, as shown in Figure 6-3, is considered. Its static loading includes the uniform weight and two moments at each end due to the internal actions of separation from the other parts. Based on structural mechanics, this is a statically indetermined structure that can be divided into two pipe elements.

For the piping system, stress is the major concern during design and analysis. Any cross section's stress can be calculated using its internal moment. For this structure, the maximum moments will occur at the positions of the supports. Thus, robustness can be achieved when the stresses are insensitive to loading changes. In turn, this requires that the moments be insensitive to those variations of supporting forces, which are determined by the loading.

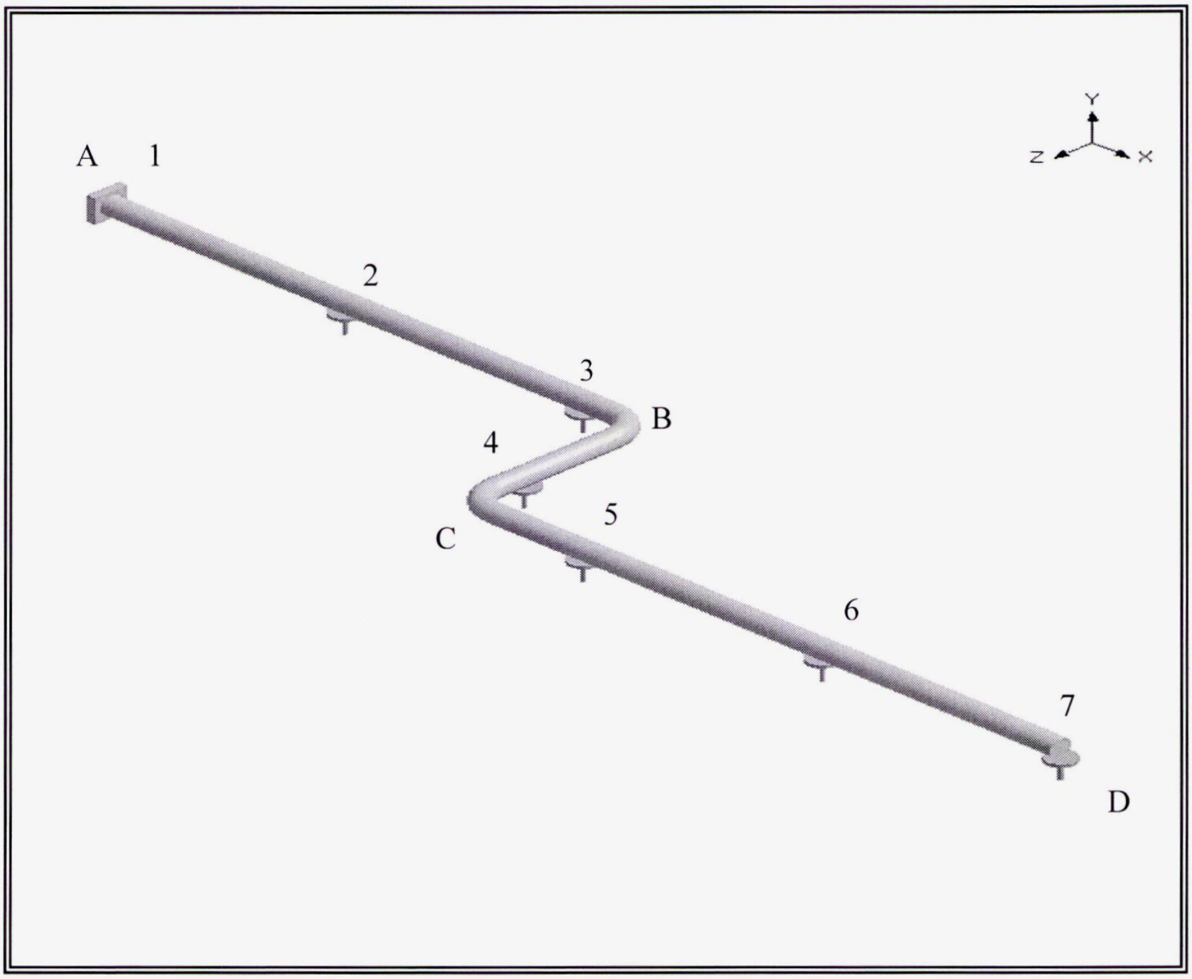


Figure 6-3. Original Design

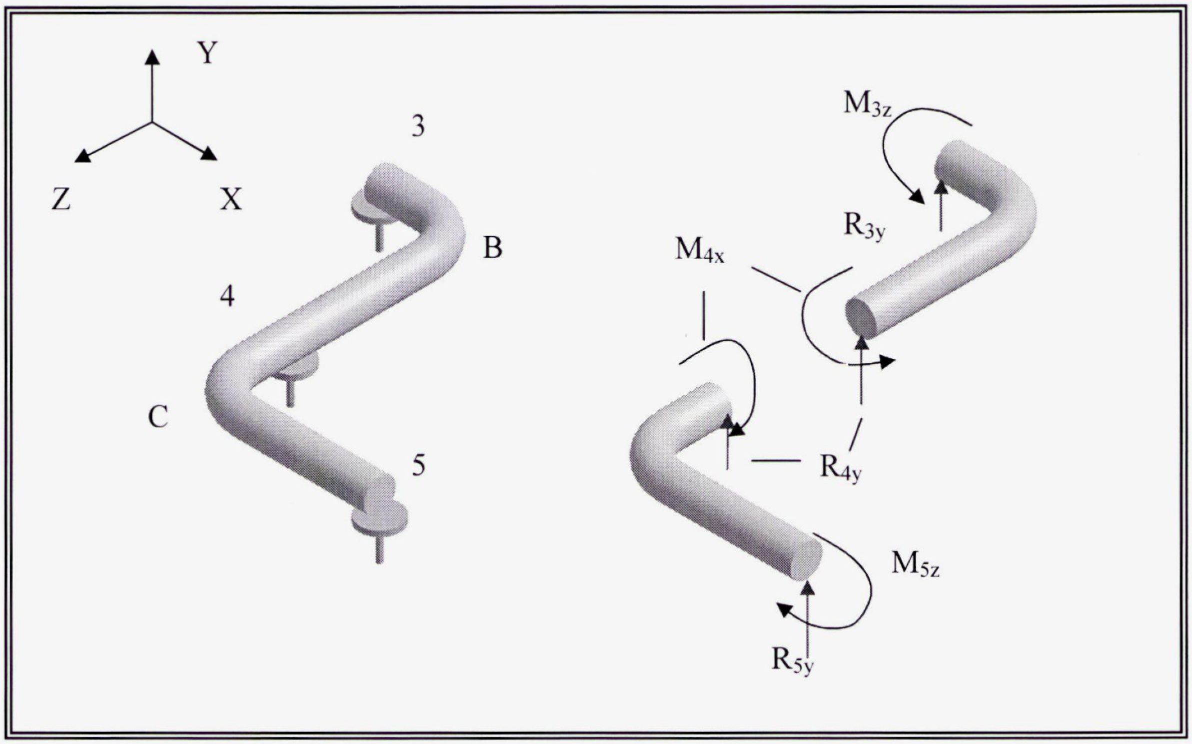


Figure 6-4. Structural Analysis

The location of Support B will be decided by the following calculation. Element 3-B-4 consists of 3-B and B-4 pipes. The lengths and weights are denoted by L_{3B}, L_{4B}, W_{3B}, and W_{4B}, respectively. Element 4-C-5 consists of 4-C and C-5 pipes. Their lengths and weights are denoted by L_{4C}, L_{5C}, W_{4C}, and W_{5C}, respectively.

Because,

$$\sum M_x = 0$$

$$\sum M_z = 0$$

$$\sum F_z = 0$$

Thus,

$M_{3z} = R_{3y} \bullet L_{3B} - W_{3B} \bullet L_{3B} /2$

$M_{4x} = R_{4y} \bullet L_{4B} - W_{4B} \bullet L_{4B} /2$, or $M_{4x} = R_{4y} \bullet L_{4C} - W_{4C} \bullet L_{4C} /2$

$M_{5z} = R_{5y} \bullet L_{5C} - W_{5C} \bullet L_{5C} /2$

$R_{3y} + R_{4y} + R_{5y} = W_{3B} + W_{4B} + W_{4C} + W_{5C}$

The above functions represent the mechanical relationship between the structural strength, supports, and loads.

6.1.5 Robust Analysis

If performance function **Fr = [D] • Dp** is constructed as

M = [D] • R

where **M** = [M_{3z}, M_{4x}, M_{5z}] and **R** = [R_{3y}, R_{4y}, R_{5y}]

Then,

$$[D] = \begin{bmatrix} \partial M_{3z} / \partial R_{3y} & \partial M_{3z} / \partial R_{4y} & \partial M_{3z} / \partial R_{5y} \\ \partial M_{4x} / \partial R_{3y} & \partial M_{4x} / \partial R_{4y} & \partial M_{4x} / \partial R_{5y} \\ \partial M_{5z} / \partial R_{3y} & \partial M_{5z} / \partial R_{4y} & \partial M_{5z} / \partial R_{5y} \end{bmatrix}$$

According to the above equations, the following relationships can be derived:

$\partial M_{3z} / \partial R_{3y} = L_{3B}$, $\partial M_{3z} / \partial R_{4y} = 0$, $\partial M_{3z} / \partial R_{5y} = 0$

$\partial M_{4x} / \partial R_{3y} = 0$, $\partial M_{4x} / \partial R_{4y} = L_{4B}$, $\partial M_{4x} / \partial R_{5y} = 0$

$\partial M_{5z} / \partial R_{3y} = 0, \quad \partial M_{5z} / \partial R_{4y} = 0, \quad \partial M_{5z} / \partial R_{5y} = L_{5C}$

Thus, the design matrix is

$$[D] = \begin{bmatrix} L_{3B} & 0 & 0 \\ 0 & L_{4B} & 0 \\ 0 & 0 & L_{5C} \end{bmatrix}$$

The sensitive matrix will be

$$[D] \bullet [D]^T = \begin{bmatrix} L_{3B}^2 & 0 & 0 \\ 0 & L_{4B}^2 & 0 \\ 0 & 0 & L_{5C}^2 \end{bmatrix}$$

According to the sensitive matrix's characters,

$$L_{3B}^2 = L_{4B}^2 = L_{5C}^2$$

If using

$$M_{4x} = R_{4y} \bullet L_{4C} - W_{4C} \bullet L_{4C} /2,$$

then the following expression can also be derived,

$$L_{3B}^2 = L_{4c}^2 = L_{5C}^2$$

The relationship is expressed as,

$$L_{3B}^2 = L_{4B}^2 = L_{4c}^2 = L_{5C}^2$$

Thus,

$$L_{3B} = L_{4B} = L_{4C} = L_{5C}$$

This is the condition that must be met in order for the design to achieve robustness. The result indicates that 3-B, B-4, 4-C, and C-5 have the same length. As shown in Figure 6-5, when the physical structure is designed with $L_{3B} = L_{4B} = L_{4C} = L_{5C}$, it is robust.

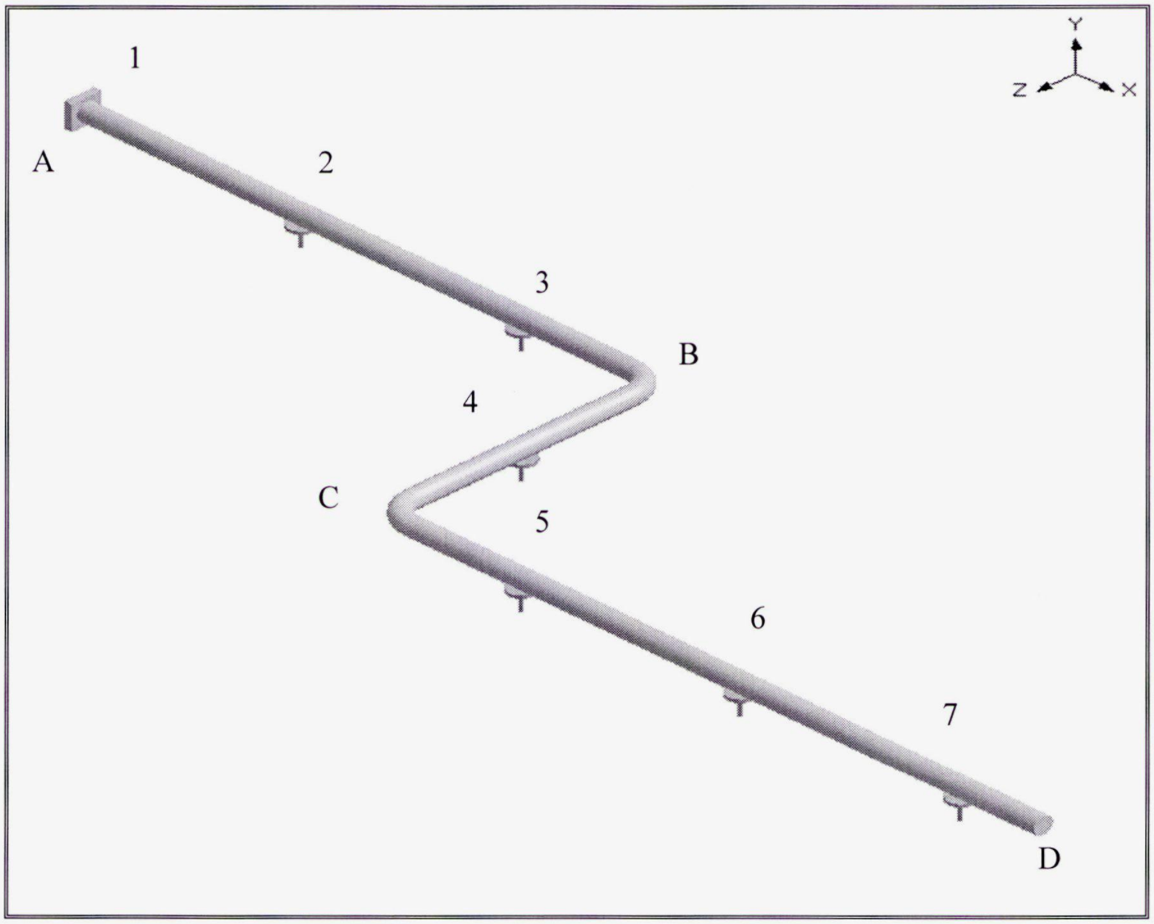


Figure 6-5. Robust Design

6.1.6 Numerical Assessment and Comparison

In order to compare two design results, both the common design and robust design parameters are used to correspond the individual models in the same application environment (in this case, CAEPIPE), within which each design can detail ~~in~~ its stresses, support forces, displacements, and so forth. Two sets of loadings are applied to the original design and the robust design. Both designs' stress changes due to the weight increase are compared here.

Table 6-1 is a part of the data from Appendices A and B. It shows the pipe stress values obtained from different loading situations. The second loading was increased 10 bl/ft from the level of the first loading.

Table 6-1. Stress Values

		1st Loading	2nd Loading	Difference
Original Design	Position 4	4092	4594	502
	Position 6	3798	4254	456
	Position 5	3489	3839	409
	Position 3	3271	3646	375
Robust Design	Position 4	4454	4913	459
	Position 6	3711	4055	344
	Position 5	3465	3770	305
	Position 3	3617	3946	329

With the increase in weight, it can be seen that the original design has bigger increases on stresses than the robust design. This means the latter structure has the best stability in term of piping stress.

This can also be explained from the perspective of geometry. As indicated in Figure 6-6, the robust design result allows the "Z" structure to get a support at its gravity centre – the only best point. Other structures whose gravity centres are apart from their structural components will have to have their supports sit on the same side as their general gravity centers. The further, the better. However, this can be limited by the physical structure's real size. It may never achieve the best point.

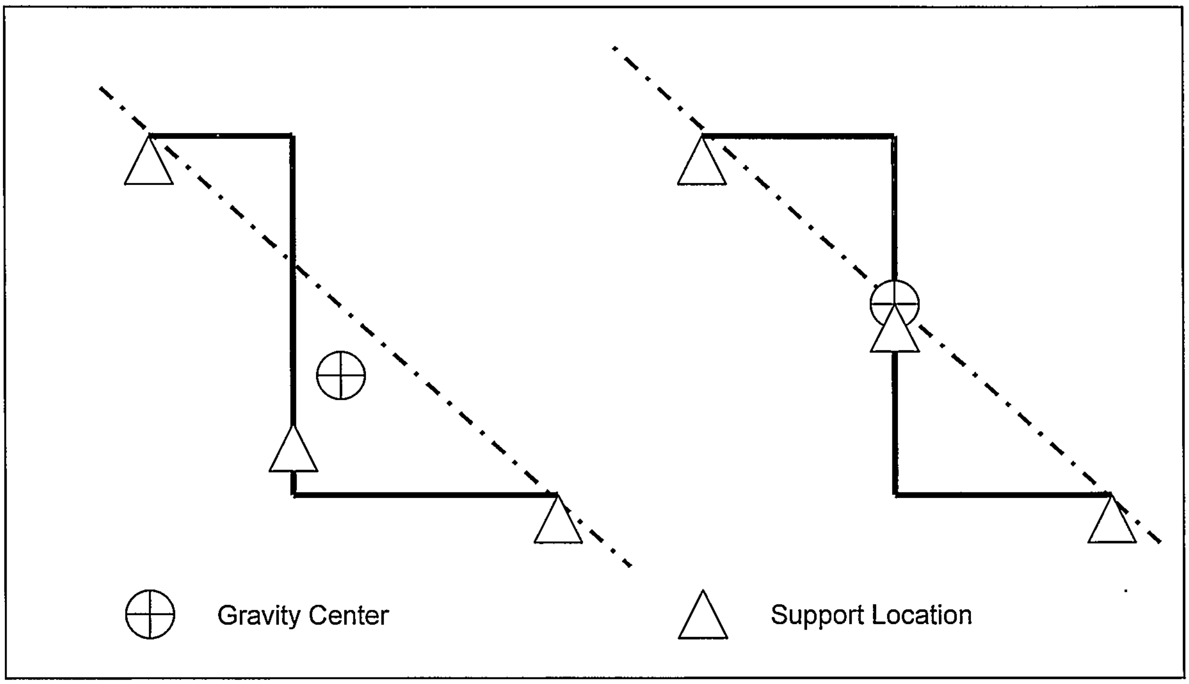


Figure 6-6. "Z" Structure and Its Stability

6.2 LCA Stream – Lifecycle Structure Design and Analysis

The same "Z" section of the piping system will be evaluated through the lifecycle assessment (LCA) stream. The section has steel pipes with concrete supports. When it arrives at the EOL (end-of-life) stage, most steel pipes can be recycled, while the concrete supports will be sent to the landfill. The initial physical structure and lifecycle structure are given as follows:

Its physical structure has,

- Pipes and fittings – Steel
- Support – Concrete

Regarding its lifecycle structure in this case, boundary conditions were set up from the production stage, through the operation stage, to the retirement stage. The extraction stage was excluded for unachievable data reasons. Thus, there were three main stages involved in the lifecycle evaluation. They were Stages 2, 3, and 4 (without Stage 1).

The lifecycle structure has,

- Production stage – the manufacturing processes
- Operation stage – a single process of use
- Retirement stage – the recycle and landfill processes

Within the assessment tables, each item was rated, based on a scale of 0 to 5. The rating value was simply decided by its impact level for the purpose of this research. In the practice, the criteria may be set up according to individual experience.

Production Stage:

Table 6-1. Process Assessment Table: (Manufacturing)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Manuf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
	Steel	3	Elect.	2					Steel	1		X
	Concrete	2	Mult.	1	Mult.	2	Mult.	1	M. tails	1		X
PA_1	100%	3	100%	2	100%	2	100%	1	100%	1	100%	X

Table 6-2. Stage Assessment Table: (Production)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	3	2	2	1	1	X
Stage Array (SA_2)	3	2	2	1	1	X

Operation Stage:

Table 6-3. Process Assessment Table: (Use)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Use	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
												X
PA_n	100%	0	100%	0	100%	0	100%	0	100%	0	100%	X

Table 6-4. Stage Assessment Table: (Operation)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)						X
Stage Array (SA_3)	0	0	0	0	0	X

Retirement Stage:

Table 6-5. Process Assessment Table: (Recycle)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Landf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
			Mult.	1					steel	0		X
PA_1	100%	0	100%	1	100%	0	100%	0	100%	0	100%	X

Table 6-6. Process Assessment Table: (Landfill)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Landf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
									Concr.	3		X
PA_2	100%	0	100%	0	100%	0	100%	0	100%	3	100%	X

Table 6-7. Stage Assessment Table: (Retirement)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	0	1	0	0	0	X
Process 2 (PA_2)	0	0	0	0	3	X
Stage Array (SA_4)	0	1	0	0	3	X

Table 6-8. Lifecycle Assessment Table: (LM)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	EcoToxicant
Stage 1 (SA_1)	X	X	X	X	X	X
Stage 2 (SA_2)	3	2	2	1	1	0
Stage 3 (SA_3)	0	0	0	0	0	0
Stage 4 (SA_4)	0	1	0	0	3	0
Subtotal	3	3	2	1	4	0
Sum	13					

The total impact value is 13, which is mostly due to the material consumption and solid wastes. The concrete supports have the most potential for improvement. This suggests that the lifecycle structure adopt a recycling process to increase the lifespan of the material and eliminate the discards. Accordingly, the physical structure may change to use recyclable steel for the supports, thereby minimizing the impact on natural resources. Thus, new physical structure will have,

- Pipes and fittings – Steel A
- Supports – Steel B

The life cycle structure will change to,

- Production stage – the manufacturing process
- Operation stage – the process of use
- Retirement stage – the recycle process

With this change, the production stage and retirement assessment arrays need to be updated. Because all major parts are capable of using recycled materials, the inputs and outputs of the manufacturing processes would change accordingly because of reduced use of new materials and reduced need for manufacturing.

Production Stage:

Table 6-9. Process Assessment Table: (Manufacturing)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Manuf.	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
	Steel A	2	Ele	1					Metal A	1		X
	Steel B	1							Metal B	1		X
PA_1	100%	2	100%	1	100%	0	100%	0	100%	1	100%	X

Table 6-10. Stage Assessment Table: (Production)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	2	1	0	0	1	X
Stage Array (SA_2)	2	1	0	0	1	X

Operation Stage:

Table 6-11. Process Assessment Table: (Use)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Use	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
												X
PA_1	100%	0	100%	0	100%	0	100%	0	100%	0	100%	X

Table 6-12. Stage Assessment Table: (Operation)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)						X
Stage Array (SA_3)	0	0	0	0	0	X

Retirement Stage:

Table 6-13. Process Assessment Table: (Recycle)

Process Name	Inputs				Outputs							
	Material		Energy		Air Emission		Water Effluent		Solid Waste		Eco Toxicant	
Reuse	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating	Item	Rating
			Mult.	1					Steel	0		X
PA_1	100%	0	100%	1	100%	0	100%	0	100%	1	100%	X

Table 6-14. Stage Assessment Table: (Retirement)

Contributors	Impact Rating					
	Inputs		Outputs			
	Material	Energy	Air Emission	Water Effluent	Solid Waste	Eco Toxicant
Process 1 (PA_1)	0	1	0	0	1	X
Stage Array (SA_4)	0	1	0	0	1	X

Table 6-15. Life Cycle Assessment Table: (LM)

Contributors	Impact Rating					
	Inputs		Outputs			
	1. Material	2. Energy	3. Air Emission	4. Water Effluent	5. Solid Waste	6. EcoToxicant
Stage 1 (SA_1)	X	X	X	X	X	X
Stage 2 (SA_2)	2	1	0	0	1	0
Stage 3 (SA_3)	0	0	0	0	0	0
Stage 4 (SA_4)	0	1	0	0	1	0
Subtotal	2	2	0	0	2	0
Sum	6					

Obviously, the new lifecycle with the conditioning and reuse processes significantly reduces the total impact.

I_{Sum} = 13 (the 1st design)

I_{Sum} = 6 (the 2nd design)

The 2nd design with changes in its physical structure (steel supports) and lifecycle structure (recycling process) has significantly decreased the environmental impact of the 1st design. It would benefit the environment.

The target plots of these two designs (Figure 6-7) show the difference between these two alternatives. The second solution has more points concentrating on the central area. It can be imagined that adding the recycling process to its retirement stage would also bring benefit to the environment and therefore improve the design.

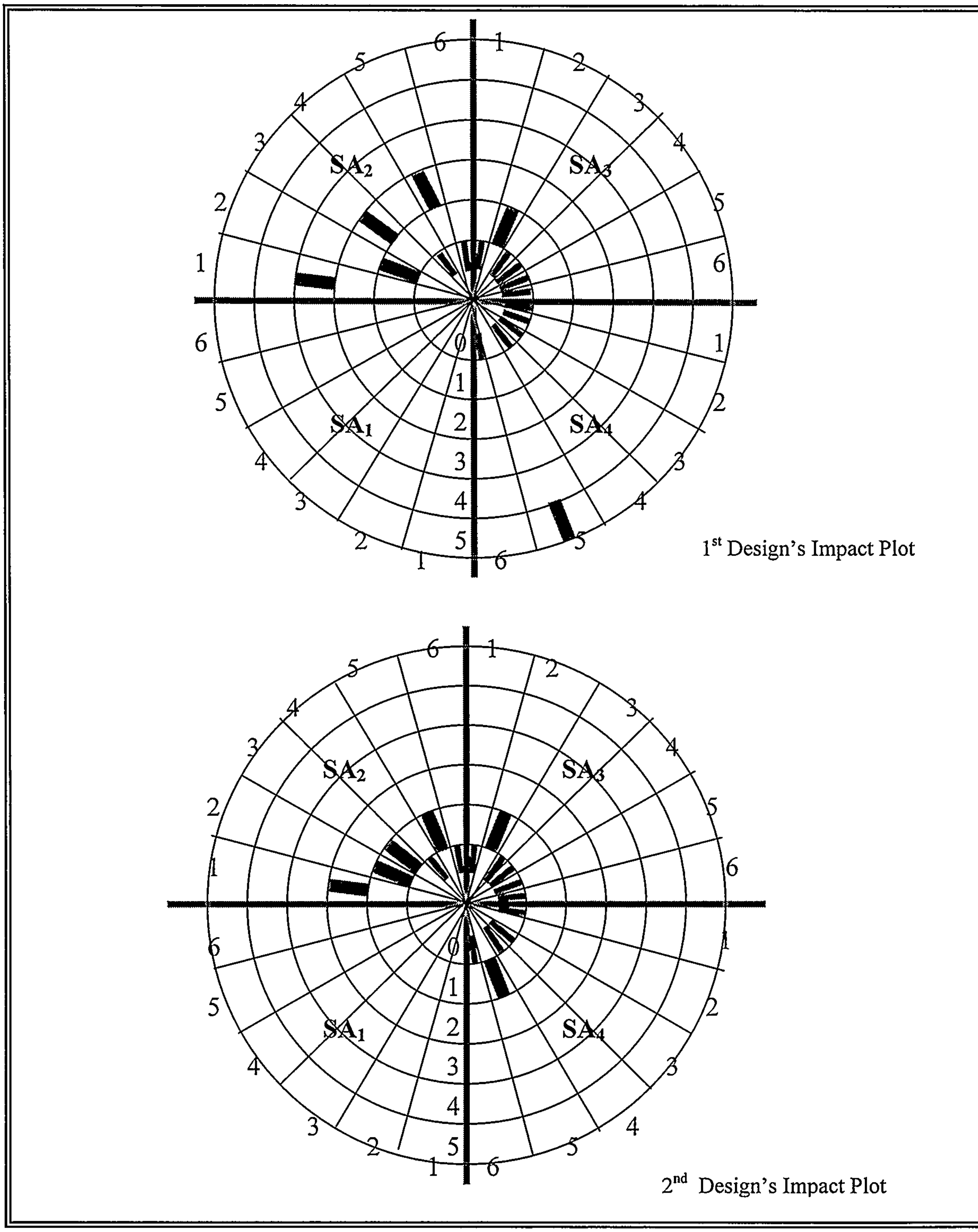


Figure 6-7. Impact Target Plots

However, any practical product design requires simultaneously consideration of the design problems based on environmental, economical and product functionality evaluations. The addition of a new process to any stage could potentially bring an extra lifecycle cost. This means that conflicts may occur among functional, environmental and economical evaluation criteria when a real design concurrently conducts these three evaluations. This will be the future work of this lifecycle design engineering research project.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This thesis summarized three dimensions – functional, environmental, and economic (FEE) – of sustainable design. Based on the FEE dimensions, a systematic lifecycle design process model was proposed consisting of the FEE requirements, two design objects in terms of physical and lifecycle structures, and the FEE evaluation streams in terms of LCQ (lifecycle quality), LCA (lifecycle assessment), and LCC (lifecycle costing).

From the perspective of lifecycle, a new concept of PBA (process-based analysis) was defined, on which the basis for FEE evaluations was founded. The three FEE evaluation streams are some of the most important parts of the design process. This thesis had very detailed discussions on both LCQ and LCA. Because a special LCC methodology has already been developed by Dr. Gu and his student [Asiedu, 2000], this research did not discuss the detailed LCC; however it, together with LCQ and LCA, is a major component of the proposed design process.

7.1 Major Discussions

The major parts of this thesis discussed the realization of the FEE evaluations, especially LCQ and LCA. A unique robust design and analysis approach was developed to conduct the functional design and evaluation. It handled LCQ well. In respect to LCA, the research developed a simplified lifecycle assessment methodology, which was specifically created for being used during the design stage.

Chapter 4 discussed LCQ and came up with a new robust design and analysis methodology that integrated the independence axiom and robust requirement. The research divided designs into three categories – feasible, robust and ideal designs. Robust design and analysis can achieve the design goals by analyzing the performance matrix **[D]** and its derived sensitive matrix **[S_V]**. The performance matrix determines if the design obeys the independence axiom or not. The sensitive matrix configures the robust conditions. When a design is independent and robust, it is called an ideal design.

An uncoupled design verifies the independence axiom. Its performance matrix can always lead to a diagonal sensitive matrix that verifies the first feature of robust design. When the second robust condition is applicable, it becomes not only a robust design but also an ideal design. A decoupled design may or may not obey the independence axiom. A coupled design is definitely not independent. But, decoupled and coupled designs might still have a chance to be robust designs – if their sensitive matrices meet the robust requirement. The ideal design must satisfy both independent and robust requirements, which means it is independent and insensitive. Thus, an uncoupled design or a decoupled design may become an ideal design. A coupled design will never be an ideal design. Although they may violate the independence axiom, all designs still may become robust, as along as their sensitive matrices have the robust features. In practice, from feasible design to robust design and to ideal design, the performance matrix and the sensitive matrix can assist designers in deciding design improvement.

Chapter 5 developed a simplified LCA approach for the LCA stream. To incorporate the environmental evaluations in design stage, full LCA may not be suitable for use as a design assistant tool because of the quantitative requirement. Simplified LCA, which is based on the lifecycle engineering approach, provides a qualitative alternative for designers to follow. The LCA approach should be able to dynamically analyze environmental impact because the product's physical structure and lifecycle structure are changing during design iterations.

A lifecycle has four stages: extraction, production, operation and retirement. Each stage has one or more processes. Process-based analysis (PBA) was proposed to deal with the assessment issues. Within each stage, process assessment arrays are constructed. Then, they are combined to generate a stage assessment array. Four stage arrays together form the lifecycle assessment matrix. This matrix can reflect the impact of the whole lifecycle on natural resource depletion (material and energy) and environmental pollution (air emission, water effluent, solid waste and eco toxicant). The lifecycle assessment matrix could indicate where improvement could be made in regard to physical and lifecycle structures.

7.2 Major Contributions

The new robust design methodology and the simplified LCA approach are two major contributions of this research.

It has not been possible for robust design and Axiomatic Design to exist in a unified design theory. It has now become possible to integrate them. The research provided a framework that combined both independence and robustness within the same approach. It can help designers in seeking the ideal design.

The proposed simplified LCA approach provided a suitable way for designers to apply a LCA technique during the design stage. As a part of the approach, the PBA (process-based analysis) concept was newly defined to guide the fundamental assessments. It is simple and flexible. Different companies may set up their own systems for their individual application purposes.

7.3 Suggestions for Future Work

The new robust design framework has been tested using several conceptual designs. In some cases, it is convenient and quite straightforward. In other cases, it is not that easy because of an incorrect performance function and difficult matrix manipulation. More engineering practices are necessary to test and upgrade it. Further theoretical exploration is still needed.

In regard to the simplified LCA approach, the cases in this thesis are missing extraction stage evaluations due to limited information. In real practice, individual users are also able to choose which stages they prefer to include in the approach, based on their own requirements. However, the assessment of all four stages is needed to truly reflect the environmental impact of the whole lifecycle.

This thesis has proposed a systematic design process model with most of the research focused on robust design and lifecycle assessment (LCA). Future work will also consider lifecycle costing (LCC) in order to complete the design system. The possibility of developing a software tool based on this system may be studied further.

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Appendix A – Original Design

MODEL

Options

```
Piping code = B31.1 (2001)
Use liberal allowable stresses
Do not include axial force in stress calculations
Reference temperature = 70 (F)
Number of thermal cycles = 7000
Number of thermal loads = 1
Solve thermal case
Use modulus at reference temperature
Include hanger stiffness
Do not include Bourdon effect
Do not use pressure correction for bends
Pressure stress = PD / 4t
Peak pressure factor = 1.00
Cut off frequency = 33 Hz
Number of modes = 20
Include missing mass correction
Do not use friction in dynamic analysis
Vertical direction = Y
```

#	Node	Type	DX(ft'in")	DY(ft'in")	DZ(ft'in")	Mat	Sec	Load	Data
1	Title = NewTest								
2	10	From							Anchor
3	20		30'0"			A53	8	1	Limit stop
4	30		30'0"			A53	8	1	Limit stop
5	40	Bend	10'0"			A53	8	1	
6	50				20'0"	A53	8	1	Limit stop
7	60	Bend			10'0"	A53	8	1	
8	70		20'0"			A53	8	1	Limit stop
9	80		30'0"			A53	8	1	Limit stop
10	90		30'0"			A53	8	1	Limit stop

Anchors

		(lb/inch)			(in-lb/deg)		Releases
Node	KX	KY	KZ	KXX	KYY	KZZ	X Y Z XXYYZZ
10	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	

Bends

Bend Node	Radius (inch)	Thickness (inch)	Bend Matl	Flex. Factor	Int. Node	Angle (deg)	Int. Node	Angle (deg)
40	12	L						

60	12	L

Limit stops

Node	Cnect Node	Lower Lmt (inch)	Upper Lmt (inch)	Direction X comp	Direction Y comp	Direction Z comp	Friction Coeff.	Stiffness (lb/inch)
20		0.000	None		1.000			Rigid
30		0.000	None		1.000			Rigid
50		0.000	None		1.000			Rigid
70		0.000	None		1.000			Rigid
80		0.000	None		1.000			Rigid
90		0.000	None		1.000			Rigid

Coordinates

Node	X (ft'in")	Y (ft'in")	Z (ft'in")
10	0	0	0
20	30'0"	0	0
30	60'0"	0	0
40A	69'0"	0	0
40	70'0"	0	0
40B	70'0"	0	1'0"
50	70'0"	0	20'0"
60A	70'0"	0	29'0"
60	70'0"	0	30'0"
60B	71'0"	0	30'0"
70	90'0"	0	30'0"
80	120'0"	0	30'0"
90	150'0"	0	30'0"

Pipe material A53: A53 Grade B

Density = 0.283 (lb/in3), Nu = 0.300, Joint factor = 1.00, Type = CS

Temp (F)	E (psi)	Alpha (in/in/F)	Allowable (psi)
-325	31.4E+6	5.00E-6	20000
-200	30.8E+6	5.35E-6	20000
-100	30.2E+6	5.65E-6	20000
70	29.5E+6	6.07E-6	20000
200	28.8E+6	6.38E-6	20000
300	28.3E+6	6.60E-6	20000
400	27.7E+6	6.82E-6	20000
500	27.3E+6	7.02E-6	18900
600	26.7E+6	7.23E-6	17300
650	26.1E+6	7.33E-6	17000
700	25.5E+6	7.44E-6	16500
750	24.9E+6	7.54E-6	13000

800	24.2E+6	7.65E-6	10800
850	23.3E+6	7.75E-6	8700
900	22.4E+6	7.84E-6	6500
950	21.4E+6	7.91E-6	4500
1000	20.4E+6	7.97E-6	2500
1050	19.2E+6	8.05E-6	1600
1100	18.0E+6	8.12E-6	1000

Pipe Sections

Name	Nominal Dia.	Sch	O.D. (inch)	Thk (inch)	Cor.Al (inch)	M.Tol (%)	Ins.Dens (lb/ft3)	Ins.Th (inch)	Lin.Dens (lb/ft3)	Lin.Th (inch)
8	8"	80	8.625	0.5	0	0.0	11	2		

Pipe Loads

Load Name	T1 (F)	P1 (psi)	T2 (F)	P2 (psi)	T3 (F)	P3 (psi)	Specific gravity	Add.Wgt (lb/ft)	Wind Load
1	600	200					0.800		
2	600	200					0.800	10	

RESULT (UNDER THE 1ST LOAD SITUATION)

B31.1 (2001) Code Compliance (Sorted Stresses)

Sustained			Expansion			Occasional		
Node	SL (psi)	SL/SH	Node	SE (psi)	SE/SA	Node	SL+SO (psi)	SL+SO/ 1.20SH
50	4092	0.24	10	0	0.00			
80	3798	0.22	20	0	0.00			
30	3489	0.20	30	0	0.00			
70	3271	0.19	40A	0	0.00			
10	3260	0.19	40B	0	0.00			
20	3146	0.18	50	0	0.00			
60B	1513	0.09	60A	0	0.00			
40B	1357	0.08	60B	0	0.00			
60A	1356	0.08	70	0	0.00			
40A	1101	0.06	80	0	0.00			
90	863	0.05	90	0	0.00			

B31.1 (2001) Code Compliance

	Press	Sustained			Expansion			Occasional		
Node	(psi) Allow	SL (psi)	SH (psi)	SL/ SH	SE (psi)	SA (psi)	SE/ SA	SL+SO (psi)	1.20SH (psi)	SL+SO/ 1.20SH
10	200	3260	17300	0.19	0					

20	2103	3146	17300	0.18	0
20	200	3146	17300	0.18	0
30	2103	3489	17300	0.20	0
30	200	3489	17300	0.20	0
40A	2103	1042	17300	0.06	0
40A	200	1101	17300	0.06	0
40B	2103	1357	17300	0.08	0
40B	200	1235	17300	0.07	0
50	2103	4092	17300	0.24	0
50	200	4092	17300	0.24	0
60A	2103	1235	17300	0.07	0
60A	200	1356	17300	0.08	0
60B	2103	1513	17300	0.09	0
60B	200	1354	17300	0.08	0
70	2103	3271	17300	0.19	0
70	200	3271	17300	0.19	0
80	2103	3798	17300	0.22	0
80	200	3798	17300	0.22	0
90	2103	863	17300	0.05	0

Loads on Anchors: Sustained (W+P)

Node	X (lb)	Y (lb)	Z (lb)	XX(ft-lb)	YY(ft-lb)	ZZ(ft-lb)
10	0	-972	0	-84	0	-4897

Loads on Limit Stops: Sustained (W+P)

Node	Lower Limit	Upper Limit	Load (lb)	Friction Force(lb)	X comp	Y comp	Z comp
20	Reached	None	-1897			1.000	
30	Reached	None	-1912			1.000	
50	Reached	None	-1953			1.000	
70	Reached	None	-1850			1.000	
80	Reached	None	-2164			1.000	
90	Reached	None	-764			1.000	

Displacements: Sustained (W+P)

Node	X (inch)	Y (inch)	Z (inch)	XX(deg)	YY(deg)	ZZ(deg)
10	0.000	0.000	0.000	0.0000	0.0000	0.0000

20	0.000	0.000	0.000	-0.0086	0.0000	0.0031
30	0.000	0.000	0.000	-0.0173	0.0000	-0.0124
40A	0.000	-0.092	0.000	-0.0199	0.0000	-0.0617
40B	0.000	-0.100	0.000	-0.0251	0.0000	-0.0545
50	0.000	0.000	0.000	0.0335	0.0000	-0.0109
60A	0.000	-0.155	0.000	0.1056	0.0000	0.0098
60B	0.000	-0.175	0.000	0.1043	0.0000	0.0195
70	0.000	0.000	0.000	0.1043	0.0000	0.0182
80	0.000	0.000	0.000	0.1043	0.0000	-0.0325
90	0.000	0.000	0.000	0.1043	0.0000	0.1121

RESULT (UNDER THE 2ND LOAD SITUATION)

B31.1 (2001) Code Compliance (Sorted Stresses)

------ Sustained ------			------ Expansion ------			------ Occasional -----		
Node	SL (psi)	SL/SH	Node	SE (psi)	SE/SA	Node	SL+SO (psi)	SL+SO/ 1.20SH
50	4594	0.27	10	0	0.00			
80	4254	0.25	20	0	0.00			
30	3898	0.23	30	0	0.00			
70	3646	0.21	40A	0	0.00			
10	3633	0.21	40B	0	0.00			
20	3502	0.20	50	0	0.00			
60B	1615	0.09	60A	0	0.00			
40B	1434	0.08	60B	0	0.00			
60A	1432	0.08	70	0	0.00			
40A	1138	0.07	80	0	0.00			
90	863	0.05	90	0	0.00			

B31.1 (2001) Code Compliance

	Press	--- Sustained ----			--- Expansion ----			--- Occasional ----		
Node	(psi) Allow	SL (psi)	SH (psi)	SL/ SH	SE (psi)	SA (psi)	SE/ SA	SL+SO (psi)	1.20SH (psi)	SL+SO/ 1.20SH
10	200	3633	17300	0.21	0					
20	2103	3502	17300	0.20	0					
20	200	3502	17300	0.20	0					
30	2103	3898	17300	0.23	0					
30	200	3898	17300	0.23	0					
40A	2103	1070	17300	0.06	0					
40A	200	1138	17300	0.07	0					
40B	2103	1434	17300	0.08	0					
40B	200	1293	17300	0.07	0					
50	2103	4594	17300	0.27	0					
50	200	4594	17300	0.27	0					
60A	2103	1293	17300	0.07	0					
60A	200	1432	17300	0.08	0					

60B	2103	1615	17300	0.09	0
60B	200	1430	17300	0.08	0
70	2103	3646	17300	0.21	0
70	200	3646	17300	0.21	0
80	2103	4254	17300	0.25	0
80	200	4254	17300	0.25	0
90	2103	863	17300	0.05	0

Loads on Anchors: Sustained (W+P)

Node	X (lb)	Y (lb)	Z (lb)	XX(ft-lb)	YY(ft-lb)	ZZ(ft-lb)
10	0	-1123	0	-97	0	-5659

Loads on Limit Stops: Sustained (W+P)

Node	Lower Limit	Upper Limit	Load (lb)	Friction Force(lb)	X comp	Y comp	Z comp
20	Reached	None	-2192			1.000	
30	Reached	None	-2210			1.000	
50	Reached	None	-2257			1.000	
70	Reached	None	-2138			1.000	
80	Reached	None	-2500			1.000	
90	Reached	None	-883			1.000	

Displacements: Sustained (W+P)

Node	X (inch)	Y (inch)	Z (inch)	XX(deg)	YY(deg)	ZZ(deg)
10	0.000	0.000	0.000	0.0000	0.0000	0.0000
20	0.000	0.000	0.000	-0.0100	0.0000	0.0036
30	0.000	0.000	0.000	-0.0200	0.0000	-0.0143
40A	0.000	-0.107	0.000	-0.0230	0.0000	-0.0713
40B	0.000	-0.115	0.000	-0.0290	0.0000	-0.0630
50	0.000	0.000	0.000	0.0387	0.0000	-0.0126
60A	0.000	-0.179	0.000	0.1221	0.0000	0.0113
60B	0.000	-0.202	0.000	0.1205	0.0000	0.0225
70	0.000	0.000	0.000	0.1205	0.0000	0.0210
80	0.000	0.000	0.000	0.1205	0.0000	-0.0375
90	0.000	0.000	0.000	0.1205	0.0000	0.1296

Appendix B – Robust Design

MODEL

Options

```
Piping code = B31.1 (2001)
Use liberal allowable stresses
Do not include axial force in stress calculations
Reference temperature = 70 (F)
Number of thermal cycles = 7000
Number of thermal loads = 1
Solve thermal case
Use modulus at reference temperature
Include hanger stiffness
Do not include Bourdon effect
Do not use pressure correction for bends
Pressure stress = PD / 4t
Peak pressure factor = 1.00
Cut off frequency = 33 Hz
Number of modes = 20
Include missing mass correction
Do not use friction in dynamic analysis
Vertical direction = Y
```

#	Node	Type	DX(ft'in")	DY(ft'in")	DZ(ft'in")	Mat	Sec	Load	Data
1	Title = NewTest								
2	10	From							Anchor
3	20		27'6"			A53	8	1	Limit stop
4	30		27'6"			A53	8	1	Limit stop
5	40	Bend	15'0"			A53	8	1	
6	50				15'0"	A53	8	1	Limit stop
7	60	Bend			15'0"	A53	8	1	
8	70		15'0"			A53	8	1	Limit stop
9	80		30'0"			A53	8	1	Limit stop
10	90		30'0"			A53	8	1	Limit stop

Anchors

		(lb/inch)			(in-lb/deg)		Releases
Node	KX	KY	KZ	KXX	KYY	KZZ	X Y Z XXYYZZ
10	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	

Bends

Bend Node	Radius (inch)	Thickness (inch)	Bend Matl	Flex. Factor	Int. Node	Angle (deg)	Int. Node	Angle (deg)

40	12	L
60	12	L

Limit stops

Node	Cnect Node	Lower Lmt (inch)	Upper Lmt (inch)	Direction X comp	Direction Y comp	Direction Z comp	Friction Coeff.	Stiffness (lb/inch)
20		0.000	None		1.000			Rigid
30		0.000	None		1.000			Rigid
50		0.000	None		1.000			Rigid
70		0.000	None		1.000			Rigid
80		0.000	None		1.000			Rigid
90		0.000	None		1.000			Rigid

Coordinates

Node	X (ft'in")	Y (ft'in")	Z (ft'in")
10	0	0	0
20	27'6"	0	0
30	55'0"	0	0
40A	69'0"	0	0
40	70'0"	0	0
40B	70'0"	0	1'0"
50	70'0"	0	15'0"
60A	70'0"	0	29'0"
60	70'0"	0	30'0"
60B	71'0"	0	30'0"
70	85'0"	0	30'0"
80	115'0"	0	30'0"
90	145'0"	0	30'0"

Pipe material A53: A53 Grade B

Density = 0.283 (lb/in3), Nu = 0.300, Joint factor = 1.00, Type = CS

Temp (F)	E (psi)	Alpha (in/in/F)	Allowable (psi)
-325	31.4E+6	5.00E-6	20000
-200	30.8E+6	5.35E-6	20000
-100	30.2E+6	5.65E-6	20000
70	29.5E+6	6.07E-6	20000
200	28.8E+6	6.38E-6	20000
300	28.3E+6	6.60E-6	20000
400	27.7E+6	6.82E-6	20000
500	27.3E+6	7.02E-6	18900
600	26.7E+6	7.23E-6	17300
650	26.1E+6	7.33E-6	17000
700	25.5E+6	7.44E-6	16500

750	24.9E+6	7.54E-6	13000
800	24.2E+6	7.65E-6	10800
850	23.3E+6	7.75E-6	8700
900	22.4E+6	7.84E-6	6500
950	21.4E+6	7.91E-6	4500
1000	20.4E+6	7.97E-6	2500
1050	19.2E+6	8.05E-6	1600
1100	18.0E+6	8.12E-6	1000

Pipe Sections

Name	Nominal Dia.	Sch	O.D. (inch)	Thk (inch)	Cor.Al (inch)	M.Tol (%)	Ins.Dens (lb/ft3)	Ins.Th (inch)	Lin.Dens (lb/ft3)	Lin.Th (inch)
8	8"	80	8.625	0.5	0	0.0	11	2		

Pipe Loads

Load Name	T1 (F)	P1 (psi)	T2 (F)	P2 (psi)	T3 (F)	P3 (psi)	Specific gravity	Add.Wgt (lb/ft)	Wind Load
1	600	200					0.800		
2	600	200					0.800	10	

RESULT (UNDER THE 1ST LOAD SITUATION)

B31.1 (2001) Code Compliance (Sorted Stresses)

Sustained Node	SL (psi)	SL/SH	Expansion Node	SE (psi)	SE/SA	Occasional Node	SL+SO (psi)	SL+SO/ 1.20SH
50	4454	0.26	10	0	0.00			
80	3711	0.21	20	0	0.00			
70	3617	0.21	30	0	0.00			
30	3465	0.20	40A	0	0.00			
10	2938	0.17	40B	0	0.00			
20	2677	0.15	50	0	0.00			
40A	1660	0.10	60A	0	0.00			
40B	1638	0.09	60B	0	0.00			
60B	1618	0.09	70	0	0.00			
60A	1618	0.09	80	0	0.00			
90	863	0.05	90	0	0.00			

B31.1 (2001) Code Compliance

Node	Press (psi) Allow	Sustained SL (psi)	SH (psi)	SL/ SH	Expansion SE (psi)	SA (psi)	SE/ SA	Occasional SL+SO (psi)	1.20SH (psi)	SL+SO/ 1.20SH
10	200	2938	17300	0.17	0					
20	2103	2677	17300	0.15	0					

20	200	2677	17300	0.15	0
30	2103	3465	17300	0.20	0
30	200	3465	17300	0.20	0
40A	2103	1464	17300	0.08	0
40A	200	1660	17300	0.10	0
40B	2103	1638	17300	0.09	0
40B	200	1448	17300	0.08	0
50	2103	4454	17300	0.26	0
50	200	4454	17300	0.26	0
60A	2103	1433	17300	0.08	0
60A	200	1618	17300	0.09	0
60B	2103	1618	17300	0.09	0
60B	200	1433	17300	0.08	0
70	2103	3617	17300	0.21	0
70	200	3617	17300	0.21	0
80	2103	3711	17300	0.21	0
80	200	3711	17300	0.21	0
90	2103	863	17300	0.05	0

Loads on Anchors: Sustained (W+P)

Node	X (lb)	Y (lb)	Z (lb)	XX(ft-lb)	YY(ft-lb)	ZZ(ft-lb)
10	0	-903	0	-321	0	-4228

Loads on Limit Stops: Sustained (W+P)

Node	Lower Limit	Upper Limit	Load (lb)	Friction Force(lb)	X comp	Y comp	Z comp
20	Reached	None	-1689			1.000	
30	Reached	None	-1856			1.000	
50	Reached	None	-1952			1.000	
70	Reached	None	-1893			1.000	
80	Reached	None	-2128			1.000	
90	Reached	None	-770			1.000	

Displacements: Sustained (W+P)

Node	X (inch)	Y (inch)	Z (inch)	XX(deg)	YY(deg)	ZZ(deg)
10	0.000	0.000	0.000	0.0000	0.0000	0.0000
20	0.000	0.000	0.000	-0.0304	0.0000	0.0065

30	0.000	0.000	0.000	-0.0608	0.0000	-0.0262
40A	0.000	-0.191	0.000	-0.0763	0.0000	-0.0636
40B	0.000	-0.186	0.000	-0.0850	0.0000	-0.0479
50	0.000	0.000	0.000	0.0053	0.0000	0.0081
60A	0.000	-0.222	0.000	0.1011	0.0000	0.0642
60B	0.000	-0.228	0.000	0.0961	0.0000	0.0784
70	0.000	0.000	0.000	0.0961	0.0000	0.0346
80	0.000	0.000	0.000	0.0961	0.0000	-0.0371
90	0.000	0.000	0.000	0.0961	0.0000	0.1144

RESULT (UNDERTHE 2ND LOAD SITUATION)

B31.1 (2001) Code Compliance (Sorted Stresses)

------ Sustained ------			------ Expansion ------			------ Occasional -----		
Node	SL (psi)	SL/SH	Node	SE (psi)	SE/SA	Node	SL+SO (psi)	SL+SO/ 1.20SH
50	4913	0.29	10	0	0.00			
80	4055	0.23	20	0	0.00			
70	3946	0.23	30	0	0.00			
30	3770	0.22	40A	0	0.00			
10	3161	0.18	40B	0	0.00			
20	2859	0.17	50	0	0.00			
40A	1684	0.10	60A	0	0.00			
40B	1659	0.10	60B	0	0.00			
60B	1636	0.09	70	0	0.00			
60A	1635	0.09	80	0	0.00			
90	863	0.05	90	0	0.00			

B31.1 (2001) Code Compliance

	Press	--- Sustained ----			--- Expansion ----			--- Occasional ----		
Node	(psi) Allow	SL (psi)	SH (psi)	SL/ SH	SE (psi)	SA (psi)	SE/ SA	SL+SO (psi)	1.20SH (psi)	SL+SO/ 1.20SH
10	200	3161	17300	0.18	0					
20	2103	2859	17300	0.17	0					
20	200	2859	17300	0.17	0					
30	2103	3770	17300	0.22	0					
30	200	3770	17300	0.22	0					
40A	2103	1458	17300	0.08	0					
40A	200	1684	17300	0.10	0					
40B	2103	1659	17300	0.10	0					
40B	200	1439	17300	0.08	0					
50	2103	4913	17300	0.29	0					
50	200	4913	17300	0.29	0					
60A	2103	1421	17300	0.08	0					

60A	200	1635	17300	0.09	0
60B	2103	1635	17300	0.09	0
60B	200	1422	17300	0.08	0
70	2103	3946	17300	0.23	0
70	200	3946	17300	0.23	0
80	2103	4055	17300	0.23	0
80	200	4055	17300	0.23	0
90	2103	863	17300	0.05	0

8 **Loads on Anchors: Sustained (W+P)**

Node	X (lb)	Y (lb)	Z (lb)	XX(ft-lb)	YY(ft-lb)	ZZ(ft-lb)
10	0	-1044	0	-371	0	-4886

Loads on Limit Stops: Sustained (W+P)

Node	Lower Limit	Upper Limit	Load (lb)	Friction Force(lb)	X comp	Y comp	Z comp
20	Reached	None	-1952			1.000	
30	Reached	None	-2145			1.000	
50	Reached	None	-2256			1.000	
70	Reached	None	-2187			1.000	
80	Reached	None	-2459			1.000	
90	Reached	None	-890			1.000	

Displacements: Sustained (W+P)

Node	X (inch)	Y (inch)	Z (inch)	XX(deg)	YY(deg)	ZZ(deg)
10	0.000	0.000	0.000	0.0000	0.0000	0.0000
20	0.000	0.000	0.000	-0.0351	0.0000	0.0075
30	0.000	0.000	0.000	-0.0703	0.0000	-0.0303
40A	0.000	-0.221	0.000	-0.0881	0.0000	-0.0735
40B	0.000	-0.215	0.000	-0.0982	0.0000	-0.0554
50	0.000	0.000	0.000	0.0061	0.0000	0.0094
60A	0.000	-0.257	0.000	0.1168	0.0000	0.0742
60B	0.000	-0.264	0.000	0.1111	0.0000	0.0906
70	0.000	0.000	0.000	0.1111	0.0000	0.0400
80	0.000	0.000	0.000	0.1111	0.0000	-0.0429
90	0.000	0.000	0.000	0.1111	0.0000	0.1322