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A Unified Enterprise-Wide Cost Modeling Framework for Engineering Applications Based on Systems Engineering Principles

Yousuf S. Mohammed
Old Dominion University

A UNIFIED ENTERPRISE-WIDE COST MODELING FRAMEWORK FOR ENGINEERING APPLICATIONS BASED ON SYSTEMS ENGINEERING PRINCIPLES

by

Yousuf S. Mohammed
B.Tech. June 1999, Jawaharlal Nehru Technological University, Hyderabad, India
M.S. Dec. 2003, Old Dominion University, Norfolk, VA

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Approved by:

Dr. Han P. Bao (Director)

Dr. Miltiadis Kotinis (Member)

Dr. Alok K. Verma (Member)

Dr. Resit Unal (Member)

ABSTRACT

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Yousuf S. Mohammed
Old Dominion University, 2012
Director: Dr. Han P. Bao

In the present research the problem of enterprise-wide cost modeling is approached from a systems engineering standpoint. What this does is to use each stage of product life cycle to obtain useful information that helps in estimating the cost of the system. Once a generic framework is developed for estimating the core cost, layers of other factors that affect the cost are applied to the core cost, such as risk and uncertainty, maintainability, supply-chain and socio-economic conditions. The cost model is expanded to accommodate a product domain ranging from a simple object to a system in the following hierarchy: System, Product, Assembly, Object. The cost model caters to the needs of cost estimation at every stage of the life cycle and for every kind of product, big or small, simple or complex. New process selection tools have been added to the field of cost estimation, which suggests the user with applicable processes given the material and production quantity. Attributes such as materials, fabrication processes etc… are ontology based. This enables a generic category to branch into increasingly specialized categories with each step. This is very useful, since in the preliminary stages of cost estimation, not much information is available as to what exact material or process is used. In such a case data pertaining to a more generalized material or process can be used.

Earlier work in the field of cost estimation has focused on specific areas of cost estimation either in terms of concept or application. In the work so far, no single-framework has been proposed

that deals with cost estimation that fits the requirements at all stages of product development. Most importantly the concept of systems engineering has not been fully exploited in the area of cost estimation. The framework that we have proposed is based on systems engineering and hence can be used at any stage of the product development.

Some of the previous work on cost estimation has applications in specific industries. The framework guides the user in process selection at the lower levels based on material and quantity using a tool called PRIMA. If data is not available for a particular process, then a more generic form of the process can be chosen to collect cost data and estimate on the basis of that data. A more generic process is obtained by using the DCLASS tool. The cost can be revised to reflect more accurate process when the data and information is available. This is possible within the proposed framework.

The economic, environmental and social impact of the product has also been taken into account through EIOLCA models to make the framework enterprise-wide in nature. The framework has the potential to be developed into umbrella-software that has capability of estimating cost of small parts as well as large systems. The software will also have the capability to determine the economic, environmental and social impact of the products. The decisions regarding the product, the materials used, the manufacturing processes and even the mechanics of the system, are all determined and weighed against the economic, environmental and social impact. Based on this analysis, the policy makers can make micro as well as macro decisions during the initial planning phase of the system. Since the framework relies on principles of systems engineering, it can be applied to systems irrespective of industry and application.

As part of future work, suggestions have been made to turn the framework into a software suite along with other capabilities such as risk analysis and uncertainty.

This dissertation is dedicated to my family.

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Chapter 1: INTRODUCTION AND LITERATURE REVIEW

Over the years a lot of work has gone into developing various techniques of cost estimation. However, the problem is far from being conquered due to the large differences in the nature, size, and complexity of the products worked with. Hence, much of the work done has concentrated itself to a specific area or kind of cost estimation problem. There has long been an effort to come up with a unified cost estimation system, which works equally well no matter what the size, shape, nature and application of the system is. The differences and variety of products, as mentioned above, is evident when we look at some sample products such as a motor, generator, a carrier, an airplane, a space shuttle, etc.

Another important difference in the cost estimation solution is that of the stage at which the cost is being estimated. Every product development process starts with an initial planning stage sometimes referred to as the conceptual stage; then comes the preliminary design stage and then a final design stage. With progress into each stage, more information is available as to the constituents of the product as well as the processes necessary at various stages of the product development. Any decision made during the conceptual design stage of the product has a strong impact on the later stages and more importantly on the cost of the product. But the problem that cost estimators face is that it is this crucial early stage that determines the cost of the product and it just so happens that in this stage that the least information is available. Companies that bid on large projects for government as well as non-government markets need to propose their bid at this stage. Most of the research performed till now has focused on techniques that deal with a certain product or a family of products. While some work has been done to implement techniques such as concurrent engineering and quality function deployment, no efforts have been made to bring the entire range of products under one umbrella using frameworks such as systems engineering.

Work has been done in the areas of not just product manufacturing but also in the areas of estimating the cost of a product throughout its lifecycle. This becomes even more significant when it comes to large government projects.

The math models used to estimate the cost of a product are also rigid in most of the studies that have been done in the past. Since the type of math model depends of the estimation technique which in turn depends on the type of product, there is little flexibility in selecting the math model. The math models can range from simple arithmetic of adding the cost of sub units to come up with the cost of the system, to more complex models developed by using regression and fuzzy logic.

As with any math model these are uncertainty and risk associated with the calculated cost of the product. The uncertainty can be due to the stochastic nature of the data and the method of collecting data from past projects.

A system may have several stages of cost estimation Whereby the stages are the smaller sub-units of the system. The stages could also be various manufacturing processes. The manufacturing processes may sometimes be classified from a generic process to a more specific one. In order to automate the process of calculating the cost in modules and adding them up, it is easier for a computer to have the sub-systems and processes designated by a number. This makes it very easy to program the cost estimation process since the computer can pick a process and if data is not available then it can use the data from a more generic process from the same process-family. This technique is called ontology.

There has been a paradigm shift in recent years to account for the cost of not only the product or system but also the cost of the system over its lifecycle. In addition to this there is interest in obtaining an estimate of the enterprise-wide cost. Enterprise-wide cost takes a holistic view of the company's operations, processes, and technology. This helps in streamlining all the company's processes.

Any product has an impact and is impacted by economic, political, social and environmental conditions. While some of these factors are directly affected, others are indirectly affected. In view of the environmental awareness of recent years the environmental impact of a product has become especially important to the consumers. An environmentally friendly product has a greater appeal among the consumers and also is easily marketable.

1.2 Literature Review

Cost is one of the most important properties of a product. Cost analysis faces several challenges. There is still a large variety of products on which cost analysis has not been done. For example in the area of power systems there has been very little information published about cost analysis. A design note by Ericsson Inc introduces methodologies for making decisions when comparing alternative power systems [1]. Even when cost analysis has been performed for a certain kind of product there is disparity between the cost models from one company to another. A study has been done by Barbara et al.[2] in this regard. The paper tries to determine if an organization can depend on cross-company-based estimation models. Prediction of cross-company models were reviewed against within-company models. The results of the comparison were inconclusive. While some companies would benefit from such application of cross-company models others would not [2]. Statistical cost estimating models have been drawn from cost data of selling price of standard models of cars in the UK. The data was also used to calibrate the model [3]. The US Air force, SAIC and The Aerospace Corporation have also come up with cost models and compared them to the actual cost [4]. Amy Salas discusses other challenges in cost analysis. There is a push from the US government to taking a more commercial approach towards acquisition. This makes cost estimation more critical as the contractor assumes more risk in advanced system procurement with unexpected challenges. Some of the challenges in cost estimating are: Access to historical data, validity and uncertainty of data, limited time to develop estimates and immaturity of requirements [5]. At a higher level, it is sometimes seen that the cost escalation in the project process plant industry have been higher than the rise in cost of material and labor [6]. Some studies like [7] have proposed a test cost model for systems as they go through a manufacturing test process. The cost model allows the company to calibrate the test process to the risk of product, while taking into account other manufacturing and development processes. Another important and probably one of the toughest challenges is to accommodate new technology in cost analysis. There is a lot that needs to be done in the particular area; however, a parametric and analogy model has been suggested by Rajkumar Roy et al. [8]. In the same paper, a case study was done in the automotive sector.

The paper by Tham discusses developing ontology to formalize ABC (Activity Based Costing) in order to incorporate costs into enterprise information systems. The causality represents activity, status of activity, time, causality, and resources [9].

A product goes through several stages before, during, and after manufacturing. In the systems engineering terminology these are called conceptual design, preliminary design, detail design, fabrication, operation, and disposal. Cost analysis needs to be performed at every stage since the information available at each stage changes. Conceptual design is the first and most important phase of system design and the development process. It is an early and high-level life-cycle activity with potential to establish, commit, and otherwise predetermine the function, form, cost, and development schedule of the desired system, product, or structure [10]. When information is not available for estimating cost at a particular stage, information from previous projects is used. This is case based reasoning [11]. In order to estimate profitability of a new system in the conceptual design stage, engineers need to estimate the cost of concept. It has been shown that a distribution about the cost of concept using knowledge-base can be obtained. This is done using a subset of information related to estimating the cost of the concept by constructing a histogram about the cost of the concept and developing a distribution [12].

The detail design stage of the product life-cycle represents continuation of the iterative system development process. At this stage the designers know the sub-system and part-level details. A rather complex model for evaluating costs at the design stage was developed by Mahmoud et al. [13]. The cost model was limited to parts with a mean diameter range of two to 50 inches [14]. The framework takes into account design, process planning and production planning aspects. Cost estimates in the product design process can be used to choose between design alternatives in order to make a cost effective decision. Two main approaches are mentioned in [15]: a) variant-based cost estimating that depends on the similarity between the product under consideration and previously manufactured products, and b) Regenerative cost estimating is based on the fact that the cost of manufacturing a product depends on the required production operations [15]. While comparing current products or projects to older ones, a strategy is proposed in [16] whereby three classes of engineering component are defined, and the methods forecasting the cost of each class are proposed. The three classes are standard selected components which are third party components such as bearings, actuators, etc. Standard designed components include gear chain drive, belt drive, etc. Bespoke designed components are one-off components tailored to meet specific requirements for the application considered. An integrated cost modeling tool for mechanical systems in the early design phase is proposed whereby the tool integrates electronic selection and sizing models for various mechanical components in a systematic manner [16].

System life-cycle engineering goes beyond the product life cycle. It works on the life cycles of design, manufacturing, distribution, operation, maintenance and phase-out. This idea of simultaneous work on all these life-cycle processes is the basis of concurrent engineering. Concurrent engineering has a significant impact on the cost. The cost estimation tools and methods such as parametric analysis, case-based reasoning, activity based and neural network based cost estimation can all be applied from a concurrent engineering perspective. Besides these, cost management topics such as value analysis, value engineering, design to cost, and risk management can also be discussed in the light of concurrent engineering [17]. Several studies have been done, but in specific areas, such as aerospace and launch vehicles. A new technology environment has been constructed for the purposes of analyzing and designing a Reusable Launch Vehicle. The new advanced engineering environment is both collaborative and distributed, facilitating the integration of the analyses by both vehicle performance disciplines and life-cycle disciplines [18]. Predicting the cost of a product 20 years before its production is complex and has a high margin of error. A concurrent engineering environment helps to reduce this error by providing cost estimators with meaningful information during the early product design stage. The paper by Roy et al. presents a novel knowledge capture methodology. This methodology makes the tacit knowledge of the cost estimator more explicit [19].

An important part of manufacturing and planning for manufacturing is process selection. Manufacturing process selection is the task of choosing a method for transforming a set of materials into a product using one or more manufacturing processes. Out of the many options, the most cost-effective process is considered to be the best choice. Researchers have devised several methods of process planning. The research by Shehab et al. aims to develop an intelligent knowledge-based system that not only estimates the cost of a machining process but also generates initial process planning and selection of machining processes, sequences, and parameters. Thus the system is developed to support concurrent engineering [20]. Other researchers have concentrated on developing a process selection method of a single part, and the results have been expressed in the form of process indices calculated as fuzzy numbers [21]. In the semiconductor industry, while regression analysis has been used to identify attributes with significant direct cost implication and rank alternatives, a distance based multi-attribute decision making method was adopted to determine preference ranking with respect to operational benefits [22]. An expert system has been developed for manufacturing process selection on a XEROX 1186 machine. The system uses an object-oriented programming environment. Parameters such as batch size, bulk, shape, etc. are entered by the user. This is very useful in the initial stages of product development [23]. A Material and Manufacturing Process Selection System (MAMPS) that integrates a formal multi-attribute decision model with a relational database has been shown by Giachetti [24]. The complexity of process plan selection increases with alternative machining processes. The Ant-colony optimization (ACO) model to resolve the complex process of selecting a manufacturing process is illustrated by Tiwari [25].

Parametric cost models have become very popular and are widely used in estimating cost of a variety of products, especially in the early stages of the life cycle. A parametric cost estimate uses Cost Estimating Relationships (CERs) and associated mathematical algorithms (or logic) to come up with a cost estimate. Phaobunjong et al. have performed a retrospective study where past data is collected; cost drivers are identified and relationships between the cost drivers are identified. This parametric cost model is limited to the conceptual stage useful for organizations involved in planning and execution of construction projects [26]. Similar parametric cost models have been built for other products such as photovoltaic, Solar Dynamic and Dynamic isotope space power system. The cost model is helpful in budgetary forecasting and cost benefit analysis. The cost model takes into consideration all major subsystems and effects such as integration, testing, management, etc. [27]. A series of cost drivers are proposed in estimating the cost of residential buildings. In the paper by Stoy, a regression model was developed using these independent variables and then applied to five buildings. An error of about 12-13% was obtained. The independent cost drivers are compactness, number of elevators, size of project, expected duration of construction, proportion of opening in external walls, and region [28]. The paper by Apgar presents the pragmatic base on which parametric cost models are developed. A parametric model for the development cost of a mechanical system, first piece manufacturing cost of a machined assembly, and annual maintenance cost of mechanical subsystem are mentioned. Basic questions such as who uses parametric cost model, how to use a parametric model and how accurate they are, are discussed [29]. The paper by Qian presents a cost estimation model that links activity-based costing (ABC) to parametric cost representations of the design and development phase of machined rotational parts. It presents several parametric cost models by using the part's feature geometry. Cost of activity is proportional to activity cost-driver in ABC. The activity drivers are parameters in the parametric cost model [30]. Stahl in this paper presents a parametric cost model for ground-based telescopes using multivariable statistical analysis of both engineering and performance parameters [31]. Parametric models rely heavily on historic data. Therefore, a clear strategy needs to be established regarding maintaining data in order to make the process of retrieving and saving data more efficient.

The database is the heart of integration in a computer integrated manufacturing system. The selection of a database model therefore, becomes vital. Different models are required for different applications. The paper by Anwarul Islam discusses the selection of an appropriate database model for a CIM system using the analytic hierarchy process (AHP) [32].

Cost estimation brings with it different challenges at various stages of life cycle. Typically cost models concentrate on either single part objects or systems. But between single parts and systems there is an intermediate stage of assembly. Boothroyd has done tremendous work at establishing the assembly times of parts and under various conditions. His research is presented in the form of several books and a handbook. The handbook was originally developed as a result of extensive university research. More recently, expanded versions in software provide systematic procedures for evaluating product design for easy assembly. This goal is achieved by providing assembly information at the conceptual design stage. General assembly guidelines are provided for manual, high-speed automatic and robotic assembly. Formulae are presented for assembly-time depending on the various features of the parts being assembled [33]. Another paper by Boothroyd presents typical assembly systems such as manual, special-purpose automatic and programmable assembly systems. For each case math models are developed to describe economic performance [34]. In the development of any cost model the first task is to identify cost driving measures. The cost model should be able to be applied at an early stage so that alternatives can be looked at in order to minimize the cost. In assemblies, the option of using automation or manual or robotic assembly may be determined by the cost [35].

In order to improve the design of products, reduce design-changes, and reduce cost and marketing-time, life cycle engineering has emerged as an effective approach to address these issues. As 70% of the cost is committed during the initial stage of design, any attempt of life cycle cost reduction should be made at this stage. The paper by Aryani provides an approximate method to estimate life cycle cost through learning algorithms that learn to estimate based on existing product cost drivers [36]. A basic LCA (Life cycle cost analysis) serves as an important tool and is easy to implement. The three ingredients of an LCA are 1. Understanding of basic math 2. Collection of life cycle data 3. A healthy dose of common sense [37]. In the conceptual design stage not only the product details and its cost are planned but also the disposal strategy after it has completed its life cycle. A product may be disposed or recycled or both depending on how it is planned. Sometimes disposal has cost associated with it. Disposal cost also needs to be taken into account in the life cycle cost. The paper by Muller illustrates how the end-of-life cost can be utilized to estimate the economic benefits of design for environment [38].

In systems engineering, risk management is defined as the recognition, assessment and control of uncertainties. The uncertainties may result in cost overruns, delays, performance problems and adverse environmental affects [39]. Cost risk analysis has become an important aspect of cost estimation for space exploration missions. There are many unknowns with high variance, hence a cost risk assessment becomes important. The fundamental problem with cost risk assessment is the accurate evaluation of uncertainty in cost model, uncertainty in the inputs and the correlation between various WBS (Work Breakdown Structure) elements [40]. Linear structural models are linear relationships between stochastic variables with both variables subjected to measurement errors. In experimental work data is generally fit using a least squares model. In the paper by Reilman maximum likelihood estimators are presented and compared with least squares estimators [41].

A learning algorithm-based estimation method is proposed for maintenance cost. In order to develop the algorithm, attributes responsible for cost of maintenance were identified. The attributes become the inputs and the cost is the output in the learning models [42].

An important part of the system cost is the cost of testing. The complexity of the system limits the number of tests that can be performed. The proposed model by Farren uses the error and failure rate under test. This data, along with the cost, forms a cost model [43].

One of the ways to setup a cost model when dealing with uncertainty is the fuzzy logic model. In [44] two query optimization techniques using fuzzy cost model are discussed. The benefits of such fuzzy query optimization are also illustrated. The computational complexity of these methods is also discussed [44]. A fuzzy regression analysis based on quadratic programming approach is proposed in the paper by Tanaka. A quadratic programming approach gives a more diverse spread of coefficients than linear approach. The proposed approach can obtain an optimal regression model representing possibilistic properties with the central tendency. The data is divided into two groups: the center-located group and the other group. Based on this and upper and lower approximation, models can be obtained. By changing the weight coefficients of the objective function in the quadratic programming problem, we can analyze the given data from various angles [45]. Fuzzy cost models have been tried in the area of software cost estimation. A software cost estimation model is developed using fuzzy set theory in [46]. An augmentation to COCOMO cost estimation is proposed and granular models of cost estimation are also introduced. Numeric examples are provided to illustrate the granular models [47].

Discrete-time Markov processes can be used to model several types of system problems associated with cost function. This paper proposes such methods for solving such models with Monte Carlo simulation when the cost matrix is given [39].

Work breakdown structure (WBS) is a systems engineering tool used to group a project's work elements in a way that helps organize all the tasks from conception to the end-of-life of the product. A work breakdown structure element may be a product, data, a service, or any combination thereof. A WBS also provides the necessary framework for detailed cost estimating and control along with providing guidance for schedule development and control. The WBS also serves as a check-off list to insure that no cost elements have been omitted and that the total program spectrum from concept through deployment is carefully observed and scrutinized [48]. The paper by Ruskin characterizes systems and system development and in the process develops a generic 100% product-oriented WBS. It also describes how such 100% product-oriented WBS can help in good systems engineering [49]. Integration of cost and schedule control systems has been an issue of great concern for researchers and practitioners in the construction industry. Nevertheless, the real-world implementation of this promising concept has not been popular enough to maximize the benefits that this integration has to offer. One of the major barriers is the overhead effort to collect and maintain detailed data. This paper by Mahmoud proposes a flexible work breakdown structure (WBS) that optimizes the overhead effort by means of reducing the amount of data to be controlled. In order to have a flexible structure, the WBS numbering system needs to utilize standard classification codes and should not have a common strict hierarchy for all components. A case study is analyzed in this paper in order to examine the proposed concept. Practical implications are also outlined [50].

Chapter 2: HYPOTHESIS

In the present research the problem of enterprise-wide cost modeling is approached from a systems engineering standpoint. What this does is to use each stage of product life cycle to obtain useful information that helps in estimating the cost of the system. Once a generic framework is developed for estimating the core cost, layers of other factors that affect the cost are applied to the core cost such as risk and uncertainty, maintainability, supply-chain and socio-economic conditions. The cost model is expanded to accommodate a product domain ranging from a simple object to a system in the following hierarchy: System, Product, Assembly, Object. The cost model caters to the needs of cost estimation at every stage of the life cycle and for every kind of product, big or small, simple or complex. New process selection tools have been added to the field of cost estimation that suggests the user about applicable processes, given the material and production quantity. Attributes such as materials, fabrication processes etc… are ontology based. This enables a generic category to branch into increasingly specialized categories with each step. This is very useful, since in the preliminary stages of cost estimation, not much information is available as to what exact material or process is used. In such a case data pertaining to a more generalized material or process can be used.

Earlier work in the field of cost estimation has focused on specific areas of cost estimation either in terms of concept or application. For example, Eversheim et al. [35] propose a generic framework but it goes up only to assembly level. The work of Williams [3] deals with a parametric cost model but only for assembled products. In the work so far, no single-framework has been proposed that deals with cost estimation that fits the requirements at all stages of product development. Most importantly the concept of systems engineering has not been fully exploited in the area of cost estimation. The framework that we have proposed is based on systems engineering and hence can be used at any stage of the product development.

Some of the previous work on cost estimation has applications in specific industries. The work of Creese et al [14] is an application of cost estimation in manufacturing industry. Phaobunjong [26] proposes a parametric model, but it is limited to buildings and Meisl [27] for solar space power systems. With the help of our framework not just cost but the basis for the estimate previously obtained can be changed as and when more information about data and priority is obtained. For example, when no detailed information is available say, at part level, the cost can be calculated by referring to Model parts, which are most similar. But as and when the detailed design of the part evolves, the same framework can be used to estimate the cost of each process that needs to be performed. The framework guides the user in process selection at the lower levels based on material and quantity using a tool called PRIMAs[1] (Process Information Maps). If data is not available for a particular process then a more generic form of the process can be chosen to collect cost data and estimate on the basis of that data. A more generic process is obtained by using the DCLASS[2] (Decision Classification) tool. The cost can be revised to reflect more accurate process when the data and information is available. This is possible within the proposed framework.

Uncertainty and Risk analysis and have also been dealt with in our proposed framework. A three-pronged approach is used to deal with uncertainty viz. probabilistic, fuzzy, and simulation using the Monte Carlo method. Most of the existing work has looked into the cost estimation process at a certain stage of product development, but the proposed framework looks at the cost from concept to fabrication and retirement. The economic impact of the product has also been taken into account through input-output models. This conforms with the idea of enterprise wide cost estimation where the cost from part level through assembly, sub-system and system is calculated along with the economic and environmental impacts of the product. So in summary, the proposed framework, works through all the levels of a system, from part to system, and in addition to that, it takes into account global effects on economy and environment. It will prove to be a great tool from policy makers to machine shop supervisors.

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[1] PRIMAs (Process Information Maps) was developed by D.J.Booker & K.G.Swift

[2] DCLASS (Decision Classification) was created by Dr.Allen Dell at Brigham Young University.

Chapter 3: FRAMEWORK

3.1. System and its Constituents

No large project can be undertaken without some form of systems engineering applied in one or more stages of its life cycle. And estimating the cost of a system at the conceptual stage should not be any different. Here a framework is proposed to estimate the cost of systems using systems engineering perspective. In this framework an algorithm is developed that can be applied repeatedly at each level of the hierarchy to obtain the cost of a system. The framework as a result applies to the entire hierarchy: system, sub-systems, assemblies and components. The hierarchy is shown below and in Figure 3.1

System

Sub-system/Product

Assembly

Part/Object

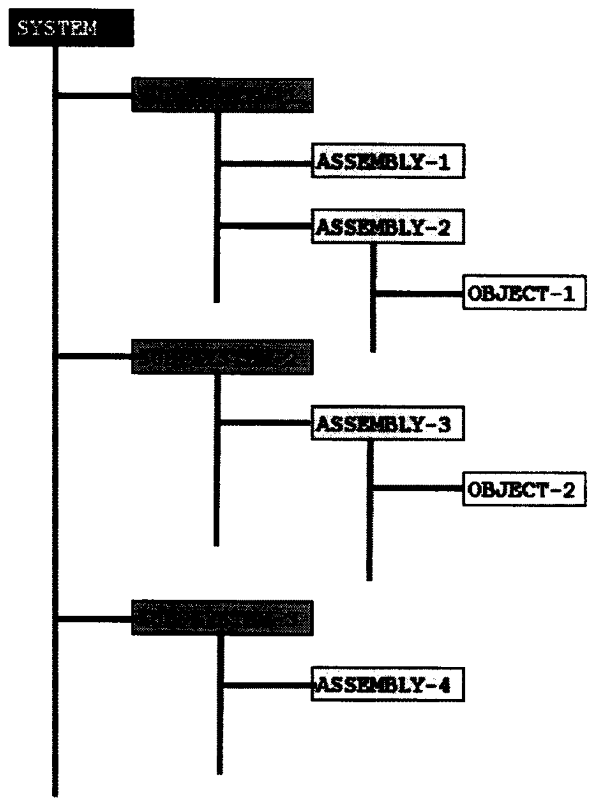

Figure 3.1: A Simple System Architecture Showing the Hierarchy

The terms in the hierarchy mentioned above need some clarification in the context of this dissertation since the terms can be used subjectively. While referring to any of the items in the hierarchy above the term 'unit' is used. A system here refers to any assemblage of smaller units that perform one or more functions. A sub-system in our context is treated similar to a system, where by it performs one or more functions. It could sometimes be bought from vendors and modified or used in as-is condition. It can also be referred to as product. An example could be an actuator, a motor, etc. As explained above, these can also be treated as systems when there is no other unit in the hierarchy. An assembly is, as the name suggests, an assemblage of components. The difference between a sub-system and an assembly is that the functionality an assembly provides changes with the context. Most of the times, they don't have a specific name. For example, it can be a weldment of two or more bars acting as a support for a structure. And mostly these are custom made. A part or an object is the smallest of all the units. These too are mostly custom made. They can be as simple as a bracket or a dowel pin. The differences in the elements of the hierarchy come from cost drivers. The cost drivers of a system and a sub-system come from functional and physical attributes where as for assemblies it is the assembly time and penalties. At part level the cost drivers are the machining time and the setup or preparation time.

The generic form of the cost model is parametric. As required in all parametric models, it is assumed that there are precedents available for the product being designed and whose cost is being estimated. If a precedent is not available then the framework is capable of developing a cost model from scratch. The new unit (either a system or a sub-system or an assembly or a part) whose cost is to be estimated will be referred to as the Target unit throughout the rest of the discussion. The Target unit may have additional functions besides the ones available in the precedents referred to as Model Units here. Once the core cost is estimated layers of risk and uncertainty, maintainability and reliability and other Life cycle cost aspects are applied. EIO-LCA (Economic Input-Output Life Cycle Assessment) is performed to further evaluate the candidate model units for economic and environmental impact. This type of analysis is very useful in the initial stage of product design where detailed information about the various sub-systems and components is not known yet.

3.2. System and Systems Engineering

A system is an assemblage or combination of elements or parts forming a complex or unitary whole [51]. Figure 3.3 shows the system constituents and hierarchy.

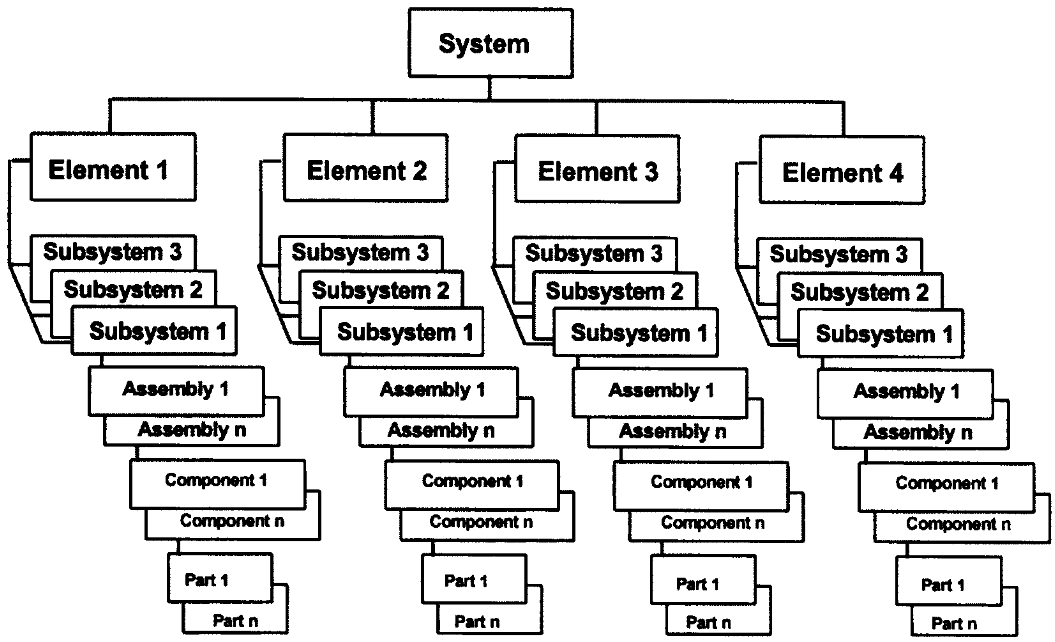

Figure 3.2: Hierarchy within a System (INCOSE handbook V2a)

In the proposed framework, we adopt the above systems engineering definition of a system, therefore here a system can be represented as

System = Sub-systems + assemblies + parts +….

The diagram in Figure 3.1 shows the structure of a system in terms of sub-systems, assemblies, parts and these are connected to each other through interfaces. Note that the sub-systems and other constituents of the system need not be arranged or assembled in the same order as shown in the diagram. The diagram merely shows the constituents of a system.

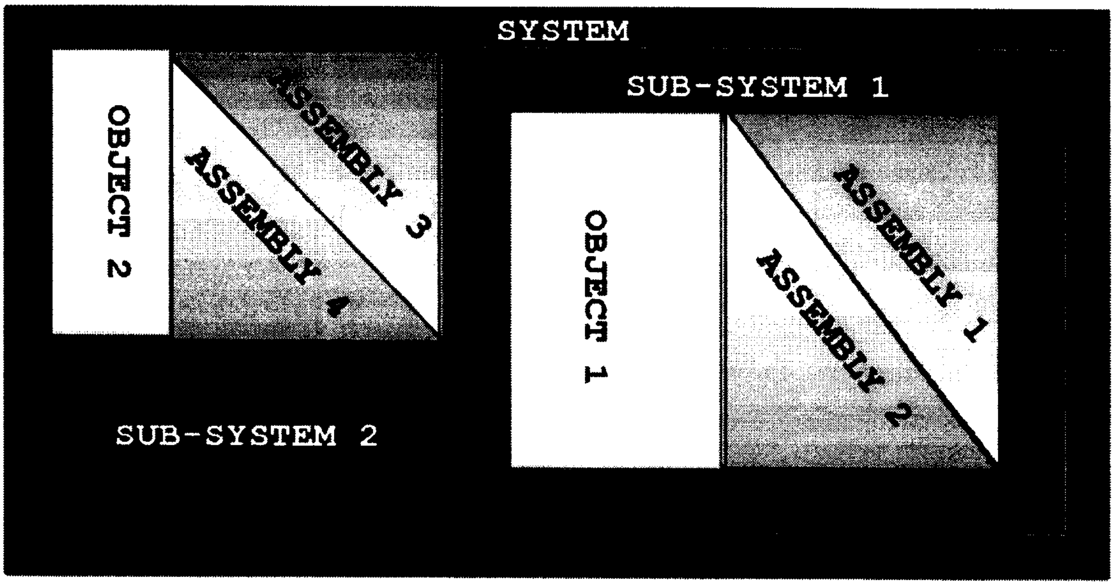

Figure 3.3: Constituents of a System and Hierarchy

Sub-system	**Interface**	**Assembly**	**Interface**	**Part**

Figure 3.4 Typical constituents of a System

According to the Systems Engineering Handbook Version 2a by INCOSE (International Counsel of Systems Engineering), systems engineering is defined as an interdisciplinary approach and means to enable the realization of successful systems.

A Systems engineering process comprises of technical management, acquisition, system design, product development and evaluation at every level of system. According to the INCOSE (International Council of Systems Engineering) a systems engineering process must include life-cycle consideration of development, deployment, operations, maintenance and disposal. System design drivers are dependent upon environmental impact of manufacturing, operation and retirement.

The Systems Engineering Process is basically an iterative approach to technical management, acquisition and supply, system design, product realization, and technical evaluation. This iteration starts at the top and propagates downwards. Several iterations lead to the final system solution. In Figure 3.5 the iterative nature of systems engineering at the product development phase of the lifecycle is shown.

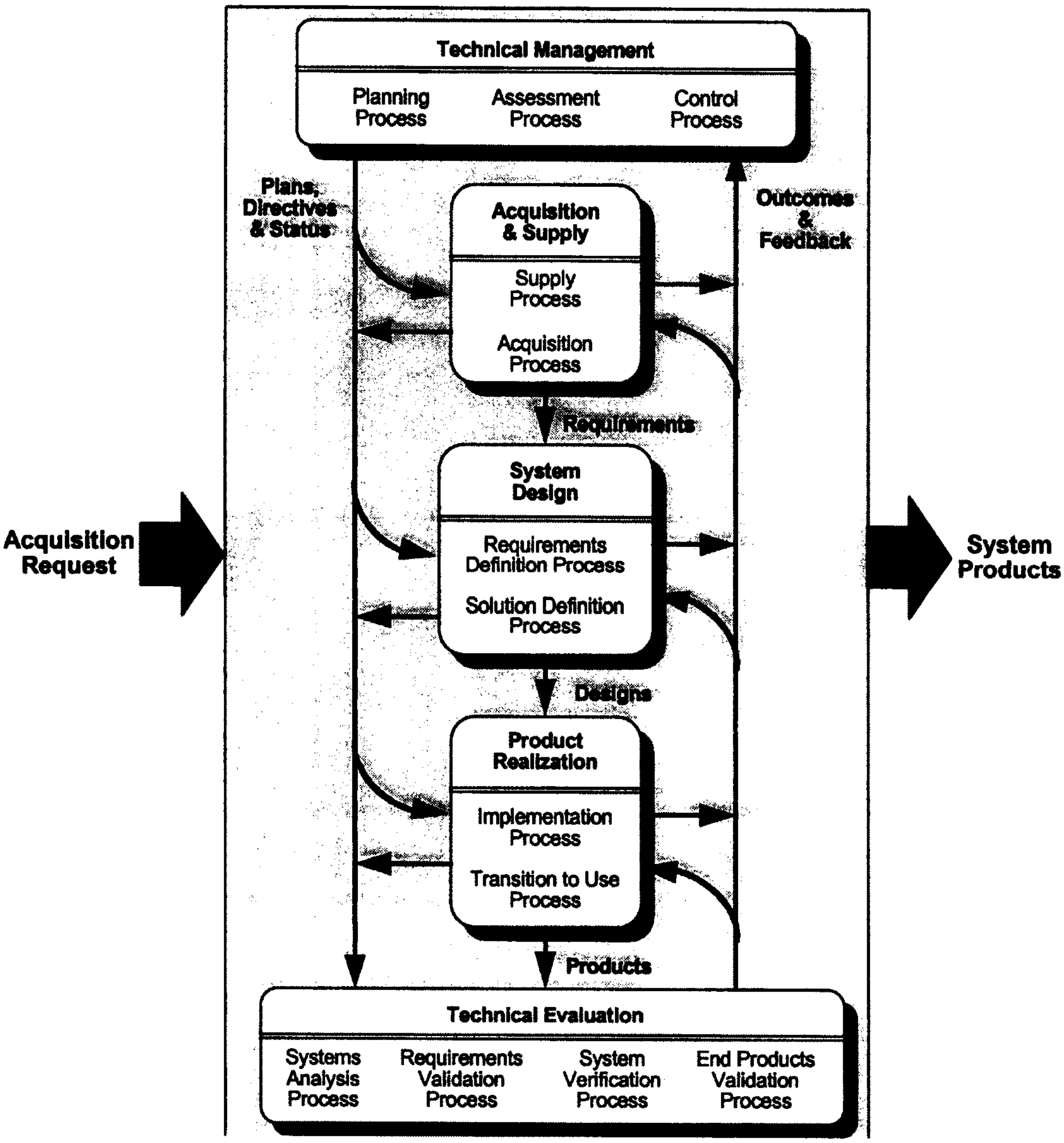

Figure 3.5: Systems Engineering Process Overview[3]

3.3 The Proposed Framework

The proposed framework is based upon the concept and working of systems engineering. Just as the systems engineering process starts with a need

[3] Source: ANSI/EIA-632

by the stakeholder so does our proposed framework. The need establishes the requirements of the stakeholder, which determine the functions that the unit will accomplish and hence affect the cost. The term "Unit" is used in the context of this framework when a general term is needed to represent a system or a sub-system or an assembly or a part. After the need is established both in systems engineering and the framework, the needs are translated into more technical attributes during requirements analysis. These technical attributes are used to come up with a design for the Target Unit. The Target Unit is the one whose cost needs to be estimated. In the proposed framework the existing units that match the target unit are called Model Units. The requirements or the functions of the target unit form the baseline when these are documented, in systems engineering terms this is called the System Requirement Document (SRD). The requirements analysis defines the boundaries of the unit. The design evolution in both cases (Systems Engineering & proposed framework) requires looking for the closest design from an archive of existing designs. In the framework the model unit that is the closest to the target unit may not possess all the functions that are required in the target unit. In that case a separate search is to be conducted to look for the unit, which possesses these functions. If a single unit does not satisfy the requirements of the Target Unit then the function needs to be broken down into sub-functions and a unit(s) for these sub-functions needs to be found. The breaking of function into sub-functions is called functional analysis shown in Figure 3.6. Functional analysis is an important part of systems engineering process.

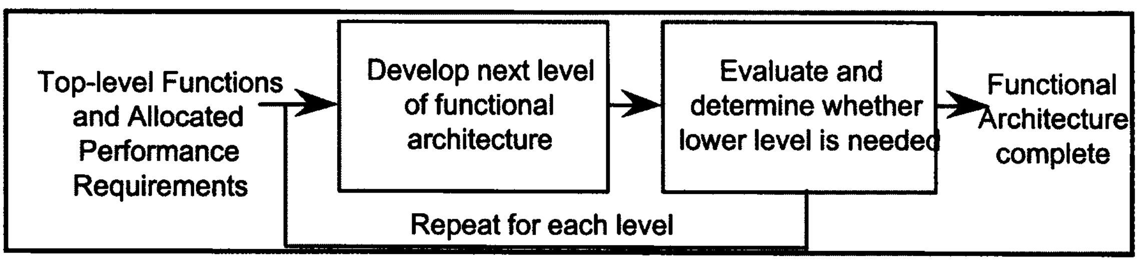

Figure 3.6: Functional Analysis Process[4]

[4] INCOSE HDBK

The model unit, which is similar to the target unit in most aspects, is called the primary model unit. The missing functions from the target unit are searched among other units. These are Supplementary (or secondary) model units. Eventually the cost of combining the primary and Supplementary units also needs to be accounted for. This cost is nothing but the cost of interface. In the proposed framework interfaces are also dealt as a separate unit called the Interface Unit. The interface units can be a part, assembly or a sub-system. Defining the interface also is part of functional analysis under systems engineering.

As explained above, a model unit is searched for which matches the functions of the target unit. But when such a search is made the cost estimator usually ends up with more than one unit which matches the functions of the target unit. Here, the framework uses the systems engineering tool of systems synthesis. According to INCOSE handbook version 2a, the process of System Architecture Synthesis is essentially a tradeoff, performed at a grand scale, leading to a selected system architecture baseline as the final output. The objective is to select the best from among a set of System Architecture candidates, which have been constructed in a manner that assures (with reasonable certainty) that one of the candidates is acceptably close to the true (usually unknowable and unattainable) optimum.

To accomplish this, a top-down approach may be used. A set of system architecture options is created, each providing a framework into which element options may be inserted. It is difficult to conceive of system element options in a vacuum without some system architecture concept in mind.

The starting point for system architecture synthesis can vary considerably. One extreme is a completely fresh start with no existing system and a minimal definition of the system concept. The other extreme is a minor modification to an existing, large operational system. It also depends on the amount of work already done by the customer or carried over from earlier studies. The process description here assumes a fresh start, since that viewpoint provides the clearest and most complete overall explanation. The process can be tailored in obvious ways to fit other cases.

The framework chooses the closest unit to the target unit from among the model units searched. This is done through a weighting process. The weighting process is explained in section 3.5. After the weighting process is completed a model unit is obtained which resembles the target unit the most among all the units. Cost data is then collected for several samples of that Primary Model Unit and a cost model is developed. The development of a system design is analogous to development of the cost model in this framework.

3.4 Differentiating Between the Units

The part/object is the smallest unit of a system usually requiring a few machining operations. An assembly is a unit, which is a combination of two, or more elements integrated using mechanical means such as fasteners, rivets, etc. The classification of parts from assembly is fairly clear. However, the discrimination between an assembly, sub-system and a system is not intuitive and is rather subjective. In the light of this framework, these units have been distinguished on the basis of application, marketability, and usability by end-user. The table 3.1 shows the distinguishing factors.

	Independently Marketable	**Serves a single Purpose**	**Independently usable by end user**	**Example**
Part				
Assembly	√			Bearing
Sub-System	√	√		Transmission
System	√	√	√	Car

Table 3.1: Unit Classification

Independently marketable means the unit can be bought and sold as a commercial product. This condition, all the three types of units viz. assembly, sub-system and system satisfy. The unit serves a single purpose means that it should be used for a unique kind of application. For example, a CRT (Cathode Ray Tube) which falls under a sub-system category has a unique application. Even though it is used inside a television or a monitor or an oscilloscope it has a unique application. Same is the case with a transmission. It has a unique application even though it is used in various kinds of automotives. In other words the units in which a particular sub-system is used belong to a family. For example, the gear transmissions used in vehicles would be considered a sub-system in this framework. Even though the transmission is used in various kinds of vehicles the family is the same (all vehicles). An assembly however, does not satisfy this condition. For example, a bearing has a much varied application than a transmission. An important attribute, which separates these units, is also their ability to be used independently by the end user. A system can be used independently by the end-user where as a sub-system or an assembly cannot. For example, a car which is a system is used independently by the end-user where as a transmission or a bearing is not.

3.5. Framework at Systems Level

A system as discussed above consists of sub-systems, assemblies and objects. The process of estimating cost of a system requires building the entire system, but only on paper. The systems engineering process at the conceptual stage of a system development begins with analyzing the needs. What is the need for the system? The stakeholder who generally is the end customer answers this crucial question about the need. The need is generally expressed in plain non-technical terms. For example: The transportation system needs to be fast, should have long range, etc. Once the needs of the system are identified the needs are converted to technical performance measures (TPMs) and compared with the most likely solution. The solution is an existing system that will accomplish the needs. This is called system feasibility analysis. Followed by the feasibility study is the requirements analysis, which determines as to how the tasks required by the system can be accomplished. One of the ways of requirements analysis is the work breakdown structure and functional allocation. In this the functions of the system are broken down to smaller tasks and sub-systems are assigned to each of the smaller tasks.

In the framework proposed here, cost estimation starts from the top level as mentioned above in the systems engineering procedure. The system-needs are converted to TPMs and a feasibility analysis is carried out to see if there are any precedent systems. The precedent systems will be called Model Systems throughout our discussion and the system being built and whose cost is being estimated will be called Target system. A set of systems which match closely with the demands of the customer are listed. This list is a broader list which needs to be refined. For example, if a new transportation mode is being developed and its cost needs to be estimated then the estimator first finds all the likely systems which provide the same functionality asked by the customer. In this example, some of the results of the feasibility analysis may be train, planes, cars, vans, SUVs, trucks, busses, etc. The conceptual design stage is a critical stage since decisions made here determine the type, technology and cost of the system. The Figure 3.7 shows the processes involved at the conceptual design stage [51].

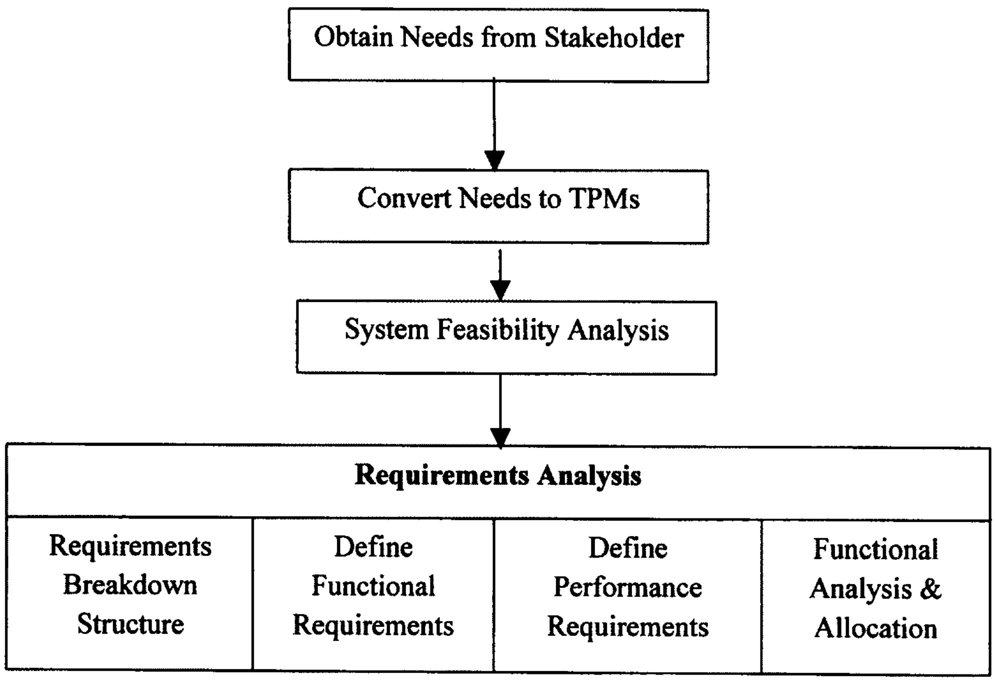

Figure 3.7. Typical Systems Engineering Process

System Level Requirements Analysis can be broken down into four main tasks

1. Requirements Breakdown Structure: This is similar to work breakdown structure
2. Defining Functional Requirements: If a system is not readily available as discussed above to meet the need of the customer, functions necessary to meet the needs, goals and objectives of the customer are obtained here. The requirements are related to functions (operations), maintenance and human factors.
3. Defining Performance Requirements: This simply answers the question: "How well should the system perform?"
4. Functional analysis & Allocation: The system level functions obtained from the steps above are allocated to sub-systems of the system performing them.

The intent is to find a Model system whose functions match close to that of the target system. The method of dealing with differences in functions is described later in this dissertation. Table 3.2 below is a selection process, to identify which model systems, have almost the same functionalities as the target system. The first column shows the functionalities (F_1, F_2, $F_3 \ldots F_n$) in the target system or the functionalities that are required. The subsequent columns represent if the candidate or model systems possess the functionalities with an 'X'.

Target	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model i**
F1	X	X	X	X	X
F2	X	X		X	
F3	X		X	X	X
F4		X	X		
.	X		X	X	X
.		X			
.	X	X	X	X	X
Fn		X		X	X

Table 3.2 Comparing Models to Target

In order to find which models most closely resemble the Target unit another matrix is derived in table 3.3. In this new matrix the Target functions (F_1, F_2, $F_3 \ldots F_n$) are listed.

	Target	Model1	Model2	Model3	Model4	Model i
TPM Metrics Comparison	F1	2	3	5	3	1
	F2	3	8		7	
	F3	1		7	4	6
	F4		3	9		
	.	6		5	6	4
	.		4			
	.	6	5	3	4	6
	.		5		3	8
	Fn	8		4		2
	SUM→	26	28	33	27	27

Table 3.3 Weighted Ranking of the Models

Table 3.3 is a feasibility analysis of various system level alternatives. A ranking procedure is applied to these alternatives to come up with the most suitable solution to the customer needs.

Each model system is rated for each function of the Target. The rating is based on the similarity of a Model's technical performance measures to that of the target Unit's. The better the metrics compare the higher the ranking. The ranking is on a scale of 1 to 10. Weights are allotted to each function based on its importance through Analytic Hierarchy Process. Once the weights are established the rank of the TPM Metric is multiplied with the weight. All the weighted rankings of each Model are summed. If the sum of a particular model is much lower than the average sum then it can be concluded that the model does not belong to the family of the models that are similar to the target.

With the net score there are a few options in choosing the model system.

Option 1: The model system, which has the highest sum, as described above is the primary model system. A primary model system is one, which contributes the most in terms of cost estimation and resembles the target system the most.

Option 2: The system, which scores the highest on a particular functionality, becomes the primary model system. This functionality is the one that brings in the most cost. A cost estimator's knowledge of the system helps him/her determine which functionality captures the most cost.

In the first option since the primary model system is the closest to the target system among all existing systems, the cost of the primary model system is a good approximation (starting point) for calculating the cost of the target system. In the second option however, a solution is picked due to a certain key function. Therefore sub-systems, which provide other functionalities, would have to be designed and made compatible to the main system so the cost of this model system may not be a good starting point. This option might be useful if the major part of the cost of the model system comes from that particular function.

By the end of the exercise above a model system is obtained which closely matches the target system in terms of functionality. If a certain function that the target system has is not present in the model systems its cost is analyzed separately and added to the cost of the target system.

3.6 Repeatability of the Framework

As mentioned above functions not found in the model system are accounted for separately. Figure 3.8 indicates the recursive nature of the cost estimation framework.

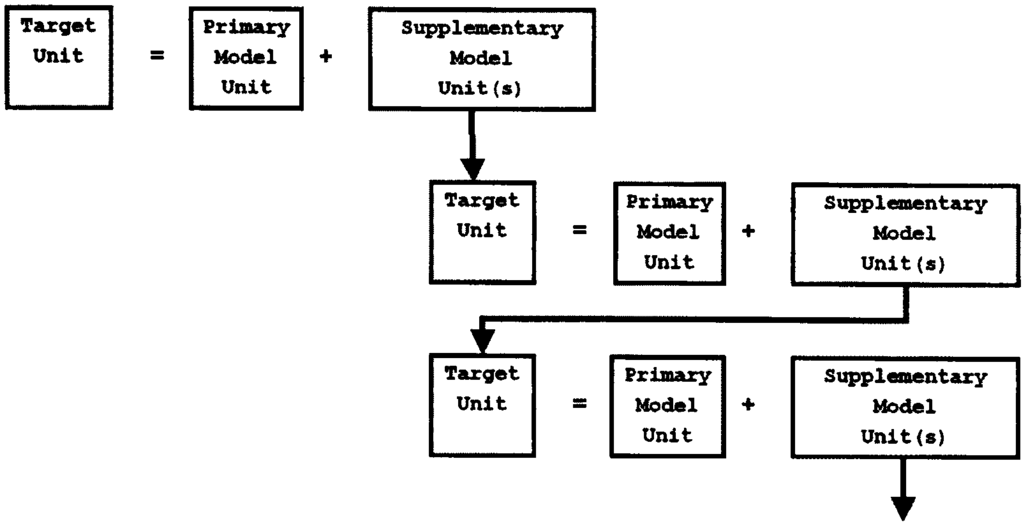

Figure 3.8.Target System Functionality is the Sum of Model System and Other Unit(s) Functionalities

In the context of this dissertation the word "Unit" is used to refer to either a system or a sub-system or an assembly or an object. The representation above means that the cost of the target Unit is obtained from the cost of the model unit, and in order to account for the functionalities missing in the model unit, a separate cost of the unit which provides this functionality is calculated and added to the cost of the Target unit. Figure 3.9 illustrates a case where a particular model system has all functionalities except a few of the target system's then these missing functionalities are provided by a sub-system whose cost is calculated separately and added to the cost of the target system. This is a repeatable process, which means if the sub-system has a precedent model-sub-system, which offers the functionalities of the target sub-system except a few then these functionalities are looked for either in another unit, which can be either an assembly or an object or a new sub-system.

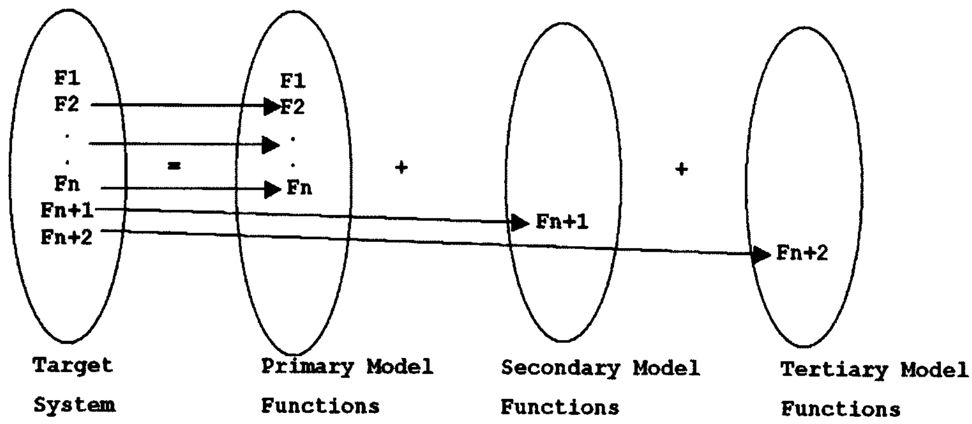

Figure 3.9.Target System Functionality Sources in Other Unit(s)

Remember, that anytime we need to estimate a sub-system separately we need to make sure it can interface with the main system. If a new interface needs to be designed then its cost must also be taken into account. An interface is also treated as a unit, which means the interface can be a system or sub-system or an assembly or an object.

3.7. Math Model

What we have seen above is the implementation of systems engineering concepts. First the voice of the customer is translated into functional requirements, which are then translated into TPM Metrics. A top down break down of system-level functions is done. A feasibility study is conducted to see which systems closely match the requirements of the customer.

Once the model system is known several samples of such models are collected. The samples provide data such as functional attributes, physical attributes, reliability attributes and cost. The data can be arranged in several forms depending on what type of math model is required. But, before that some basic analysis needs to be performed on the data as shown in the Figure 3.10.

3.7.1 Correlation

In order to figure out how each function affects other functions, physical characteristics of the system and also the cost of the system, a correlation matrix is setup. A sample is shown in Figure 3.10. The correlation plots are obtained by plotting each attribute against other attributes. A random spread indicates that there is no interdependence between the attributes. The cost estimator will look at these plots to make sure that the independent variables are not highly correlated [52]. Such cost drivers can be removed. In the cost matrix in the equation-1 below, it should be noted that the cost of the model systems is adjusted for the year the estimation is made and also adjusted for production quantity. This is called normalization.

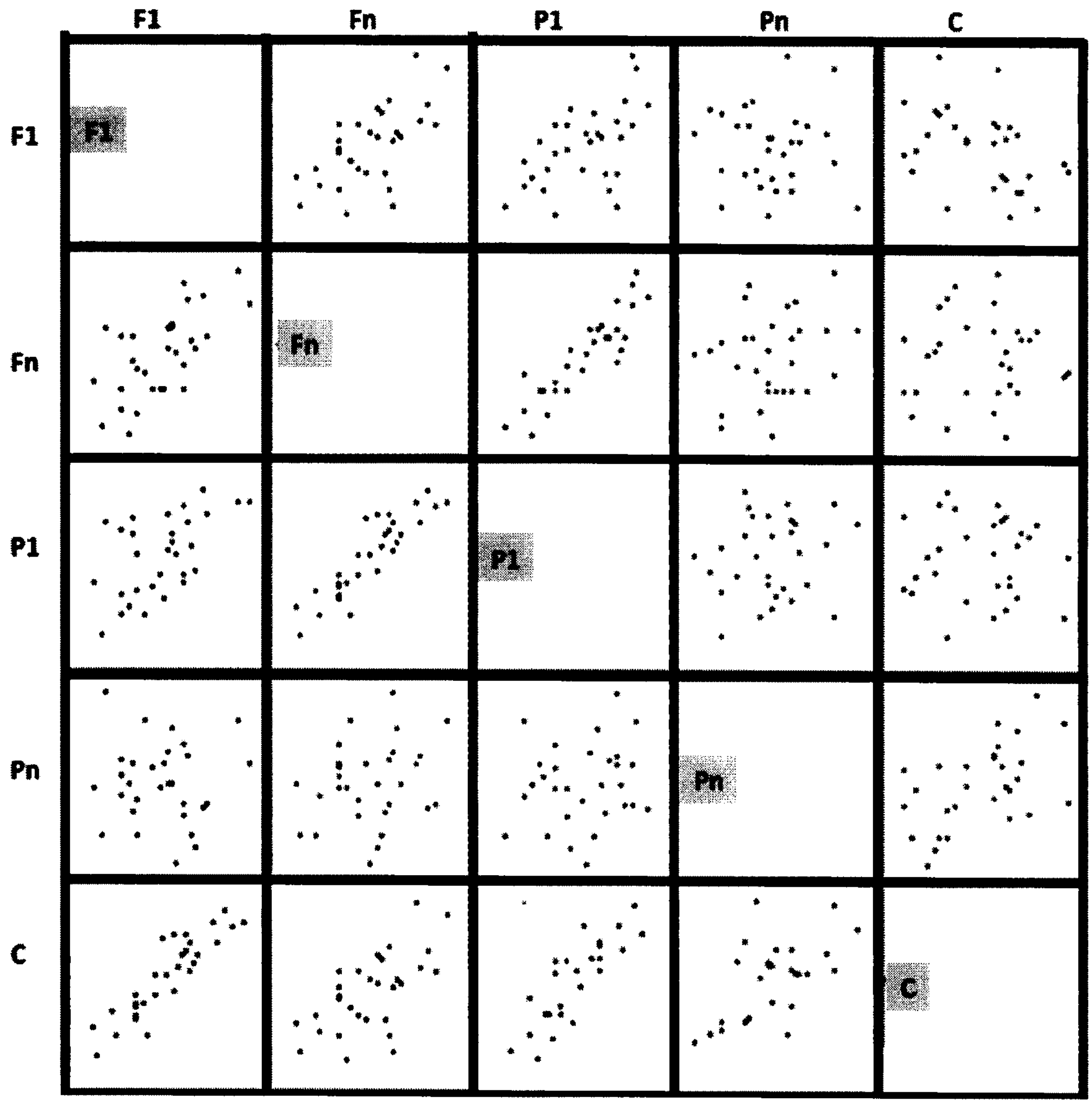

Figure 3.10.Sample Showing Correlation Between Functions and Cost

Where:

F1 to Fn: Functionalities (TPMs of the functionalities)of the Primary Model Unit (PMU)

P1 to Pn: Physical Attributes of the PMU

C: Acquisition Cost of the PMU available from various samples of data.

Once the data is overviewed and massaged it can be setup to give the cost coefficients. This can be done in several ways one of which is shown in equation 1.

$$\left\{\begin{matrix} F^1_1 & F^1_2 \ldots & P^1_1 & P^1_2 & P^1_n \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ F^Q_1 & F^Q_2 \ldots & P^Q_1 & P^Q_2 & P^Q_n \end{matrix}\right\} X \left\{\begin{matrix} K1 \\ K2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ Kn \end{matrix}\right\} = \left\{\begin{matrix} C^1 \\ C^2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ C^Q \end{matrix}\right\}$$

Data arranged in Matrix form **(Eqn-1)**

Where

F^1_1 to F^1_n: Functionalities 1 to n of sample PMU number 1.

P^1_1 to P^1_n: Physical Attribute 1 to n of sample PMU number 1.

n: Number of Functionalities and physical attributes

Q: Number of samples of PMUs

K: Cost coefficient of each functional or physical attribute

C: Acquisition Cost of the Sample PMUs.

The matrix operation above can be simplified as [F] x [K] = [C]. The aim is to obtain the K matrix, which consists of cost-coefficients. Matrices F and C consist of known data obtained from the samples. The superscript in the F matrix refers to the sample number and the subscript refers to the attribute number. In the C matrix the superscript is the sample number. Each row in the F matrix consists of the metrics of the functional, physical and reliability attributes of the sample model. Rows 1 through Q are the various samples of the model system. K matrix can be obtained by matrix manipulation using software such as MATLAB. A second order solution to the problem would give coefficient based on not just the cost drivers, but the interaction between the cost drivers. Once the K matrix is obtained from equation above it can be directly applied to the target functions to estimate the cost of the target system.

Cost(Acquisition) of Target = $K_1F^T{}_1 + K_2F^T{}_2 + \ldots K_iP^T{}_1 + K_jP^T{}_2 + \ldots$
(Eqn-2)

F^T, P^T and R^T represent the functional, physical and reliability metrics of the Target system. Note that the equation-2 above is only one of many possible models. A variety of data fits can be obtained using the data from model samples. The flowchart in Figure 3.11 explains how the framework works at systems level.

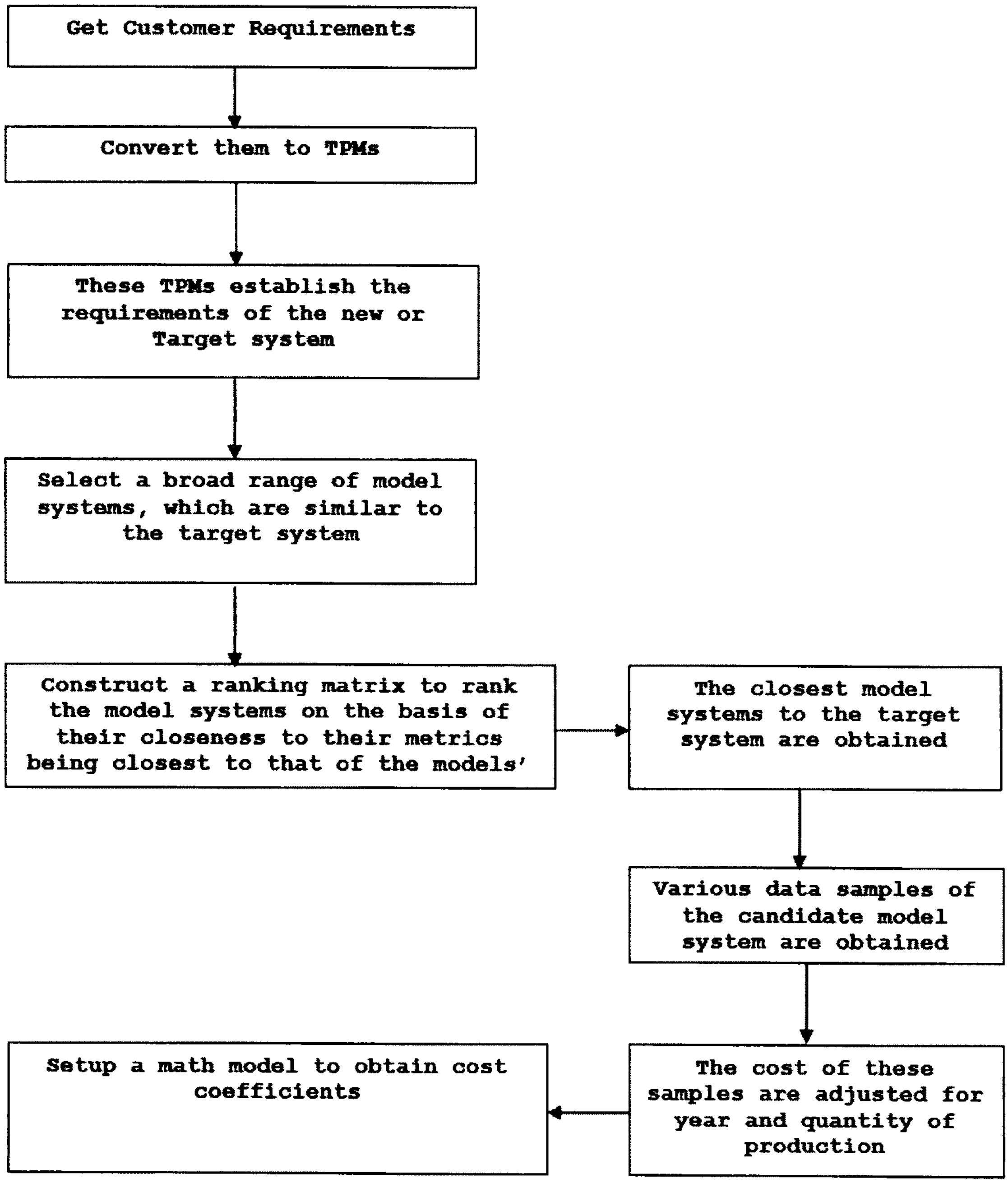

Figure 3.11. Flowchart of the Framework at Systems Level

As mentioned earlier, the framework works on the principles of systems engineering. The flowchart in Figure 3.12 shows a comparison of the similarities in the systems engineering process and the process followed in the framework to estimate the cost of a unit.

The systems engineering process starts with definition of the system objectives by the stakeholders. The stakeholders are anyone who owns the system; a sub-contractor or the end user of the system. The stakeholder's definition is usually in very general non-engineering terms. The cost estimation framework also adapts the same first step towards estimating the cost of the unit. The second step common to both the framework and systems engineering is, converting the stakeholder requirements into a more technical language. These requirements when converted to metrics are called Technical Performance Measures (TPMs). Once the technical requirements are known, systems engineering employs architecture synthesis where the system architecture and likely solutions are researched. This process is matched in the framework by doing a comprehensive search for Model Units which are most similar to the Target unit based on the number of TPMs common to both. The Model Unit thus selected forms the baseline as mentioned in the systems engineering process. Once the Model Unit is finalized the TPMs are verified against the requirements. This process brings out the TPMs that are not present in the Model Unit and other units need to be searched or developed in order to satisfy all the requirements set by the stakeholder. This process in systems engineering is called Validation. The final process in both systems engineering and the framework is to iterate the process at lower levels to come up with the requirements missing in the initial Model Unit.

Thus the framework matches closely to the general systems engineering process [10].

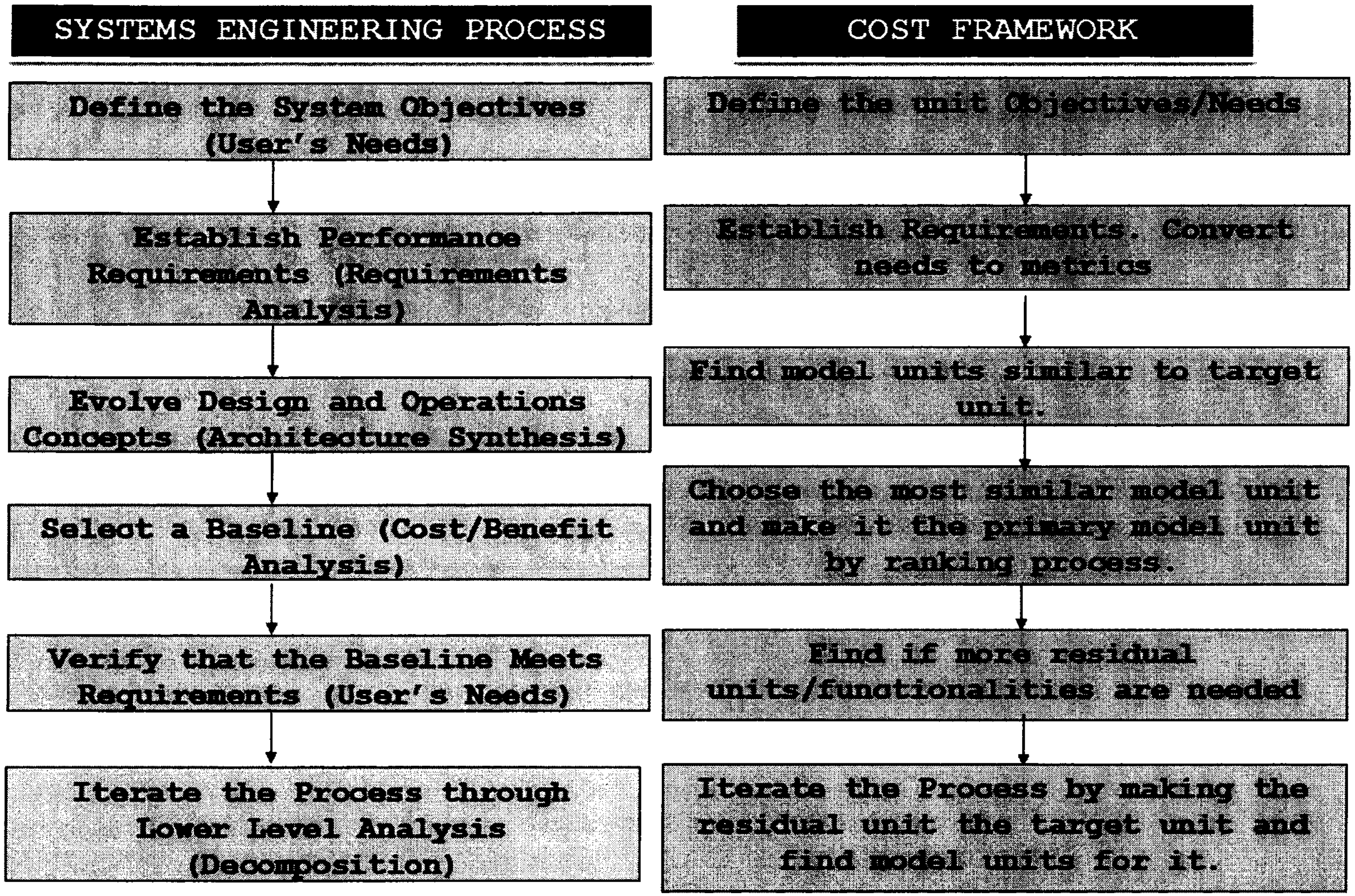

Figure 3.12. Flowchart of the Framework at Systems Level

3.8. Methodology at Sub-Systems Level

As discussed in the previous section the cost of the target system-functions that are not available in the primary model unit can be calculated separately by following the same steps. If the missing functions are accomplished by a certain sub-system calculate the cost of the sub-system and add it to the cost of the target system. By the same token if the model system has a redundant function not required by the target system its cost can be calculated and subtracted from the cost of the target system. In either case the cost of this unit (sub-system/assembly/object) should be calculated. The procedure for calculating the cost of a sub-system is shown in this section. Procedure for calculating the cost of a sub-system is the same as that of a system shown in the flowchart in Figure 3.13. The only difference being that the application and hence the stakeholders of a sub-system are different from that of a system as discussed in section 3.7.

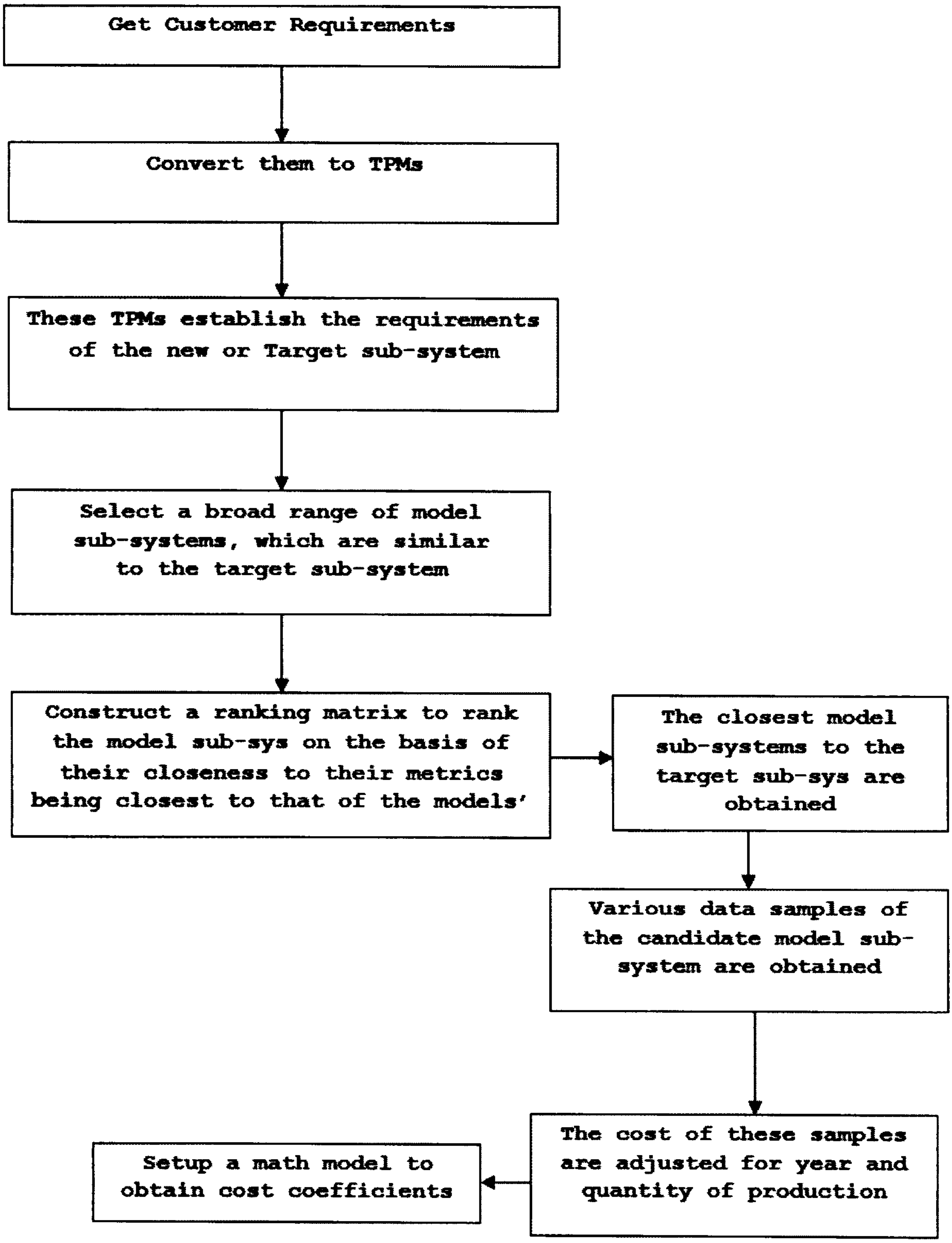

Figure 3.13. Flowchart of the Framework at Sub-Systems Level

As an example, a cost model of a Rotary Air compressor is developed here. The data is collected from *MSC 2002/2003 Industrial Supply Co. catalogue*

	Rotary Air Compressor		
	CFM	HP	PRICE($)
1	27	7.5	5015
2	35	10	6545
3	53	15	6824
4	79	20	7912
5	97	25	8361
6	112	30	9256

Table 3.4: Model Samples for Rotary Air Compressor

The first five records were used to come up with a cost model and it was used to predict the cost of the sixth item. The cost model setup was a simple MLR (Multiple Linear Regression). The details are shown in table 3.5.

R Square	0.90
Adjusted R Square	0.80

Coefficients

Intercept	4055.37
CFM	-35.07
HP	317.22

Table 3.5: Results from MLR

Cost = 4055.37 + (-35.0661)*(CFM) + 317.218*(HP)

When this model is applied to the sixth item in the table 3.4 (CFM of 112 and HP of 30) the cost comes to $9645, which is 5% off from the actual cost of $9256.

This is fairly accurate since the attributes and cost of an off the shelf product are well defined. The more information is available the more accurate the estimation. According to experts in the conceptual stage an estimate of 80% is good enough.

In the example above, the coefficient of CPM is negative. This is because of Multicollinearity in the data. The term Multicollinearity however, is used when the correlation between the independent variables is too high. The variance of the estimated regression coefficients depends on the inter-correlation of the independent variables. Multicollinearity does not make the regression model wrong, but the variance of the regression coefficients can be inflated so much that the individual coefficients are not statistically significant - even though the overall regression equation is good. Some coefficients and their sign may not make sense. Multicollinearity and the way to account for it and correct it is mentioned in detail in Appendix II.

3.9. Methodology at Assembly Level

The next unit in the hierarchy is assembly. Cost of assemblies is a little more difficult to estimate then the cost of sub-systems since sub-systems exhibit functions or part of the functions of the system. But assemblies do not perform a function per se hence do not have cost drivers similar to that of sub-systems or systems. Also most often assemblies are one of a kind and will have to be custom made. This makes it difficult to obtain cost and cost-driver data from off the shelf items or industry. Typically at the conceptual stage not much information is available to calculate the cost in detail. But the cost can be revised as the design progresses and more information and data is available.

Assembly Cost Estimation: Assemblies can be classified into mainly three categories

1. Manual
2. Automatic
3. Robotic

Depending on the production quantity, quality and size one of the above options of assembly is chosen. The assembly cost comes from mostly from material cost and labor cost which essentially is, the time taken to assemble. Boothroyd [53] has studied the assembly timings of vast variety of cases. We will show in Figure 3.14 how the assembly process is incorporated into the framework of cost estimation.

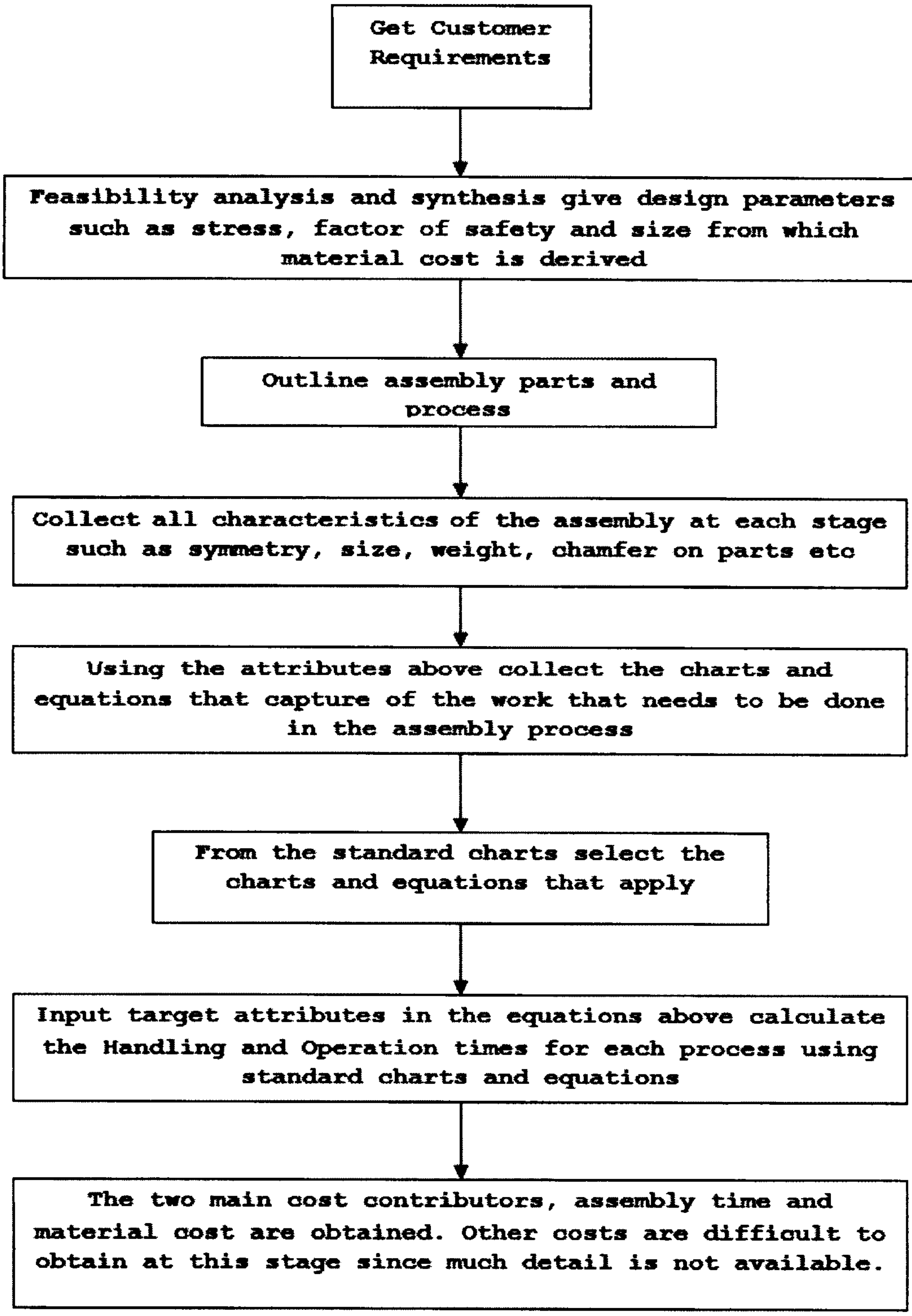

Figure 3.14. Flowchart of the Framework at Assembly Level

If the data collected in the charts and tables is not close to the situation then a custom chart/table can be created by experimentally finding assembly time for each assembly-process involved.

3.9.1 Manual Assembly

A lot of work has gone into calculating the cost of manual assembly. The scope of this paper does not permit to go into the details, but the aim here is to include manual assembly into the fold of the framework. The equations and charts form the Model Assembly in this case. Some sample variables are shown in tables 3.6 and 3.7. Each of these attributes contribute to the time taken to assemble and hence the cost. The standard charts developed by Boothroyd [53] give the time penalties.

			Thickness													
	symmetry	No of parts	Cylindrical	Non-cyl	long cyl, thick = dia	tangling	Handling 1 or 2 hands	Grasping tool	no-secure	Secure by snap fit	Screw by power tool	no access	Restricted vision	Obstructed Access	Weight	Tweezers
Handling Time																

Table 3.6 Handling Time for Various Attributes of an Assembly and its Parts

	Threads	Slot-head	Philips-head	Allen	Philips w/tool	Slot-head w/tool
Operation Time						

	Clearance	boxend wrench	openend wrench	socket ratchetwrench	nuit driver
Run down time/rev					

Table 3.7 Operation Time for Various Attributes of an Assembly and its Parts

3.9.2 Automatic and Robotic Assembly

Charts similar to the one for manual assembly have been developed by G. Boothroyd [53]. These charts act as model in our case. In the context of this framework a model helps in building a math model of the cost through equations. The charts by G.Boothroyd are based on data collected for several assembly processes and with penalties for time lost due to several factors. The values obtained from these charts can directly be applied to the target.

3.10. Methodology at Object Level

A part is the simplest unit in the hierarchy. As mentioned earlier a system consists of sub-systems, assemblies, and parts. But the smaller units are not always part of larger units. That is, not all components in the system are part of a higher sub-system. Sometimes parts can directly interface with the system, in such cases the cost of the parts would have to be calculated separately and added to the cost of the system. Cost of objects needs to be calculated since they form interface between the target system and the sub-system, which may not be part of the model system. Objects are also constituent of assembly so their cost is important. The framework shown in Figure 3.15 applies the same technique as shown in the previous section to calculate the cost of the part. The cost drivers in the case of a part cost estimate are the physical attributes of the features and processes used to machine, plus the cost of the material. At this stage a tool has been introduced into the framework called PRIMAs[5] (Process Information Maps) [54]. PRIMAs helps select the process based on material and the quantity of parts required. Cost data pertaining to the process and feature attributes of model parts is collected. A math model gives the coefficients, which are then used to calculate the cost of the target part. As mentioned above PRIMAs gives a process, but sometimes might be a very specific process for which data might not be available. In such cases another tool called the DCLASS[6] (Decision CLASSIFICATION) [55] is used. Dr.Allen Dell at Brigham Young University originally created DCLASS. DCLASS is the classification of processes into more and more specialized processes. Whenever detailed information about the process that needs to be employed is known then model parts on which those processes have been employed are used to draw a parametric model. When

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[5] PRIMAs (Process Information Maps) was developed by D.J.Booker & K.G.Swift

[6] DCLASS (Decision Classification) was created by Dr.Allen Dell at Brigham Young University.

detailed information about the process is not known then DCLASS helps identify a generalized category of a fabrication process. Model parts with these generalized processes are then used to calculate cost model.

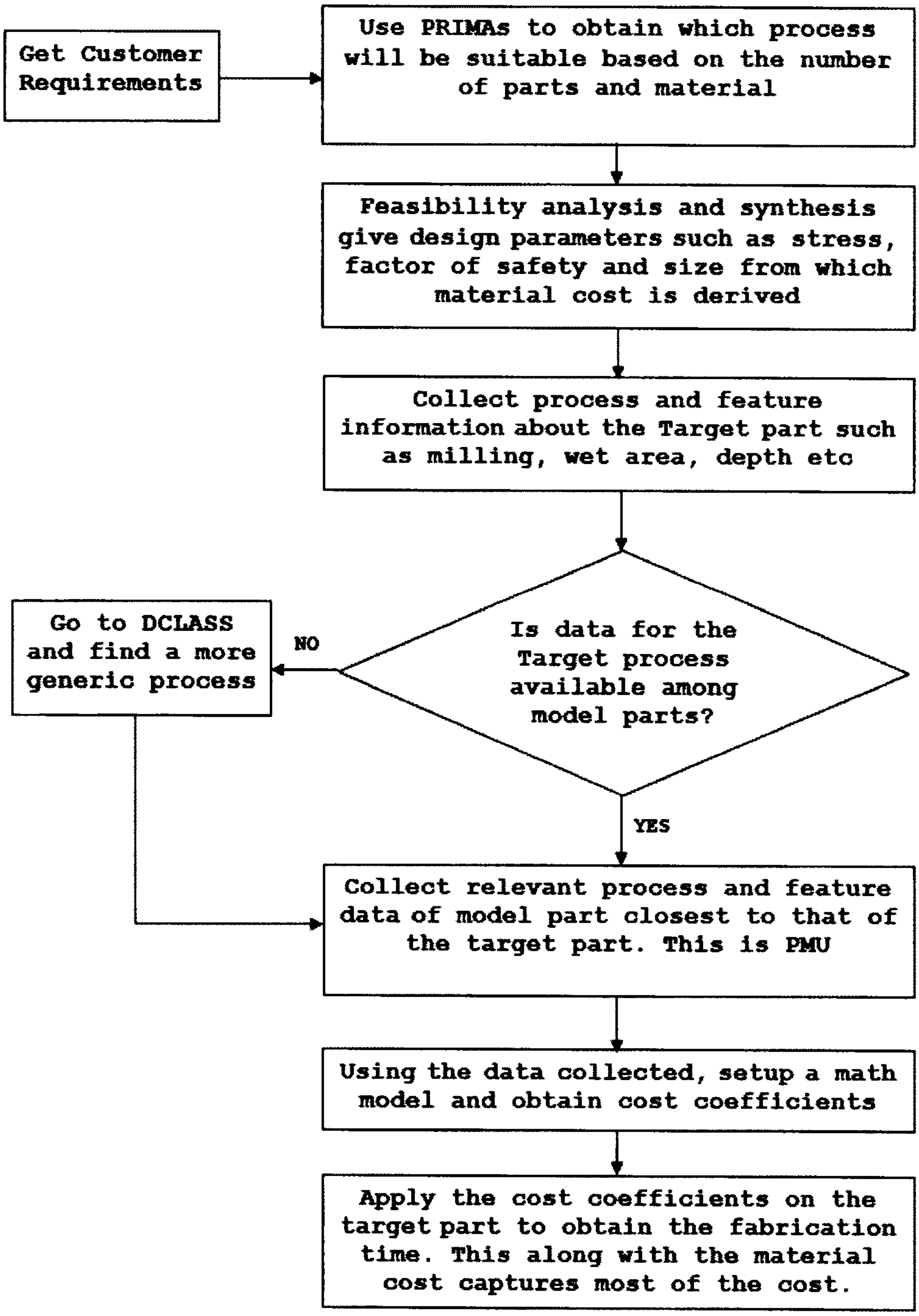


Figure 3.15. Flowchart of the Framework at Object Level

3.10.1 DCLASS

The purpose of classifying manufacturing processes is to group together similar processes into families. This helps in saving and retrieving data. This technique is very comprehensive in classifying fabrication processes. The general technique used is that each generic process is divided into specialized categories. A taxonomy or classification of manufacturing processes can aid in process selection by providing a display of potential manufacturing options available to the process planner. As seen in Figure 3.16 the sample classification from the DCLASS the fabrication processes are given a number [55]. This makes it easier to save the fabrication parameters such as the wet area, depth, machining speed, etc; along with the fabrication process which is saved as a numeric value rather than a string in an electronic database.

Benefits of a Well-Designed Classification and Coding System

- Facilitates formation of part families
- Permits quick retrieval of part design drawings
- Reduces design duplication
- Promotes design standardization
- Improves cost estimating and cost accounting
- Facilitates NC part programming by allowing new parts to use the same part program as existing parts in the same family
- Computer-aided process planning (CAPP) becomes feasible

Three structures used in classification and coding schemes

- Hierarchical structure, known as a mono-code, in which the interpretation of each successive symbol depends on the value of the preceding symbols
- Chain-type structure, known as a polycode, in which the interpretation of each symbol in the sequence is always the same; it does not depend on the value of preceding symbols
- Mixed-mode structure, which is a hybrid of the two previous codes

John Deere has been using and developing GT (Group Technology) systems since 1976. Recently, Deere Tech Services was created to sell GT systems and consulting services. The Deere Tech system employs a 35-digit code. The code is not shown to the user, while communicating in a natural language style computer queries. In order to employ Group Technology, instead of employing a commercial system, firms may choose to combine an existing company database with a database organization and extraction tool. One such generic tool is a general-purpose information tree processor called the decision and classification information system (DCLASS). In addition to providing a mechanism for classifying and organizing data, DCLASS allows a company to capture expert logic, e.g. for computer-aided process planning (CAPP) purposes (Whiteside 1987).

The D-Class system is a computerized generic approach to coding. It can accommodate user-defined logic. It uses a tree structured decision system where each branch represents a condition. A specific code value is assigned at the junction of each branch. The D-class has good coding and retrieval facilities. Some of the D-Class codes are shown in figures 3.16.1 to 3.16.6.

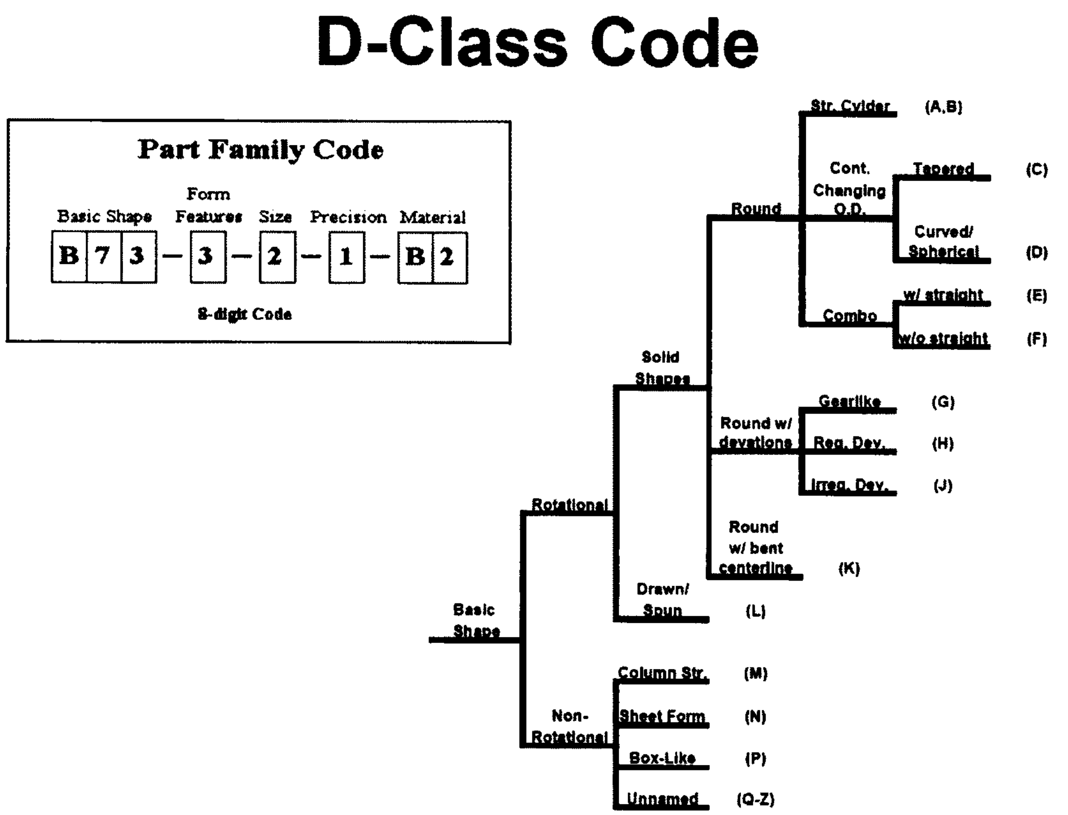


Figure 3.16.1 Part Family Code [55]

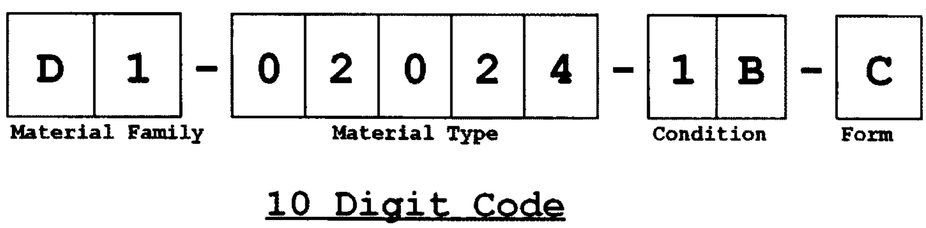


Figure 3.16.2 Material Code as per DCLASS [55]

Engineering Material Families	
Family	Description
A	Steel
B	Cast Iron
C	Coated, Clad, Bonded Metals
D	Light Metals
E	Non-Ferrous Engineering Metals
F	Low Melting Point Metals
G	Refractory Metals
H	Precious Metals
J	Semi conductor and Special Metals
K	Nuclear Metals
L	Rare Earth Metals
M	Composites
N	Minerals, Refractories and Ceramics
P	Wood and Wood Products
Q	Paper and Paper Products
R	Textile Fibers and Products
S	Glass
T	Polymers
U	Rubber and Elastomers

Figure 3.16.3 Engineering Material families as per DCLASS [55]

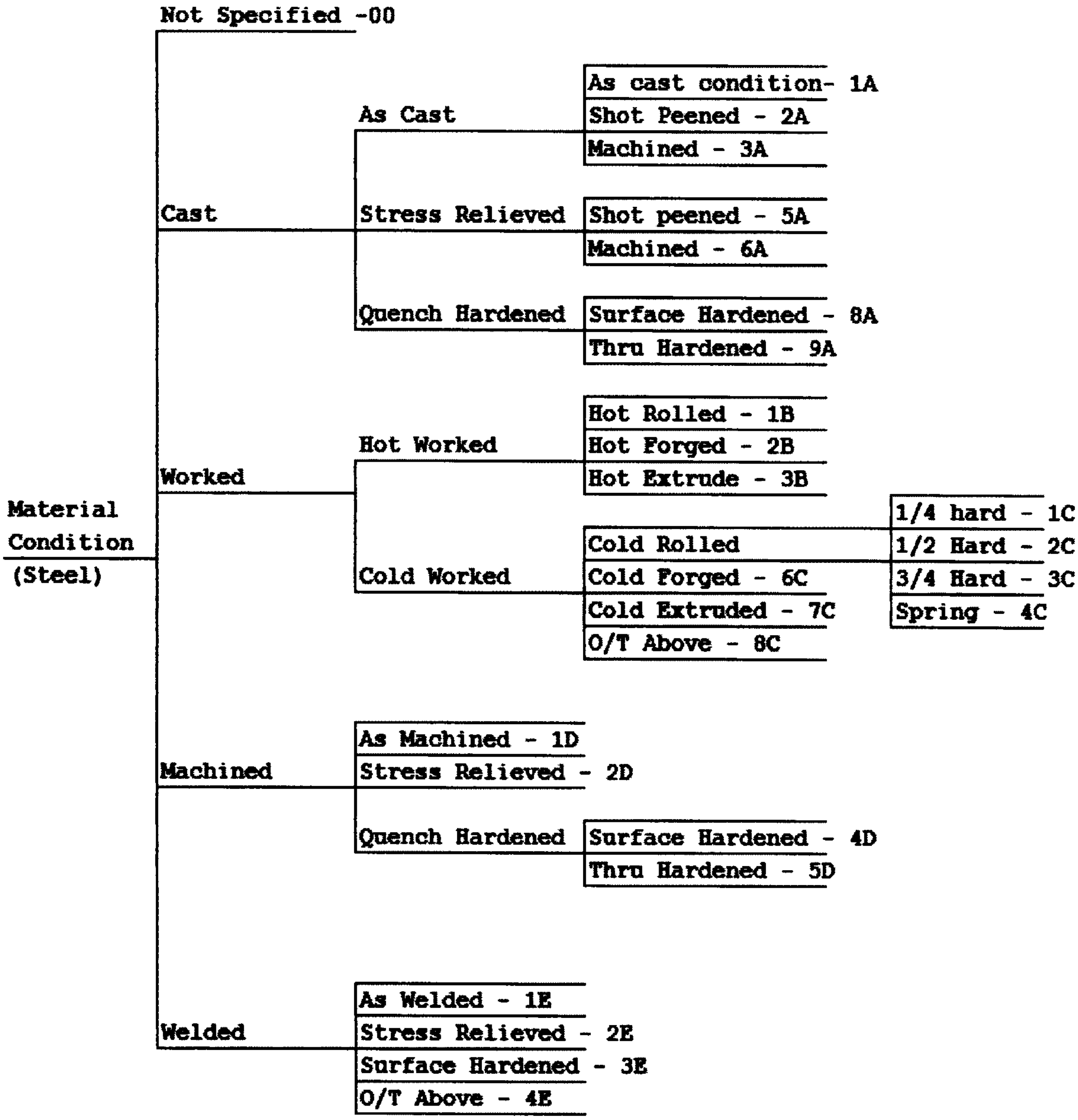


Figure 3.16.4 Material Condition as per DCLASS [55]

O - Unspecified

ROTATIONAL SOLIDS

A - Rod/Wire

B - Tubing/Pipe

FLAT SOLIDS

C - Bar, Flats

D - Hexagon/Octagon

E - Sheet/Plate

STRUCTURAL SHAPES

F - Angle

G - T-Section

H - Channel

I - H, I-Sections

J - Z-Sections

K - Specisl Sections (Extruded, Rolled etc)

FABRICATED SOLID SHAPES

L - Forging

M - Casting/Ingots

N - Weldment

P - Power Metal

Q - Laminate

R - Honeycomb

S - Foam

SPECIAL FORMS

T - Resin, Liquid, Granules

U - Fabric, Roving, Filament

V - Putty, Clay

W - Other

Y - Reserved

Z - Reserved

Figure 3.16.5 Code for Raw Material Form as per DCLASS [55]

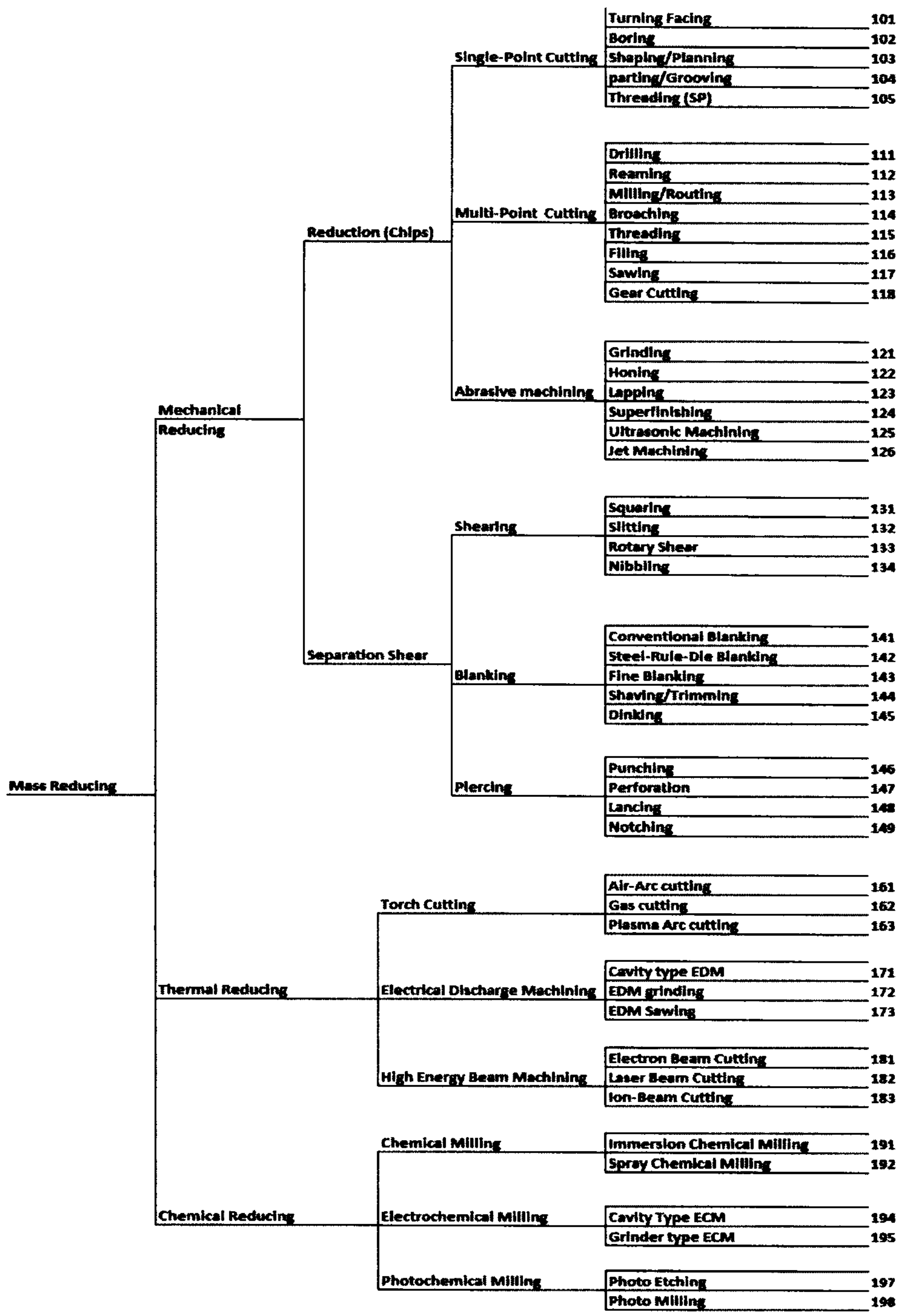


Figure 3.16.6 Breakdown of processes as per DCLASS [55]

3.11. Life Cycle Cost

Life cycle cost (LCC) is the total cost of ownership of a unit. The life cycle cost can be expressed as the sum of the cost of acquisition, operation, maintenance and decommissioning (SAE 1999). These sub-costs are the costs that are accrued from inception to the end of the unit's life cycle. The purpose of performing LCC analysis is to choose the most cost effective solution, to the needs of the stakeholders. LCC illustrates the economics of developing and operating the model unit during the entire lifespan of the model. It has been observed that the acquisition cost is the least among all other costs mentioned above. The aim of the product development team is to keep the overall LCC to a minimum.

In the current framework, if the stakeholders wished, the life cycle cost could be one of the factors in selecting the primary model unit. In case of small capital expenditures, a simple payback method is employed instead of a full LCC analysis. The simple payback method does not take into account the time value of money.

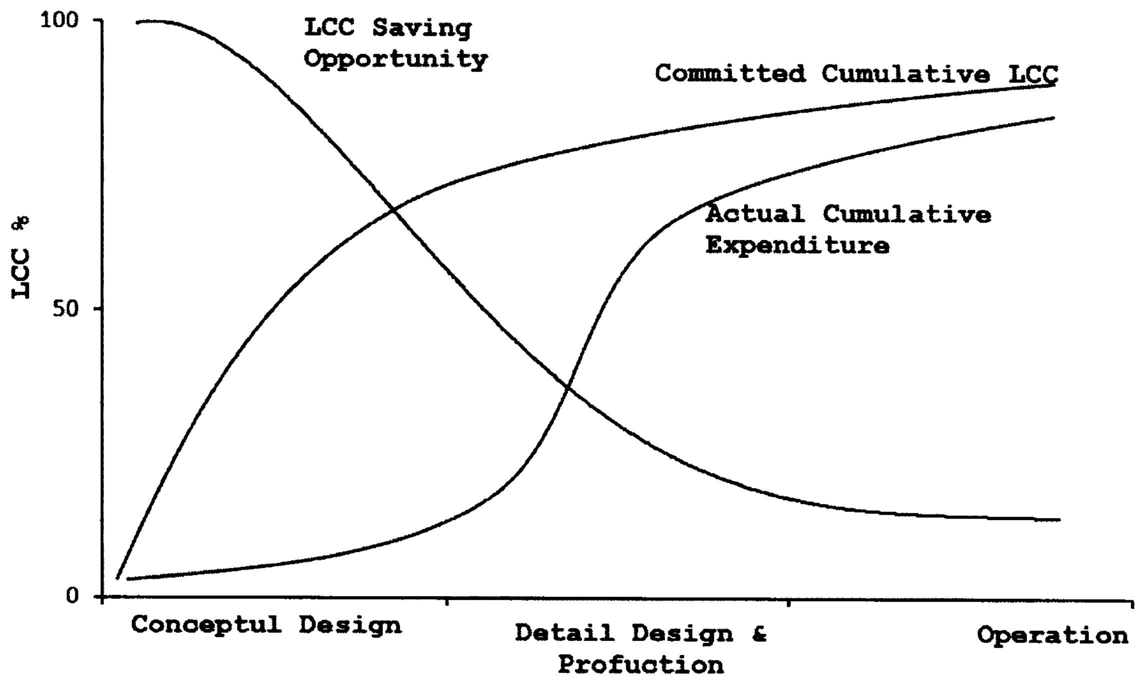


Figure 3.17: Life Cycle Cost Saving [51]

As seen in the Figure 3.17 the conceptual design stage has the most impact on the life cycle cost of a unit. Any design decision chosen impacts the not only the kind of product the stakeholder is going to end up with, but also heavily affects the cost. As the work progresses from conceptual stage to design and fabrication stage the opportunity to control the cost a;lso decreases rapidly.

LCC normally includes the following, which are depicted in Figure 3.18.

1. Research and Development (R&D) phase costs
2. Investment (Production and Deployment/Installation) phase costs
3. Operation and Support (O&S) phase costs
4. Disposal and Termination costs

The above costs should include hardware, software, material, personnel, support agencies and suppliers, operations, and logistics.

Figure 3.18 shows the cost accrued during various stages of the life cycle process. The maximum cost is accrued during the production and deployment stage of the life cycle.

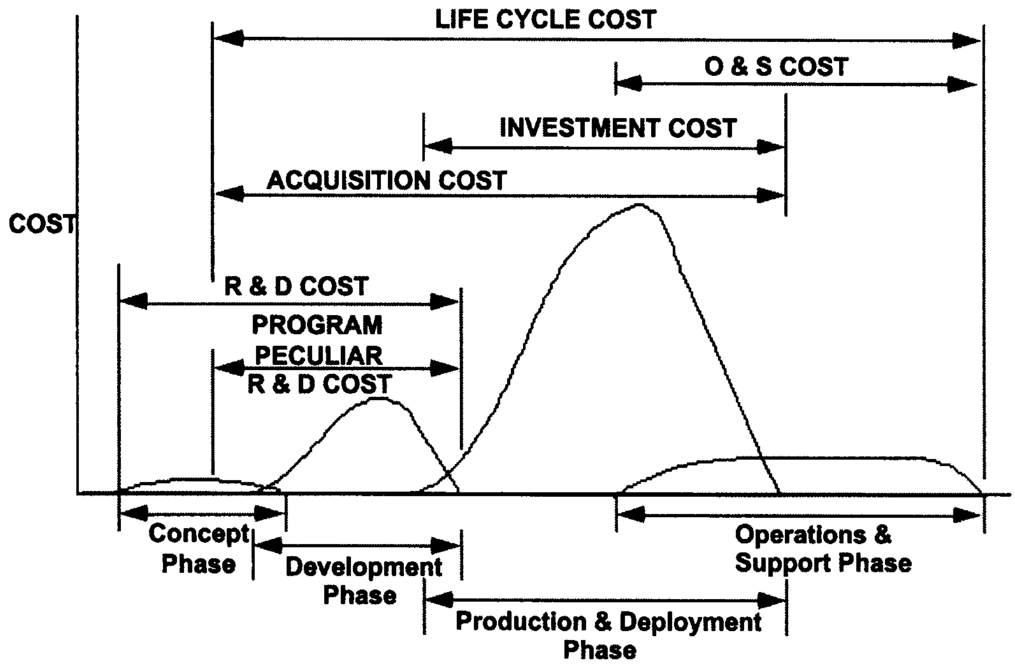


Figure 3.18: Life Cycle Cost Stages [56]

As seen in the Figure 3.18 most of the cost comes from the production stage of the acquisition phase. The acquisition phase consists of conceptual design, detail design and production stages. After the acquisition phase comes the utilization phase which consists of stages such as operational use, support, phase-out and disposal.

Life cycle cost depends a lot on the requirements of the stakeholder. Sometimes they might just need the cost of acquisition and other times the entire life cycle cost. If a comprehensive life cycle cost is to be calculated then it is the summation of the cost of research and development, production, operation and finally retirement. Each of these four major categories is in fact a summation of other costs. Tables-A and B (Appendix IV) give a comprehensive list of the variables, which determine the life cycle cost of a typical unit. The variables in Table-A are the independent variables, which are determined by the stakeholders based on their requirements. Table B is a list of dependent variables, which are calculated from the independent variables.

The proposed framework is capable of calculating the cost of the unit at acquisition as well as the utilization phase as shown in Figure 3.19. The cost drivers, which belong to the acquisition phase, are parametric in nature since they include the physical functional attributes of the unit. For example, an airplane in the acquisition phase has cost drivers such as engine power, range, capacity, size, etc. However, while calculating cost of maintenance, repair, warehousing, disposal, etc the cost drivers cannot be parameterized. Hence a summation of these costs (maintenance, repair, warehousing, disposal, etc) is obtained by the formulae shown in Appendix IV.

Depending on the requirements of the stakeholders not all of these costs need to be calculated. The cost terms which the stakeholders require form the Target Unit according to our framework. In order to calculate the cost of the target Unit, we need to look at several model units. The Model Units here are the set of life-cycle cost equations (see Appendix IV), which calculate the comprehensive cost of utilization. But the target Unit may not require all the costs present in the model units, hence a primary model unit needs to be found. The primary model unit in this case is the set of equations which are applicable to the utilization cost with respect to the requirements of the target Unit as dictated by the stakeholders. According to our framework we first need to find a PMU (Primary model unit), here the PMU is the set of equations, which need to be calculated in order to obtain the utilization cost of the unit.

An important point to note is that the framework in the case of systems and sub-systems obtains a primary model unit that matches closely to the target system. The samples of the primary model unit are used to come up with a math model and set of equations. But in case of life-cycle cost, the life-cycle cost equations (See Appendix IV), are themselves a precedent Model that is a primary model unit for estimating the cost of life-cycle.

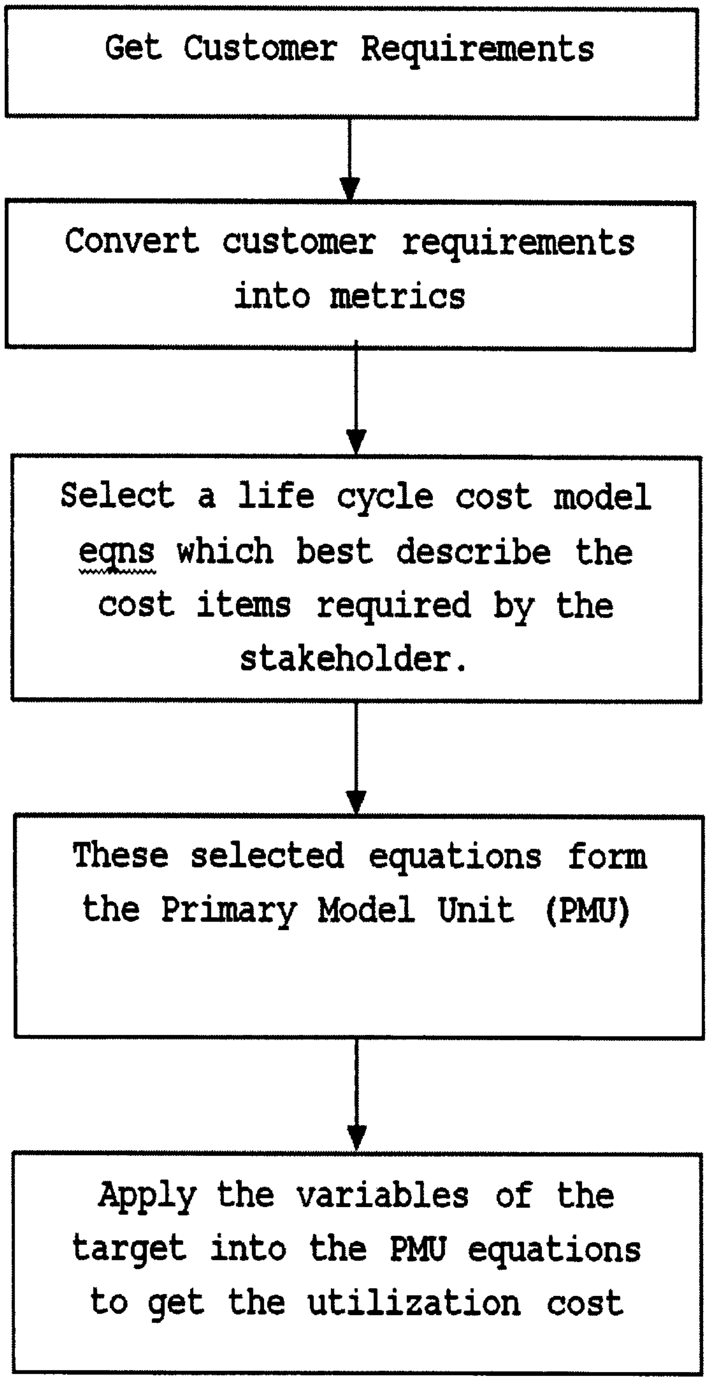


Figure 3.19. Flowchart of the Framework for Life Cycle Cost

The cost categories mentioned below are some of the broad costs in life-cycle cost estimate.

LIFE CYCLE COST

Research and Development Cost

- System Life cycle cost management
- Product Planning
- Product Research
- Engineering Design
- Design Documentation
- System Software
- System Test and Evaluation

Production & Construction Cost

- Industrial Engineering & Operations Analysis
- Manufacturing
- Construction
- Quality Control
- Initial Logistics Support

Operation & Support Cost

- System Operations
- System Distribution
- Sustaining Logistics Support

Retirement & Disposal Cost

- Disposal of Non-repairable System/Sub-system
- System Ultimate Retirement

Depending upon the information available at the conceptual stage and the request of the stakeholders, some or all of the above costs can be calculated. The detailed calculations for each of the categories and subcategories are mentioned in the Appendix IV.

3.12 Database Methodology

In order to obtain an estimate of the cost of a target unit, it is important in this framework to have a database that caters to its needs at various stages of cost estimation viz. cost estimation of a part, assembly, sub-system or a system.

3.13 Database at the Part/Object Level

Following the methodology of the framework the cost of a target Part is the sum of the cost of a Model part, which is the most similar part whose cost is available, plus the cost of including more features in the model part as required by the target part.

Target Part needs n Units	=	Model Part has n-k features	+	Cost of k features

The data in the database can be stored in the format shown below. This format is easily transferable from xls to xml format. Using PRIMA and DCLASS the process based on the quantity of parts to be manufactured and the material, the process can be figured out. And using DCLASS a more generic form of a particular process can be figured out if the data for that specific process is not available.

Mtrl	Process DCLASS	len	wdt	Vol	wt	tk	area	peri	pwr	rpm	con	shap	size	prec	cost	units	xvar	tag
A1	221	0	0	0	50	0	0	0	0	0	0	0	0	0	52.8	0	5	1
A1	221	0	0	0	100	0	0	0	0	0	0	0	0	0	78.08	0	5	1
A1	221	0	0	0	150	0	0	0	0	0	0	0	0	0	94.016	0	5	1
A1	201	0	0	0	50	0	0	0	0	0	0	0	0	0	33	0	5	2
A1	201	0	0	0	100	0	0	0	0	0	0	0	0	0	48.8	0	5	2
A1	201	0	0	0	150	0	0	0	0	0	0	0	0	0	58.76	0	5	2
D1	121	1	0	0	0	0	0	0	0	0	0	1	0	0	0.25	1	3	3
D1	121	5	0	0	0	0	0	0	0	0	0	1	0	0	1.15	1	3	3
D1	121	12	0	0	0	0	0	0	0	0	0	1	0	0	2	1	3	3
D1	182	0	0	0.5	0.01	0	0	0	0	1500	0	1	0	0	0.001	1	5	4
D1	182	0	0	0.06	10	0	0	0	0	1500	0	1	0	0	0.126	1	5	4
D1	182	0	0	0.125	10	0	0	0	0	1500	0	1	0	0	0.242	1	5	4
D1	182	0	0	0.25	10	0	0	0	0	1500	0	1	0	0	0.449	1	5	4
D1	182	0	0	0.5	10	0	0	0	0	1500	0	1	0	0	1.047	1	5	4

Table 3.8 Object Level Sample Cost Data

Where,

Mtrl: Material Code in DCLASS

Process DCLASS: Process Code in DCLASS
Len: Length of Machined Surface

Wdt: Width of Machined Surface

Vol: Volume of Material Machined

Wt: Weight of material Machined

Tk: Thickness of Material Machined

Area: Machined Area

Peri: Perimeter

Pwr: Power setting during the machining process

RPM: RPM setting during the machining process

Con: Condition of the material

Shape: Shape of the Raw material

Size: Size of the raw material

Precision: Precision attained on the part

Cost: Cost of the part

Units: Sometimes the cost is in dollars and sometimes in minutes or hours which should be converted into dollars by using appropriate labor rate.

XVAR: The cost driver for the given dataset.

Tag: Chronological order of the dataset in the database.

DCLASS MATERIAL A1: In the DCLASS, A1 stands for cast iron

DCLASS MATERIAL D1: In the DCLASS, A1 stands for light metal

DCLASS PROCESS 221: DCLASS Process 221 stands for Die Casting.

DCLASS PROCESS 201: DCLASS process 201 stands for Investment casting

DCLASS PROCESS 182: DCLASS process 182 stands for laser Cutting.

Example:

Suppose the cost of a part needs to be estimated. The part is fabricated with Aluminum. The fabrication engineer has determined that the operation will require a grinding process followed by a laser cutting procedure.

These two processes are looked up in the DCLASS-based database to see if there is data available for the them, if not then the general form of that machining process is picked.

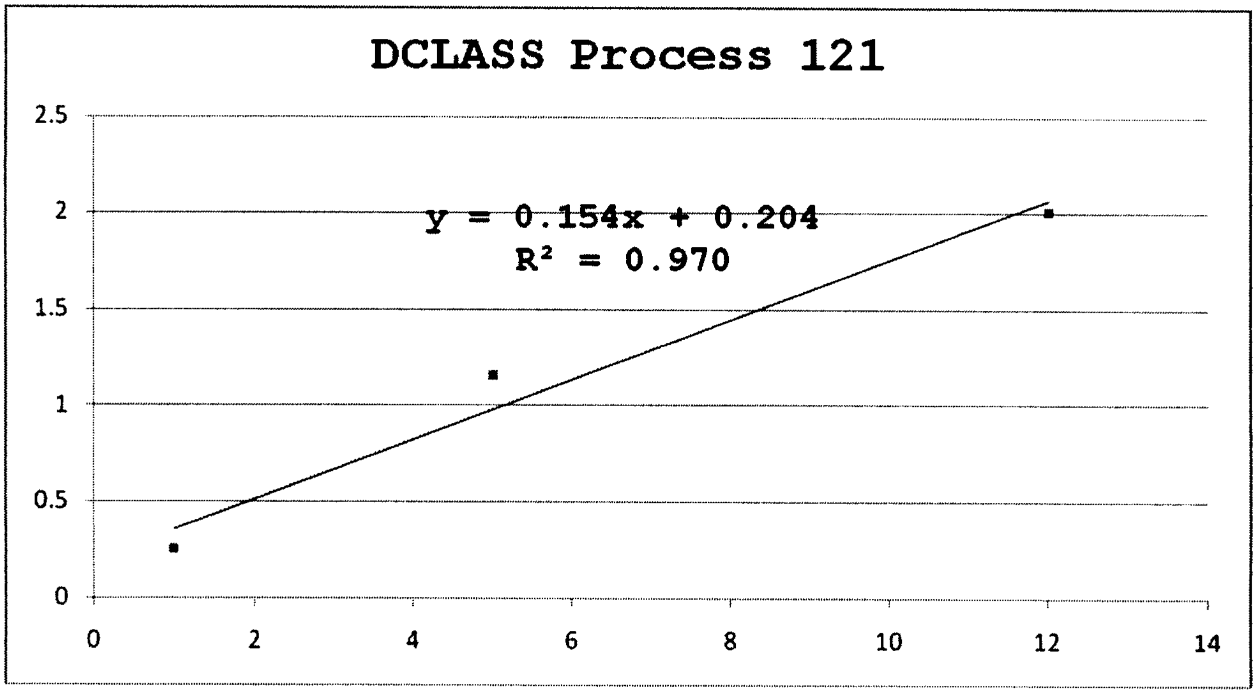


Figure 3.20: Cost(Minutes) Vs Length of the Grinding (in)

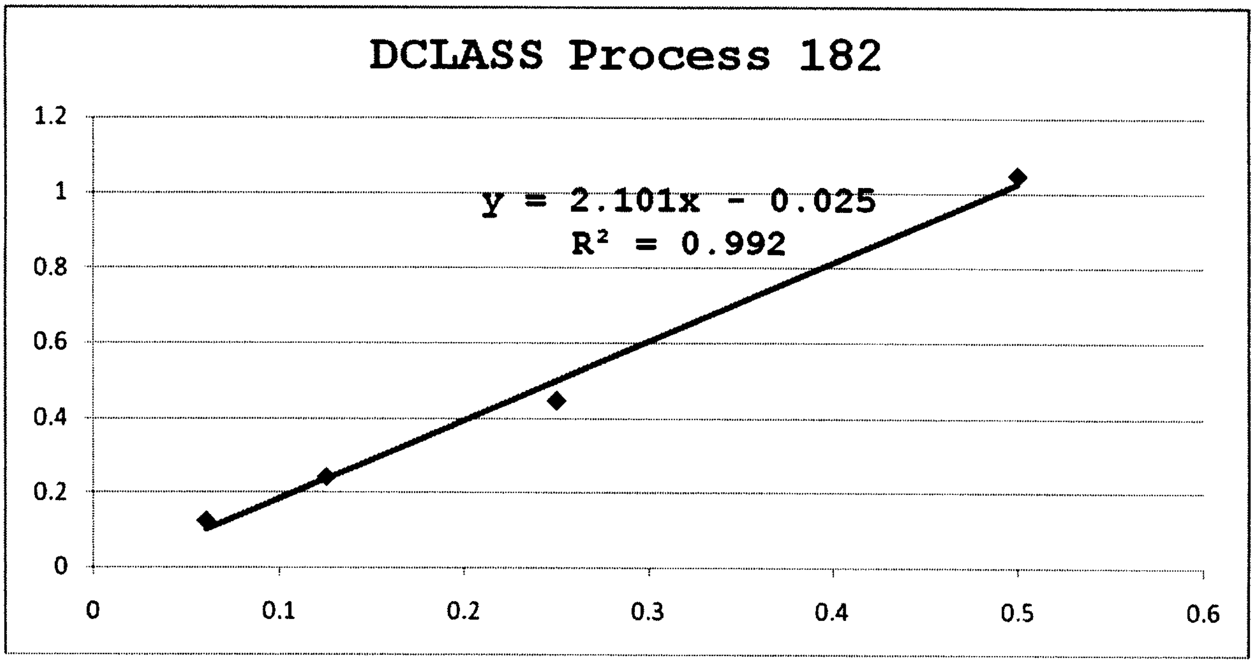


Figure 3.21: Cost (Minutes) Vs Volume of Material Removed (in^3)

From the requirements, the materials and processes were derived. The cost data was looked up in the database shown above in table 3.10. Once the data similar to our requirements is obtained, a cost model is derived as shown in Figures 3.20 and 3.21. The cost model usually a regression model can then be used to calculate the cost of the process mentioned in the requirements. The R^2 value is a good indicator of how accurate the cost data has been fit. The cost as in the both the cases chosen in this example, is in minutes. This is actually the machining time of the process. The cost in dollars can be obtained by multiplying the time by appropriate labor rate.

3.14 Database at the Assembly Level

At assembly level, the vast amount of data created by the experiments of professor Boothroyd under various assembly conditions can be used. The data for each condition has been converted into equations and these equations form the Model Assembly unit for the framework as shown in Figure 3.22.

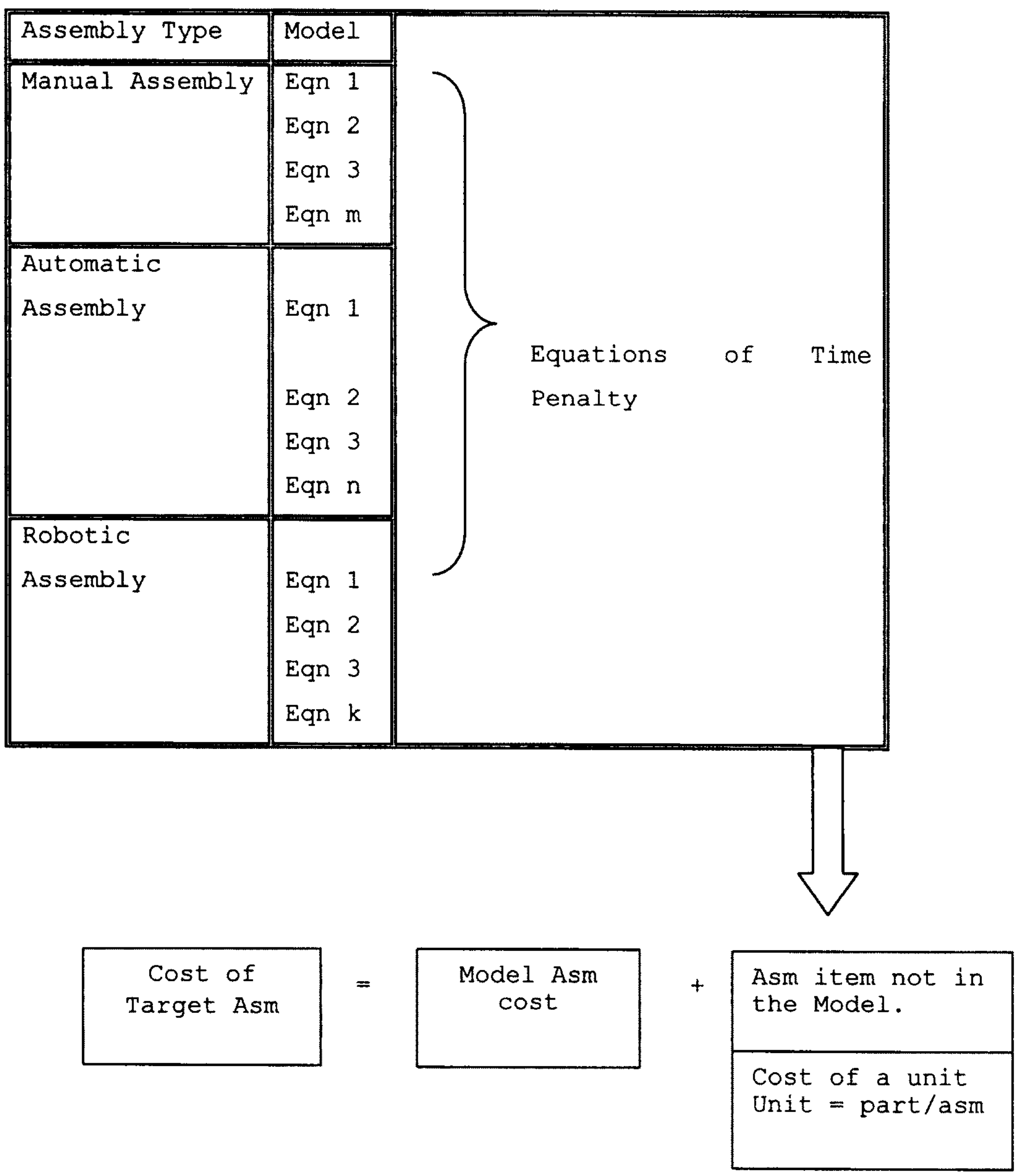


Figure 3.22: Obtaining Cost Data for Assembly from the Database

Once assembled, sometimes extra machining process might be needed to be done. In that case the cost of the extra machining can be calculated from the parts database and added to the cost of "Target Asm" in the figure above. Machining after the parts have been assembled is done sometimes to maintain alignment of the machined features. For example, a hole is sometimes drilled after assembly of the parts so that the hole on each of the assembled parts lines up.

3.15 Database at Sub-system Level

At this stage a pre-formatted database is not available to pull data from and come up with a math model. A Math model based on the database which consists of the cost drivers and costs of various samples, should be created on the fly.

Cost of Target Sub-System = $C_m + C_{m'}$

C_m = Cost of Model Sub-System

$C_{m'}$ = Cost of Features not in the Model Sub-system

$C_{m'}$ = Cost of one of more units (part or assembly)

A computer program written in either Visual Basic or any other language can be used to convert data of the model samples entered in an excel sheet to an xml (Extensible Markup Language). An xml format is converted to database structures by a Matlab code. The Matlab code also creates the cost model and calculates the cost based on the feature-parameters of the target sub-system.

3.16 XML and its Advantages

XML (Extensible Markup Language) has been used in the database methodology in the proposed framework. The reason is that the XML provides several distinct advantages over flat format type data storage file types such as Microsoft Excel and .CSV (comma delimited). XML's user friendliness comes from the fact that it is easily understood by user. One does not need extensive and in-depth knowledge to start using XML and is compatible with most platforms and programming languages. The tags used in XML can be customized and made compatible with the jargons used in the specific application. These tags are "understood" as data structures by programming languages like MATLAB. The proposed framework uses MATLAB for data analysis and cost modeling.

A disadvantage of using a flat database such as Excel is that in it, finding data can be tedious going over each row or column of data. Having a structure in the data greatly cuts this time to find a data element. XML being highly structured, makes it easy for searching using tags. Since the framework uses classification tool such as DCLASS to save cost data pertaining to materials, fabrication processes, form, etc, a structured database is highly recommended. XML also provides features such as being able to represent data in a tabular format using style sheets.

Conforming to a methodology similar to that of DCLASS where a material or process is continuously branched into a more specific category, the XML data is structured into roots, branches and leaves. The XML codes are easily understood by even non-programmers due to the simplicity of the language used. Historical cost data sometimes is present in the forms of documents and not really in a tabulated format. Documents in an enterprise may be spread across various departments. In these cases XML may be used to search for specific data and put them in a structure.

XML has various advantages over flat format methodology of data storage. One could arrange data in various tables and establish relations between the tables. However, this can become extremely complex as the relations and the data size grows where as XML has the benefit of being inherently object oriented.

In XML, besides the data value the elements also have one or more attributes. This is immensely helpful in the context of the proposed framework since the cost data can be diverse win in itself and yet needs to be stored in a single database.

Chapter 4: INCORPORATING EIO-LCA INTO THE FRAMEWORK

We have seen so far the capabilities of the framework in determining the acquisition cost as well as the life cycle cost of units irrespective of their size, complexity, or the industry to which the unit belongs.

The next phase is to incorporate economic, social, and environmental effects of the design decision at the conceptual stage, into the cost estimation framework. This is accomplished by using the EIO-LCA (Economic Input Output Life Cycle Assessment) methodology.

4.1 EIO-LCA (Economic Input-Output Life Cycle Assessment)

The explanation of EIO-LCA can be broken down into two topics viz. EIO and LCA. EIO (economic input-output model) predicts the effect of changes in one industry on others due to the activity by consumers and government. This is done through a matrix representation of the inter-industry transactions. Wassily Leontief (1905-1999) was awarded the Nobel Prize in Economic Sciences for his development of this model. The International Input-Output Association is dedicated to advancing and developing the field of input-output studies. In the matrix, a given input into an industry is enumerated in the column of that industry and its outputs are enumerated in its corresponding row. The matrix therefore, shows how dependent each industry is on all others in the economy both as customer of their outputs and as supplier of their inputs. So the EIO model gives the user is the ability to observe, predict, and even direct changes in the economy of a country, region, or an industrial sector. This has usually been studied as an after-effect; however, the current framework proposes to use the EIO model during the decision making process of design and cost estimation of a system.

The second aspect of EIO-LCA is the Life Cycle Assessment. LCA is the study of environmental effects of a product from its fabrication to the disposal or reuse. This life cycle is generally called "cradle-tograve." It also includes not just the production but also the environmental effects of the raw materials used.

The term 'life cycle' refers to the fact that the assessment of not only the product but also of the raw material, production, distribution, use/operation, and disposal is done. The sum of all those steps, or phases, is the life cycle of the product. A typical life cycle model is shown in the figure 4.1

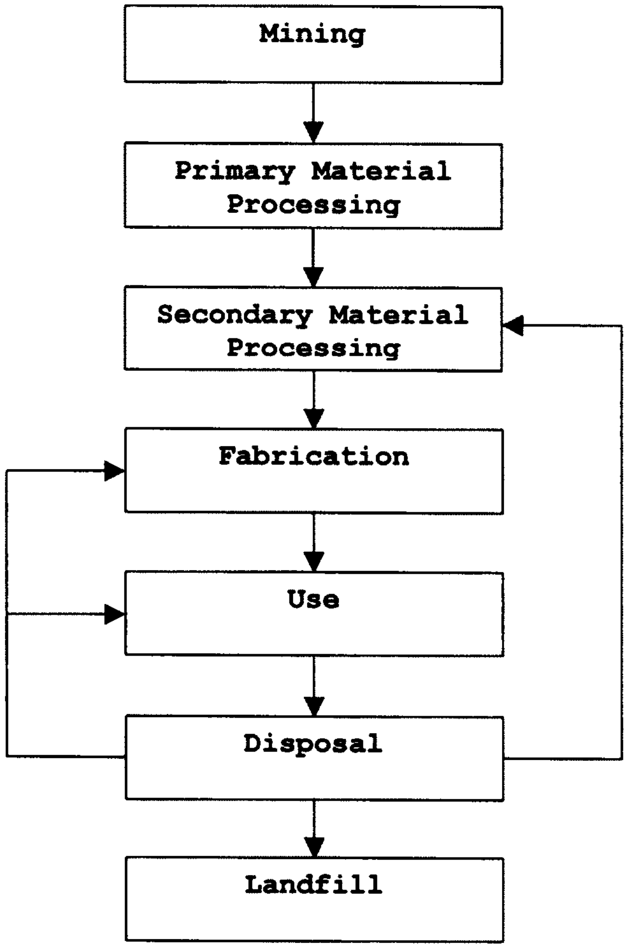


Figure 4.1: A Generic Supply Chain Life Cycle Model (Hendrickson)

4.2 Life Cycle Assessment

Life Cycle Assessment gives information about a product's impact on the environment and also the information as to what aspect of the life cycle causes the most environmental impact. For example, an automobile has the most impact on the environment at the utilization phase.

The goal of LCA is to evaluate the environmental and social effects caused due to products and services. Once this knowledge is available, then the stakeholders can optimize between the cost and the environmental burden.

The concept also can be used to optimize the environmental performance of a product or to optimize the environmental performance of a firm. Some of the common categories of assessed damages are global warming (greenhouse gases), acidification (soil and ocean), smog, ozone layer depletion, eutrophication, eco-toxicological and human-toxicological pollutants, habitat destruction, and land use as well as depletion of minerals and fossil fuels.

The EIOLCA analysis shows the energy used to produce a given amount of economic activity along with the Ozone Depleting Potential of the emissions as a result of the economic activity. By sorting the data, it is possible to determine which sectors have the maximum impact. The conventional Pollutants data list the SO_2, CO, NO_x, Lead, VOC, and PM_{10} resulting for the economic transactions throughout the entire supply chain of about 500 sectors. Again the data may be sorted to determine which sectors are predominantly contributing to the emissions. Several sectors that contribute to producing a product also contribute to the release of greenhouse gases, toxic waste into land, air, and water. Through similar analysis the amount of pollutants used through the supply chain can be calculated. The analysis of fuels shows the amounts of various fuels required throughout the supply chain for the production of the product.

With all this information, the stakeholders can estimate the impact on the environment for a certain amount of demand (in terms of dollars) in a sector.

4.3 Mathematical Setup of the EIO-LCA Model

A tremendous amount of data is generated in the daily transactions in the economic world. The transactions are between various sectors of the economy. The data generated during the transactions helps the economists understand the economic condition of an industry, region, country, or the world. The main concept of the input-output analysis is that there is a fundamental relationship between the volume of inputs going into an industry and its output. The input-output data can be tabulated in such a way that the horizontal rows show how the output of each sector is consumed by other sectors of the economy. The vertical columns show how each sector obtains from other sectors the input it needs in terms of goods and services. Upon some consideration one finds that every number is related to other numbers in the table.

	Sector 1 Agriculture	Sector 2 Mfg	Sector 3 Households	Total Output
Sector 1	25	20	55	**100**
Sector 2	14	6	30	**50**
Sector 3	80	180	40	**300**
	119	**206**	**125**	

$$\left.\begin{aligned} X_1 &= Z_{11} + Z_{12} + \ldots + Z_{1n} + Y_1 \\ X_2 &= Z_{21} + Z_{22} + \ldots + Z_{2n} + Y_2 \\ &\ldots \ldots \qquad \ldots \\ X_n &= Z_{n1} + Z_{n2} + \ldots + Z_{nn} + Y_n \end{aligned}\right\} \text{Eqn 1}$$

Framework developed by Wassily Leontief (1936)

X_i = Total output (or production) of sector i

Y_i = Total demand for sector i's products

Z_{ij} = Inter-industry sales from sector i to sector j

The relationship between various sectors reflects the structure of the economy. They are expressed in input-output analysis as ratios or coefficients of each input to the total output of that sector. These ratios represented by a_{ij} may be used to estimate the demand for materials used in the output of a sector in other years.

$$a_{ij} = \frac{Z_{ij}}{X_j}$$ → Eqn 2

Equation 1 and 2 can be combined in the following way [57]

$$\left.\begin{aligned} X_1 &= a_{11}X_1 + a_{12}X_2 + \ldots + a_{1n}X_n + Y_1 \\ X_2 &= a_{21}X_1 + a_{22}X_2 + \ldots + a_{2n}X_n + Y_2 \\ &\ldots\ldots \quad \ldots\ldots \quad \ldots\ldots \\ X_n &= a_{n1}X_1 + a_{n2}X_2 + \ldots + a_{nn}X_n + Yn \end{aligned}\right\} \text{Eqn 3}$$

Where

A: Matrix of input-output coefficients

X: Matrix of outputs

Y: Matrix of demands for sector's products

$(I-A)X = Y$ Eqn 4

$X = (I - A)^{-1} Y$ → Total Output = Leontief's Inverse * Demand Eqn 5

$X = IY + AY + AAY + AAAY\ldots$

$(I + A)Y$: First Level of Supply Chain

AAY: Second level of Supply chain

Input-output analysis plays a crucial role in dealing with cost and supply problems. It can also deal with import-export of a region or a country. In the table shown above a column can be added in which a positive number represents an export, while a negative number represents import.

Eqn 3 above can be rewritten as follows [57]

$$\left.\begin{array}{l} X_1 - \{a_{11}X_1 + a_{12}X_2 + \ldots + a_{1n}X_n\} = Y_1 \\ X_2 - \{a_{21}X_1 + a_{22}X_2 + \ldots + a_{2n}X_n\} = Y_2 \\ \ldots\ldots \quad \ldots\ldots \quad \ldots\ldots \\ X_n - \{a_{n1}X_1 + a_{n2}X_2 + \ldots + a_{nn}X_n\} = Yn \end{array}\right\} \quad \text{Eqn 6}$$

$$\left.\begin{array}{l} (1-a_{11})X_1 - a_{12}X_2 - \ldots - a_{1n}X_n = Y_1 \\ -a_{21}X_1 + (1-a_{22})X_2 - \ldots - a_{2n}X_n = Y_2 \\ \ldots\ldots \quad \ldots\ldots \quad \ldots\ldots \\ -a_{n1}X_1 - a_{n2}X_2 - \ldots + (1-a_{nn})X_n = Yn \end{array}\right\} \quad \text{Eqn 7}$$

Considering the same example given above, the table shows the inter-sector transactions [57].

	Sector 1 Agriculture	Sector 2 Mfg	Sector 3 Households	Total Output X
Sector 1	25	20	55	**100**
Sector 2	14	6	30	**50**
Sector 3	80	180	40	**300**
	119	**206**	**125**	

As discussed earlier, Z11 = 25, Z12 = 20, X1 = 100 and so on.

a31 = Z31/X1 a31 = 80/100 = .80

	Sector 1 Agriculture	Sector 2 Mfg	Sector 3 Households
Sector 1	.25	.40	.133
Sector 2	.14	.12	.1
Sector 3	.80	3.60	.133

$$\left.\begin{array}{l} (1-a_{11}) - a_{12} - \ldots - a_{1n} \\ -a_{21} + (1-a_{22}) - \ldots - a_{2n} \\ \ldots\ldots \qquad \ldots\ldots \\ -a_{n1} - a_{n2} - \ldots + (1-a_{nn}) \end{array}\right\}$$

Eqn 8

$$\begin{bmatrix} (1-.25) & -.4 & .13 \\ -.14 & (1-\ .12) & .10 \\ -.80 & -3.6 & (1-.13) \end{bmatrix}$$

Inverse of the above matrix is

$$\begin{bmatrix} 6.61 & 13.53 & 2.57 \\ 3.30 & 9.81 & 1.53 \\ 19.80 & 49.50 & 9.90 \end{bmatrix}$$

$$\mathbf{X = (I - A)^{-1}\ Y}$$

$$X1 = 6.61\ y1 + 13.53\ y2 + 2.57\ y3$$

$$X2 = 3.30\ y1 + 9.81\ y2 + 1.53\ y3$$

$$X3 = 19.80\ y1 + 49.50\ y2 + 9.90\ y3$$

As discussed in the previous sections the main theme of this research is using system engineering tools and techniques in cost estimation through different stages of product/system development, operation, and retirement. System engineering stresses the need for a framework for representing the relationship between various disciplines.

It is also important in systems engineering to plan for later stages of the life of the product/system very early in the conceptual design stage. This general systems theory along with the concept of enterprise-wide cost modeling compel the user to plan the product/system not just for the later life-cycle stages such as development, operation, and retirement, but also for the changes in the economic situation of the region or country or the world. A cost estimate cannot be said to be complete unless a forecasting of the cost of the system being produced and related systems are predicted. Of course, as in any forecast, there is uncertainty attached. But the forecast gives a range in which the cost of the product/system will mostly lie. an economic Input-Output model helps us in this regard. The economic Input-Output model is a very powerful tool developed by Professor Vassily Leontief in the 1930s. A simple economic Input-Output model can be considered as a table (see table 4.1) showing the distribution of the products of each industry into others. From this the consequences of change in demand or output can be estimated. The table itself is constructed by collecting data from a specific region.

	Processing Sectors		Household Consumption	Final Demand	Total Output
	1	*2*	*(C)*	*(Y*)*	*(X)*
Processing Sectors 1	150	500	50	300	1000
Processing Sectors 2	200	100	400	1300	2000
Labor Services (L)	300	500	50	150	1000
Other Payments (N+M)	350	900	500	400	2150
Total Outlays (X)	1000	2000	1000	2150	5150

Table 4.1 Input-Output Analysis of Sample Sectors [57]

According to equation 1 and 2 above, the matrix of input coefficients A can be found out.

$X_3 = Z_{31} + Z_{32} + Z_{33} + Y_3 = 300 + 500 + 50 + 150 = 1000$

$$a_{ij} = \frac{Z_{ij}}{X_j}$$

$a_{31} = Z_{31}/X_1 = 300/1000 = 0.3$

Similarly other elements of the A matrix are obtained.

$$A = \begin{pmatrix} 0.15 & 0.25 & 0.05 \\ 0.2 & 0.05 & 0.4 \\ 0.3 & 0.25 & 0.05 \end{pmatrix}$$

$$I - A = \begin{pmatrix} 0.85 & -0.25 & -0.05 \\ -0.2 & 0.95 & -0.4 \\ -0.3 & -0.25 & 0.95 \end{pmatrix}$$

Where, I is an identity matrix of the same order as A.

$$(I - A)^{-1} = \begin{pmatrix} 1.3651 & 0.4253 & 0.2509 \\ 0.5273 & 1.3481 & 0.5954 \\ 0.5698 & 0.4890 & 1.2885 \end{pmatrix}$$

Suppose the final demand changes such that Y1 changes from 350 (50 + 300) to 600, and Y2 changes from 1700 (400 + 1300) to 1500. Suppose the entire final demand change was coming from Other Final Demand Y.

$$Y = \begin{pmatrix} 600 \\ 1500 \\ 0 \end{pmatrix}$$

$$X = (I-A)^{-1} * Y = \begin{pmatrix} 1456.94 \\ 2338.51 \\ 1075.48 \end{pmatrix}$$

The new necessary gross outputs are X_1 = \$1456.94 and X_2 = \$2338.51 and X_3 = \$1075.48.

As demonstrated above, any predicted changes in the final demand can be used to estimate the necessary outputs of a certain sector or sectors of a region or nation. The output matrix X can also be calculated at a future point in time provided there is a projection of the A matrix and the demand matrix Y of that time. The econometric models provide the forecast of final demands upon which the input-output model can be implemented. Several measures derived from the matrix $(I-A)^{-1}$ are used in impact analysis. These measures are called input-output multipliers. Some of the most commonly used multipliers are [57]

a. Output Multipliers

b. Income Multipliers

c. Employment Multipliers

An Output multiplier for a sector j is defined as the total value of production in all the sectors of the economy required to satisfy a dollar's worth of final demand for sector j's output [57]. If the elements of the matrix $(I-A)^{-1}$ are represented by α_{ij} then

$$O_j = \sum_{i=1}^{n} \alpha_{ij}$$

An Income multiplier translates the impact of final demand spending changes into changes in the income of the households [57].

$$Hj = \sum_{i=1}^{n} a_{n+1,i}\alpha_{ij}$$

Using the matrix A (for a) and $(I-A)^{-1}$ (for α), n=2

	0.15	0.25	0.05
A =	0.20	0.05	0.40
	0.30	0.25	0.05

	1.365	0.43	0.25
$(I-A)^{-1}$ =	0.527	1.35	0.60
	0.57	0.49	1.29

$H_1 = (.3)*(1.365) + (.25)*(.527) = .541$

$H_2 = (.3)*(.43) + (.25)*(1.35) = .466$

A dollar's worth of final demand for the output of sector 2 becomes $0.466 worth of new household income. The Leontief's Inverse helps take care of all direct and indirect affects.

4.4 Implementation of the EIO-LCA Model

4.4.1 Information Obtained from an LCA and its Uses

The LCA data can be used to differentiate the impacts of two comparable products, which in the case of our framework are the various possible Model Units which are similar to the Target Unit. For example, there is the case of plastic versus paper bags. The inter sector impact, energy requirements, environmental impact and employment generated are different for these two types of product. The decision makers make the choice between the Model Units based on their preference.

In this section we demonstrate how to use an input-output database such as the one provided by Carnegie Mellon University (www.EIOLCA.net) to implement EIO-LCA in order to predict economic, environmental and social impact.

4.4.2 The Steps to Using the EIOLCA:

The steps to using the EIOLCA according to www.EIOLCA.net are:

1) Determine the amount of materials required for a unit amount of production of the product, for example, for the production of a unit length of a concrete pavement.

2) Calculate the dollar costs for the materials. The EIOLCA software only accepts inputs in the form of dollar amounts for materials.

3) Adjust the dollar values to match those of the EIOLCA database. The price indices can be used to convert current dollars into the dollars of that year as the EIOLCA database.

4) Find the name of the economic sector responsible for producing the material, use appropriate keywords to allow the EIOLCA database to search for the appropriate sector. This can be determined through the descriptions of the search-results. Similarly, a search of other materials will yield information about their respective sectors.

The actual sector used to approximate the material or product depends on the estimator's knowledge of the manufacturing process. At this point we know the dollar amount of materials needed for producing a unit quantity of the product. The EIOLCA analysis can now be performed to understand the economic and environmental impact of the product.
Once the names of the sectors being used are known, analyze the data for the dollar purchase of that sector. Sort each column to obtain dominant economic sectors. This can be repeated to obtain dominant employment generating sectors and also sectors contributing the most towards pollution.

4.5 Implementation of EIO-LCA According to the Framework

In the discussion about the methodology of the framework, we have discussed that the process of cost estimation starts with referring to the product or system whose cost is to be estimated, as a Target unit. Once the target unit is established, primary and secondary model units are searched which would match the functionality of the target unit. Typically if the target unit is a large system then the primary and secondary units will be sub-systems or product. At this stage there is data available for sub-systems in the EIOLCA database either as the sub-system itself forming a sector or the constituents of the sub-system forming sectors. EIOLCA analysis can be done on the individual constituent sectors and then added up. The EIOLCA analysis can be conducted on each of the models (likely candidates to become a PMU) and the one which is having the desired effect on economy, environment and employment can be chosen as the Primary Model Unit. As shown in the figure 4.2. First, find if the target unit has a sector of its own in the EIOLCA database. If the sector exists then perform EIOLCA analysis upon it. If not, then split up the target unit into constituent units until a sector is obtained for each of the constituent units. Sometimes the constituent units might happen to be the materials that make up the unit. Once all the sectors are obtained, an EIOLCA analysis is performed on three aspects

1. The economic effect on other sectors
2. Effect on Environment due to each sector
3. Effect on employment due to each sector

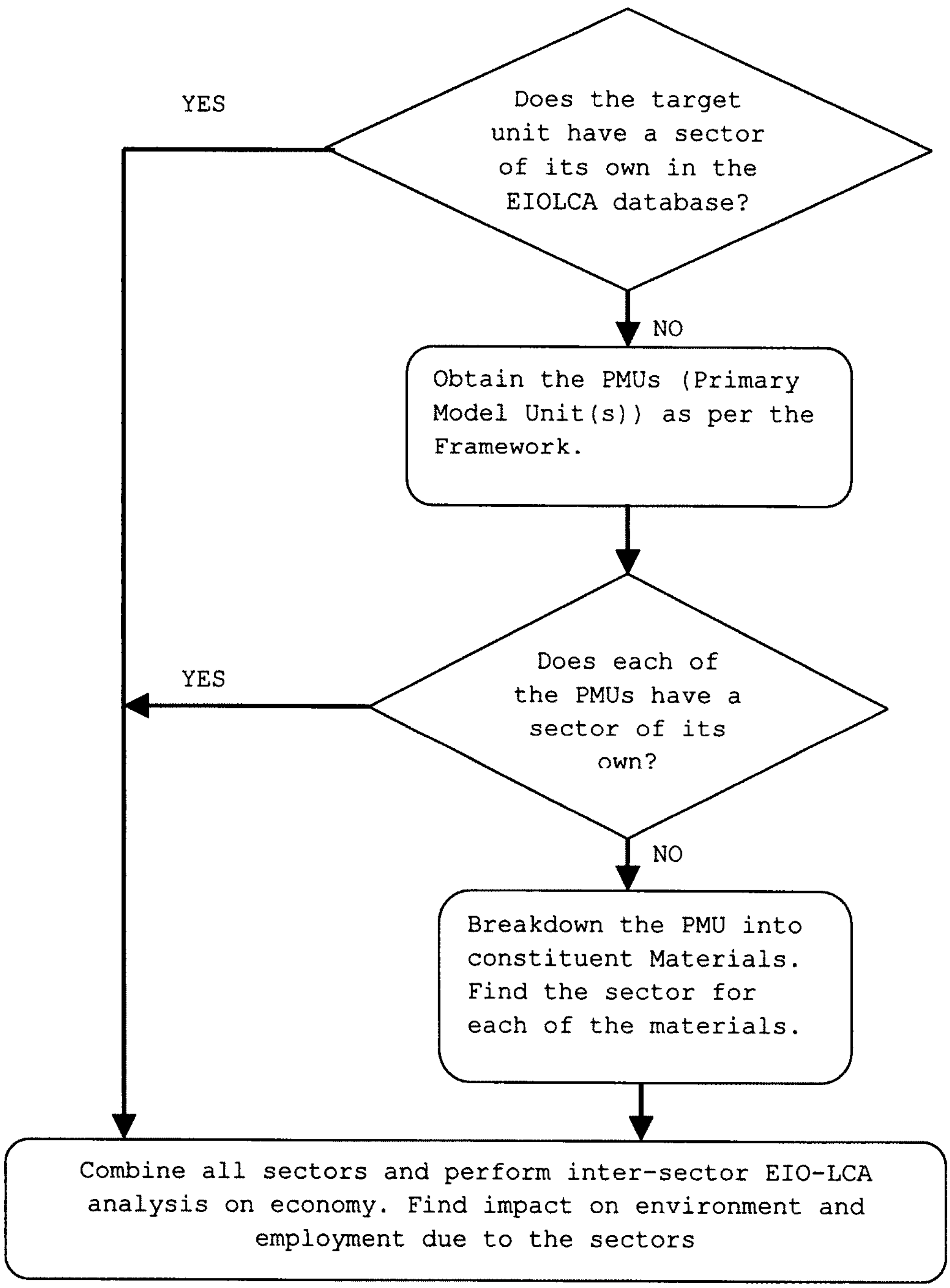


Figure 4.2 Implementation of EIO-LCA According to the Framework

4.5.1 Example 1 [58]

Suppose a pavement is to be constructed that is 1km-long asphalt then according to the flowchart above we first see if a sector already exists which can supply EIOLCA data for analysis. Once the appropriate sector is found, calculate the outputs in terms of economic, environmental and social aspects per a dollars worth of the pavement. Once the per-dollar effects of this sector are known from the EIOLCA database, the effects for the total cost of the pavement can be calculated. However, the decision makers are mostly interested in the per-dollar values since it gives a relative comparison of the effect on each sector. In this and all the EIO-LCA analysis the data has been obtained from www.EIOLCA.net.

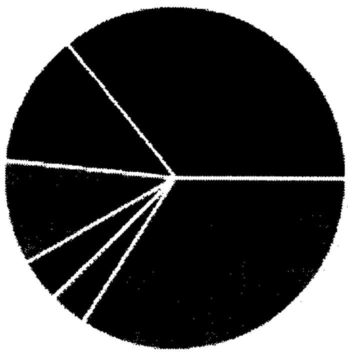
In the current example, the most appropriate commodity sector is asphalt paving mixtures and blocks.

	Sector	**Direct Economic $mill**	**Direct Economic %**
324121	Asphalt paving mixture and block manufacturing	1.013473	100
324110	Petroleum refineries	0.307019	85.9
212320	Sand, gravel, clay, and refractory mining	0.092669	94.4
550000	Management of companies and enterprises	0.072466	62.5
420000	Wholesale trade	0.052884	53.2
484000	Truck transportation	0.047789	73.3
221200	Natural gas distribution	0.019883	74.6
221100	Power generation and supply	0.019405	48.6
211000	Oil and gas extraction	0.016488	5.93
541700	Scientific research and development services	0.013043	62.3
483000	Water transportation	0.012345	88.4
482000	Rail transportation	0.012145	74.3
212310	Stone mining and quarrying	0.010279	84
52A000	Monetary authorities and depository credit intermediation	0.006927	34
541100	Legal services	0.006848	35.4
325110	Petrochemical manufacturing	0.006535	57
5419A0	All other miscellaneous professional and technical services	0.006176	46.1
493000	Warehousing and storage	0.005686	57.5

Table 4.2: Economic Effect on Other Sectors Due to the Asphalt Sector

In the table 4.2 the results of the economic effect have been sorted according to the "Direct Economic $mill" column. The sectors are therefore arranged in descending order of direct dollars. The Direct Economic effect can be explained as the purchase made by the Asphalt sector from other sectors in monetary terms to produce $1 million of its product. The table shows that the most purchase is made from the Petroleum Refining sector, which is expected.

The Asphalt paving mixture and block manufacturing sector is at the top of this list. The Direct Economic effect for the Asphalt sector is $1.013 million. This includes the $1 million of economic activity entered for the Asphalt sector plus the $0.013 million of purchases within the sector. The $0.013 million represents purchases by facilities in this sector from other facilities also in this sector. Figure 4.3 shows this data as a pie-chart.



324121 Asphalt paving mixture and block manufacturing	1.0
324110 Petroleum refineries	0.4
211000 Oil and gas extraction	0.3
550000 Management of companies and enterprises	0.1
420000 Wholesale trade	0.1
All Other Sectors(486 remaining sectors)	1.0

Figure 4.3: Economic Effect on Other Sectors Due to the Asphalt Sector

As discussed in the introduction to this section, the life cycle assessment of a product examines the environmental impact due to the product life-cycle. In order to study the environmental impacts, the pollutants (solid, liquid and gases) emitted into land, water and the atmosphere must be calculated. The EIO-LCA study looks at

1. conventional air pollutants such as SO2, CO, NOx, volatile organic compounds, and particulate matter;
2. greenhouse gas emissions such as CO2, CH4, N2O, and chloro-Floro Carbons;
3. Toxic Releases which include toxic waste released into land, water and air.

For the Asphalt example the conventional air pollutants are shown in table 4.3. Table 4.4 shows the greenhouse gas emissions and table 4.5 shows the toxic releases. Table 4.6 looks at the energy demand and table 4.7 shows the employment generated in each sector for a dollars input into the asphalt industry.

On the other hand the same impacts such as conventional air pollutants, greenhouse gas emissions, toxic releases, energy demand and employment, for the concrete sector are reflected in tables 4.8, 4.9, 4.10, 4.11 and 4.12, respectively.

Once the data shown in the tables above is obtained, the stakeholders can make a choice between different options of the product (asphalt or concrete) to best balance cost and social, economic and environmental effects.

	Sector	SO2 mt	CO mt	NOx mt	VOC mt	Lead mt	PM10 mt
	Total for all sectors	4.8400	12.9000	4.5200	3.8600	0.0000	2.4200
484000	Truck transportation	0.0217	7.1220	0.5134	0.5300	0.0000	0.0126
324121	Asphalt paving mixture and block manufacturing	1.4167	2.0464	1.2593	1.4167	0.0000	2.0324
420000	Wholesale trade	0.0023	0.6610	0.0595	0.0499	0.0000	0.0016
48A000	Scenic and sightseeing transportation and support activities for transportation	0.0000	0.4972	0.0000	0.0000	0.0000	0.0000
211000	Oil and gas extraction	0.2705	0.4599	0.2015	0.3096	0.0000	0.0095
562000	Waste management and remediation services	0.0033	0.3144	0.0161	0.0526	0.0001	0.0476
212310	Stone mining and quarrying	0.1455	0.2723	0.1024	0.0516	0.0000	0.0301
324110	Petroleum refineries	0.4065	0.2356	0.0917	0.3252	0.0000	0.0417
486000	Pipeline transportation	0.0010	0.1605	0.0084	0.0042	0.0000	0.0001
492000	Couriers and messengers	0.0007	0.1410	0.0200	0.0111	0.0000	0.0006
221100	Power generation and supply	2.1317	0.1053	0.9637	0.0094	0.0000	0.0451
115000	Agriculture and forestry support activities	0.0001	0.1029	0.0004	0.0095	0.0000	0.0131
331111	Iron and steel mills	0.0120	0.1013	0.0093	0.0057	0.0001	0.0084
213112	Support activities for oil and gas operations	0.1098	0.0910	0.0651	0.0288	0.0000	0.0165
483000	Water transportation	0.0913	0.0628	0.4822	0.4635	0.0000	0.0446
S00202	State and local government electric utilities	0.0031	0.0521	0.0032	0.0132	0.0000	0.0003
482000	Rail transportation	0.0226	0.0492	0.4249	0.0199	0.0000	0.0094
493000	Warehousing and storage	0.0015	0.0492	0.0031	0.0000	0.0000	0.0249
327310	Cement manufacturing	0.0473	0.0307	0.0604	0.0473	0.0000	0.0073
331312	Primary aluminum production	0.0040	0.0224	0.0000	0.0002	0.0000	0.0010
212320	Sand, gravel, clay, and refractory mining	0.0142	0.0220	0.0155	0.0128	0.0000	0.0080

Table 4.3: Environmental Effect (Conventional Air Pollutants) by Other Sectors Due to the Asphalt Sector

VOC: Volatile organic compounds
PM10: Particulate matter less than 10 microns in diameter
mt: metric tons

	Sector	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E
	Total for all sectors	1920.00	1590.00	314.00	8.23	13.10
324121	Asphalt paving mixture and block manufacturing	533.61	533.61	0.00	0.00	0.00
221100	Power generation and supply	392.98	388.26	0.00	0.00	4.73
211000	Oil and gas extraction	259.25	43.50	215.75	0.00	0.00
324110	Petroleum refineries	249.39	248.01	1.38	0.00	0.00
484000	Truck transportation	100.88	99.34	0.15	1.39	0.00
486000	Pipeline transportation	83.41	40.13	43.28	0.00	0.00
212320	Sand, gravel, clay, and refractory mining	53.71	53.71	0.00	0.00	0.00
562000	Waste management and remediation services	27.26	4.31	22.92	0.03	0.00
221200	Natural gas distribution	20.44	4.37	16.08	0.00	0.00
483000	Water transportation	14.65	14.42	0.06	0.17	0.00
S00202	State and local government electric utilities	14.40	14.40	0.00	0.00	0.00
482000	Rail transportation	13.77	13.60	0.04	0.13	0.00
327310	Cement manufacturing	13.48	13.48	0.00	0.00	0.00
212100	Coal mining	12.81	0.85	11.95	0.00	0.00
331111	Iron and steel mills	10.43	10.43	0.00	0.00	0.00
481000	Air transportation	8.85	8.75	0.01	0.09	0.00
493000	Warehousing and storage	8.42	8.42	0.00	0.00	0.00
325120	Industrial gas manufacturing	8.08	2.31	0.00	0.00	5.77
325110	Petrochemical manufacturing	7.51	7.51	0.00	0.00	0.00
420000	Wholesale trade	7.11	7.11	0.00	0.00	0.00
325180	Other basic inorganic chemical manufacturing	6.58	6.58	0.00	0.00	0.00

Table 4.4: Greenhouse Gas Emissions Due to the Asphalt Sector

Greenhouse Gases
GWP: Global Warming Potential is a weighting of greenhouse gas emission into the air.
MT: Metric Tons

	Sector	Non-Point Air kg	Point Air kg	Tot Air Releases kg	Water Releases kg	Land Releases kg
	Total for all sectors	34.900	133.000	168.000	37.200	185.000
221100	Power generation and supply	0.023	58.494	58.517	0.313	21.482
324110	Petroleum refineries	21.174	31.746	52.920	20.047	1.079
324121	Asphalt paving mixture and block manufacturing	0.967	5.593	6.559	0.000	0.009
325110	Petrochemical manufacturing	2.429	3.393	5.822	2.405	0.137
325180	Other basic inorganic chemical manufacturing	1.001	3.401	4.402	1.381	2.776
211000	Oil and gas extraction	1.044	2.557	3.601	3.521	4.845
3221A0	Paper and paperboard mills	0.118	3.212	3.330	0.369	0.330
325190	Other basic organic chemical manufacturing	1.138	1.935	3.074	1.152	0.066
331419	Primary nonferrous metal, except copper and aluminum	0.089	2.762	2.851	0.220	3.801
322110	Pulp mills	0.198	2.491	2.690	0.335	0.232
325211	Plastics material and resin manufacturing	0.478	1.036	1.514	0.113	0.006
327310	Cement manufacturing	0.020	1.391	1.411	0.000	0.621
32619A	Plastics plumbing fixtures and all other plastics products	0.245	1.107	1.352	0.003	0.001
325311	Nitrogenous fertilizer manufacturing	0.116	1.123	1.239	0.155	0.007
325120	Industrial gas manufacturing	0.532	0.611	1.143	0.655	0.034
327992	Ground or treated minerals and earths manufacturing	0.020	1.072	1.092	0.123	0.039
332812	Metal coating and nonprecious engraving	0.275	0.573	0.848	0.001	0.001
332430	Metal can, box, and other container manufacturing	0.286	0.513	0.799	0.001	0.000
32311A	Commercial printing	0.364	0.418	0.782	0.000	0.000

Table 4.5: Environmental Effect (Toxic Releases) on Other Sectors Due to the Asphalt Sector

	Sector	Total TJ	Elec MkWh	Coal TJ	NatGas TJ
	Total for all sectors	26.100	0.672	4.040	12.900
324121	Asphalt paving mixture and block manufacturing	10.161	0.232	0.000	6.747
221100	Power generation and supply	4.661	0.000	3.692	0.826
324110	Petroleum refineries	4.648	0.085	0.000	2.253
212320	Sand, gravel, clay, and refractory mining	0.978	0.082	0.091	0.548
211000	Oil and gas extraction	0.972	0.100	0.000	0.759
484000	Truck transportation	0.723	0.002	0.000	0.015
486000	Pipeline transportation	0.660	0.015	0.000	0.643
483000	Water transportation	0.613	0.000	0.001	0.002
482000	Rail transportation	0.233	0.000	0.000	0.001
325110	Petrochemical manufacturing	0.156	0.003	0.000	0.141
325180	Other basic inorganic chemical manufacturing	0.148	0.013	0.000	0.124
481000	Air transportation	0.137	0.000	0.000	0.000
493000	Warehousing and storage	0.133	0.004	0.000	0.020
331111	Iron and steel mills	0.132	0.006	0.006	0.112
420000	Wholesale trade	0.130	0.008	0.000	0.057
S00202	State and local government electric utilities	0.129	0.000	0.129	0.000
327310	Cement manufacturing	0.116	0.004	0.075	0.033
221200	Natural gas distribution	0.083	0.000	0.000	0.061
550000	Management of companies and enterprises	0.080	0.019	0.000	0.054
48A000	Scenic and sightseeing transportation and support activities for transportation	0.076	0.001	0.000	0.000
3221A0	Paper and paperboard mills	0.069	0.004	0.018	0.035
562000	Waste management and remediation services	0.067	0.001	0.000	0.009
325190	Other basic organic chemical manufacturing	0.064	0.004	0.010	0.045
324191	Petroleum lubricating oil and grease manufacturing	0.059	0.000	0.000	0.001
212310	Stone mining and quarrying	0.059	0.007	0.001	0.007

Table 4.6: Energy Demand by Other Sectors Due to the Asphalt Sector

	Sector	Total Employees
	Total for all sectors	11.6000
324121	Asphalt paving mixture and block manufacturing	2.4211
420000	Wholesale trade	2.2956
212320	Sand, gravel, clay, and refractory mining	0.6492
550000	Management of companies and enterprises	0.6195
484000	Truck transportation	0.5096
211000	Oil and gas extraction	0.3373
561300	Employment services	0.3353
722000	Food services and drinking places	0.1635
541700	Scientific research and development services	0.1599
493000	Warehousing and storage	0.1498
324110	Petroleum refineries	0.1489
541100	Legal services	0.1318
52A000	Monetary authorities and depository credit intermediation	0.1210
541200	Accounting and bookkeeping services	0.1152
221100	Power generation and supply	0.1059
4A0000	Retail trade	0.1018
48A000	Scenic and sightseeing transportation and support activities for transportation	0.0998
482000	Rail transportation	0.0955
541300	Architectural and engineering services	0.0935
7211A0	Hotels and motels, including casino hotels	0.0882
522A00	Non-depository credit intermediation and related activities	0.0858
230340	Other maintenance and repair construction	0.0711
492000	Couriers and messengers	0.0697
212310	Stone mining and quarrying	0.0690
561700	Services to buildings and dwellings	0.0689
332710	Machine shops	0.0627
32311A	Commercial printing	0.0576
561400	Business support services	0.0568
33441A	All other electronic component manufacturing	0.0557
513300	Telecommunications	0.0538
491000	Postal service	0.0536
531000	Real estate	0.0535
561600	Investigation and security services	0.0523
541610	Management consulting services	0.0517
611A00	Colleges, universities, and junior colleges	0.0514
221200	Natural gas distribution	0.0514

Table 4.7: Employment Effect Due to the Asphalt Sector

As mentioned earlier in this section, the purpose of EIO-LCA is also to look into the effects of industrial activity on the employment. A dollar of money spent on a certain sector results in employment. By performing an EIO-LCA analysis, the decision makers can visualize the geographical impact on employment. The figure 4.4 shows the employment generated or sustained in each of the states.

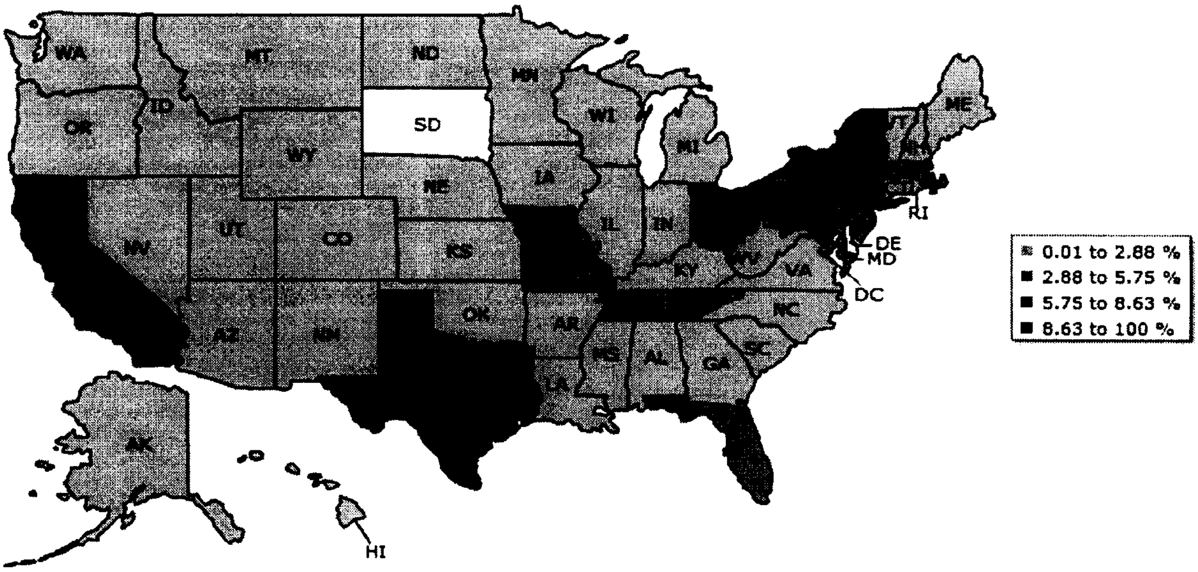


Figure 4.4: Effect on Employment on Each of the States of the USA

4.5.2 Example 2:[58]

The previous example involved a single sector; that is, the product on which EIOLCA analysis is to be applied happened to be a sector by itself. This is relatively easy case. Sometimes, the product does not fall under one sector; or, in other words, one sector does not encompass the product. In these cases as discussed in the flowchart, the product would have to be broken into constituent sub-systems or materials.

For example, if the same road discussed in the previous example were to be constructed out of steel reinforced concrete, then first the database would have to be searched for an appropriate sector. Due to the nature of the product a single sector cannot be found that is appropriate to capture the effect of the product on the economy, environment, and employment. So the product is separated out into its constituents, concrete and steel. The database is again searched to see if there are sectors which represents these constituents. The sector that closely resembles concrete is the Ready-mix concrete manufacturing sector. So an EIOLCA analysis is performed on this sector. Below is a partial table of the results of economic effect on other sectors due to a dollars spending in the Ready-mix concrete manufacturing sector.

	Sector	Total Economic $mill	Value Added $mill	Direct Economic $mill	Direct Economic %
	Total for all sectors	2.180	0.993	1.630	74.800
327320	Ready-mix concrete manufacturing	1.012	0.370	1.011	99.900
327310	Cement manufacturing	0.177	0.091	0.165	93.200
484000	Truck transportation	0.103	0.050	0.079	76.500
212320	Sand, gravel, clay, and refractory mining	0.075	0.044	0.071	94.200
212310	Stone mining and quarrying	0.048	0.026	0.042	86.700
550000	Management of companies and enterprises	0.059	0.042	0.029	49.700
420000	Wholesale trade	0.056	0.037	0.027	49.100
325180	Other basic inorganic chemical manufacturing	0.026	0.011	0.023	85.900
482000	Rail transportation	0.018	0.010	0.014	75.700
483000	Water transportation	0.011	0.003	0.010	87.000
811300	Commercial machinery repair and maintenance	0.013	0.008	0.008	64.000
52A000	Monetary authorities and depository credit intermediation	0.016	0.012	0.008	46.400
327992	Ground or treated minerals and earths manufacturing	0.011	0.007	0.006	53.000
5419A0	All other miscellaneous professional and technical services	0.010	0.008	0.006	59.700
221100	Power generation and supply	0.030	0.019	0.006	18.500
S00203	Other State and local government enterprises	0.010	0.005	0.005	55.600
334413	Semiconductors and related device manufacturing	0.011	0.007	0.005	49.400
8111A0	Automotive repair and maintenance, except car washes	0.011	0.005	0.005	50.900
811200	Electronic equipment repair and maintenance	0.008	0.005	0.005	59.900
221200	Natural gas distribution	0.014	0.005	0.005	35.000

Table 4.8: Economic Effect on Other Sectors Due to the Concrete Sector

	Sector	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E
	Total for all sectors	2030	1930	76.7	9.73	9.59
327310	Cement manufacturing	1068.142	1068.142	0.000	0.000	0.000
221100	Power generation and supply	296.916	293.345	0.000	0.000	3.570
327320	Ready-mix concrete manufacturing	163.011	163.011	0.000	0.000	0.000
484000	Truck transportation	159.869	157.429	0.244	2.197	0.000
212320	Sand, gravel, clay, and refractory mining	41.017	41.017	0.000	0.000	0.000
325180	Other basic inorganic chemical manufacturing	27.221	27.221	0.000	0.000	0.000
562000	Waste management and remediation services	24.895	3.936	20.929	0.030	0.000
211000	Oil and gas extraction	22.974	3.855	19.119	0.000	0.000
212100	Coal mining	18.114	1.206	16.908	0.000	0.000
486000	Pipeline transportation	17.423	8.383	9.041	0.000	0.000
482000	Rail transportation	15.399	15.206	0.048	0.144	0.000
212310	Stone mining and quarrying	13.438	13.438	0.000	0.000	0.000
324110	Petroleum refineries	12.657	12.587	0.070	0.000	0.000
S00202	State and local government electric utilities	11.773	11.773	0.000	0.000	0.000
483000	Water transportation	11.613	11.431	0.045	0.136	0.000
221200	Natural gas distribution	10.613	2.267	8.346	0.000	0.000
327410	Lime manufacturing	8.877	8.877	0.000	0.000	0.000
481000	Air transportation	7.638	7.547	0.010	0.081	0.000
212390	Other nonmetallic mineral mining	6.746	6.746	0.000	0.000	0.000
331111	Iron and steel mills	6.488	6.488	0.000	0.000	0.000
325311	Nitrogenous fertilizer manufacturing	6.081	2.746	0.000	3.335	0.000
3221A0	Paper and paperboard mills	4.259	4.259	0.000	0.000	0.000
420000	Wholesale trade	3.974	3.974	0.000	0.000	0.000
325190	Other basic organic chemical manufacturing	3.593	2.471	0.000	1.122	0.000

Table 4.9: Greenhouse Gas Emissions Due to the Concrete Sector

	Sector	Total Employees
	Total for all sectors	12.7
327320	Ready-mix concrete manufacturing	5.350802
420000	Wholesale trade	1.283759
484000	Truck transportation	0.807631
212320	Sand, gravel, clay, and refractory mining	0.495773
327310	Cement manufacturing	0.473357
550000	Management of companies and enterprises	0.3169
212310	Stone mining and quarrying	0.270328
561300	Employment services	0.222654
722000	Food services and drinking places	0.141834
4A0000	Retail trade	0.126334
482000	Rail transportation	0.106775
48A000	Scenic and sightseeing transportation and support activities for transportation	0.105827
541200	Accounting and bookkeeping services	0.099929
52A000	Monetary authorities and depository credit intermediation	0.097323
493000	Warehousing and storage	0.086061
221100	Power generation and supply	0.079981
7211A0	Hotels and motels, including casino hotels	0.073628
522A00	Non-depository credit intermediation and related activities	0.072159
325180	Other basic inorganic chemical manufacturing	0.066257
811300	Commercial machinery repair and maintenance	0.064543
541300	Architectural and engineering services	0.062868

Table 4.10: Effect on Employment Due to the Concrete Sector

After performing the EIOLCA analysis for concrete, perform the same analysis for steel, which is the other constituent in steel reinforced concrete pavement. Once the analysis is performed on steel, add the results of concrete and steel together to get the complete picture.

Similarly, a search of the word 'concrete' gives a list of choices including **"ready mixed concrete."** This appears to be the best match for the type of concrete in pavement. A search for "steel" reveals a list of choices which **"iron and steel mills"** appearing to be the most appropriate.

	Sector	Total Economic $mill	Value Added $mill	Direct Economic $mill
	Total for all sectors	2.32	0.87	1.66
331111	Iron and steel mills	1.122	0.265	1.093
420000	Wholesale trade	0.137	0.092	0.091
212210	Iron ore mining	0.045	0.015	0.037
484000	Truck transportation	0.058	0.028	0.035
212100	Coal mining	0.043	0.020	0.031
221100	Power generation and supply	0.048	0.030	0.026
482000	Rail transportation	0.030	0.017	0.022
331112	Ferroalloy and related product manufacturing	0.026	0.011	0.021
550000	Management of companies and enterprises	0.046	0.033	0.017
335991	Carbon and graphite product manufacturing	0.017	0.009	0.015
811300	Commercial machinery repair and maintenance	0.016	0.010	0.012
331210	Iron, steel pipe and tube from purchased steel	0.015	0.005	0.012
331419	Primary nonferrous metal, except copper and aluminum	0.016	0.002	0.011
221200	Natural gas distribution	0.015	0.005	0.010
331221	Rolled steel shape manufacturing	0.014	0.003	0.010
327410	Lime manufacturing	0.012	0.004	0.010
8111A0	Automotive repair and maintenance, except car washes	0.012	0.006	0.008
52A000	Monetary authorities and depository credit intermediation	0.018	0.013	0.008
331492	Secondary processing of other nonferrous	0.011	0.002	0.007
811200	Electronic equipment repair and maintenance	0.010	0.006	0.007
325120	Industrial gas manufacturing	0.008	0.004	0.006
5419A0	All other miscellaneous professional and technical services	0.011	0.008	0.006

Table 4.11: Economic Effect on Other Sectors Due to the Steel Sector

	Sector	Total Employees
	Total for all sectors	11.8
420000	Wholesale trade	3.170315
331111	Iron and steel mills	2.877179
484000	Truck transportation	0.453291
561300	Employment services	0.257935
550000	Management of companies and enterprises	0.247933
212210	Iron ore mining	0.184847
482000	Rail transportation	0.178122
212100	Coal mining	0.161782
722000	Food services and drinking places	0.149964
221100	Power generation and supply	0.127094
52A000	Monetary authorities and depository credit intermediation	0.104157
332710	Machine shops	0.08982
48A000	Scenic and sightseeing transportation and support activities for transportation	0.089795
811300	Commercial machinery repair and maintenance	0.084173
335991	Carbon and graphite product manufacturing	0.08307
4A0000	Retail trade	0.082836
7211A0	Hotels and motels, including casino hotels	0.079853
541200	Accounting and bookkeeping services	0.079176
522A00	Nondepository credit intermediation and related activities	0.072176
331112	Ferroalloy and related product manufacturing	0.071493
33441A	All other electronic component manufacturing	0.066013
492000	Couriers and messengers	0.064484
8111A0	Automotive repair and maintenance, except car washes	0.061929
493000	Warehousing and storage	0.06032
331510	Ferrous metal foundries	0.059874
332600	Spring and wire product manufacturing	0.0598

Table 4.12: Employment Effect on Other Sectors Due to the Steel Sector

4.6 Conclusion of the EIOLCA

The EIOLCA analysis shows the energy used to produce a given amount of economic activity along with the Ozone Depleting Potential of the emissions resulting from the economic activity. By sorting the data, it is possible to determine which sectors have the maximum impact. The conventional Pollutants data lists the SO2, CO, NOx, Lead, VOC, and PM10 resulting for the economic transactions throughout the entire 500 sector supply chain. Again the data may be sorted to determine which sectors are predominantly contributing to the emissions. In the asphalt example, many of the contributing sectors to the asphalt sector also contribute to the release of NOx, and the asphalt sector itself is the largest contributor of CO emissions. Through similar analysis the amount of pollutants as well as fertilizers used through the supply chain can be obtained. The analysis of fuels shows the amounts of various fuels required throughout the supply chain for the production of the commodity.

4.7 Environmental Valuation

In section 4.7 we have seen the EIO-LCA implications of the decisions made during the conceptual design of any unit. However, some of the environmental implications are in terms of a certain amount of solid liquid or gaseous waste in units of weight. Since cost of the unit is the primary purpose of the proposed enterprise-wide cost estimation framework, the environmental implications also need to be converted into a dollar amount. Once this is done, the cost of the unit can be written as

Enterprise Cost = Acquisition Cost + Life Cycle Cost (if data available) + EIO-LCA Cost

Conversion of EIO-LCA data to a dollar value helps in making comparative analysis of various design options during conceptual design stage.

Congress required the Environmental Protection Agency (EPA) to examine the costs and benefits of the Clean Air Act retrospectively from 1970 to 1990 and then prospectively from 1990 to 2010 [Hendrickson 58].

4.7.1 Damage Functions

In order to make design-decisions based on environmental aspects of EIO-LCA, the monetary valuation of pollution or in other words the monetary benefits of controlling pollution should be estimated. The way this is accomplished is by estimating the effect of pollution on things important to the ecosystem such as health, visibility, material deterioration and damage to environment [58]. The next step is to estimate the cost of preventing damage to human health, ecology and cost of repairing material damages. The effort in estimating the damage or cost of preventing/repairing that damage is relatively easy when it comes to material damages as compared to estimating the damage to human health or the environmental.

4.7.2 Willingness to Pay

As discussed earlier, it is relatively easy to estimate the cost of replacing material such as a steel structure affected by pollution as compared to monetizing the value of fewer asthma attacks or having better visibility [58]. Consumers determine the price of the products in the market but there is no market for human health. The economists have therefore created a surrogate market by asking people how much they would be willing to pay for improvement in health conditions, visibility etc. What is being monetized is a small change in the likelihood of premature death of an individual already at risk. The economists ask for willingness to pay in order to reduce the probability of dying from 0.01% to say 0.02% [58].

Initially this small probability of premature death was evaluated by estimating the amount of earnings the individual would make during the rest of his life. Another valuation was the amount that would be awarded to the victims in a wrongful death lawsuit.

In the 1990s several U.S. states conducted an Externality Adders study to take into account the social cost of power generation plants. Some studies have been conducted to estimate social damages. Below is a sample of studies and the costs [58].

Emission	Number of Studies	Estimated External Costs $ per metric ton of air emission			
		Min	Median	Mean	Max
Carbon monoxide (CO)	2	1	580	580	1,200
Nitrogen Oxides (NOx)	9	230	1,200	3,100	11,000
Sulphur Dioxide (SO2)	10	850	1,900	2,200	5,200
Particulate Matter (PM10)	12	1,000	3,100	4,700	18,000
Volatile Organic Compounds (VOCs)	5	200	1,500	1,800	1,900
Global Warming Potential (CO2 equivalents)	4	2	15	15	25

Table 4.13: Social Damage Estimates (1997$) from Air Emissions [58]

Thus, incorporating the externality adders to the cost of acquisition and life cycle, the total cost of the unit can be obtained.

Applying the externality cost to the Asphalt Paving Mixture example (Table 4.3) we get the following results.

Sector	SO2 mt	CO mt	NOx mt	VOC mt	PM10 mt	CO2 mt
Total for all sectors	4.8400	12.9000	4.5200	3.8600	2.4200	1,500
$ per Ton of Air Emission	2,200	580	3,100	1,800	4,700	15
$ due to each of the Emissions	10,648	7,482	14,012	6,948	11,374	22,500
Grand Total due to all of the Emissions ($)						**72,964**

Table 4.14: Environmental Cost of Asphalt Road

Thus, the external effects of certain design decisions made during the conceptual design process can be measured and used in the feedback loop to improve the design or optimize its effects on acquisition cost and/or the environmental effects of the design. All the EIO-LCA data for the sectors have been obtained from www.eiolca.net.

Chapter 5: CASE STUDY

5.1 Synopsis of the Case Study

In this case study, the cost of a CTM-Structure (Chemical Transfer Module) has been estimated following the steps of the proposed framework. In addition to the cost of the CTM, the economic, environmental, and social impact of the various design alternatives have also been obtained. The case study starts with introduction to OASIS (Orbital Aggregation & Space Infrastructure Systems) and knowing the various elements in it [59]. Sections 5.2 through 5.10.1 are excerpts from [59] in order to give the reader an insight into the architecture of the OASIS system. Then the requirements of the CTM-Structure are obtained. These requirements are provided by the stakeholders and are in non-technical terms. Using the Systems Engineering methodology these requirements are converted into technical performance measures (TPMs).

These TPMs form the baseline for the system being designed and cost of which is being estimated. Once the baseline is setup a search is done to obtain various Model Units that are similar to the CTM structure in terms of the TPMs. The two Model Units that were obtained as result of thorough research are the Space Shuttle ET (External Tank) and the Hybrid Propellant Module (HPM) structure. Using techniques such as AHP (Analytical Hierarchy Process), the Model Units are compared quantitatively, not just to the TPMs but they are also compared on the basis of EIOLCA (Economic Input Output Life Cycle Assessment) elements such as Economic Activity, Pollution, Energy and Employment in several sectors of the US economy.

The HPM Structure emerged as the Primary Model Unit (PMU) for the CTM structure. In order to estimate the cost of the CTM Structure, a preliminary design was proposed and tested using FEA (Finite Element Analysis) to confirm that the design can handle the load requirements. Based on the cost drivers and parameters of the HPM Structure, a similar cost model was derived for the CTM structure.

5.2 Introduction to the OASIS Program

OASIS (Orbital Aggregation & Space Infrastructure Systems) is a set of concepts that provide a common infrastructure for enabling a large class of space missions. The concepts include communication, navigation, propellant modules, tank farms, habitats, and transfer systems using several propulsion technologies. The anticipated benefits of OASIS are lower costs and increased mission flexibility for future space exploration and commercialization initiatives [59].

OASIS Elements

1. HPM
2. CTV
3. CTM
4. SEPS
5. LG

5.2.1 Hybrid Propellant Module (HPM)

HPM is a module that combines both chemical and electrical propellant in conjunction with modular orbital transfer/engine stages and was targeted as the core OASIS element [59]. The fundamental concept for an HPM-based transportation architecture requires two HPMs and two propulsive transfer stages-one chemical-based and one electric-based. The basic philosophy is to utilize the chemical propellant stored onboard the HPM along with the chemical transfer/engine stage to provide high thrust during the time critical segments of a mission (e.g. crew transfer), and utilize the electricity with a solar transfer/engine stage during non-time critical segments of the mission (e.g. pre-positioning an HPM for crew return segment of the mission, and return of an HPM to its parking orbit)[59]. This architecture can save a significant amount of propellant when compared to a chemical-only mission. That is, assuming that the efficiency of the electrical propulsion system is significantly greater than the chemical propulsion system. For the currently base-lines propellants, liquid oxygen (LOX) and liquid Hydrogen (LH2)are assumed to have a specific impulse of 466 seconds, and the electrical and the electric propellant Xenon has an Isp(Specific Impulse) of 3000 seconds [59]. The larger the difference between the chemical and electrical specific impulse values, the greater the benefit of employing an HPM-based architecture [59].

5.2.2 The Chemical Transfer Module (CTM)

CTM is an OASIS element that serves as a high-energy injection stage when attached to HPM. The CTM also functions independently of the HPM as an autonomous orbital maneuvering vehicle for proximity operations. These operations could be ferrying payloads a short distance, refueling and servicing. The CTM has high thrust cryogenic LOX/LH2 engines for orbit transfers and high-pressure LOX/LH2 thrusters for proximity operations and small Delta-V maneuvers [59]. The CTM can store roughly 4000 kg of LOX/LH2 and a small amount of Xenon (Xe) and may utilize the internally stored chemical propellant or burn propellant directly transferred from the HPM. The CTM does not incorporate zero boil-off technology [59].

5.2.3 The Solar Electric Propulsion (SEP)

The SEP stage serves as a low-thrust transfer stage when attached to an HPM for pre-positioning large or massive elements or for the slow return of elements for refurbishing and refueling [59].

5.2.4 The Crew Transfer Vehicle (CTV)

CTV is used to transfer crew in a shirt sleeve environment from LEO (Low Earth Orbit) to the Lunar Gateway and back. It can also be used to transfer crew between the International Space Station (ISS) and any other crewed orbiting vehicle.

5.2.5 The Lunar Gateway (LG)

The Lunar Gateway is a unique crew habitation and mission staging platform for expanding and maintaining human presence beyond LEO. The Gateway will serve as a technology tested for future human exploration beyond Earth's neighborhood [59].

5.3 OASIS Requirements

These requirements are intended to provide general guidance for NASA exploration study activities [59].

1. The NASA Exploration Team shall establish the integrated, cross-agency exploration strategy for NASA through the 21st century.
2. Exploration shall be science and discovery driven.
3. Exploration shall extend human presence beyond low-earth orbit when appropriate.
4. Humans and Robots shall explore together.
5. Identify technology development opportunities and identify and enable commercialization opportunities.
6. Exploration shall be safe and affordable.
7. The exploration strategy shall facilitate the NASA outreach efforts to inspire future generations of scientists and engineers.

5.4 HPM (Hybrid Propellant Module)

The Hybrid propellant module is a combination fuel depot and drop tank. It provides chemical propellant for transfers where time is critical and electrical propellant for pre-positioning or return of OASIS elements.

Modules or Sub-Systems of the HPM are [59]:

1. Structures and Mechanism
2. Propellant Management System

3. Guidance, Navigation and Control

4. Command and Data Handling/Communication and Tracking System

5. Electrical Power System

5.5 CTM (Chemical Transfer Module)

The CTM needs to serve as a high-energy injection stage when attached to the HPM. It also needs to act as an autonomous orbital maneuvering vehicle for proximity operations such as ferrying payloads a short distance, refueling and servicing. It should have a high thrust H_2O_2 engines for orbit transfer and high-pressure H2O2 thrusters for proximity operations and small delta-V translational and rotational maneuvers [59]. It should be capable of transferring and storing approximately 3000kg of cryogenic hydrogen and oxygen [59].

The CTM should be designed for launch by a shuttle-class launch vehicle. Four active longeron trunnions and a single keel trunnion may support the CTM in the launch vehicle cargo bay. Based on the requirements, the CTM deployed length is approximately 9.4m. The CTM width with solar arrays deployed is approximately 12.6m

The major components required to satisfy the CTM Requirements are [59]:

- Dual RL10 67KN class engines
- LOX tank
- Liquid Hydrogen tank
- Gaseous oxygen (GOX) RCS tank
- Six gaseous hydrogen (GH2) RCS tanks
- Two deployable solar arrays
- Avionics ORUs
- Two radiator panels

- Four sets of tri-pod RCS thrusters
- Four sets of tri-pod cold gas thrusters
- Docking adapter

The dual RL10 should be mounted twenty degrees off the CTM centerline on a fixed thrust structures. Two engines are required for reliability requirement. Only one engine is used at a time; the engine thrust must always be directed towards the vehicle centerline. A new gimbal system is required for this.

Two sets of tri-pod RCS thrusters and two sets of tri-pod cold gas thrusters will be mounted on the forward and aft end of the CTM. These are to prevent plume impingement on an attached HPM. The MMOD (Micro Meteoroid and Orbital Debris) shielding will be used to enclose the CTM tankage and plumbing to satisfy safety requirements.

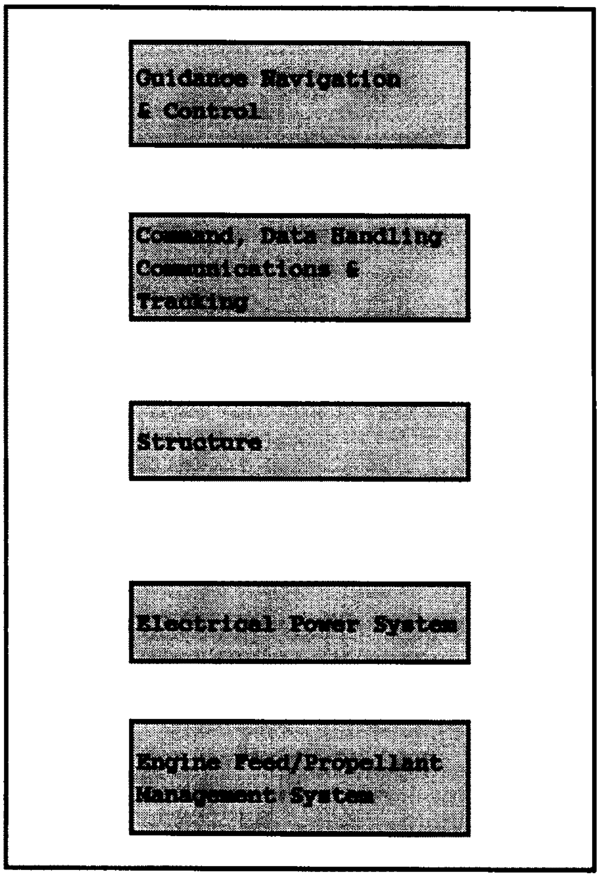


Figure 5.1 System and Sub-systems of CTM [59]

Figure 5.1 above shows the various sub-systems in the CTM. Since it is a very complicated system and out of the scope of this study, in this case study we will concentrate only on obtaining the cost of the structure of the CTM based on the framework developed so far.

5.6 Structure

The structural components of the CTM shall accomplish the following:

1. Provide a frame to carry loads
2. Protect the internal systems from micrometeoroid debris
3. Provide a means of attachment of internal systems
4. Protection against thermal and radiation environment

5.6.1 Mechanical Loads

The CTM design should meet the requirements of NASA Standard 5001 (Structural Design and Test Factors of Safety for Space Flight Hardware). The structural system shall withstand the launch loads from Shuttle class RLV or an augmented Delta IV-Heavy ELV. The in-service maximum loads case is assumed to be a 4 g acceleration resulting from CTM thrusters firing without an HPM attached [59].

a) Shuttle launch (maximum loads): -2.0to +3.0 g axial load; -1.0 to +1.0 g lateral load; -2.5 to +2.0 g normal load

b) CTM thrust (maximum): +4.0 g axial

5.6.2 Thermal Control

Since the storage tanks and the CTM do not have zero-boil off technology, a thermal shielding is required. The double wall shielding shall provide protection from the thermal environment. The empty space between the walls can be filled with insulating material to increase the system's effectiveness. The materials and weights used are the same as those for HPM, which are modeled from the non-critical shielding on the ISS. Radiation protection is required to protect CTM systems and components.

5.6.3 Micrometeoroid and Orbital Debris Protection

The exterior of the CTM could be comprised of two layers of syntactic aluminum foam filled with thermal blankets to protect the central elements of CTM from MMOD impacts. To allow on orbit accessibility to the internal ORUs a constant outer shell diameter is required. A Whipple shield system can be used on the CTM.

5.6.4 System Description

The CTM primary structure can be made of long carbon fiber metal matrix composites (MMC) that provide strength to weight ratio three times better than spacecraft aluminum. A Whipple type debris shield is used to protect the CTM from MMOD and incorporates materials to help with thermal control and radiation protection.

The CTM connects the HPM or the ISS through the IBDM and is outfitted with a fluid transfer interface so that it may utilize propellants from HPM.

An engine mount gimbal mechanism can be used to rotate the structure for proper engine alignment.

The engine mounts, engine alignment struts and IBDM connection points are MMC structural shapes that allow the loads to transfer into the reinforced shell structure. Trunnion fittings are required for launch systems and connect directly to the ring frames under the shield skin.

5.6.5 Technology Needs

An integrated primary multifunction structure including radiation protection and MMOD shielding is a structural system technology requirement for all OASIS elements.

Based on the requirements mentioned above of the stakeholders, the information is converted to technical performance measures. This process is shown below for the structure-system of the CTM.

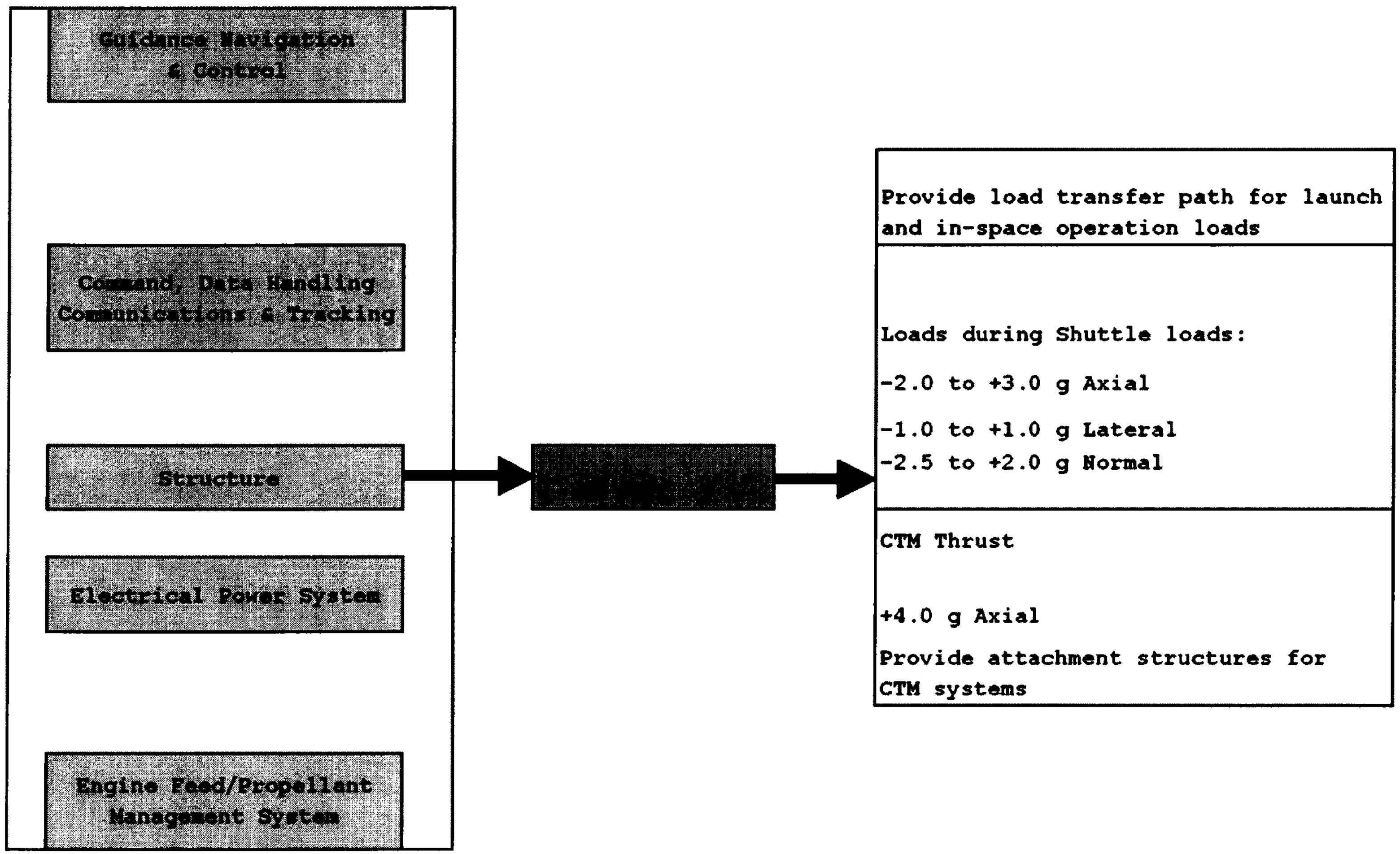


Figure 5.2 CTM Configuration and Structure TPMs [59]

We have seen above that the generic requirements supplied by the stakeholders are converted into technical terms. The process of converting to technical measures is further refined until a large super-system is broken down to smaller systems. The requirements for these systems are further analyzed to obtain lower level technical performance measures as shown above in the figure 5.2.

These technical performance measures are shown in detail below for each of the sub-systems of the CTM. It should be noted here that this information comes from literature and subject matter experts. The information, though vital, may not be complete.

5.7 Target Unit (CTM) Metrics

CTM Dimensions [59]

Length: 5.94 m (structure)

Max Diameter: 3.39 m

Lower Diameter: 2.67 m

Thrust Experienced: 4.0 Gs

Tanks Contained: LH2, LOX and LXe

LH2 Tank [59]

Barrel Length: 2.10 m

Inner Diameter: 2.79 m

LOX Tank [59]

Barrel Length: 1.50 m

Inner Diameter: 2.01 m

LXe Tank [59]

Barrel Length: 0.94 m

Inner Diameter: 0.91 m

Mechanical Loads [59]

Max Axial Load (During CTM engine burn): 4Gs

Max Axial Load (During Shuttle Launch): -2.0 to +3.0 g axial

Max Lateral Load (During Shuttle Launch): -1.0 to +1.0 g

Max Normal Load (During Shuttle Launch): -2.5 to +2.0 g

5.8 Search for Primary Model Unit (PMU)

Now that the technical performance measures are obtained, the next step according to the proposed framework is to do a search for similar systems. The search results are then further refined to obtain a system which resembles the Target Unit (CTM Structure) the most and is the best starting point to calculate the cost of the CTM Structure. The most similar unit is called the Primary Model Unit.

Likely candidates for the Target Unit: Structure are

1. Space Shuttle External Tank

2. HPM

5.9 Model Unit 1: Space Shuttle External Tank

External Tank TPMs [60]

Weight

Empty: 78,100 pounds

Propellant: 1,585,379 pounds

Gross: 1,667,677 pounds

Propellant Weight

Liquid oxygen: 1,359,142 pounds

Liquid hydrogen: 226,237 pounds

Gross: 1,585,379 pounds

Propellant Volume

Liquid oxygen tank: 143,060 gallons

Liquid hydrogen tank: 383,066 gallons

Gross: 526,126 gallons

The External Tank, or ET, is the "gas tank" for the Orbiter; it contains the propellants used by the Space Shuttle Main Engines. It also forms the structural support for the orbiter itself. The tank is not reused after it is jettisoned into the ocean, so its lifetime is about 8.5 minutes. The external tank absorbs the total (7.8 million pounds) thrust loads of the three main engines and the two solid rocket motors [60].

The three main components of the external tank are an oxygen tank, located in the forward position; an aft-positioned hydrogen tank; and a collar-like intertank, which connects the two propellant tanks, houses instrumentation and processing equipment, and provides the attachment structure for the forward end of the solid rocket boosters [60].

The skin of the external tank is covered with a thermal protection system that is a 2.5-centimeter (1-inch) thick coating of spray-on polyisocyanurate foam. The purpose of the thermal protection system is to maintain the propellants at an acceptable temperature, to protect the skin surface from aerodynamic heat and to minimize ice formation.

The external tank includes a propellant feed system to duct the propellants to the orbiter engines, pressurization and vent system to regulate the tank pressure, an environmental conditioning system to regulate the temperature and render the atmosphere in the inter-tank area inert, and an electrical system to distribute power and instrumentation signals and provide lightning protection.

The tank's propellants are fed to the orbiter through a 43-centimeter (17-inch) diameter connection that branches inside the orbiter to feed each main engine.

5.9.1 Model Unit-1 Metrics

SLWT (Super Light Weight Tank) Specifications [60]

- Length: 153.8 ft (46.9 m)
- Diameter: 27.6 ft (8.4 m)
- Empty Weight: 58,500 lb (26,500 kg)
- Gross Liftoff Weight: 1,680,000 lb (760,000 kg)

LOX tank

- Length: 54.6 ft (16.6 m)
- Diameter: 27.6 ft (8.4 m)
- Volume (at 22 psig): 19,541.66 cu ft (146,181.8 US gal; 553,358 l)
- LOX mass (at 22 psig): 1,387,457 lb (629,340 kg)
- Operation Pressure: 20-22 psi (140-150 kPa) (gauge)

Inter-tank

- Length: 22.6 ft (6.9 m)
- Diameter: 27.6 ft (8.4 m)

LH_2 tank

- Length: 97.0 ft (29.6 m)
- Diameter: 27.6 ft (8.4 m)
- Volume (at 29.3 psig): 52,881.61 cu ft (395,581.9 US gal; 1,497,440 l)
- LH_2 mass (at 29.3 psig): 234,265 lb (106,261 kg)
- Operation Pressure: 32-34 psi (220-230 kPa) (absolute)
- Operation Temperature: -423 °F (-252.8 °C)

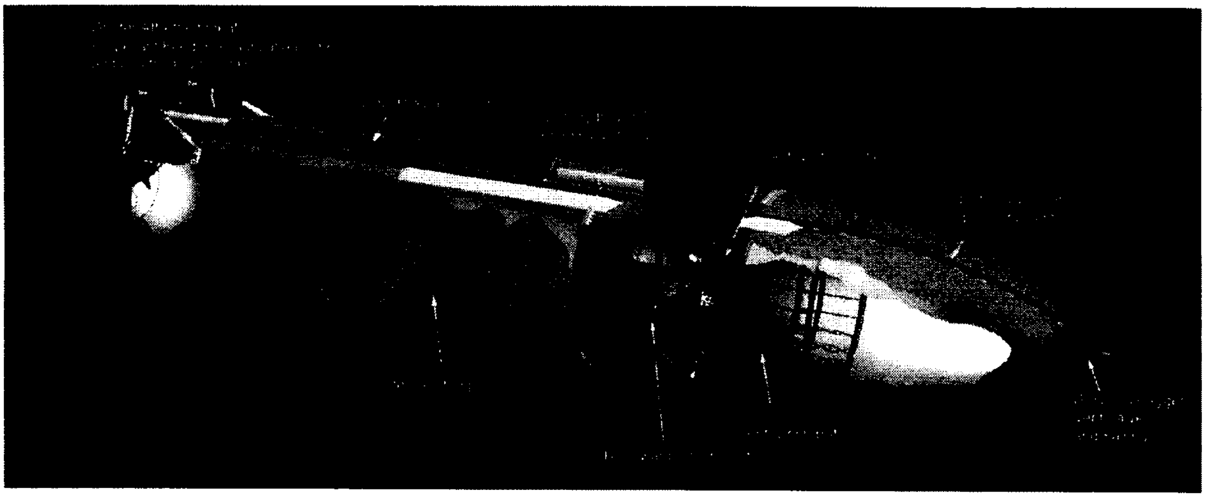


Figure 5.3 Space Shuttle External Tank [60]

The ET has three primary structures: an LOX tank, an inter-tank, and an LH_2 tank. Both tanks are constructed of aluminum alloy skins with support or stability frames as required. The inter-tank aluminum structure utilizes skin stringers with stabilizing frames. The primary aluminum materials used for all three structures are 2195 and 2090 alloys. AL 2195 is an Al-Li alloy designed by Lockheed Martin and Reynolds for storage of cryogenics. Al 2090 is a commercially available Al-Li alloy.

5.10 Model Unit-2: HPM-Structure

HPM Structure Technical Performance Measures [59]

The CTM design meets the requirement of NASA Standard 5001 (Structural Design and Test Factors of Safety for Space Flight Hardware). The structural system is designed to withstand the launch loads from Shuttle class RLV or an augmented Delta IV-Heavy ELV. The in-service maximum loads case is assumed to be a 4g.

1. Provide a load transfer path for launch and in-space operational loads.

   a) Shuttle launch (maximum loads): -2.0to +3.0 g axial load; -1.0 to +1.0 g lateral load; -2.5 to +2.0 g normal load

   b) CTM thrust (maximum): +4.0 g axial

2. Provide attach structure for CTM systems.

5.10.1 Model Unit-2 Metrics

The space shuttle cargo bay is responsible for most of the dimensional cost drivers for the HPM system [59].

HPM Dimensions

Length: 14.2 m

Max Diameter: 4.5m

Lower Diameter: 4.0 m

Thrust Experienced: 4Gs

Tanks Contained: LH2, LOX and LXe

LH2 Tank

Mass: 4,450 Kg

Volume: 65.8 m^3

Barrel Length: 4.44 m

Inner Diameter: 3.68 m

LOX Tank

Mass: 26,750 Kg

Volume: 24.19 m^3

Barrel Length: 1.27 m

Inner Diameter: 3.30 m

LXe Tank

Mass: 13,600 Kg

Volume: 3.85 m^3

Mechanical Loads

Max Axial Load (During CTM engine burn): 4Gs

Max Axial Load (During Shuttle Launch): -2.0 to +3.0 g axial

Max Lateral Load (During Shuttle Launch): -1.0 to +1.0 g

Max Normal Load (During Shuttle Launch): -2.5 to +2.0 g

5.11 Model Units Comparison

The two Model Units are compared using AHP (Analytical Hierarchy Process) based on various factors. The two Model Units Shuttle ET (External Tank) and HPM are compared based on the following factors

Weight: Weight of the Model Unit

Size: Size of the Model unit (diameter and length)

Load Gs: Max Load in terms of Gs

Econ: Economic impact in the EIOLCA (Economic Input Output Life Cycle Assessment)

Poll: Conventional pollutants in the EIOLCA analysis

Empl: Employment generated in the EIOLCA analysis

First, the weightage of the factors against each other needs to be evaluated. The table 5.1 below is the first step in the AHP (Analytical Hierarchy Process) process as explained in the appendix I. A relative ranking is given to each factor against others.

Weightage of Each Factor						
Factors	**Weight**	**Size**	**Gs**	**Econ**	**Poll**	**Empl**
Weight	1.00	2.00	0.50	3.00	4.00	6.00
Size	0.50	1.00	0.25	3.00	5.00	4.00
Load(Gs)	2.00	4.00	1.00	7.00	6.00	6.00
Econ	0.33	0.33	0.14	1.00	3.00	0.75
Poll	0.25	0.20	0.17	0.33	1.00	0.50
Empl	0.17	0.25	0.17	1.33	2.00	1.00
[redacted]						

Table 5.1: Paired Comparison Matrix

	Weight	**Size**	**Gs**	**Econ**	**Poll**	**Empl**	**Priority Vector**
Weight	0.24	0.26	0.22	0.19	0.19	0.33	**0.24**
Size	0.12	0.13	0.11	0.19	0.24	0.22	**0.17**
Load(Gs)	0.47	0.51	0.45	0.45	0.29	0.33	**0.42**
Econ	0.08	0.04	0.06	0.06	0.14	0.04	**0.07**
Poll	0.06	0.03	0.07	0.02	0.05	0.03	**0.04**
Empl	0.04	0.03	0.07	0.09	0.10	0.05	**0.06**

Table 5.2: Priority Vector

Once the priority vector of the factors is obtained, as shown in table 5.2, a pair wise comparison of each choice (Model Units) with respect to each of the factors is made as shown in the calculations below.

Shuttle ET Vs HPM with Respect to Weight

	Shuttle ET	HPM	
Shuttle ET	1.00	0.25	
HPM	4.00	1.00	
SUM	5.00	1.25	
	Shuttle ET	HPM	**Priority**
[redacted]	0.20	0.20	[redacted]
[redacted]	0.80	0.80	[redacted]
SUM	1.00	1.00	1.00

Shuttle ET Vs HPM with Respect to Size

	Shuttle ET	HPM	
Shuttle ET	1.00	0.13	
HPM	8.00	1.00	
SUM	9.00	1.13	
	Shuttle ET	HPM	**Priority**
[redacted]	0.11	0.11	[redacted]
[redacted]	0.89	0.89	[redacted]
SUM	1.00	1.00	1.00

Shuttle ET Vs HPM with Respect to Load(Gs)

	Shuttle ET	HPM	
Shuttle ET	1.00	1.25	
HPM	0.80	1.00	
SUM	1.80	2.25	
	Shuttle ET	HPM	**Priority**
[redacted]	0.56	0.56	[redacted]
[redacted]	0.44	0.44	[redacted]
SUM	1.00	1.00	1.00

Shuttle ET Vs HPM with Respect to Economy

	Shuttle ET	HPM
Shuttle ET	1.00	0.75
HPM	1.34	1.00
SUM	2.34	1.75

	Shuttle ET	HPM	**Priority**
[redacted]	0.43	0.43	[redacted]
[redacted]	0.57	0.57	[redacted]
SUM	1.00	1.00	1.00

Shuttle ET Vs HPM with Respect to Pollution

	Shuttle ET	HPM
Shuttle ET	1.00	0.37
HPM	2.68	1.00
SUM	3.68	1.37

	Shuttle ET	HPM	**Priority**
[redacted]	0.27	0.27	[redacted]
[redacted]	0.73	0.73	[redacted]
SUM	1.00	1.00	1.00

Shuttle ET Vs HPM with Respect to Employment

	Shuttle ET	HPM
Shuttle ET	1.00	0.79
HPM	1.26	1.00
SUM	2.26	1.79

	Shuttle ET	HPM	**Priority**
[redacted]	0.44	0.44	[redacted]
[redacted]	0.56	0.56	[redacted]
SUM	1.00	1.00	1.00

Now that the Model Units are compared to each other based on each factor, a composite weightage of the two units needs to be obtained.

Factors->	Weight	Size	Load(Gs)	Economy	Pollution	Employment	
Weightage	0.24	0.17	0.42	0.07	0.04	0.06	Composite Weightage
[illegible]	0.2	0.11	0.56	0.43	0.27	0.44	[illegible]
HPM	0.8	0.89	0.44	0.57	0.73	0.56	[illegible]

Table 5.3 Composite Weightage of the two Model Units

Comparing the two Model Units, Space Shuttle External Tank and HPM structure with the requirements of the Target Unit, using the AHP, it is concluded that the Primary Target Unit for the CTM-Structure is the HPM structure (63% preference level).

Now the cost model of the Primary Model Unit (PMU) can be used to calculate the cost of the Target Unit. But in order to use the PMU cost model, first the cost drivers of the Target Unit must be detected along with the cost coefficients from the PMU.

5.12 Typical Cost Drivers:

Width
Height
Thickness
Area
Outer Diameter
Inner Diameter
Volume
Density
Weight

5.13 CTM-Structure Preliminary Design

Based on these cost drivers a First-Order Process Velocity Model (FOPVM) for the PMU is investigated. Since the Target Unit closely matches the PMU, the same process velocity parameters are used to calculate the cost of the target Unit. The cost drivers and their values are shown below. In order to come up with the values of the cost drivers, a preliminary CTM-Structure is designed as shown in the figure 5.4 below.

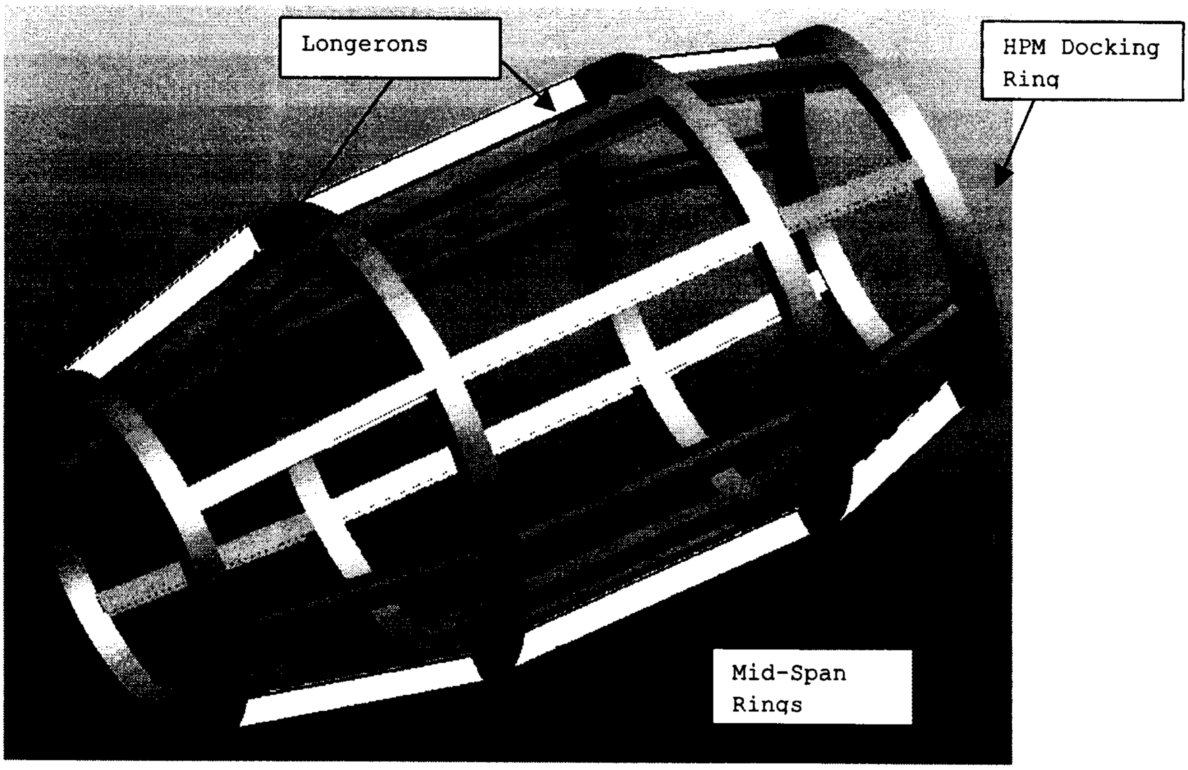


Figure 5.4 Preliminary Design of the CTM Structure

The preliminary design has been analyzed using FEA (Finite Element Analysis) to observe the stresses in the structure when a 4g axial load is applied. The analysis shows that the stresses are not high and it has a good factor of safety. The structural design proposed above in the preliminary design stage passes the mechanical load requirements.

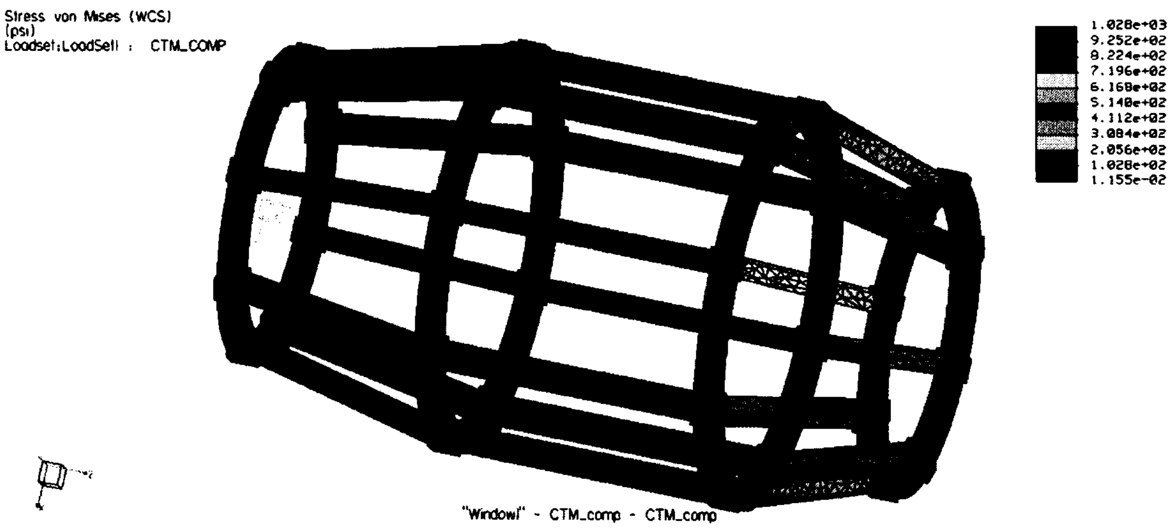


Figure 5.4(b) Stresses in the CTM Structure Based on a 4g Axial Load

The CTM structure will be made of metal matrix composite with carbon reinforcement.

Based on the design the cost drivers and the cost of the CTM structure is calculated below.

Two estimates have been shown

1. TFUC: Theoretical First Unit Cost

2. NR Cost: Non-Recurring Cost

Process Velocity model equation and data is based on the work by TRW Space & Technology Group. The complexity factors used for material, manufacturing, and escalation are from The Boeing Inc. research.

NR Cost W/O TDC = Wt * K'_1 * K'_2 * K'_3 *Rate

NR Cost with TDC = NR Cost W/O TDC + Wt * K'_3 * NR Rate

$$TFUC = Rate * K_1 * K_2 * K_3 * \sqrt{\left(\frac{wt}{V_0}\right)^2 + \frac{2 * wt * \tau}{V_0}}$$

K'_1 = NR Cost Material Complexity Factor

K'_2 = NR Cost Manufacturing Factor

K'_3 = NR Cost Escalation Factor

K_1 = Material Complexity Factor

K_2 = Manufacturing Factor

K_3 = Escalation Factor

V_0 = Steady-State Rate of Change of Extensive Parameter (gm/hr)

τ (tau) = Setup Cost of the Process (hrs)

TDC = Technology Development Cost

5.14 First Order Process Velocity Cost Model (FOPV)

The research group at MIT first proposed this cost model. The model describes how a manual or automated process can be captured by a first-order velocity response represented by the equation below and the graph in figure 5.5.

$V = V_0(1-e^{-t/\tau})$

V is process velocity and has a dimension of λ/time and λ is the cost driver and t is the process time. V_0 is the Steady-State process velocity and tau (τ) is the time constant to capture the delay in attaining full speed, which depends on the setup required for that manufacturing process. The process velocity V can be represented as the time derivative of λ

$V = d\lambda /dt$

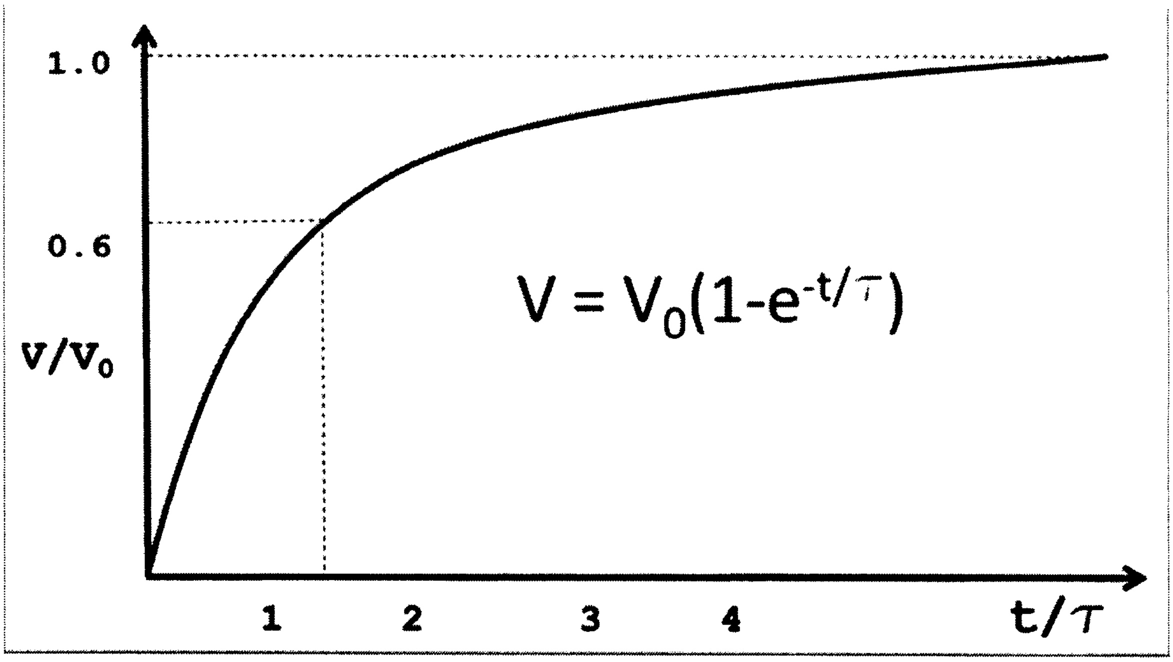


Figure 5.5 Process Velocity Model Graph

Units in CGS System

Engine Side Ring	
Width	20.00
Height	20.00
Thick	0.64
Area	49.19
OD	261.00
ID	221.00
Mid Dia	241.00
CTM Vol	37,240.73
Density	1.10
Weight	40,964.80
FOPV Parameters	
V0	32.67
Tau	35.64
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	196,547
NR Cost W/O TDC	1,933,129
NR Rate=	1.29
NR Cost With TDC	2,008,609

MID SPAN RING	
Width	20.00
Height	20.00
Thick	0.64
Area	49.19
OD	339.00
ID	299.00
Mid Dia	319.00
CTM Vol	49,293.74
Density	1.10
Weight	54,223.11
FOPV Parameters	
V0	32.67
Tau	35.64
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	258,443
NR Cost W/O TDC	2,558,789
NR Rate=	1.29
NR Cost With TDC	2,658,698

UPPER SPAN RING	
Width	20.00
Height	20.00
Thick	0.64
Area	49.19
OD	339.00
ID	299.00
Mid Dia	319.00
CTM Vol	49,293.74
Density	1.10
Weight	54,223.11
FOPV Parameters	
V0	32.67
Tau	35.64
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	258,443
NR Cost W/O TDC	2,558,789
NR Rate=	1.29
NR Cost With TDC	2,658,698

DOCKING RING	
Width	20.00
Height	20.00
Thick	0.64
Area	49.19
OD	267.00
ID	227.00
Mid Dia	247.00
CTM Vol	38,167.88
Density	1.10
Weight	41,984.67
FOPV Parameters	
V0	32.67
Tau	35.64
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	201,309
NR Cost W/O TDC	1,981,257
NR Rate=	1.29
NR Cost With TDC	2,058,616

Length	119.00
Qty	8.00
Width	15.00
Height	20.00
Web	0.64
Flange	0.89
Density	1.10
Area	38.24
Volume	36,405.40
Weight	40,045.94
FOPV Parameters	
V0	2.00
Tau	92.00
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	3,067,002
NR Cost W/O TDC	1,889,768
NR Rate=	1.29
NR Cost With TDC	1,963,555

Length	250.00
Qty	8.00
Width	15.00
Height	20.00
Web	0.64
Flange	0.89
Density	1.10
Area	38.24
Volume	76,481.94
Weight	84,130.13
FOPV Parameters	
V0	2.00
Tau	92.00
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	6,427,891
NR Cost W/O TDC	3,970,101
NR Rate=	1.29
NR Cost With TDC	4,125,115

Length	174.00
Qty	8.00
Width	15.00
Height	20.00
Web	0.64
Flange	0.89
Density	1.10
Area	38.24
Volume	53,231.43
Weight	58,554.57
FOPV Parameters	
V0	2.00
Tau	92.00
K_1=	1.20
K_2=	1.30
K_3=	1.43
Rate=	68.35
NR Cost W/O TDC Parameters	
K'_1=	5.00
K'_2=	5.00
K'_3=	1.43
Rate=	1.32
TFUC(Manual Autoclave)	4,478,065
NR Cost W/O TDC	2,763,190
NR Rate=	1.29
NR Cost With TDC	2,871,080

Total Vol	**340,115**	**cm^3**
Total Wt	**374**	**Kg**
Total NR Cost W/O TDC Parameters	**17,655,022**	**$**
Total NR Cost With TDC	**18,344,371**	**$**
TFUC(Manual Autoclave)	**14,887,701**	**$**

5.15 EIOLCA of the CTM Structure

The CTM structure, which is made of the longerons and the mid span rings, can be made of composite. The composite can be a magnesium metal matrix with long fiber carbon reinforcement. If this material and technique is used then the EIOLCA sector, which it falls under, is the 331491 sector of the EIOLCA database. This sector is comprised of one or more NAICS sectors, as described below. The EIO-LCA data throughout this chapter has been obtained from www.eiolca.net

5.15.1 EIOLCA of CTM Structure Made From MMC (Sector 331491)

331491 Nonferrous Metal (except Copper and Aluminum) Rolling, Drawing, and Extruding

This U.S. industry comprises establishments primarily engaged in

(1) Rolling, drawing, or extruding shapes (e.g., bar, plate, sheet, strip, tube) from purchased nonferrous metals) and/or

(2) Recovering nonferrous metals from scrap and rolling, drawing, and/or extruding shapes (e.g., bar, plate, sheet, strip, tube) in integrated mills.

- Magnesium and magnesium alloy bar, rod, shape, sheet, strip, and tubing made from purchased metal.
- Magnesium foil made by rolling purchased metals or scrap.
- Magnesium rolling, drawing, or extruding purchased metals or scrap.

	Sector	Total Economic
	Total for all sectors	2.82
331491	Nonferrous metal, except copper and aluminum, shaping	1.032646
331411	Primary smelting and refining of copper	0.197476
420000	Wholesale trade	0.14899
212230	Copper, nickel, lead, and zinc mining	0.134621
331421	Copper rolling, drawing, and extruding	0.109554
331419	Primary nonferrous metal, except copper and aluminum	0.083343
332720	Turned product and screw, nut, and bolt manufacturing	0.060341
550000	Management of companies and enterprises	0.059535
331492	Secondary processing of other nonferrous	0.05378
335929	Other communication and energy wire manufacturing	0.042432
221100	Power generation and supply	0.039791

Table 5.4: Economic Activity in Other Sectors Due to Input of $1Mil in 331491 Sector

	Sector	Total TJ
	Total for all sectors	11.5
221100	Power generation and supply	4.643888
331491	Nonferrous metal, except copper and aluminum, shaping	0.994329
212230	Copper, nickel, lead, and zinc mining	0.902025
484000	Truck transportation	0.403254
331411	Primary smelting and refining of copper	0.360982
331419	Primary nonferrous metal, except copper and aluminum	0.31459
331111	Iron and steel mills	0.305108
324110	Petroleum refineries	0.213025
420000	Wholesale trade	0.194974
481000	Air transportation	0.192299
482000	Rail transportation	0.178256

Table 5.5: Energy Requirement in Other Sectors Due to Input of $1Mil in 331491 Sector

	Sector	GWP MTCO2E
	Total for all sectors	1040
221100	Power generation and supply	391.574079
331419	Primary nonferrous metal, except copper and aluminum	161.402887
484000	Truck transportation	56.270584
212230	Copper, nickel, lead, and zinc mining	42.14997
562000	Waste management and remediation services	35.67029
331491	Nonferrous metal, except copper and aluminum, shaping	30.997864
331111	Iron and steel mills	24.108893
331312	Primary aluminum production	23.659941
211000	Oil and gas extraction	19.068052
212100	Coal mining	17.707124
S00202	State and local government electric utilities	17.128915
327410	Lime manufacturing	15.38394

Table 5.6: Greenhouse Gas Emission Due to Input of $1Mil in 331491 Sector

GWP: Global Warming Potential is a weighting of greenhouse gas emission into the air.

MTCO2E: Metric tons of CO2 equivalent

	Sector	SO2 mt	CO mt	NOx mt	VOC mt	Lead mt	PM10 mt
	Total for all sectors	4.75	9	2.56	2.23	0.025	2.13
221100	Power generation and supply	2.12	0.105	0.96	0.009	0	0.045
331411	Primary smelting and refining of copper	2.11	0.059	0	0.099	0	0.225
212230	Copper, nickel, lead, and zinc mining	0.08	0.67	0.38	0.846	0	0.558
331312	Primary aluminum production	0.071	0.396	0	0.004	0	0.018
331311	Alumina refining	0.064	0	0.016	0.014	0	0.006
331491	Nonferrous metal, except copper and aluminum, shaping	0.045	0.017	0.091	0.003	0	0.023
331111	Iron and steel mills	0.028	0.234	0.022	0.013	0	0.019
211000	Oil and gas extraction	0.02	0.034	0.015	0.023	0	0
324110	Petroleum refineries	0.019	0.011	0.004	0.015	0	0.002
482000	Rail transportation	0.017	0.038	0.326	0.015	0	0.007
327310	Cement manufacturing	0.015	0.01	0.019	0.015	0	0.002
483000	Water transportation	0.015	0.01	0.077	0.074	0	0.007
484000	Truck transportation	0.012	3.97	0.286	0.296	0	0.007
325110	Petrochemical manufacturing	0.009	0.003	0.007	0.021	0	0
212310	Stone mining and quarrying	0.009	0.016	0.006	0.003	0	0.002
325180	Other basic inorganic chemical manufacturing	0.008	0	0	0	0	0
213112	Support activities for oil and gas operations	0.008	0.007	0.005	0.002	0	0.001
33361A	Speed changers and mechanical power transmission equipment	0.008	0	0.002	0	0	0
2122A0	Gold, silver, and other metal ore mining	0.007	0.022	0.007	0.15	0	0.018
325998	Other miscellaneous chemical product manufacturing	0.006	0	0.006	0.001	0	0
541300	Architectural and engineering services	0.005	0.008	0.004	0.002	0	0.001
221200	Natural gas distribution	0.005	0	0.01	0.035	0	0
562000	Waste management and remediation services	0.004	0.411	0.021	0.069	0	0.062

Table 5.7: Conventional Air Pollution Due to Input of $1Mil in 331491 Sector

PM10: Particulate Matter less than 10 microns in diameter.

5.15.2 Environmental Valuation of the CTM Structure made from MMC

In section 4.7 we have seen the EIO-LCA implications of the decisions made during the conceptual design of any unit. However, some of the environmental implications are in terms of a certain amount of solid liquid or gaseous waste in units of weight. Since cost of the unit is the primary purpose of the proposed enterprise-wide cost estimation framework, the environmental implications also need to be converted into a dollar amount.

We will now calculate the environmental impact, in dollars, of fabricating the CTM structure with composites. According to the proposed framework, the EIO-LCA has been performed above on the constituents of the CTM structure.

Sector	**SO2 mt**	**CO mt**	**NOx mt**	**VOC mt**	**PM10 mt**	**CO2 mt**
Total for all sectors per Million $ of Input	4.75	9	2.56	2.23	0.025	2.13
$ per Ton of Air Emission	2,200	580	3,100	1,800	4,700	15
$ due to each of the Emissions	10,450	5,220	7,936	4,014	118	32
Grand Total due to all of the Emissions ($)						**27,769**

Table 5.7(a): Environmental Cost of Making CTM Structure with MMC

	Sector	Total Employees
	Total for all sectors	14.9
331491	Nonferrous metal, except copper and aluminum, shaping	3.712188
420000	Wholesale trade	3.44142
332720	Turned product and screw, nut, and bolt manufacturing	0.502644
212230	Copper, nickel, lead, and zinc mining	0.471827
550000	Management of companies and enterprises	0.31829
331421	Copper rolling, drawing, and extruding	0.306966
561300	Employment services	0.291456
484000	Truck transportation	0.28427
331419	Primary nonferrous metal, except copper and aluminum	0.240545
331411	Primary smelting and refining of copper	0.22849
722000	Food services and drinking places	0.206851
331492	Secondary processing of other nonferrous	0.20135

Table 5.8: Employment Generated Due to Input of $1Mil in 331491 Sector

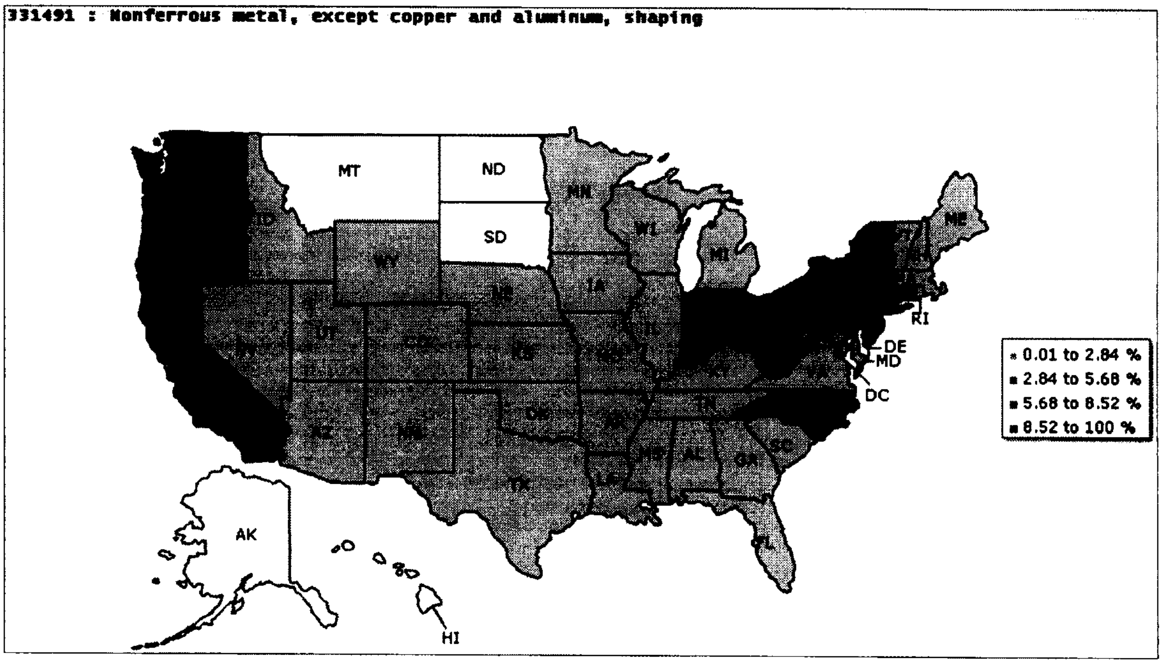


Figure 5.6 Geographic Distribution of Employment Generated Due to Input of $1Mil in 331491 Sector

Using the framework, several options for the Target Unit can be evaluated not just on the basis of the cost but also on the basis of economical, environmental, and social impact.

Previously we have seen the impact of making the CTM Structure out of Metal matrix Composite of Magnesium. We will see below, the impact if the same structure is made from Aluminum just like the space shuttle.

This sector is comprised of one or more NAICS sectors, as described below:

5.15.3 EIOLCA of CTM Structure made From Aluminum Alloy (Sector 331314)

331314 Secondary Smelting and Alloying of Aluminum

This U.S. industry comprises establishments primarily engaged in

(1) Recovering aluminum and aluminum alloys from scrap and/or dross (i.e., secondary smelting) and making billet or ingot (except by rolling)

(2) Manufacturing alloys, powder, paste, or flake from purchased aluminum.

Examples of activities in this sector:
* Alloying purchased aluminum metals
* Aluminum alloys made from scrap or dross
* Aluminum billet made from purchased aluminum
* Aluminum billet made in integrated secondary smelting and rolling mills
* Aluminum extrusion ingot (i.e., billet), secondary
* Aluminum flakes made from purchased aluminum
* Aluminum ingot made from purchased aluminum
* Aluminum ingot, secondary smelting of aluminum and manufacturing
* Aluminum ingot, secondary, manufacturing
* Aluminum recovering from scrap and making ingot and billet (except by rolling)
* Aluminum smelting, secondary, and making ingot and billet (except by

rolling)

* Flakes, aluminum, made from purchased aluminum
* Metal powder and flake made from purchased aluminum
* Paste made from purchased aluminum
* Powder made from purchased aluminum
* Refining aluminum, secondary

	Sector	**Total Economic $mill**
	Total for all sectors	2.11
331314	Secondary smelting and alloying of aluminum	1.044079
420000	Wholesale trade	0.220183
484000	Truck transportation	0.092011
331312	Primary aluminum production	0.077749
550000	Management of companies and enterprises	0.034308
221100	Power generation and supply	0.028811
331311	Alumina refining	0.022437
482000	Rail transportation	0.020312
531000	Real estate	0.018166
211000	Oil and gas extraction	0.016961
331419	Primary nonferrous metal, except copper and aluminum	0.015667
52A000	Monetary authorities and depository credit intermediation	0.015245
212230	Copper, nickel, lead, and zinc mining	0.013976
324110	Petroleum refineries	0.013243
331492	Secondary processing of other nonferrous	0.012909
331315	Aluminum sheet, plate, and foil manufacturing	0.012723

Table 5.9: Economic Activity in Other Sectors Due to Input of $1Mil in 331314 Sector

	Sector	PM10 mt
	Total for all sectors	5.7
331314	Secondary smelting and alloying of aluminum	4.983065
331419	Primary nonferrous metal, except copper and aluminum	0.180169
331312	Primary aluminum production	0.158165
562000	Waste management and remediation services	0.092611
331311	Alumina refining	0.058795
212230	Copper, nickel, lead, and zinc mining	0.057881
221100	Power generation and supply	0.032524
484000	Truck transportation	0.017729
115000	Agriculture and forestry support activities	0.011906
482000	Rail transportation	0.011648
483000	Water transportation	0.010924
493000	Warehousing and storage	0.009955
331411	Primary smelting and refining of copper	0.009724
2122A0	Gold, silver, and other metal ore mining	0.007323
331111	Iron and steel mills	0.006673

Table 5.10: Conventional Air Pollution Due to Input of $1Mil in 331314 Sector

	Sector	GWP	CO2	CH4	N2O	CFCs
		MTCO2E	MTCO2E	MTCO2E	MTCO2E	MTCO2E
	Total for all sectors	*963*	*695*	*83.7*	*6.41*	*178*
221100	Power generation and supply	284	280	0	0	3.41
484000	Truck transportation	142	140	0.217	1.96	0
331312	Primary aluminum production	210	70.8	0	0	139
331311	Alumina refining	37.7	37.7	0	0	0
482000	Rail transportation	17.1	16.9	0.053	0.16	0
420000	Wholesale trade	15.7	15.7	0	0	0
481000	Air transportation	12.4	12.3	0.016	0.132	0
S00202	State and local government electric utilities	12	12	0	0	0
324110	Petroleum refineries	9.24	9.19	0.051	0	0
562000	Waste management and remediation services	53	8.39	44.6	0.065	0

Table 5.11: Greenhouse Gases Due to Input of $1Mil in 331314 Sector

5.15.4 Environmental Valuation of the CTM Structure made From Aluminum Alloy

In section 4.7 we have seen the EIO-LCA implications of the decisions made during the conceptual design of any unit. However, some of the environmental implications are in terms of a certain amount of solid liquid or gaseous waste in units of weight. Since cost of the unit is the primary purpose of the proposed enterprise-wide cost estimation framework, the environmental implications also need to be converted into a dollar amount.

We will now calculate the environmental impact, in dollars, of fabricating the CTM structure with Aluminum (Shuttle External Tank). According to the proposed framework, the EIO-LCA has been performed above on the constituents of the CTM structure.

Sector	**SO2 mt**	**CO mt**	**NOx mt**	**VOC mt**	**PM10 mt**	**CO2 mt**
Total for all sectors per Million $ of input	3.110	17.500	2.620	1.770	5.700	695
$ per ton of air emission	2,200	580	3,100	1,800	4,700	15
$ due to each of the emissions	6,842	10,150	8,122	3,186	26,790	10,425
Grand Total due to all of the Emissions ($)						**65,515**

Table 5.11(a): Environmental Cost of CTM Structure from Al Alloy

	Sector	Total Employees
	Total for all sectors	11.8
420000	Wholesale trade	5.08586
331314	Secondary smelting and alloying of aluminum	1.952874
484000	Truck transportation	0.718925
561300	Employment services	0.256666
331312	Primary aluminum production	0.199245
550000	Management of companies and enterprises	0.18342
722000	Food services and drinking places	0.15154
482000	Rail transportation	0.118709
52A000	Monetary authorities and depository credit intermediation	0.090508
48A000	Scenic and sightseeing transportation and support activities for transportation	0.089756
4A0000	Retail trade	0.080823
7211A0	Hotels and motels, including casino hotels	0.076694
221100	Power generation and supply	0.076373

Table 5.12: Employment Generated in Other Sectors Due to Input of $1Mil in 331314 Sector

	Sector	Total TJ
	Total for all sectors	9.16
221100	Power generation and supply	3.362445
484000	Truck transportation	1.019841
331312	Primary aluminum production	0.858761
331311	Alumina refining	0.773834
482000	Rail transportation	0.289149
420000	Wholesale trade	0.28814
331314	Secondary smelting and alloying of aluminum	0.278984
481000	Air transportation	0.192071
324110	Petroleum refineries	0.172207
483000	Water transportation	0.150026
562000	Waste management and remediation services	0.130602
S00202	State and local government electric utilities	0.107459
331111	Iron and steel mills	0.104941
212230	Copper, nickel, lead, and zinc mining	0.093646
486000	Pipeline transportation	0.089539

Table 5.13: Energy Requirement in Other Sectors Due to Input of $1Mil in 331314 Sector

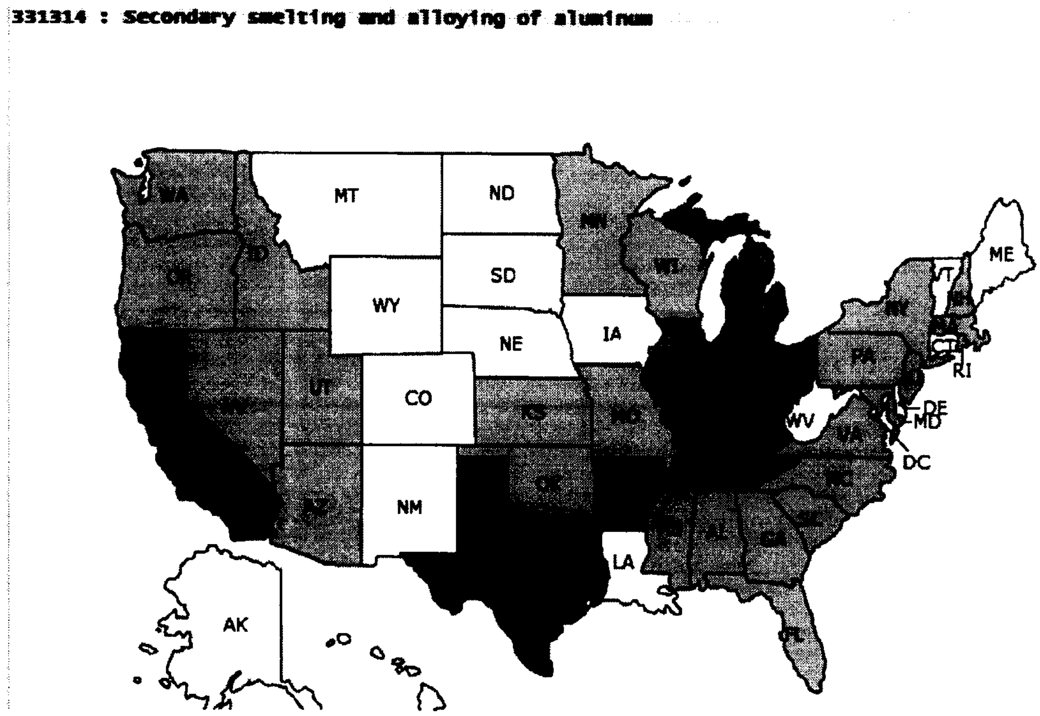


Figure 5.7 Geographic Distribution of Employment Generated Due to Input of $1Mil in 331314 Sector

5.16 Case Study Conclusion

Through this case study we have shown how the framework can be applied to any system at the conceptual design stage. Based on the features of the Target Unit and how they compare with model units, the closest Model Unit (Primary Model Unit) can be selected. The Primary Model Unit can also be selected from among various Model Units based on their EIOLCA performances.

Chapter 6: CONCLUSION

6.1 Summary and Discussion

In this dissertation we have proposed a Cost Estimation Framework based on the principles of Systems Engineering. The framework takes into account the needs of various industries involving cost estimation of a wide range of systems in terms of size and complexity. This is a robust framework that addresses the cost estimation methodology for simple parts involving simple machining operations, to more complex systems, which are themselves an assemblage of other systems. The current research in cost estimation has not addressed the issue of a single-methodology framework. The work so far has been more specifically targeted either towards a particular industry (for example Aerospace or Automotive industry) or a cost estimation technique.

First, a system and what constitutes a system is defined in the framework. A hierarchy is established among the constituents as System, Sub-system, Assembly, and Object. Specific rules are provided which help the cost estimator in deciding whether a unit is a part or an assembly or a sub-system, etc. The system does not have to have its constituents in any particular hierarchical order. Some of the constituents could be part of the system without being part of the next hierarchy in order, the example being that of a simple part attached directly to a system without being part of an assembly or a sub-system.

Once the system is defined, the framework looks at the most important aspect of the framework, which is the Systems Engineering perspective. The Systems Engineering principles form the backbone of the framework. In estimating the cost of a something as complex as a system or a simple part, it is important to understand the design and the manufacturing processes. The parameters of design and manufacturing are obtained by the requirements set by the stakeholders. The stakeholder is the party that needs the system designed and built. The stakeholder could be either a technical user of the system or a business entity. In either case, the requirements set by them form the basis for the design and the cost. This forms the first step in applying systems engineering methodology to the framework. This principle has been applied recursively to all levels of the framework (System, Sub-system, Assembly and Object).

A detailed explanation of the framework and its functioning follows the explanation of the systems engineering aspect of the framework. A unit (System/Sub-system/Assembly/Object) whose cost needs to be estimated is called the Target Unit. Through a series of searches and application of techniques such as AHP (Analytical Hierarchy Process), a best match to the target unit is found. The best match is called the Primary Target Unit. The matching is done based on the similarity between the functional attributes of the Target Unit and the Model Units. Model Units are the candidate units which are similar to the target unit. Whatever functionalities are not present in the primary model unit, a supplementary unit is looked up in the same way. The supplementary unit is in turn treated as primary unit and a search is performed to find a best match. This process is recursively applied until all the functionalities of the target unit are obtained in a series of primary model units.

At each stage of searching for a primary model unit, once the primary model unit is finalized, several samples of the primary model unit are collected along with their costs. A parametric cost model is set up based on the technical performance measures of the functionalities and the cost of each sample.

If more than one primary model unit is necessary to complete the target unit, then the interface unit must also be searched and its cost estimated and added to the cost of the target unit.

At each level several tools have been added to the framework in order to facilitate decision making. For example, at the object level, a tool called PRIMAs (Process information Mapping) has been used in the framework. This tool suggests the manufacturing process for small objects based on the quantity and the material of parts being manufactured. The manufacturing process could be casting, milling or lathe work. Based on the suggestion from this tool the cost of the manufacturing of the object can be estimated. This tool is helpful because during conceptual design and estimation of the unit, many details may not be available, so the tool helps in suggesting a few that are applicable.

Another major tool that has been added to the framework is the DCLASS, which helps in choosing either a material, or a manufacturing process when the exact information is not available. The exact information could be about the type or cost of the material or process. As mentioned earlier, at the conceptual stage not much information is available at the lower level such as object or assembly level. In such cases, if cost of a certain material or certain manufacturing process is not known, then a more generic material or manufacturing process may be selected for the purpose of cost estimation. This will of course lead to some approximation in the exact cost of the unit but at the conceptual stage this is the best option. However, as the design is more refined and more information is available, the exact material or process information can be obtained and the initial approximate information can be replaced.

At the assembly level, where two or more objects are joined together, penalty times for specialized assembly cases have been converted into equations and these equations serve a primary model unit.

The framework also looks at the lifecycle cost of the unit. The lifecycle cost has been classified into major items. In order to estimate the cost of a unit over its entire life, a great deal of information is required, which may not available at the conceptual design stage. In such cases the framework will calculate the lifecycle cost from whatever information is available. As with the rest of the framework the part that deals with the lifecycle cost is also based on the principles of systems engineering. The methodology is consistent with the rest of the framework, where a primary model unit is searched for which is the closest to the required target unit whose cost is to be estimated. With respect to the framework, the target unit is the lifecycle cost model, while the primary model unit is the set of equations that are used to estimate the lifecycle cost. Since not many of the lifecycle parameters are defined at the conceptual stage, the lifecycle cost is only based on the available information and can be revisited as and when more information is available.

The framework now takes up an even bigger challenge of incorporating the social, economical, and environmental effects of developing the unit into the framework. Once the effects are calculated, they are evaluated in terms of monetary cost. Using the framework, an EIO-LCA (Economic Input-Output Lifecycle Assessment) is performed on the primary model unit. Under the EIO-LCA, first an economic analysis is done whereby the economic effect of each sector on other sectors is calculated. For example, if the target unit belongs to sector X, then for every dollar spent on the target unit sector, the amount of products required from other sectors is calculated. This helps the stakeholders understand how the economy is affected by opting to adopt a certain primary model unit as a solution to its target unit. Stakeholders can also boost business in specific sectors as part of stimulus by opting for a particular primary model unit.

The next step in applying EIOLCA to the primary model unit is to determine the amount of employment generation in each sector that contributes to the primary model unit sector. In other words, the framework calculates the number of jobs that are created in each sector of the economy as a result of spending a certain amount of money (cost) in developing the primary model unit.

Besides the economic impact and the employment generated, the amount of money spent on developing the target unit also affects the environment. With the economic impact on each sector of the economy, there is also a certain amount of environmental impact from each of the sectors due to the added business. The environmental impact is in the form of the amount of greenhouse gases emitted into the atmosphere and the amount of waste generated from each of the contributing sectors. The framework not only calculates the environmental impact but goes a step further to evaluate the monetary equivalent of the environmental impact.

These are all the aspects of cost estimation at the conceptual stage that this framework accomplishes. These aspects of the framework make it robust and independent of the industry that the unit belongs to or the complexity of the unit.

6.2 Future Work

Now that the framework has been established future attempts can be made to adopt it into software. The software would have modules to calculate the costs of the unit, such as acquisition cost, lifecycle cost and EIOLCA cost. The acquisition module can be divided into sub modules to estimate the costs of an object, assembly, sub-system, or a system. The module responsible for lifecycle cost will have all possible cost items and as and when information is available, the lifecycle cost can be calculated. The program for this module will basically consist of the equations of lifecycle cost. The assembly cost module also will work on the basis of equations related to the assembly features and assembly time. The data collected from the work of Dr. Boothroyd in the field of assemblies has been converted to equations which can be used to calculate the time required to assemble two parts consisting of certain features. The assembly time is then converted to dollar amount based on the labor rate. At the object level, a databank will be created consisting of cost data for various machining processes. The data will be stored using advanced data management methodology such as XML. In the initial stages of unit development and cost estimation, not much information is available; hence, the cost models are typically parametric in nature. In order to save the various attributes of the unit or the manufacturing process, the data needs to be saved in a structured manner rather than a flat model like MS Excel.

The software will consist of DCLASS method of classification, which allows the user to select a more generic material or process where exact information is not available. The future work will also involve extending the DCLASS methodology to sub-systems and systems. the idea is to have the software pick a more generic product or a system, given some attributes required by the target system. Another important characteristic of the software will be to keep track of the hierarchy of the primary model units required to build the target unit. The lifecycle module of the software will incorporate a set of elaborate lifecycle cost estimating equations.

A very important aspect of the software would be to have a comprehensive EIOLCA database. The EIOLCA database consists of input-output information of inter-sector trade. Besides this, the database will consist of employment generation information as well as environmental burden due to activities in various sectors. The software will have capability to pull information from the database based on queries. This will be helpful when design decisions are made at the conceptual design stage of the units.

6.2.1 Uncertainty and Risk

Statistical analysis of any data set that is stochastic in nature involves risk and uncertainty. Uncertainty is the amount of variation in the collected data. Both types of data, the cost of the model samples, as well as the cost drivers can have uncertainty in them. The variation in the data can have any of the probability distributions such as normal, Weibull etc. Risk, on the other hand, is the penalty that will be incurred as a result of uncertainty in the data. Uncertainty in the cost model arises because the cost driver data were not taken properly or because of other varied reasons. Several techniques exist to evaluate uncertainty and risk, such as the Monte Carlo Method, the fuzzy regression method, the stochastic method, etc. Work is being done to more effectively incorporate uncertainty and risk into the framework.

The future work will also involve a module in the software to handle uncertainty in the cost data collected as well as uncertainty in the method applied in obtaining the cost using a cost model. Tools such as Monte Carlo simulation or Fuzzy regression can be incorporated to account for uncertainty.

The entire software suite can be used to calculate the cost of target units irrespective of the unit being an object, assembly, a product or a system.

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APPENDIX I: ANALYTICAL HIERARCHY PROCESS

Assigning the Weights Based on AHP (Analytical Hierarchy Process)

Decision-making is the process of choosing among alternatives based on multiple criteria. One makes a decision of choosing one of the alternatives based on certain criteria. These criteria and alternatives are more obvious and must be determined first before we start ranking the alternatives.

The determination of criteria and alternatives are subjective. Most of decision-making is based on individual judgments. One needs to try to make decisions as rational as possible and try to quantify these opinions. The rankings are numbers within any certain range; say from 1 to 10 or -10 to 10. The rankings can have a different range for each factor. Higher the ranking, higher is the level of preference for that factor.

The simplest multi criteria decision-making is to put into a cross table of criteria and alternatives [61]. Then we put a subjective score value on each cell of the table. The sum (or normalized sum) of all factors for each alternatives is calculated.

For example, we have 3 alternative choices X, Y and Z and four criteria to decide the alternatives A, B, C and D. You can input any name for alternatives and criteria. The values assigned for each factor from a certain range are shown in table 2. The only similarity between these numbers is that they have the same interpretation, that is, higher values signify higher preference [61].

Criteria	**Choice X**	**Choice Y**	**Choice Z**	**Range**
Factor A	2	3	3	0-5
Factor B	21	73	55	1-100
Factor C	-1	0	2	-2 to +2
Factor D	0.2	0.8	0.6	0 to 1
Sum	22.2	76.8	60.6	
Normalized Score	13.91%	48.12%	37.97%	

Table 1: Evaluation Based on Scores of Each Factor

13.91% = 22.2*100/(22.2 + 76.8 + 60.6)

With many alternatives, it is easier to compare the sum value of each choice by normalizing them. Total sum is 159.6 (=22.2 + 76.8 + 60.6). The sum of each choice is normalized by division of each sum with the total sums. For instance, choice X is normalized into 22.2/159.6*100= 13.91%. Hence, in the example above, choice Y is preferable to choice Z, while choice Z is better than X.

However, in the example above the range of ranking for each of the factors is not the same. The problem, however, is that since the range of ranking of factor B is higher than others, it alone can sway the selection results. There are two solutions to deal with this [61]:

1. Instead of using arbitrary values for each factor, rank the choice for each factor. Smaller rank value is more preferable than higher rank.
2. Transform the score value of each factor according to the range value such that each factor will have the same range.

Analytic Hierarchy Process (AHP) is one of Multi Criteria decision making method that was originally developed by Prof. Thomas L. Saaty [61]. It is a method to derive ratio scales from paired comparisons. The input can be obtained from actual measurement such as price, weight etc., or from subjective opinion such as satisfaction feelings and preference. AHP allows a slight inconsistency in judgment. The ratio scales are derived from the principal Eigen vectors and the consistency index is derived from the principal Eigen value.

Paired Comparison

Let us look at an example to understand this concept. Suppose we have two fruits, **Pineapple** and **Pear**. If one is asked which fruit he/she likes better compared to the other, then the preference can be measured on a relative scale as shown below.

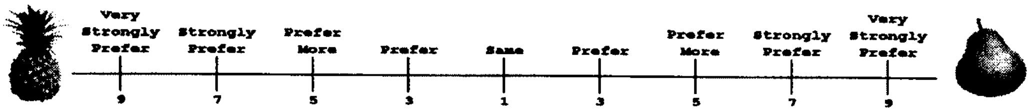


Figure 1: Pair-wise Comparison

If one likes pineapple better than pear, it can be represented by a number on the scale between 1 and 9 on the side of the fruit one prefers. For instance, if pear is preferred to pineapple, then the rank would be 5, according to the scale shown below.

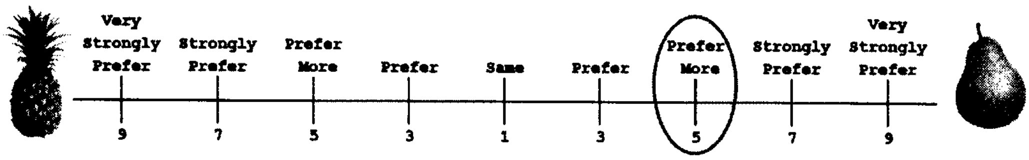


Figure 2: Numerical Value to Pair-wise Comparison

If there are more than two fruits, then the pair-wise comparisons would also increase as discussed below.

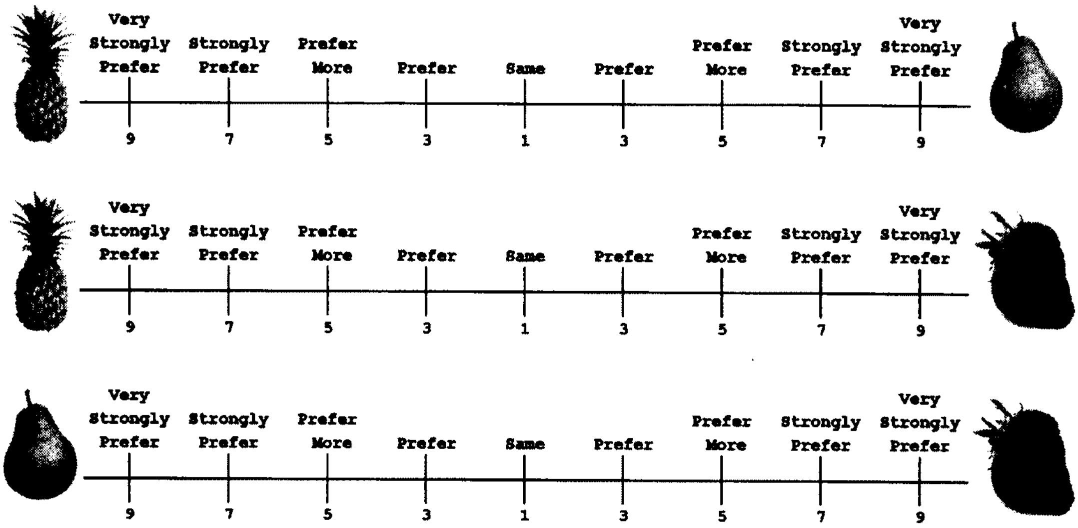


Figure 3: Successive Pair-wise Comparison of All Factors

The number of comparisons is a function of the number of items to be compared. For three objects (Pineapple, Pear, and Cherry), there would be three comparisons. The table below shows the number of comparisons [61].

Number of Items	1	2	3	4	5	6	7	N
Number of Comparisons	0	1	3	6	10	15	21	n(n-1)/2

Table 2: Number of Comparisons

Once the paired comparisons are made a reciprocal matrix is generated from the pair-wise comparisons.

Suppose the following ranking is obtained in each pair wise comparison, then the following section shows how to calculate the reciprocal matrix.

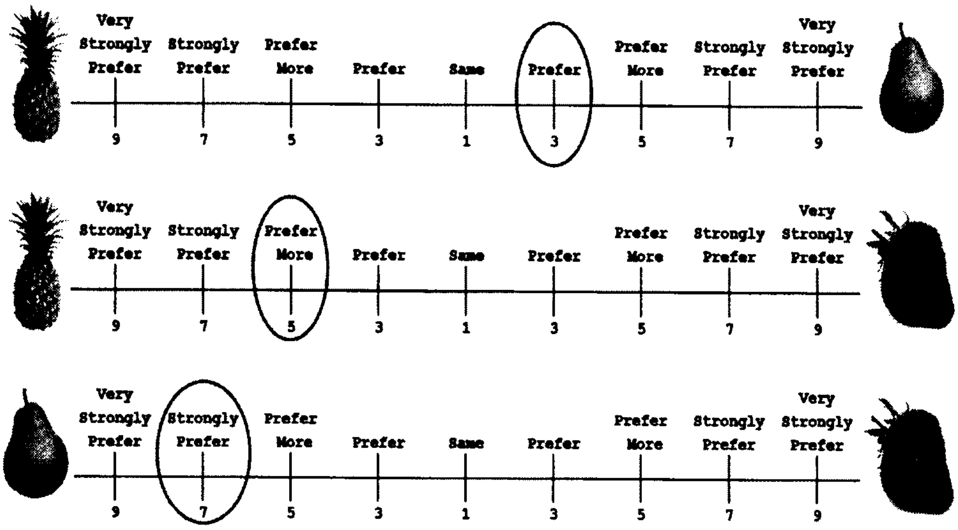


Figure 4: Successive Pair-wise Comparison of All Factors

From the three comparisons above a 3x3 matrix is generated. The diagonal elements of the matrix are always 1 and only the upper triangular part of matrix needs to be filled since the lower triangular part will be the same. The upper triangular matrix is filled by following the rules below [61].

1. If the judgment value is on the left side of "same" or 1, we use the value as is.
2. If the judgment value is on the right side of "same" or 1, we use the reciprocal of the value.

Comparing pineapple and pear, if one "prefers" a pear, we use 1/3 in row 1, column 2 of the matrix. Comparing Pineapple and Strawberry, if one "prefers more" a pineapple, we use the actual ranking value of 5 on the first row, last column of the matrix. Comparing pear and strawberry, pear is dominant. This value goes into the second row, third column of the matrix. Then based on his preference values above, we have a reciprocal matrix shown below:

	Pineapple	Pear	Strawberry
Pineapple	1	1/3	5
Pear		1	7
Strawberry			1

A = (matrix above)

To fill the lower triangular matrix, we use the reciprocal values of the upper diagonal. If a_{ij} is the element of row i column j of the matrix, then the lower diagonal is filled using this formula [61]

$a_{ji} = 1/a_{ij}$

Thus, now we have a complete comparison matrix

	Pineapple	Pear	Strawberry
Pineapple	1	1/3	5
Pear	3	1	7
Strawberry	1/5	1/7	1

A = (matrix above)

Notice that all the elements in the comparison matrix are positive, or $a_{ij}>0$.

Now compute the priority vector, which is the normalized Eigen vector of the matrix. Tools such as Matlab or other programs can be used to calculate the Eigen values and Eigen vector. The Solver option in MS Excel can also be used.

The normalized principal Eigen vector is also called **priority vector**. Since it is normalized, the sum of all elements in priority vector is 1. The priority vector shows relative weights of the factors being compared. In our example above, Pineapple is 27.9%, Pear is 64.91% and Strawberry is 7.19%. So the most preferable fruit is Pear, followed by Pineapple and Cherry. In this case, we know more than their ranking. In fact, the relative weight is a ratio scale that we can divide among them. For example, we can say that John likes pear 2.27 (=64.34/28.28) times more than pineapple, and he also like pear 8.72 (=64.34/7.38) times more than cherry.

We get three Eigen vectors concatenated into 3 columns of matrix W. The corresponding Eigen values are the diagonal of matrix 'Lambda'.

Using Matlab the Eigen values and Eigen vectors represented by Lambda and W can be calculated by

```
>> [W,Lambda] = eig(A)
```

$$\mathbf{W} = \begin{pmatrix} 0.3928 & -0.1964 + 0.3402i & -0.1964 - 0.3402i \\ 0.914 & 0.914 & 0.914 \\ 0.1013 & -0.0506 - 0.0877i & -0.0506 + 0.0877i \end{pmatrix}$$

$$\mathbf{Lambda} = \begin{pmatrix} 3.0649 & 0 & 0 \\ 0 & -0.0324 + 0.4448i & 0 \\ 0 & 0 & -0.0324 - 0.4448i \end{pmatrix}$$

The largest Eigen value is called the Principal Eigen value. In our case it is equal to 3.0649. The principal Eigen vector is the Eigen vector that corresponds to the highest Eigen value.

$$\overline{\mathbf{W}} = \begin{pmatrix} 0.3928 \\ 0.914 \\ 0.1013 \end{pmatrix}$$

The sum is 1.4081 and the normalized principal Eigen vector is

$$\mathbf{W^*} = \begin{pmatrix} 0.279 \\ 0.6491 \\ 0.0719 \end{pmatrix}$$

Thus the sum of the Eigen vector is not one. When you normalized an Eigen vector, then you get a priority vector. The sum of priority vector is one.

So, we know from the normalized vector that the preference is decreasing in the order of Pear, Pineapple, and Strawberry.

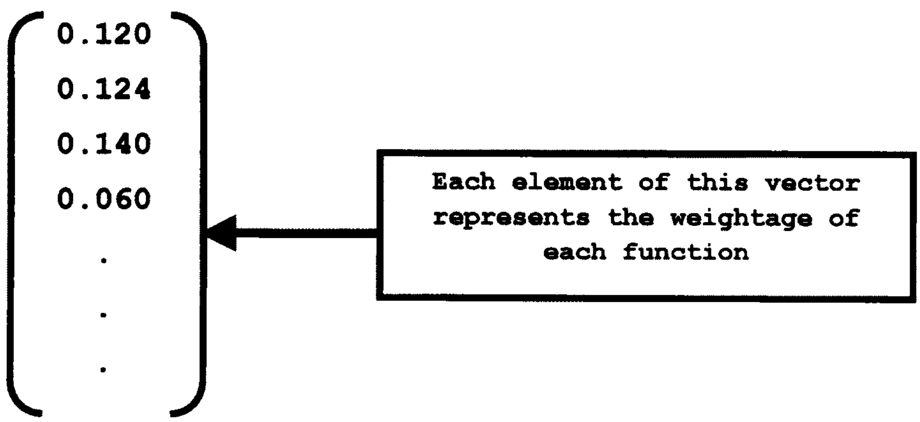
Application of AHP to our Framework

For convenience, table 3.2 is shown below

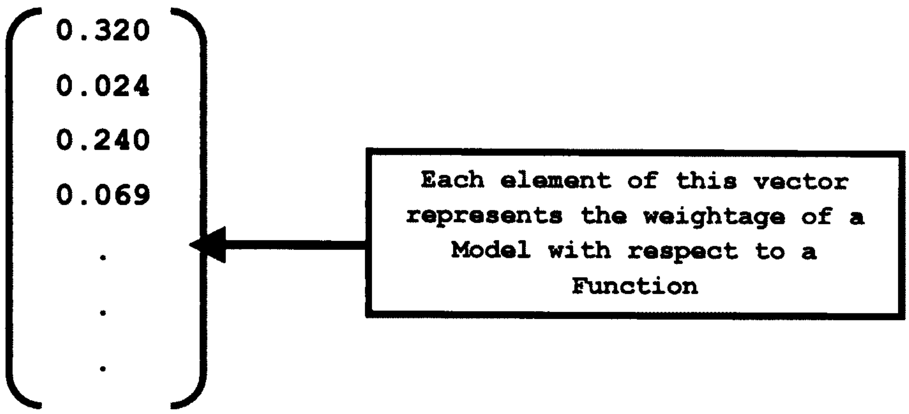
Target	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model i**
F1	X	X	X	X	X
F2	X	X		X	
F3	X		X	X	X
F4		X	X		
.	X		X	X	X
.		X			
.	X	X	X	X	X
Fn		X		X	X

Table 3: Functionalities Present in Models

First, the functions F1 through Fn are ranked as shown in the procedure and example above. This yields an Eigen vector with each element representing the weight of each of the functions.



The second step is to rank each of the Models 1 through i with respect to each of the functions F1 through Fn. Each Model might have a specific importance for each function; therefore the models are also compared in pairs with respect to each function. The AHP procedure explained above using pair-wise comparison gives a vector of weightages. A sample vector is shown below:



Weightage of each model with respect to a particular function is shown in the vector above. If the vector above is denoted by WFi, then it means it is a Weightage vector of all models with respect to function i. Thus repeating the process several times, we obtain as many vectors as the number of functions.

The third step involves combining these vectors into a matrix which looks similar to the table 3.2 above. However the elements of the matrix here represent the weightage of each Model with respect to each function.

Target	Model 1	Model 2	Model i-a	Model i-1	Model i	Total
F1	0.186	0.098	.	.	0.184	1
F2	0.184	0.002	.	.	0.175	1
F3	0.094	0.115	.	.	0.149	1
F4	0.137	0.134	.	.	0.074	1
.	0.007	0.025	.	.	0.027	1
.	0.061	0.062	.	.	0.084	1
.	0.064	0.044	.	.	0.154	1
Fn	0.093	0.169	.	.	0.058	1

Table 4: Weightage of a Particular Function in a Particular Model

The weightage of model 2 with respect to function F1 is .098. Once this matrix is obtained, the best Model can be chosen by multiplying the weights of a particular Model pertaining to each function with the weights of the functions derived in the first step. So the weight of Model 2 would be

0.12*0.098 + 0.124*0.002 + ...

The sum obtained is the overall ranking of the Model. Thus the best Model which suits the requirements of becoming a Primary Model Unit can be found.

APPENDIX II: MULTICOLLINEARITY AND VARIANCE INFLATION FACTOR

Multicollinearity [62]

The predictors in a regression model are often called the independent variables. But the independent variables may not be totally independent of each other. In most systems there is a certain amount of correlation between the independent variables. The term multicollinearity, however, is used when the correlation between the independent variables is too high. The variance of the estimated regression coefficients depends on the inter-correlation of the independent variables. Multicollinearity does not make the regression model wrong, but the variance of the regression coefficients can be inflated so much that the individual coefficients are not statistically significant even though the overall regression equation is good. Some coefficients and their sign may not make sense. The best solution is to understand the cause of multicollinearity and remove it. Multicollinearity occurs because two (or more) variables are related - they measure essentially the same thing. If one of the variables doesn't seem logically essential to the model, removing it may reduce or eliminate multicollinearity. One way could be to combine the variables. For example, if height and weight are collinear independent variables, perhaps it would make scientific sense to remove height and weight from the model, and use surface area (calculated from height and weight) instead [62].

Signs of Multicollinearity

1) High correlation between independent variables.

2) Regression coefficients whose signs or magnitudes do not make good physical sense.

3) Statistically non-significant regression coefficients on important predictors.

4) Extreme sensitivity of sign or magnitude of regression coefficients to inclusion or deletion of an independent variable.

Variance inflation factor (VIF) quantifies the level of Multicollinearity in an ordinary least squares regression analysis. It measures how much the variance of an estimated regression coefficient (the square of the estimate's standard deviation) is increased because of collinearity among the independent variables.

Multicollinearity results when the columns of X (independent variable) and in the case of a cost model, the cost drivers, have significant interdependence. When multicollinearity exists, a small change in X can result in large changes to the estimated regression coefficients.

Pair-wise collinearity can be determined from viewing a correlation matrix of the independent variables.

Another way of explaining this is that a variance inflation factor (*VIF*) quantifies how much the variance is inflated. We know that the standard errors and hence the variances of the estimated coefficients are inflated when multicollinearity exists. So, the variance inflation factor for the estimated coefficient b_k denoted by VIF_k is the factor by which the variance is inflated.

For the model in which x_k is the only predictor [63]:

$$y_i = \beta_0 + \beta_k X_{ik} + \varepsilon_i$$

the variance of the estimated coefficient b_k is given by [63]:

$$Var(b_k)_{\min} = \frac{\sigma^2}{\sum_{i=1}^{n}(x_{ik} - \bar{x}_k)^2}$$

The subscript "min" denotes that it is the smallest the variance can be for the given set of independent and dependent variables. This is the baseline variance, so we can see how much the variance of b_k is inflated when multicollinearity exists in the model.

Let's consider such a model with correlated predictors [63]:

$$y_i = \beta_0 + \beta_1 X_{i1} + \ldots + \beta_k X_{ik} + \ldots + \beta_{p-1} X_{i.p-1} + \varepsilon_i$$

Now, again, if some of the predictors are correlated with the predictor x_k, then the variance of b_k is inflated. It can be shown that the variance of b_k is [63]:

$$Var(b_k) = \frac{\sigma^2}{\sum_{i=1}^{n}(x_{ik} - \bar{x}_k)^2} x \frac{1}{1-R_k^2}$$

Where, R^2_k is the R^2-value obtained by regressing the k^{th} predictor on the remaining predictors. The greater the linear dependence among the predictor x_k and the other predictors, the larger the R^2_k value. And, the larger the R^2_k value, the larger the variance of b_k.

Taking the ratio of the two variances, we obtain how much larger b_k would be.

$$\frac{Var(b_k)}{Var(b_k)\min} = \frac{1}{1-R_k^2}$$

The above quantity is the variance inflation factor for the k^{th} predictor. That is:

$$VIF_k = \frac{1}{1-R_k^2}$$

Where, R^2_k is the R^2-value obtained by regressing the k^{th} predictor on the remaining predictors. Note that a variance inflation factor exists for *each of the k predictors* in a multiple regression model.

A VIF of 1 means that there is no correlation among the k^{th} predictor and the remaining predictor variables, and hence the variance of b_k is not inflated at all. The general rule of thumb is that VIFs exceeding 4 warrant further investigations, while VIFs exceeding 10 are signs of serious multicollinearity requiring correction.

Dealing with Variance Inflation Factor (VIF).

There are a number of approaches to dealing with multicollinearity. Some of these include:

1. Delete one or more of the independent variables from the fit.

2. Perform a principal components regression.

3. Compute the regression using a singular value decomposition approach.

For example in the example of the Rotary Air compressor, multicollinearity is evident from the fact that the coefficient of the variable CFM (Cubic feet per Minute) is negative. This, as discussed above is one of the signs of multicollinearity. The solution in this example would be to drop the variable CFM since and use only Hp (horsepower) as the cost driver.

Regression Statistics	
Multiple R	0.94822551
R Square	0.899131618
Adjusted R Square	0.865508823
Standard Error	479.5187798
Observations	5

	Coefficients
Intercept	*4246.95122*
HP	*173.1902439*

Cost = 4246.951 + 173.190*(HP)

Cost of Sixth item = 4246.951 + 173.190*(30) = $9442.66

This predicted cost is about 2% off of the actual value.

Therefore we have seen that applying VIF not only improves the performance of the cost model but also provides cost coefficients, which make logical sense.

APPENDIX III: PROGRAMS TO SUPPORT THE DATABASE METHODOLOGY

Below is a sample of an XML code which shows cost drivers and cost data.


```
<?xml version="1.0" encoding="ISO-8859-1" ?>
- <meadinkent>
  - <record>
      <mtrl>10</mtrl>
      <proc>221</proc>
      <len>0</len>
      <wdt>0</wdt>
    </record>
  - <record>
      <mtrl>10</mtrl>
      <proc>221</proc>
      <len>0</len>
      <wdt>0</wdt>
    </record>
  - <record>
      <mtrl>10</mtrl>
      <proc>221</proc>
      <len>0</len>
      <wdt>0</wdt>
    </record>
  - <record>
      <mtrl>10</mtrl>
      <proc>201</proc>
      <len>0</len>
      <wdt>0</wdt>
    </record>
  - <record>
      <mtrl>10</mtrl>
      <proc>201</proc>
      <len>0</len>
      <wdt>0</wdt>
    </record>
  - <record>
      <mtrl>10</mtrl>
```

```
  <proc>201</proc>
  <len>0</len>
  <wdt>0</wdt>
</record>
```

APPENDIX IV: LIFE CYCLE COST IN DETAIL

The cost categories mentioned below are some of the broad costs in life cycle cost estimate.

LIFE CYCLE COST

Research and Development Cost

- System Life Cycle Cost Management
- Product Planning
- Product Research
- Engineering Design
- Design Documentation
- System Software
- System Test and Evaluation

Production & Construction Cost

- Industrial Engineering & Operations Analysis
- Manufacturing
- Construction
- Quality Control
- Initial Logistics Support

Operation & Support Cost

- System Operations
- System Distribution
- Sustaining Logistics Support

Retirement & Disposal Cost

- Disposal of Non-repairable System/Sub-system
- System Ultimate Retirement

Depending upon the information available at the conceptual stage, some or all of the above costs can be calculated. The detailed calculations for each of the categories and subcategories are mentioned below [56].

Average cost of material purchase order ($/order)	C_a
Cost of item disposal	C_{dis}
Cost of system/product ultimate retirement	C_{dr}
Cost of maintaining a spare item in inventory	C_h
Cost of spare parts	C_m
Cost of inventory in warehouse	C_{odi}
Cost of marketing and sales	C_{odm}
Cost of transportation and traffic management	C_{odt}
Cost of maintenance of the test and support equipment at the depot and supplier level	C_{oed}
Cost of maintenance of the test and support equipment at the intermediate level	C_{oei}
Cost of maintenance of the test and support equipment at the organizational level	C_{oeo}
Cost of maintenance of the test and support equipment scheduled maintenance	C_{oes}
Cost of maintenance of the test and support equipment unscheduled maintenance	C_{oeu}
Cost of operational facility ($/site)	C_{ofs}
Cost of utilities ($/Site)	C_{ofu}
Technical data cost	C_{old}
Cost of special modification kits	C_{olk}
Cost of training equipment support	C_{oll}
Cost of maintenance facility support	C_{omm}
Cost of training facility support	C_{omt}
Cost of operator labor $/hr	C_{opp}
Cost of consumables	C_{osc}
Cost of spare/repair parts at the depot level	C_{osd}
Cost of spare/repair parts at the intermediate level	C_{osi}
Scheduled or preventive maintenance labor cost ($/mmhs)	C_{osl}
Cost of spare/repair parts at the organizational level	C_{oso}
Cost of spare /repair parts at the supplier level	C_{oss}
Cost of maintenance training ($/student week)	C_{otm}
Cost of training equipment and facility support	C_{ots}
Cost of operator training ($/student week)	C_{ott}
Cost of documentation per unscheduled maintenance action	C_{oud}
Unscheduled or corrective maintenance labor cost ($/mmhu)	C_{oul}
Cost of material handling for unscheduled maintenance action	C_{oum}
Cost of warehouse facility support ($/warehouse)	C_{ows}
Cost of utilities ($/warehouse)	C_{owu}
Acquisition cost of consumer facilities (system operation)	C_{pcc}
Cost of special test facilities	C_{pce}
Acquisition of maintenance facilities	C_{pcm}

Cost of manufacturing facilities	C_{pcp}
Acquisition cost of training facilities	C_{pct}
Acquisition cost of inventory warehouses	C_{pcw}
Cost of production control	C_{pic}
Cost of methods engineering	C_{pie}
cost of manufacturing engineering	C_{pim}
Cost of plant engineering	C_{pip}
Cost of sustaining engineering	C_{pis}
Initial customer service cost	C_{plc}
Initial technical data cost	C_{pld}
Initial training equipment cost	C_{ple}
Initial transportation and handling cost	C_{plh}
Initial training cost	C_{plp}
Initial supply support cost	C_{pls}
Initial test and support equipment cost	C_{plt}
Non-recurring manufacturing cost	C_{pmp}
Recurring manufacturing cost	C_{pmr}
Quality assurance cost	C_{pqa}
Cost of qualification test	C_{pqc}
Cost of production sampling test	C_{pqs}
Design documentation cost	C_{rd}
Engineering design cost	C_{re}
Cost of engineering model fabrication and assembly labor	C_{rea}
Cost of engineering model material	C_{reb}
Reclamation value	C_{rec}
System/Product life cycle management cost	C_{rm}
Product planning cost	C_{rp}
Product research cost	C_{rr}
Software development cost	C_{rsd}
Software modification cost	C_{rsm}
Software production cost	C_{rsp}
Cost of test operations and support (engineering model)	C_{rtt}
Cost of packing	C_{s}
Packing cost ($/kg)	C_{sc}
Cost of transportation	C_{t}
Shipping cost ($/kg)	C_{tc}
Cost of transportation and handling equipment maintenance	C_{x}

Table-A Independent Variables of the Life Cycle Cost Equations

Total System/Product Life Cycle Cost	C	Calculated
Total system/product retirement and disposal cost	C_d	Calculated
Total operations and support cost	C_o	Calculated
System/Product distribution cost	C_{od}	Calculated
Sustaining logistics support	C_{ol}	Calculated
Cost of unscheduled or corrective maintenance	C_{ola}	Calculated
Cost of scheduled or preventive maintenance	C_{olb}	Calculated
Customer service (life cycle support) cost	C_{olc}	Calculated
Test and support equipment	C_{ole}	Calculated
Transportation and handling cost	C_{olh}	Calculated
Maintenance facility and training facilities cost	C_{olm}	Calculated
Supply support (spares and inventory support) cost	C_{ols}	Calculated
Maintenance personnel training cost	C_{olt}	Calculated
Warehouse facilities cost	C_{olw}	Calculated
System/Product operations cost	C_{oo}	Calculated
Cost of operational facilities	C_{oof}	Calculated
Operating or user personnel cost	C_{oop}	Calculated
Cost of operator training	C_{oot}	Calculated
Total production and construction cost	C_p	Calculated
Construction cost	C_{pc}	Calculated
Industrial engineering and operations analysis cost	C_{pi}	Calculated
Initial logistics support cost	C_{pl}	Calculated
Manufacturing cost	C_{pm}	Calculated
Quality control/quality assurance cost	C_{pq}	Calculated
Total research and development cost	C_r	Calculated
System/product software cost	C_{rs}	Calculated
System test and evaluation cost	C_{rt}	Calculated

Table-B Dependent Variables of the Life Cycle Cost Equations

Below are the set of equations which calculate the comprehensive life cycle cost.

Life Cycle Equations from Blanchard and Fabrycky [56]

$C = [C_R + C_P + C_O + C_D]$
$C_R = [C_{RM} + C_{RP} + C_{RR} + C_{RE} + C_{RD} + C_{RS} + C_{RT}]$
$C_{RM} = \sum_{i=1}^{N} C_{RM_i}$ C_{RM_i} = Cost of specific activity "i" N = Number of activities
$C_{RP} = \sum_{i=1}^{N} C_{RP_i}$ C_{RP_i} = Cost of specific planning activity "i" N = Number of activities
$C_{RR} = \sum_{i=1}^{N} C_{RR_i}$ C_{RR_i} = Cost of specific research activity "i" N = Number of activities

$$C_{RE} = \sum_{i=1}^{N} C_{RE_i}$$ C_{RE_i} = Cost of specific design activity "i" N = Number of activities
$$C_{RD} = \sum_{i=1}^{N} C_{RD_i}$$ C_{RD_i} = Cost of data item "i" N = Number of data items
$$C_{RS} = [C_{RSD} + C_{RSM} + C_{RSP}]$$ C_{RSD} = Software development C_{RSM} = Software modification C_{RSP} = Software production
$$C_{RT} = [C_{RTA} \cdot N_{RT} + C_{RTB} \cdot N_{RT} + \sum_{i=1}^{N} C_{RTT_i}]$$ C_{RTA} = Cost of engineering model fabrication and assembly labor C_{RTB} = Cost of engineering model material C_{RTT_i} = Cost of test operations and support associated with specific test "i" N_{RT} = Number of engineering models N = Number of identifiable tests

$C_P = [C_{PI} + C_{PM} + C_{PC} + C_{PQ} + C_{PL}]$
$C_{PI} = [C_{PIP} + C_{PIM} + C_{PIE} + C_{PIC} + C_{PIS}]$ C_{PIP} = Cost of plant engineering C_{PIM} = Cost of manufacturing engineering C_{PIE} = Cost of methods engineering C_{PIC} = Cost of production control C_{PIS} = Cost of sustaining engineering
$C_{PM} = [C_{PMR} + C_{PMN}]$ C_{PMR} = Recurring manufacturing C_{PMN} = Nonrecurring manufacturing cost
$C_{PC} = [C_{PCP} + C_{PCE} + C_{PCC} + C_{PCM} + C_{PCT} + C_{PCW}]$ C_{PCP} = Cost of manufacturing facilities C_{PCE} = Cost of special test facilities C_{PCC} = Acquisition cost of consumer facilities (system operations) C_{PCM} = Acquisition cost of maintenance facilities C_{PCT} = Acquisition cost of training facilities C_{PCW} = Acquisition cost of inventory warehouses

$$C_{PQ} = [C_{PQA} + \sum_{i=1}^{N} C_{PQC} + \sum_{i=1}^{N} C_{PQS}]$$

C_{PQA} = Quality assurance cost
C_{PQC} = Cost of qualification test "i"
C_{PQS} = Cost of production sampling test "i"

$$C_{PL} = [C_{PLC} + C_{PLS} + C_{PLT} + C_{PLH} + C_{PLD} + C_{PLP} + C_{PLE}]$$

C_{PLC} = Initial customer service cost
C_{PLS} = Initial supply support cost
C_{PLT} = Initial test and support equipment cost
C_{PLH} = Initial transportation and handling cost
C_{PLD} = Initial technical data cost
C_{PLP} = Initial training cost
C_{PLE} = Initial training equipment cost

$$C_O = [C_{OO} + C_{OD} + C_{OL}]$$

$$C_{OO} = [C_{OOP} + C_{OOT} + C_{OOF}]$$

C_{OOP} = Operating or user personnel cost
C_{OOT} = Cost of operation training
C_{OOF} = Cost of operational facilities

$$C_{OOP} = [(C_{OPP})(Q_{OP})(T_O)(N_{OP}) \times (\%\ \text{Allocation})]$$

- C_{OPP} = Cost of operator labor
- Q_{OP} = Quantity of operators per system
- N_{OP} = Number of operating systems
- T_O = Hours of system operation

$$C_{OOT} = [(C_{OTT})(Q_{OT})(T_T) + (C_{OTS})\ (\%\ \text{Allocation})]$$

- C_{OTT} = Cost of operator training ($/student-week)
- C_{OTS} = Cost of training equipment and facility support
- Q_{OT} = Quantity of student operators
- T_T = Duration of training (weeks)

$$C_{OOF} = [(C_{OFS} + C_{OFU})(N_{OF}) \times (\%\ \text{Allocation})]$$

- C_{OFS} = Cost of operational facility support ($/site)
- C_{OFU} = Cost of utilities ($/site)
- N_{OF} = Number of operational sites

Alternate approach - it may be more feasible to relate facility cost in terms of: ($/square meter of space/site) X (number of operational sites); or on the basis of volume requirements ($/cubic meter)

$$C_{OD} = [C_{ODM} + C_{ODT} + C_{ODI}]$$

C_{ODM} = Cost of marketing and sales

C_{ODT} = Cost of transportation and traffic management

C_{ODI} = Cost of inventory in warehouses

$$C_{OL} = [C_{OLC} + C_{OLW} + C_{OLM} + C_{OLS} + C_{OLT} + C_{OLE} + C_{OLH} + C_{OLD} + C_{OLK}]$$

$$C_{OLC} = [C_{OLA} + C_{OLB}]$$

C_{OLA} = Cost of unscheduled or corrective maintenance

C_{OLB} = Cost of scheduled or preventive maintenance

Total cost (C_{OLC}) is the summation of C_{OLA} and C_{OLB} for <u>all</u> levels of maintenance support.

$$C_{OLA} = [(C_{OUL})(M_{MHU})(Q_{MAU}) + (Q_{MAU})(C_{OUM}) + (Q_{MAU}) \cdot (C_{OUD})](N_{MS})$$

C_{OUL} = Unscheduled maintenance labor cost ($\$/M_{MHU}$)

M_{MHU} = Unscheduled maintenance manhours per maintenance action

Q_{MAU} = Quantity of unscheduled maintenance actions

$Q_{MAU} = (T_O)(\lambda)$

C_{OUM} = Cost of material handling per unscheduled maintenance action C_{OUD} = Cost of documentation per unscheduled maintenance action N_{MS} = Number of maintenance sites T_O = Hours of system operation λ = System/product failure rate in failures/hour Determine unscheduled maintenance cost for each appropriate level of maintenance.
$$C_{OLB} = [(C_{OSL})(M_{MHS})(Q_{MAS}) + (Q_{MAS}) \cdot (C_{OSM}) + (Q_{MAS})(C_{OSD})](N_{MS})$$ C_{OSL} = Scheduled maintenance labor cost ($\$/M_{MSH}$) M_{MHS} = Scheduled maintenance man-hours per maintenance action Q_{MAS} = Quantity of scheduled maintenance actions. Q_{MAS} relates to fpt. C_{OSM} = Cost of material handling per scheduled maintenance action C_{OSD} = Cost of documentation per scheduled maintenance action N_{MS} = Number of maintenance sites
fpt = Frequency of scheduled maintenance Determine scheduled maintenance cost for each appropriate level of maintenance.

$$C_{OLW} = [(C_{OWS} + C_{OWU})(N_{OW}) \quad X$$

$$(\% \text{ Allocation})$$

C_{OWS} = Cost of warehouse facility support (\$/warehouse)
C_{OWU} = Cost of utilities (\$/warehouse)
N_{OW} = Number of warehouses

$$C_{OLM} = [(C_{OMM})(N_{OM}) + (C_{OMT})(N_{OR})]$$

$$X \quad (\% \text{ Allocation})$$

C_{OMM} = Cost of maintenance facility support
N_{OM} = Number of maintenance facilities
C_{OMT} = Cost of training facility support
N_{OT} = Number of maintenance training facilities

$$C_{OLS} = [C_{OSO} + C_{OSI} + C_{OSD} + C_{OSS} + C_{OSC}]$$

C_{OSO} = Cost of spare/repair parts at organizational level
C_{OSI} = Cost of spare/repair parts at intermediate level
C_{OSD} = Cost of spare/repair parts at depot level
C_{OSS} = Cost of spare/repair parts at supplier
C_{OSC} = Cost of consumables

$$C_{OSO} = \sum_{N_{MS}} [(C_A)(Q_A) + \sum (C_{M_i})(Q_{M_i}) + \sum_{i=1} (C_{H_i})(Q_{H_i})]$$

C_A = Average cost of material purchase order ($/order)
Q_A = Quantity of purchase orders
C_{M_i} = Cost of spare part "i"
Q_{M_i} = Quantity of "i" items demanded
C_{H_i} = Cost of maintaining spare item "i" in the inventory ($/$ value of the inventory)
Q_{H_i} = Quantity of "i" items in the inventory
N_{MS} = Number of maintenance sites

C_{OSI}, C_{OSD}, and C_{OSS} are determined in a similar manner.

$$C_{OLT} = [(C_{OTM})(Q_{OM})(T_T) + (C_{OLL})$$
$$(\%\ \text{Allocation})]$$

C_{OTM} = Cost of maintenance training ($/student week)
Q_{OM} = Quantity of maintenance students
C_{OLL} = Cost of training equipment support
T_T = Direction of training (weeks)

$$C_{OLE} = [C_{OEO} + C_{OEI} + C_{OED}]$$

C_{OEO} = Cost of maintenance of the test and support equipment at organizational level

C_{OEI} = Cost of maintenance of the test and support equipment at intermediate level
C_{OED} = Cost of maintenance of the test and support equipment at depot and supplier level

$$C_{OEO} = [C_{OEU} + C_{OES}]$$

C_{OEU} = Cost of equipment unscheduled maintenance
C_{OES} = Cost of equipment scheduled maintenance

C_{OEI} and C_{OED} are derived in a similar manner.

$$C_{OLH} = [(C_T)(Q_T) + (C_S)(Q_T) + C_X]$$

C_T = Cost of transportation

C_S = Cost of packing

Q_T = Quantity of one-way shipments

C_X = Cost of transportation and handling equipment maintenance

$$C_T = [(W)(C_{TC})]$$

W = Weight of item (kilogram)

C_{TC} = Shipping cost ($/kilogram)

$$C_S = [(W)(C_{SC})]$$

C_{SC} = Packing cost ($/kilogram)

Shipping cost will vary with the distance (in kilometers) of the one-way shipment. Packing cost and weight will vary depending on whether reusable containers are employed.

$$C_{OLD} = \sum_{i=1}^{N} C_{OLD_i}$$

C_{OLD_i} = Cost of specific data item "i"

N = Number of data items

$$C_{OLK} = \sum_{i=1}^{N} C_{OLK_i}$$

C_{OLK_i} = Cost of specific modifications "i"

N = Number of system/product modifications

$$C_D = [(F_C)(Q_{MAU})(C_{DIS} - C_{REC})] + C_{DR}$$

F_C = Condemnation factor

Q_{MAU} = Quantity of unscheduled maintenance actions

C_{DIS} = Cost of item disposal

C_{REC} = Reclamation value

C_{DR} = Cost of system/product ultimate retirement

CURRICULUM VITAE
YOUSUF S. MOHAMMED

EDUCATION

Doctor of Philosophy (Mechanical Engineering), Old Dominion University, Norfolk, VA, May 2012
Master of Engineering in Mechanical Engineering, Old Dominion University, Norfolk, VA, Dec 2003
Bachelor of Science in Mechanical Engineering, Jawaharlal Nehru Technological University, Hyderabad, India, June 1999

PROFESSIONAL CHRONOLOGY

Modern Machine & Tool Co., Inc., Newport News, VA
Lead Mechanical Engineer
Nov 2001- Present

ODU Research Foundation, Old Dominion University, Norfolk, VA
Research Assistant
Sept 1999 - Dec 2000

Suryodaya Hi-Tech Engineering Pvt. Ltd., India
Intern
Jan 1999-May 1999

SCIENTIFIC AND PROFESSIONAL MEMBERSHIPS

American Society of Mechanical Engineers (ASME)
International Society of Parametric Analysts (ISPA)
Society of Cost Estimating and Analysis (SCEA)

AWARDS AND PUBLICATIONS

- Mohammed, Y. "*Incorporating EIO-LCA Into Enterprise Wide Cost Modeling Using System Engineering Principles*", 2010 Department of Energy (DOE) Cost Analysis and Training Symposium. Santa Clara, CA May 19 - 20, 2010.
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