GENERIC COST ESTIMATION FRAMEWORK FOR DESIGN AND MANUFACTURING EVALUATION

by

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ABSTRACT

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A major drawback of current cost estimation models is their incapability of embracing effectively complete product development stage. Parametric estimation works well in early stages of design, but in detail design stage, a more complete estimation is provided by process model based and detail estimation techniques. A major paradigm shift is proposed in this work whereby 'Cost' is to be considered as a design parameter from scientific perspective, and it is to be treated as a design consequence rather than as an operational outcome. A comprehensive framework using System Analysis fundamentals is designed to study 'Process Cost' aspects of part or design. The work gives detailed implementation of this new approach for objects manufactured largely by milling operation. The thesis also suggests a methodology to extend this approach to other operations. The proposed Generic Cost Estimation Model shows good agreement with cost estimation by commercial estimation software. It also promises integration of 'Cost' with other disciplines in Multidisciplinary Optimization and Collaborative Engineering. The integration is achievable through new technologies like API, OLE and similar interface tools.

This thesis is dedicated to my beloved wife Mohini
and
daughter Shivani.

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My parents taught me the importance of education in life. They have been at the core of my desire in pursuing higher education and reaching this level. I would like to express my deep sense of gratitude to them for the hardships they have taken in raising me and bringing me to this day. I would like to thank my brother Umesh and sister Ujwala and their respective families for the support and encouragement during these vital years of my life.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: INTRODUCTION*

1.1 The Cost:

Generally, cost is referred to as the overall monetary resources spent on producing an object, process, service or completing a project. Costs are of different types, e.g., cost of design, cost of manufacturing, cost of operation, cost of construction, cost of salvage, etc. The overall, or total, cost of a product or service from its concept to its salvage is referred to as 'Life Cycle Cost'. It is a well-known fact that 'cost' is one of the most important attributes of any design, product or service. Every organization's aim is to make profit; thereby, 'cost' becomes an indispensable aspect of the business. If not cost effective, any product or design or service is bound to encounter economic failure in the long run. Traditionally, 'cost' is considered as a result of various engineering and operation decisions taken at every stage of the life cycle of the product, process or service. Industrial Engineers, Economists, Money Managers and Specialist Engineers have studied cost from their respective perspectives. But the purpose of all these studies has been the same to reduce cost and increase profitability. One of the important realizations by researchers is that almost 70% of the product life cycle cost is committed at the early design stage and preliminary design decisions affect cost the most [1]. That means any cost control measures taken in later part of product development or life cycle is likely to affect only 30% of product life cycle cost. And to make the product or service more cost effective, it is imperative to have some reasonably accurate measure of its costs at early design stage. The same cost measure can be used to compare various initial designs and to select the best one. This is the reason why an early 'Cost Estimation' is an important activity to make product, process or service more cost effective and competitive. An accurate, fast and robust cost estimation technique can give a competitive advantage to an organization.

1.2 Cost Estimation and Cost Engineering:

An Estimate is a forecast, an outcome of a judgment or a prediction. Cost Estimation can be described as the process by which a forecast of cost required to manufacture a product

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* The journal model for this work is *the Transactions of the ASME Journal of Manufacturing Science.*

or to complete a task is made. Gallagher stated that cost estimation consists of calculating and projecting future costs of men, materials, methods and management [2]. As it is with any other estimate, the accuracy of cost estimation depends on (i) details available at the time of estimation, (ii) time available for making the estimate and (iii) method adopted for the estimation [3]. In general, more accurate estimates need more resources to be spent on them and are thereby more costly. Another important point to note is that many of the factors on which the 'cost' is dependent are stochastic or time dependent, e.g., labor rate, raw material unit cost, etc.

The American Association of Cost Engineers (AACE) defines cost engineering as "that area of engineering practice where engineering judgment and experience are utilized in the application of scientific principles and techniques to the problem of cost estimation, cost control and profitability." This definition clearly emphasizes that cost estimation and control are in fact areas of *engineering* practice using *scientific* principles and techniques [4].

The importance of cost estimation can be realized by asking a simple question "Why cost estimation?" One of the principal aims of cost estimation is to facilitate economic feasibility of a new product, process, service or a project as a whole. On the basis of the estimated cost and anticipated profits the product can be priced and its economic survival can be tested in suggested market model. Cost estimation serves as a comparison basis for selecting alternatives when multiple scenarios are possible. Cost-benefit analysis serves as a method to select the best possible alternative within given constrains. Cost estimation along with production or project plan serves as a basis for budgeting, planning and cost control. Cost estimation helps to identify major cost drivers and suggests critical activities for economic success of the product, process or activity. Cost estimation as a means to develop more cost effective ways to produce the goods or services can be a worthwhile approach to boost productivity. These are some of the direct benefits of having reasonably accurate cost estimates [1].

1.3 Cost Accounting:

The process of cost estimation involves first identifying resources spent. As these resources can be of different nature, e.g., man-hours, material cost, machine time, etc; summing them up means first assigning a single common unit of measure of 'cost' to all of those resources and then adding up together to arrive at final dollar figure. Assigning 'dollar' figure to other type of resources is a function of 'cost accounting' practices [5]. So, cost accounting becomes the basis of source of information for cost estimation and hence, accuracy of the estimate largely depends on the legitimacy and appropriateness of the cost accounting data. Legitimate assignment of various costs incurred at different stages of product development and actual production is a responsibility of a cost accounting system. Various cost accounting techniques evolved over a period of time have the fundamental aim of assigning cost in more accurate and effective manner. But, still there is no "one right way" of performing this cost accounting task in its best way.

1.4 Cost Estimation Techniques:

There are two traditionally well-known approaches for cost estimation: the "direct" or parametric approach and the "detail" or industrial engineering approach. There are some cost estimation approaches that are principally similar but slightly different. One such approach is based on effective use of 'analogy' or similarity between various processes or products to be estimated and known standard processes or products. As mentioned above, the measure of cost is provided by various cost estimation tools based on (a) parametric analysis, (b) industrial engineering estimates, (c) analogy based estimates, (d) others (includes remaining techniques like standard estimates, expert consensus approach) and (e) combinations of the other form [6].

(i) Parametric Estimation [6]: Parametric cost estimation uses Cost Estimating Relationships (CERs) and associated mathematical algorithms. Cost Estimating relations are nothing but mathematical relations between predominant cost drivers and final cost of product or process. The process of generating parametric estimation model starts with data collection and normalization of that data with respect to varying conditions. The CERs are then established by critically analyzing the data. The model is then proposed by incorporating the logic behind the estimates and validated against available case studies. The method gives fair estimates in its data availability range. The estimates are not exact but serve the purpose of suggesting most likely range of estimate with certain estimated probability.

(ii) Process Model Based Estimate: This is called detailed or process model based cost approach. In this approach, a detail process script is required. Equations are set up for calculating time based on design variables and process parameters. The time is then translated as cost for estimates.

A more detail version of process estimate is the Predetermined Motion Time Study (PTMS) estimate, which estimates process time and resources based on detail step-by-step motion study analysis. The estimated process time is used to get cost estimates as in the earlier case. The details involved in this method are enormous and sometimes impossible to visualize or forecast.

Process script based estimates are faster to make but are less accurate than PMTS based estimates. So, there is always this tradeoff between quickness and accuracy of estimate.

(iii) Analogy: Analogy or similarity between two processes or products can be used effectively for cost estimation of certain relatively new processes [6]. For example: the process of applying adhesive layers in composite manufacturing can be equated with painting or varnishing [7]. The process time estimates of relatively new processes in such cases can be made based on estimates of existing processes in the similar ways suggested earlier.

(iv) Other Estimating Techniques: Some of the current prevailing practices are discussed below to get the feel of state of the art techniques and tools.

1. NASA's Multidisciplinary Optimization division uses 'Weight' as an optimization parameter. Although, weight is important from the space science consideration, evaluating designs on the sole basis of weight may be misleading. There can be 'n'

number of designs with same weight and costing over a broader range than expected. So, weight, as a cost parameter approximation, is not good beyond certain confidence, especially so when more details of design are available. But still it is a prevailing practice in aerospace industry to use overall 'weight' as an optimization parameter [8].

2. There are various commercial models available like PRICE, SEER, MicroFASTE, which can be used for parametric based life cycle costing [6]. The models ask for some specific details of the design and are based on large historical data. As the product development takes place in phases, specific phases can also be evaluated for the given product. They handle large domain of products from hardware, software, large engineering systems, etc.

It is to be noted that the design details required by parametric estimation, analogy based estimation, process script based estimation and predetermined motion time study based estimation are increasing in that order, and accuracy of estimates is also increasing thereof. This means that, in the early design stage when there are not many details available, only parametric estimation can be used and later process model based estimates and predetermined motion time study estimates can be used when complete details are available. Also, none of the above methods can take care of estimates from early design stage to final detail design.

1.5 Use of Computer in Cost Estimation [9]:

In the absence of computer in cost estimation, there was ample room for using personal judgments, errors and non-standard practices. With computers playing major roles in today's cost estimates, the process has changed significantly. Computers have enabled us to handle and store large cost data, integrate and network various cost systems. It also has increased the speed of estimation. Some of the major impacts of the use of computers are listed below.

i. Speed – Always important for cost estimation, speed is one of the major advantages of using computer for cost estimation.

ii. Accuracy – As there is very little scope for error in calculation by computers if the input data is correct, the estimates are accurate, error free and repeatable.

iii. Adaptability – Various kinds of estimates for different situations can be made based on computer software capability.

iv. Credibility – Certain basic rules and standards can be implemented in the software by which estimates become legitimate.

v. Continuous improvement – Learning curve philosophy can be implemented inherent in the software so that estimates can be improved as more and more data becomes available.

With these certain advantages, the use of computers for cost estimation is growing day by day. There are various methods of use of computers for cost estimation purpose:

i. Special programs – Linear programs can be used to cost estimate certain specific products or processes that require complicated logical approach.

ii. Spreadsheet estimates – Spreadsheets with macros can be used for cost estimation more simpler products and processes.

iii. Estimating with Databases – These are the estimations that use large, real-time cost accounting data as their basis of the estimation

1.6 Manufacturing Cost Estimation:

In product life cycle, there are several stages like conceptual design, detail engineering, production, operation, service and maintenance and retirement. Cost is associated with each of these stages. But, as operation, maintenance and salvation do not contribute to the wealth of the product, cost of first three stages, which come under 'manufacturing cost', becomes more important from an economics point of view. There are two major types of manufacturing: durable goods manufacturing, such as cars, refrigerators, etc., generally referred to as 'mechanical manufacturing' and non-durable goods manufacturing, such as food items, services, etc. In 1995, mechanical manufactures accounted for about 15% of GDP [10]. Mechanical manufacturing is a significant portion (65%) of 'wealth creating' activities in the United States [11]. Although it is only 15% of GDP, manufacturing affects performance of all other industries [10]. This in short demonstrates how important manufacturing is in our daily lives and so does its cost. Success or failure of products largely hinges on their cost effectiveness. All of the cost estimating techniques discussed in section 1.4 can be applied to evaluate manufacturing cost. The selection of which technique to apply for manufacturing cost estimation depends on availability of information and time, and at which stage of its life cycle the product is in. As mentioned earlier, almost 70% of the total life cycle cost of product gets defined at its early design stage and only 15% of it is expended at the end of product detail design stage [1]. Figure 1 shows cost committed and cost expended as against the product life cycle time. As it is seen, the preliminary design decisions are the most decisive factors for product life cycle cost and have the highest potential for bringing the cost saving. That means if we are to optimize any product stage for cost saving or for better cost-benefit ratio, then we ought to do it in the early design stage of the product. That is why cost estimation of various product stages at an early design stage is a key to identifying product success or failure. One can estimate cost of production, operation, maintenance and salvage at the early design stage and add up to get total life cycle cost and product can be optimized for that total cost function. Generally, cost of operation, maintenance and salvage are born by users and cost of design engineering and production together, so called cost of manufacture, are the ones that are born by manufacturer. Within cost of manufacture, production costs are predominant and are the topic of discussion henceforth in this dissertation.

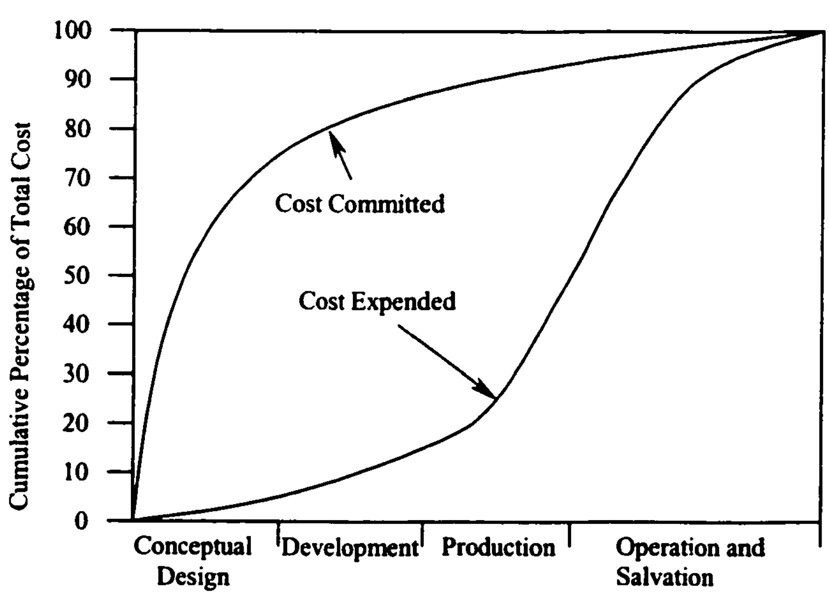


Figure 1. Cost committed and cost expended as against product life cycle time.

1.7 Design for Manufacture:

Product design and its manufacture are intimately related. No longer designer can ignore manufacturing aspects of the product during its design. The philosophy that emphasizes the concept that each component or part of a product must be designed so that it not only meets design requirements and specifications, but also can be manufactured economically and with relative ease [12]. This broad view is recognized as the area of design for manufacture. This approach integrates effectively the design process with materials, manufacturing methods, process planning, assembly, testing and quality control. For effective implementation of Design for Manufacture philosophy, designer is required to possess fundamental ability to understand characteristics, capabilities and limitations of materials, processes, related operations, machinery and equipment. Designer must also be able to assess impact of design modifications on manufacturing process, methods and machinery selection, and thereby impact on product cost. Establishing quantitative relationships is essential in order to optimize design for ease of manufacture at minimum cost. This is a fundamental purpose of 'cost estimation' model in the context of product development and it is central to this research. Cost serves as a common denominator for comparison of alternative designs and helps selecting optimal design.

1.8 'Manufacturing Cost' for Designers:

Majority of engineering design problems are essentially multiple criteria problems. In designing automobiles, aircrafts, plants an effort is made to increase strength, reliability, longevity, utilization factor and efficiency. At the same time, it is seen that initial cost, maintenance requirement, operation cost, breakdown time, manpower requirement are kept at minimum possible. This forms a problem of multicriteria optimization [13].

While designing a complex system like that of aircraft, there are various disciplines involved in it, like aerodynamics, structural design, acoustics, controls, telecommunication, manufacturing, ergonomics, engineering economics, etc. These disciplines are not independent. During optimization of function of one discipline, it is quite possible that function of some other discipline is affected. For example, a perfect aerodynamic wing design may cause the structure to be heavier than desired or with undesired stress pattern. An optimal structure may put economic and cost consideration in jeopardy. In such cases of design optimization, multiple disciplines must be considered at same time. As emphasized in previous sections, manufacturing cost is one of the decisive design characteristics that can critically affect economic fate of the product. In context of this multidisciplinary design optimization, it is important to include manufacturing cost as one of the disciplines that affect economic performance of product. As 'cost' is being studied with other scientific disciplines in multidisciplinary designs, it is important to describe 'cost' from scientific perspective and not from accounting perspective, which has been the case until now. Designers are not much aware of and not much willing to know about cost accounting details, as they are focused in essential designing practices. What they need are scientific equations, which they are familiar with, for cost estimation. These equations can be put in computer that can work with other design equations. This is a major focus of this research.

1.9 Dissertation Outline:

After this initial background discussion, this thesis presentation follows this outline. The following chapter, Literature Review (Chapter 2), discusses work of other researchers in context with cost estimation modeling work presented here. Chapter 3 elaborates specific objective of this research. It also discusses motivation behind the work and its importance to academia and industry. The research is conducted keeping in view Systems Analysis framework; in that context, Chapter 4 presents the technical foundation of the manufacturing processes and their economics. Chapter 5 presents analysis of requirements of proposed cost estimation system. The framework of the cost estimation model is suggested in Chapter 6, which suggests a paradigm shift in thinking about cost. Chapter 7 presents technical foundation of the framework. It explains how individual design specifications are related to cost and how their effect on cost can be quantified. Chapter 8 consolidates the previous Chapter 7 and suggests how these individual effects are brought together in order to get single process cost estimate. Commercially available cost estimating software is used to validate the suggested model. Chapter 9 presents details of the implementation, testing and validation of the model. Finally, Chapter 10 summarizes the work and presents conclusions and learning from the work, and suggests scope for the future work.

Chapter 2: LITERATURE REVIEW

2.1 Materials and Manufacturing Processes:

Materials and manufacturing processes are closely related. Noted researchers like Tlusty [10], Lindberg [11] and Kalpakjian [12] presented some of the comprehensive reviews of materials and associated manufacturing processes. With the advent of new materials new processes need to be invented to effectively manufacture them. Solid-state electronics, composite materials, ceramics and super alloys are some of the examples of categories of new materials that are growing in their importance and use. Apart from conventional machining processes, ultrasonic, laser, plasma, electro discharge, electro chemical and electro spark machining are some of the non-conventional machining processes. Solid-state electronics and composites require a whole different set of tooling for their manufacture. Solid-state electronics uses 'photolithography' and requires high precision processing [12]. The use of composites is growing in aircraft and automobile industry [14]. But its manufacturing is still costlier and pressure is on manufacturing engineers for developing fabrication techniques that reduce cost, maintain quality and reduce lead time. Flower gives a special account of materials in aerospace industry and their processing [15].

2.2 History of Cost in Manufacturing:

Engineers have studied cost for almost a century now. Credit of exploring economics of machining goes to Taylor F. W. for his famous work on tool life equation [16]. He is also the originator of 'Time Study' in 1880's– another important discipline of Industrial Engineering [17]. Taylor's 'Time study' was used to establish standard times for conducting certain tasks and determining wage incentives. Gilbreth F. B., proponent of 'Motion Study', came up with carefully studying motions of workmen and thereby suggesting elimination of unwanted motions [18]. He later devised systematic way of recording motions in 'Process Charts' [19]. When applied together, Motion and Time Study formed great tool for improving productivity [20]. Summary of both these great contributors, F. W. Taylor and F. B. Gilbreth, could be found in Reference [22] and [23] respectively. Although, these two methods were originated for different purposes, P.

Carroll, advocated their use for cost control [24]. He proposes methodology for planning, budgeting, estimating, standardizing costs and comparing them to actual costs to come up with profit-loss statement. This is how engineers arrived at 'scientific' manufacturing cost estimation.

Over the period of time various researchers have contributed to this field of study. Following section describe some of the important works cited and used as a background for this research.

2.3 Mechanics and Economics of Metal Cutting:

As this research focuses on exploring cost estimation from scientific perspective, it is important to know manufacturing science behind various manufacturing processes. The word 'Manufacturing' encompasses numerous types of processes. It is practically not possible to conduct and present research on all these process together in this single thesis. Certainly, metal cutting is one of the most important processes and study is kept limited to this process.

The basics of mechanics of metal cutting can be found in some of the most comprehensive and well-known texts written by Armarego and Brown [25], Boothroyd [26], Trent [27], and Johnson and Mellor [28]. One of the first attempts understanding of how metal chips are formed was made by the famous French scientist Tresca and later Mallock suggested that cutting is nothing but shear phenomenon [26]. As mentioned in previous section, F. W. Taylor had conducted experiments to investigate effects of tool materials and cutting conditions on tool life. He came up with an empirical power law that relates cutting speed and tool life under given conditions [16]. This tool life equation, Eq. (1), is used even today as a basis of machining economics.

$$VT^n = C \qquad \text{Eq. (1)}$$

Where;

V = Cutting speed

T = Tool life

n, C = Constants depending on tool-work material combination

Another fundamental contribution in metal cutting mechanics comes from Ernst and Merchant [29]. Their analysis showed how cutting forces are related to tool geometry, base material properties and cutting conditions in orthogonal (a metal cutting process in which the cutting edge is held at right angles to velocity of cutting) cutting. Johnson and Mellor give a good account of various theories and mathematical construct behind them in their text [28]. Armarego and Brown present one of the most comprehensive collection of theoretical treatments of metal cutting issues ranging from orthogonal cutting, oblique cutting, to tool wear and tool life [25]. He also shows treatments of individual cutting operations like turning, milling, drilling along with mathematics behind machining economics. Although it may seem like lot of work has been done on machining economics the fact is that most of these works tend to get into specifics like cutting tool angles, cutting conditions, etc., which are hard to predict for a product designer while he wants to know cost of his decisions.

The costs in metal cutting are of four major types and can be put together by Eq. (2) [26] [30]:

i. Handling or Work Setup cost
ii. Machining cost
iii. Tool changing cost
iv. Tool cost

$$C_o = Mt_1 + Mt_m + M\left(\frac{N_t}{N_b}\right)t_{c_t} + \left(\frac{N_t}{N_b}\right)C_t \qquad \text{Eq. (2)}$$

Where;

C_o = Production cost per piece

M = Total machine and operator rate

t_1 = Work setup time

t_m = Machining time per component

N_t = Number of tools used

N_b = Number of components in a batch

t_{c_t} = Tool change time

C_t = Cost of each tool

These costs vary depending on metal cutting parameters that are chosen. It is the duty of processes engineer to select proper cutting parameters. The aim of process planning engineer is generally multifold. Sometimes it may be desired to maximize production rate while at others it may be desired to have most economical cutting conditions or else to maximize profit in given time. The parameters that generally are varied include proper combination cutting speed, feed, depth of cut, use of cutting fluid and tool specifications. One of the most significant effects on cost of cutting comes form cutting speed choice [26]. The effects of cutting speed on cost of metal cutting operation are shown in Figure 2 [30]. The cost of work setup is independent of cutting speed. Cost of actual machining operation reduces inversely with increasing cutting speed. But, as cutting speed increases, tool life decreases and tool changing cost and tool cost increases. The total cost therefore follows a curve as shown in Figure 2. There exists a cutting speed for which cost per component is minimum.

Above analysis can be used to select proper cutting speed for an operation. Selection of other parameters like feed and depth of cut is also important. The effect of change of feed

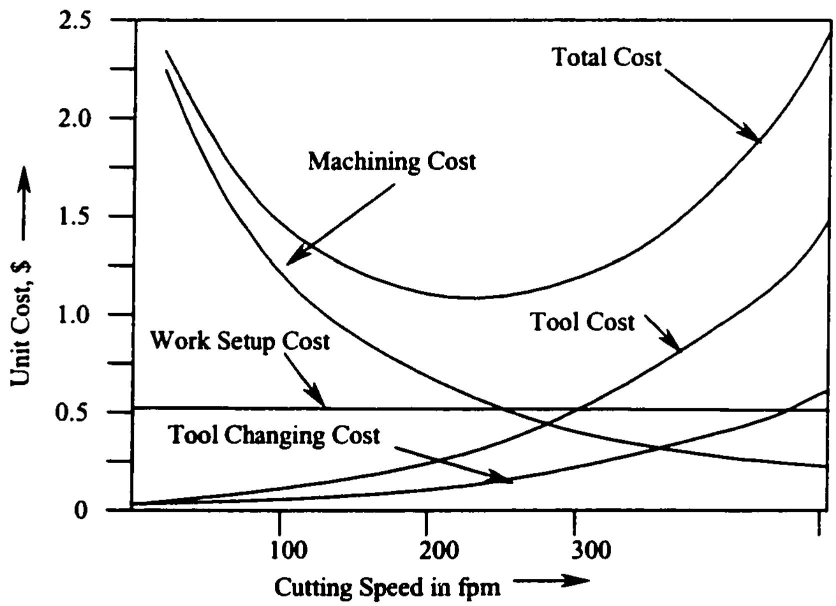


Figure 2. Variation in Production Cost with Cutting Speed.

and depth of cut on tool life can be expressed by modified Taylor's equation, Eq. (3)[25].

$$T = \frac{K}{V^{1/n} f^{1/n_1} d^{1/n_2}} \qquad \text{Eq. (3)}$$

Where;

T	= Tool life
V	= Cutting speed
f	= Feed
d	= Depth of cut
n, n_1, n_2, K	= Constants depending on tool-work material combination

Here in this equation, it is usually found that [25]: $\frac{1}{n} > \frac{1}{n_1} > \frac{1}{n_2}$

Meaning, tool life is least sensitive to depth of cut than feed and it is most sensitive to cutting speed. Using this information, for higher material removal or faster machining, it is recommended to keep maximum possible depth of cut, then keep higher feeds. Last preference is given to increase in cutting speeds. But, the real limitations on depth of cut and feed come from cutting forces resulting from them. The tool itself and machine tool structure has to be strong enough to resists any deformation from cutting forces that can cause deterioration of quality of machining. Chatter is also another reason, which is more likely with increased tool contact. Moreover, higher forces mean higher required power at the spindle and drives to keep the motion of cutting tool. In rough cutting, while aim is to have faster material removal rate, the upper limit on these parameters is 'power' available at the machine spindle. In finish cutting, resultant surface finish is important. Designer specifies surface finish requirements. Feed is an important factor in generating geometry of resultant surface and for finer surface finish feed is required to be kept low. This essentially limits finishing speed of the process and is related to the finishing cost [26].

At the same time lot of experimental work has been done and standards evolved so as to facilitate selection of operating conditions. These are cutting conditions tabulated by Machinability Data Center (MDC), Metcut Research Associates Inc., in two volumes of Machining Data Handbook [31]. American Society of Metals (ASM) also publishes data on metal cutting parameter [32]. All this information is essential to get an exact picture of metal cutting economics and estimation.

2.4 Economic Design:

Designer has to keep in mind mechanics and economics of machining to make his designs cost effective. Every aspect of design, like material selection, tolerancing and geometry features, needs to be inspected from manufacturer's point of view to keep the cost in check. Although there will be trade off in selecting functionality over manufacturability or vice versa in designer's decision, a right balance between them is required to achieve better product design. Many authors have chosen these aspects as topics of their books [33]. Trucks discusses materials, tolerance and surface finish specifications from economic machining point of view [33]. He also elaborates on design aspects in context with other processes like casting, forging, extrusions, metal stamping and powder metallurgy. Mills and Redford focus more on material specifications of designs [34]. The emphasis is there on 'machinability index' of material. As he mentions in his book, definition of machinability is still not unique and it means 'all things to all men'. Nevertheless, his discussion gives insight into various types of tool wear and their material causes. Boothroyd presents philosophy of design for manufacture and framework for its implementation [35]. In addition to guidelines for designing part for manufacture, he gives account of methodologies for process selection. Design for manufacture and assembly are just two out of various other considerations that are looked upon until recently. Huang et al. presents broad spectrum of other considerations like maintainability, modularity, reliability, environment friendliness, inspectability, quality and life cycle in general [36]. This generally is referred to as 'Design for X' philosophy, which is essentially Concurrent Engineering. Tolerance and surface finish specifications are part of design specifications that affect its cost. Mathematical analysis of tolerancing and its effect on manufacturing cost is presented by Creveling et al. [37].

A fundamental shift in thinking about product cost came from a relatively new philosophy called 'Design to Cost' or 'Target Costing' [40]. According to this philosophy, a product ought to be designed to cost. So, cost is an input to the designer rather than an out put from his actions. This 'cost' input comes from the market forces and competitors.

More detailed discussion on these effects of material, process selection and tolerancing on manufacturing cost will be presented in later chapters. Nevertheless, it can be stated that pressure is on the designers to cut the unwanted costs and make product not only functionally efficient, but also economically.

2.5 Traditional Engineering Cost Estimation Process:

Traditional cost and price structure is shown in Figure 3 [41]. To estimate these costs engineers have following information and tools for the use [42].

- Methodology, Algorithms, Rules of thumb, Equations
- Cost estimating Database (Factors and constants used in equations)
  Data Sourcing (obtaining, manipulating and creating cost estimating data)
  Data Management (coding, structuring and storing data for future use)
- Cost feedback (Historical cost data, benchmarking and calibration)
- Tools (forms, hardware and software)
- Procedures (organization)

The first task in estimation is to estimate direct labor and materials. Generally, engineering purchase department information help direct material estimation. Estimation becomes easier if raw material required is of standard stock type. Parametric relations give fair estimate of direct material. Direct labor is estimated using previously discussed metal cutting equations and predetermined motion time study standards [43].

Allocating overheads to this prime cost is basically governed by cost accounting. Traditional cost accounting allocates overheads on volume-based measures such as labor hours, machine hours or material cost. As these allocations are aggregate based they tend to distort the cost information [44]. An advanced management accounting technique is developed in recent past called 'Activity Based Costing'. In this practice, cost is captured at the smallest level possible. After estimation of these individual elements, it is their summation that gives cost of manufactured goods.

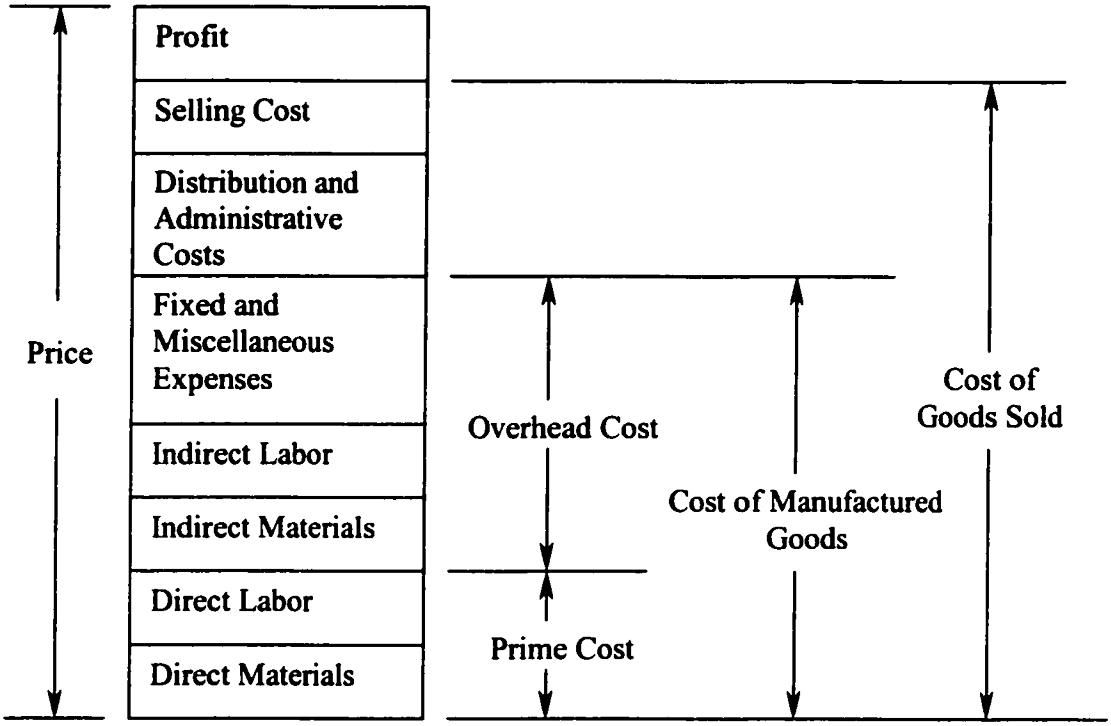


Figure 3. Cost and Price Structure [41].

2.6 Advances in Cost Estimating Methodologies:

With dynamics of the manufacturing systems Cost Estimation has never been same as before, especially after increasing influence of computer technology on the Industry. Following are some of the newly developed methodologies for manufacturing cost estimation.

2.6.1 Computer Based Detailed Estimates: Malmgren-Hansen et al. report one of the comprehensive computer aided cost estimation systems developed in their paper at CIM Europe Conference [45]. The system is developed by a project team of CIM.REFLEX, a part of a consortium for improving European manufacturing competitiveness. The system consists mainly of three modules: CAPS, CONFIG and COST. CAPS uses knowledge-based or AI approach and help production scheduling in real time. CONFIG is designed to evaluate customer order in terms of manufacturing capability of the system. COST performs cost estimation based on bottom-up approach or detailed estimation approach using traditional rule base and data. The paper reports plentiful uses of this product.

There are commercial Computer Aided Cost Estimating softwares that can do detailed rule based estimation. Costimator® is one such product installed in the ODU Intelligent Design and Manufacturing Solutions (iDMS) lab.

2.6.2 Top-Down Approach: As mentioned before, there are two major approaches: parametric and detailed, or summation. The third approach suggested by Samid, which he calls the 'Top-Down' approach, is based on Cost Knowledge [46]. In principle, in order to estimate entity 'X' one would analyze set of entities 'Sx' of which 'X' is a member. 'Sx' elements are considered to be well known in respect to their characteristics and their costs. So, if such 'Sx' is known then cost of 'X', 'Cx', is also known. But the problem according to the author is to identify which element of 'Sx' is close to or same as 'X'. Further, the author proposes methodology and strategy to identify 'Cx' based on the available knowledge about 'X'. This method narrows down estimation tolerance, as more and more knowledge is made available. This method could be effective where it is critical to quickly formulate estimation strategy and terminate the effort before a complete data acquisition for its own cost.

2.6.3 Generic Cost Estimation Framework: Weustink et al. identify four cost drivers: Geometry, Material, Production processes and Production planning [47]. The generic framework proposed by Weustink et al. relates different elements of design objects to each other that are described in completeness along with their cost attributes described above. The framework has three levels of aggregation: feature level, component level and assembly level. When all information at the bottom most level, i.e., feature level is known, it can be integrated to get final cost of component or assembly. This information framework is one way or organizing cost information but it does not address how the basic cost of features is calculated. For this purpose it has to take help of process based or parametric estimation method.

2.6.4 Resource Based Estimation Framework: This model was proposed by Ashby and Esawi and it assesses the resources of materials, energy, capital, time, space and information associated with manufacture of the product [48]. The cost model used underneath is a technical cost estimation model. This procedure is approximate but broad and equally applicable to all processes. This makes the method well suited for assessing relative cost of different processes and their ranking.

2.6.5 Activity Based Costing based systems for cost estimation: Traditional Cost Accounting systems are based on the mass production of mature product with known characteristics and a stable technology. Overhead costs in such systems are considered to be exogenous. Recent manufacturing experience suggests that these assumptions are no longer valid for today's advanced manufacturing systems [44][49]. Thus, Activity Based Costing (ABC) is being used by many organizations for product cost control and activity performance monitoring [50]. ABC inherently generates lot of cost relevant information that can be used for early cost estimation. The key issue is how to use this information for cost estimation at early stage. Authors propose methodology to use this ABC information for cost estimation. The methodology suggests identifying activity drivers from design specifications and at the same time generates the cost information for those activities from ABC database [44][49]. Finally, this information is linked together and processed to get cost of the design. Anand et al. propose a conceptual model for integration this cost estimation process. The process starts with generating a CAD model then features extraction algorithms are applied to conceive process related CAD information [52]. Recognized features are then translated as process plan and finally using ABC data the process plan is estimated for its cost. Although it looks promising, the initial cost of ABC and cost of additional information processing could be a decisive factor in final implementation of this system.

2.6.6 Cost Estimation Framework for 'Request for Quotation' Purpose: Veeramani and Joshi identify need of a rapid response to quotation request and discuss how today's cost estimating techniques fail to address the issue [53]. They suggest framework that divides product in to three main categories as: Standard products, Modified Standard Products and Custom Products. Estimation of Standard products is based on historic cost where as estimation of modified standard product is based on variant approach. The custom products are estimated by combined variant-generative method. Although the framework suggested is geared for fast quotation generation, with Computer Aided Cost Estimation (CACE) software it may be less significant because of efficient quote generation in such systems. Authors present implementation model based on suggested framework for sheet metal components and show efficacy of the system.

2.6.7 Integrating Cost in Design Optimization: Thurston and Essington suggest methodology to integrate cost in design decisions. They report use of their system as a means to formulate multicriteria design optimization problem, compare various alternatives and determine optimal materials and geometry [55].

2.7 Cost estimating Models:

Models are more specific implementations of methodologies. As early cost estimation became more and more important, researchers made effort to resolve this problem from various perspectives. They tried to use techniques well known to other areas of engineering, science and mathematics for this purpose. The following are some of the important models.

2.7.1 Approximate cost of Typical Turned parts: Boothroyd and Reynolds in their paper propose an approximate method for cost estimation of typical turned components [56]. They consider volume removed in rough cutting and finish cutting as a 'process time' driving parameter and equipment weight as equipment cost driving parameter. First productive and non-productive times are calculated using specific cutting power, tool life equation constant 'n', machine spindle power based on machine size, and other material handling specifics based on component weight. Machine cost is calculated based on a power law relating machine size and its cost. Further machine hourly rate is calculated assuming other details like time period over which the cost is amortized and number of operating shifts during that period. The model helps analyzing cost as against material specifications, surface area generation and material volume removal.

The proposed methodology tries to make cost estimation simple for designers but it is not just enough because of two important reasons:

- Specifics like tool life equation constants are not readily available for all specific materials but cutting speed data are.
- The model does not address design requirements like surface finish, tolerance and shape complexity.

2.7.2 Fuzzy Multi-Attribute Utility Theory for Cost Estimation: Multi-Attribute Utility Theory (MAUT) is based on following ideas [57]:

- When possible evaluation should be comparative
- Programs normally serve multiple constituencies
- Programs normally have multiple goals that are not equally important
- Judgments are inevitable part of any evaluation
- Judgments of magnitudes are best when made numerically
- Evaluations typically are, or at least should be, relevant to decisions

The mathematical formulation of the technique is as follows:

Let R be a general binary relation and X a set with general elements x and y. If R is negative transitive and weakly connected, and set is not uncountably large, then a real-value function exists such that, xRy if and only if U(x) > U(y). Here, 'R' can be equated to "is more expensive than" and 'U' can be considered to be a cost function, meaning:

x is more expensive than y if and only if U(x) > U(y); where U is a cost function.

This is a very general formulation of the cost evaluation problem in MAUT framework. All the functions and variables in MATU are 'crisp', meaning well defined, but in reality they are not. Dean Ting et al. propose to include fuzzy cost variables to formulate Fuzzy MATU. They conclude that this way cost could be estimated with incomplete or uncertain object information. They also claim that this method is efficient than traditional cost estimation because it does not require collection of great deal of historic data [57]. But an important point here to be noted that, expert's opinions are required initially to generate utility values of specific cost drivers.

2.7.3 Analogy Models: One of the basic problems in cost estimation is that there is no complete theoretical model for estimation. When sufficient data is available, analogies can be drawn and data analysis can be carried out to establish relationships between design parameters and cost that are called Cost Estimating Relationships, or CERs. To understand these CERs effectively, it is important to know the significance of coefficients involved in it. Analogy helps relating observations and theory. Gutowski et al. made an attempt to explain the theoretical significance of power law coefficients that underlie CERs for composite manufacturing and address the issue of how they change with part complexity [58]. His model agrees favorably with experiments and other detail estimating methods at the same time enhances understanding of basics of CERs in composite manufacturing.

One of the interesting analogies used by researchers is that of Information Theory first used by Suh, Goddard and Bell [59]. They showed that information theory used in communications technology could be applied to highlight manufacturing complexity. Hoult and Meador use a similar complexity theory approach for manufacturing cost estimation. They conclude that manufacturing time could be estimated fairly for manual lathe and milling operations based on availability of dimensional information and suggest that similar estimates could be made for other operations [60].

2.7.4 Function Costing: As the name suggests this method uses function or product specifications for costing estimation. French and Widden suggest that number of commonly used components show a close relationship between quantified functions and the cost [61]. In their paper they explain the construct of this method of costing and how it is beneficial in early costing of mechatronics or similar systems that have large number of components bought from outside.

2.7.5 Total System Model: Most real products are composed of multiple subparts. Kirchain and Field suggest the need of looking at cost and/or process/material substitution at not only individual part level but in the whole system context [62]. He suggests what he calls 'Extrapolative Method' or 'Total System Model' for evaluating cost effects. Extrapolative method is based on relative estimates where as Total System model uses technical or process based model.

2.7.6 Using Learning Curve Approach: Learning curve has been of interest to many researchers. Learning curve implies that when process is performed in similar way for number of times, the efficiency of the execution of the process improves. The conventional view of learning curve considers one factor at a time as a major influence on productivity improvement. Badiru suggests a multivariate approach to learning curve implementation [63]. This way learning curve can be used to extrapolate average cost of design if manufactured in multiples, i.e., cost of 'i^{th}' unit of production can be estimated from cost of initial units.

2.7.7 Artificial Neural Network Based Estimation: A Neural Network (NN), sometimes referred as Artificial Neural Network (ANN), is a novel form of Artificial Intelligence (AI) which empowers computers to handle intuitive types of problems that require integration of experience from often seemingly unrelated sources, and make decision that cannot be clearly defined in mathematical terms [64]. Neural network, which consists of multiple interconnected processing units, tries to simulate the structure of human brain and its method of processing data. These networks when trained under supervised data can identify patterns without any mathematical model. This method when applied to cost estimation was found effective in estimation of purchase price of certain items like electrolytic capacitors [65]. Smith and Meson present comparison of three techniques, namely Parametric, Fuzzy Logic method and Artificial Neural Network method [66].

2.8 Cost Estimation of Specific Processes and Products:

While applications of these cost models and methodologies to specific processes, researchers have advantage of using large process knowledge base related to that process. So, these specific approaches covering one or more similar processes, and typically come with 'knowledge based' approaches. Following are some of the approaches meant for processes like Composite manufacture, Injection molding and Die-casting. Cost estimation in Aerospace industry has its own sets of equations and generally they are handled separately because of factors like reliability, safety, security, etc. They are discussed in the last subsection.

2.8.1 Cost Estimation of Composites Manufacturing: Composite materials manufacturing being more recent development and being cost sensitive for its application are probably the most investigated than many other specific manufacturing processes. Mostly these models use knowledge-based methods combined with parametric and empirical data, and generally uses learning curve, as most of the processes of manual lay-up may tend to improve over the period of time [67]. One of the pioneering works in this area is done by Busch and Poggiali. They developed microcomputer based cost estimation program that takes various data and design parameters from user and computes various costs [67]. Veldsman and Basson explain significance of cost estimation in context with thermoplastic composites and resin transfer molding. They conducted various experiments to statically identify relationship between design parameters and their cost effects [73]. Li et al. use complex cost estimating relationships developed at MIT by Gutowski et al. and develop general framework based on Object Oriented Analysis and Design for life cycle cost estimation and manufacturability assessment of composites [70][75]. Farag and Al-Magd propose material selection approach on the basis of cost and performance [72].

2.8.2 Injection Molding and Die-casting Cost estimation: A knowledge-based approach or expert system is presented by Chin et al. and McIlhenny et al. for cost estimation of Injection mold parts [76]. El-Mehalawi and Miller suggest that cost of die-casting part depends mainly on part geometry complexity and tolerance [78]. They developed a system to quantify cost of die-casting components based on part geometry complexity and tolerance that uses a database of predetermined component designs of known cost. When a new design is encountered, the system finds the closest design in the database of objects and then adjusts its complexity based on the differences in the new design to arrive at a cost. Lenau and Egebol have studied cost estimation of die-casting products [79]. They have proposed algorithm based cost estimation system. Their results shows fair agreement with actual costs of components and suggest that the methodology could be used for cost estimation in early design stages for comparative study of alternatives. Dixon and Poli propose a comprehensive strategy for implementing Design for Manufacturing for Injection molding, Die-casting and Stamping parts. They use rules of thumb and several tables to account for part, process and equipment complexity that governs the cost [80].

2.8.3 Cost Estimation of Fabricated Parts: Schreve et al. develop a tool for cost estimation of fabricated parts during its design. They develop cost models based on regression analysis of the data collected by time studies during various operations. Their study shows very large estimation tolerance, -40% to +35%, which is good only for rough estimates [81].

2.8.4 Space Systems Estimation: Bing et al. describe a computer system for estimation space systems, e.g., launch vehicles. They identify cost database, aerospace inflation factor and correction factors that take care of risk and technical expertise as other important factors apart from the basic model for cost estimation [82]. Brown presents technical overview of almost 21 cost estimating tools used at Kennedy Space Center. They include estimating specifications, price books and KSC cost index. The significant cost factors that are considered typically in such estimates are: design, electronics, environment, security, cleanliness, hazardous operation, test and checkout, local and international location factors [83]. Herbig et al. present a study based on 'algorithms' for cost estimation of Spaceborne Radar System [84]. As it is with most of the algorithm based systems they remain specific to the topic.

2.9 Literature Summary:

In perspective, many researchers have contributed towards this subject of cost estimation and modeling. The various purposes of cost estimates are:

- Early design evaluation
- Process selection
- Process plan and scheduling optimization
- Together design, manufacturing and facility optimization
- Budgeting
- Cost planning and control

- Issuing quotation

Requirement of each type of estimate are different from others and there is no single estimation system that takes care of all kinds of estimation needs. Hardly any theoretical model entirely based on technical reasoning and data but no empirical equations exists that can be used at early design stage. The consequently early design decisions in part design are based on statistics, fuzzy logic or combination of similar inferring tools. The goal of this research would be to eliminate these drawbacks of current systems.

Chapter 3: PROBLEM DEFINITION

3.1 Foundation of the Problem:

3.1.1 Cost as a Design Attribute: As emphasized earlier, 'the cost' today is one of the most important attributes of any design, product or service. Traditionally, cost is being looked at as a resultant of the engineering and operation decisions. But, as cost is becoming more and more important, it is being viewed as an attribute more closely associated to design itself. This transition in view can be justified because, although cost is a direct outcome of engineering and operation decisions, principally product or process design is inherent cause of those operation decisions. The philosophy of 'Design for Cost' is a resultant of this transition.

3.1.2 Cost Estimation – an engineering discipline: Originally, cost estimation activity heavily depended on Cost Accounting department of an industry. But when it comes to improvement or optimization of the product cost aspects, engineers must be involved in decision making as they are the ones who make design decisions that reflect as various product costs. Due to this important fact, engineers should be aware of 'the cost' aspects of their decisions when they design a product. This requires integrating cost estimation within design framework. Today, Computer tools have been developed for product design, analysis and for cost estimation as well. Almost every design is made on computer today, and the idea is to incorporate Computer Aided Cost Estimation (CACE) tool in Computer Aided Design (CAD) and Analysis. This integration will help in quickly analyzing cost aspects of design. A CAD part file can be analyzed for stresses using Finite Element Analysis (FEA) or it can be analyzed for aerodynamic properties using Computational Fluid Dynamic Analysis (CFD) tools integrated with CAD. Similarly, Computer Aided Cost Estimation (CACE) should be integrated with CAD such that, like stress failures and aerodynamic failures, product economic failures could be predicted. This research is aimed at fundamental and groundwork of implementation of above concept. It is an engineering approach to cost estimation. There is a paradigm shift suggested in this research, which insists on thinking cost as a design attribute rather than an operation decision. The idea is to display cost of a part or product as an engineering attribute. The way engineers see weight, moment of inertia or failure load of a part as characteristics of it; they should see the cost the same way. The cost represented to engineers in such way could then be compared with anticipated cost for economic failure of a product or service and based on the comparison economic failures can be predicted. Similarly, the same cost estimation can be used for faster product and process optimization. This can bring revolution in engineering design process.

3.1.3 Disadvantages of current cost estimation methods: Presently available cost estimation techniques viz. parametric estimation, grassroot estimation, analogy estimation and other specific models (described in Chapter 1 and 2), fail to address some of the important requirements for implementation of the revolutionary concept mentioned above. These concerns are discussed below.

1. **Lack of universality** - It can be pointed out that none of these techniques are completely encompassing the product life cycle. Parametric estimation is useful at conceptual design stage but grassroot estimate fails miserably due to lack of details at that point of time. On the contrary, parametric estimation fails to take care of estimation at detail design stage. [Standard estimates are sometimes not too accurate due to stochastic nature of the cost which demand constant revision of standard data.]
2. **Large dependency on cost accounting** – Most of these methods use historic cost accounting data to come up with coefficients, rates, etc. This means, cost accounting methods within the company can easily affect those critical cost-estimating factors. Under such condition, same process in spite of consuming same resources will have different cost under two cost accounting setups. Activity based costing is one way to eliminate this difference.
3. **System integration ability** – Although many softwares based on existing technique are available for cost estimation, none of them is fully integrated with CAD and product optimization tools. More so, their integration in current form may be very difficult due to the fact that the details required by cost estimation software are not directly available with CAD system alone. For example, in case PMTS based estimate, one has to generate process plan from part design, then detailed activity chart should be prepared and only then detailed estimate can be made. So, in such

cases currently there is no scope for the direct integration of CAD and CACE systems.

4. **Inherent drawbacks of the use of statistical data** – when some of these techniques use statistical data as their basis for estimation, they inherit associated drawbacks too. Meaning, the estimates are valid only under the conditions for which the data is valid. The accuracy of the estimate depends on the accuracy of the base data.

The proposed cost modeling work is intended to study and eliminate the weaknesses of current practices and to consolidate strengths of previous approaches. The research basically investigates following aspects related to the topic and suggests ways to accomplish integration of cost fundamentals in CAE environment:

1. Cost estimation from engineering perspective
2. Computer aided cost estimation and analysis
3. Integration of CACE with CAD and Enterprise Information System
4. Use of integrated CACE/CAD system for Multidisciplinary Design Optimization (MDO)

3.2 Motivation:

The proposed study of cost related aspects of a product and process is driven by the following important developments in engineering field.

Cost is one of the most important factors in the market as it is always been and product success largely hinges on its cost and its affordability. Researchers have realized that almost 70% of the product cost is committed at the early design stage and preliminary design decisions affect cost the most. This makes it vary important to engineers to look into cost as an engineering parameter and study cost relations with engineering or physical characteristics of product. So, the primary motivation of this research is to provide engineers a tool that is easy to use and can exploit cost saving potential at early design stage.

There are various cost contributors in the entire product life cycle and pressure is on for cost reduction at each stage of the product. But, each of these stages is not entirely independent and cost reduction or performance optimization in one may affect the cost or performance, respectively, in the others. Thus, an integrated cost approach is necessary to have product performance optimization in real sense.

There are various technical difficulties involved in the process of technical integration of various disciplines. The fundamental reason is the variety of data handled by the large-scale engineering systems. The information technology has developed various tools based on 'Object Oriented' concepts that can be of immense help in solving the problem of integrating cost and other disciplines. The object technology enables us to communicate back and forth between different kinds of applications and exchange necessary data.

Another concern about the cost is that current cost modeling largely uses statistical base for its design and validation. Using statistics brings its fundamental drawbacks into picture. For Example: Extensibility of the model beyond the data availability range, Validity and accuracy of data itself. This prompts us to have an attempt to study cost as a science and investigating cost beyond mere statistical relations. Including the technical reasoning based approach to make cost more palatable to engineers is another motivation in this direction.

3.3 Research Objective:

The fundamental objective of this study is to investigate 'cost' as a product design attribute from scientific perspective. The goal will be to construct a cost estimation model based on scientific principles, which can be integrated using object oriented database and tools with other analytical disciplines to demonstrate the concept of multi-disciplinary optimization and its use in evaluating affordability of designs. The approach is one of the pioneering of its kind and is aimed at suggesting a generic framework for cost modeling that can be extended in different directions keeping the philosophy same. The contribution of this work in this regard is aimed to be the one similar to the efforts by scientists and engineers in early days of developing numerical analysis techniques like finite element method.

3.4 Benefits:

The proposed study will be helpful in many senses as discussed below.

1. Breakthrough cost analysis for engineers – Today's engineering designers have little idea of cost when they design a product. The proposed cost model will be very handy to those engineers during designing. Engineers will be able to see the cost as a design characteristic like other characteristics such as weight, moment of inertia, etc.
2. Cost forecasting – The study will provide a true means of cost forecasting for products that have been produced never before. The other methods, predominantly parametric estimation technique, increase the risk involved in estimation beyond the data range.
3. Collaborative engineering – Using Information technology based on Object Oriented principles will enable integration and promote Collaborative Engineering within entire organization and its affiliates.
4. User-friendly tool for cost estimation – Another problem with cost estimation is that it largely depends on the experience of the team working on it. Cost estimation based on scientific principles and not on specific data will result in least interaction with the user during the estimation process. This is important for the user-friendliness of the proposed method and will most likely produce same estimates by users with different cost estimation experience.

3.5 Methodology of Study:

Its evident that to achieve the objective of construction of effective cost estimation model, a holistic approach is necessary. Systems Analysis approach is one such promising approach that is goal centered and complete. Systems Analysis (SA) covers the whole spectrum from problem definition, to goals analysis, to requirement specifications and the rest of the steps in systems development. It is a 'goal centered' approach, meaning the focus is always on 'solving the correct problem' rather than solving the problem correctly'. The SA methodology allows multi-disciplinary team to come together, generates structured information and suggests continuous improvement by iterations. This method is chosen because of vast nature of the problem, multi-disciplinary nature of the problem and the need of continuous improvement.

The steps followed here in this research to study and propose cost model are listed below.

- Identifying Goals and Objectives
- Study of Subject Matter, i.e., Manufacturing Processes
- Input: What data is available for costing?
- Output: What is expected out of a proposed model?
- Identify Other Requirements
- Existing Costing Systems
- Futuristic Costing System: What is it? – A generalized concept
- Axiological Component
- Identify Solutions
- Evaluate, Rank Them and Select one on the basis of Criterion of Evaluation
- Iterations of previous steps
- Implementation

Iterations are the part of this approach. Initial a few iterations are expected to give good idea of the problem and later iterations are intended to find more details of the problem. The approach gives consistent framework to follow for future work.

Chapter 4: SUBJECT MATTER ANALYSIS – MANUFACTURING PROCESSES

4.1 Manufacturing Processes:

General facts and figure show importance of manufacturing in US Industry. In the US in 1990, 24% of GNP was due to manufacturing, 13% in extractive Industry, 64% service industry. As service industry do not produce wealth, manufacturing accounts for 65% of the America's wealth each year [11]. Different processes that come under manufacturing can be classified into the following categories:

- Machining
- Forming
- Joining
- Sheet metal processes
- Casting and Powder compacting
- Molding
- Surface Treatment

Among all these processes, probably the most important is 'Machining'. Machining operations are performed on metals or non-metals and having variety of raw material formats from simple ingots, bars, castings, and sheet metals. It is one of the most versatile methods of processing and one of the most widely used one. Simple Shear, abrasion, thermal, chemical or possible combination these mechanisms are used to dislodge unwanted material from the parent material. Traditional machining operations use 'mechanical shear' to remove unwanted material with the help of single point cutting tool or multipoint cutting tool. Use of other mechanisms or combinations thereof for machining are termed as non-conventional machining processes. Each of these processes has characteristic advantages and disadvantages over the other. In general, machining processes are characterized by attributes such as kind of tools used, nature of material removed (chip formation), amount of material removal possible, processing parameters, shapes that are produced, sizes of components that can be handled, tolerances and precision achieved and kinds of raw materials processed. As machining processes are reduction processes, the time required to machine a component or part is directly related to amount of material removed from the base material. Higher the material volume to be removed from the base material, higher is the time required to finish the operation. As time is cost for manufacturing, it is the material volume removal that is important from identifying cost of machining operation. Due this fact 'material volume removal' is termed as predominant variable for machining processes. More detail analysis for the metal cutting processes of machining group of operations in this regard is presented in section 4.2.

Forming processes are no-addition-no-subtraction of material processes. Typical of these processes are: forging, extrusion, rolling, drawing and sheet metal forming. The fundamental mechanics of these processes is plastic deformation. The permanent deformation may be carried out at an elevated temperature or at a normal temperature. The permanent deformation of the material is nothing but 'the plastic strain' and the difficulty of operation is related to plastic strain energy required to produce that strain. In totality, it is the volume of material deformed, the extent to which it is deformed and material properties of the base material decide major characteristics of the process and thereby the cost of the operation. Out of these principal variables, extent of deformation or the amount of strain is a 'process time' related parameter. Larger the plastic strain, more are the number of steps of deformation required and more the process time. So the predominant variable here is the 'average plastic strain'. The size of the object to be deformed decides the size and capacity of the equipment required for carrying out the operation that in turn decides the setup cost rate for the operation. Shape decides tool complexity involved and there by tool cost. So, overall cost of forming process depends on: volume to be deformed, plastic strain, physical size, material, shape and tolerance of part to be manufactured.

Welding, riveting, adhesive bonding are some of the joining processes. Joining process may be with or without substantial addition of material. Generally, a joint is created between two different pieces of materials at a common edge. Obviously, the length of that edge is an important process time related variable, which becomes predominant variable for joining processes.

Sheet metal processes are typical from the sense that they handle relatively 'thin' or 'wafer' type of raw materials. Sheet metal processes can be broadly categorized in two groups: forming and shearing. The discussion of general forming processes presented previously holds good for sheet metal forming also. That means, the amount of plastic strain becomes the predominant variable from cost point of view. In case of shear, it is the length of the shear or cut and thickness of cut that represents time related process parameters and are responsible for the cost of operation.

Casting and compacting processes are truly material addition processes. In case of a regular casting, the process time depends on time required for metal poring and subsequently cooling of the same metal thereof. Cooling rate is generally a function of surface area to volume ratio, heat-transfer properties of the material and shape of the component in general. Similar argument can be made for the powder compacted part. In essence, relative process time and cost can be identified after knowing the material of the part, process parameters and geometry of the part. Molding is also a material addition process used in context with ceramics and plastics. Process time in these cases can be evaluated with the help of geometry and material used in these processes. In case of Surface Treatments, it is the surface area and thickness of the coat or the altered surface becomes the predominant variables for identifying process cost.

Above discussion briefly summarizes the relation of process time to design parameters and identifies some of the most important variables in deign which can determine the process time and process cost of the design. The discussion is not the conclusion of the study of these individual groups of processes but it is an initial assessment. More detailed investigations are needed to comprehensively establish these relations. But as stated previously, detailed investigations are carried out for the machining and particularly in case of milling operation. These are presented in the following sections.

4.2 Metal Cutting Mechanics and Economics:

In metal cutting, one of the most commonly used manufacturing process; a sharp cutting tool edge in contact with the work piece ploughs material from it. Mallock suggested that the cutting action was due to continuous shear in the metal being removed [85]. Taylor presented his comprehensive work on effects of tool material and cutting conditions on tool life. The empirical law relating cutting speed to tool life, Eq (1), is still in use today for studying machining economics. Later, Ernst and Merchant presented their model of mechanics of orthogonal metal cutting, assuming the shear zone in the material is thin enough to be considered as a plane [29]. Some other researchers have also suggested their models of metal cutting including finite element analysis of the processes. The goal is to represent relation between cutting forces and cutting conditions. Cutting forces are namely: cutting force – a force in the direction of cutting velocity, feed force – a force in the direction of feed velocity, and thrust force – force in the third mutually perpendicular direction to cutting and feed force. The 'work' is mainly performed or energy is mainly consumed in cutting process by the cutting force. Cutting conditions are identified by work material specification, tool specification, cutting speeds and other relevant surrounding conditions such as work piece temperature, use of coolants etc. Cutting forces further decide machine tool design, tool life and optimal process parameters and thereby economics of metal cutting. One important fact to be noted is that there is no single theory or model presented by these researchers that completely agrees quantitatively to experimental results for all possible cases of metal cutting [26]. According to the model presented by Ernst and Merchant (Refer Figure 4), for an orthogonal cutting, cutting in which cutting velocity is perpendicular to principal cutting edge of the tool, cutting force is given by:

$$F_c = \left(\frac{\tau_s A_c}{\sin\phi}\right)\left(\frac{\cos(\beta - \gamma_{ne})}{\cos(\phi + \beta - \gamma_{ne})}\right) \qquad \text{Eq. (4)}$$

Where;

$F_c =$ Cutting force

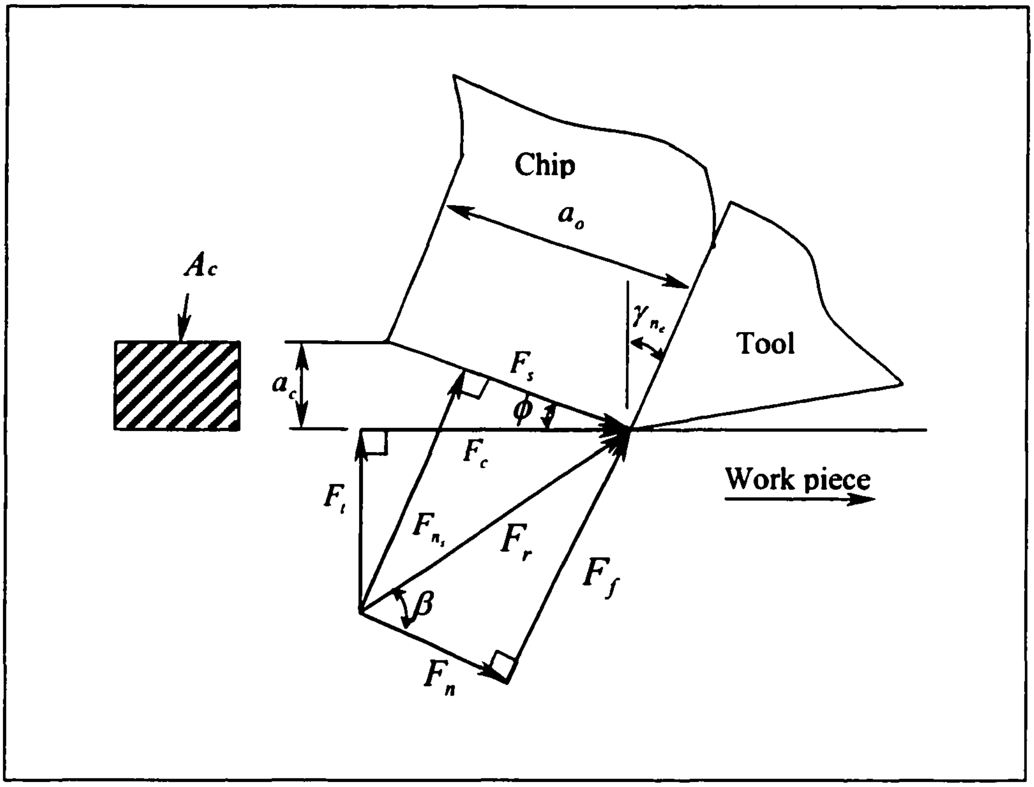
$\tau_s =$ Apparent shear strength of the material at the shear plane

$A_c =$ Cross-sectional area of uncut chip

$\phi =$ Shear angle

$\beta =$ Mean angle of friction between chip and tool

$\gamma_{ne} =$ Working normal rake angle of tool



F_c = Cutting force

F_t = Thrust force

F_f = Frictional force on Tool rake face

F_n = Normal force on Tool rake face

F_{n_s} = Normal force on Shear Plane

F_s = Shear force

A_c = Cross-sectional area of uncut chip

ϕ = Shear angle

β = Mean angle of friction between chip and tool

γ_{n_e} = Working normal rake angle of tool

a_c = Uncut-chip thickness

Figure 4. Force Diagram for Orthogonal Cutting (Theory of Ernst and Merchant) [29].

Work material is very important from the point of view that it governs plastic shear phenomenon in metal cutting. From the above equation, τ_s - the apparent shear strength of the material is a property of material itself. Cross sectional area of uncut chip, A_c, is an operational parameter expressed by depth of cut times width of cut. Working normal rake 'γ_{ne}' - a tool property, the mean friction angle 'β' and shear angle 'ϕ' are qualitatively related in a linear way as found by experiments [86]. Friction mechanism between chip and tool face is of two types, sliding friction and sticking friction – friction in which frictional force is constant and equal to shear strength of chip material times area of contact. Therefore the coefficient of friction is dependent on normal stress distribution of the tool face, which in effect is dependent on uncut chip thickness, tool geometry and material property – the shear strength.

Cutting speed has two major roles to play in the mechanics of metal cutting. Firstly, it decides the shear rate or the rate of deformation in shear zone. This is a complex phenomenon, there is direct effect of strain rate on shear strength of the material and also it affects the energy input rate in the system thereby increasing temperatures. Through this mechanism cutting velocity affects shear angle and friction angle used in the equation above. The second important effect of cutting velocity is on tool wear. Increase in cutting velocity means higher temperatures; faster abrasion and more accelerated tool wear thereby shorter tool life. As the tool life is reduced due to higher cutting speed, more frequent tool changes are required and nonproductive operating cost increases. But at the same time, due to higher cutting velocities more material volume is removed or cut from the base material in the same time. So, there is a tread-off between faster material removal and shorter tool life for a given tool and part material. So in general it can be stated that:

Cutting Speed = f(base material, tool material, cutting temperature, tool geometry)

F.W. Taylor studied this phenomenon experimentally and came up with an equation that relates cutting speed and expected tool life for that tool provided all other variables remain constant. The equation was presented in Chapter 2 and also given below as:

Taylor's Equation:

$$VT^n = C \qquad \text{Eq. (1)}$$

Where;

V = Cutting speed

T = Tool life

C = Constant, representing cutting speed which gives 1 min of tool life

n = the slope of the tool life v/s cutting speed line on log-log plot

Selection of other parameters, like feed and depth of cut, is also important. The effect of change of feed and depth of cut on tool life can be expressed by modified Taylor's equation, as mentioned in Chapter 2, Eq. (3)[25].

$$T = \frac{K}{V^{1/n} f^{1/n_1} d^{1/n_2}} \qquad \text{Eq. (3)}$$

Where;

T = Tool life

V = Cutting speed

f = Feed

d = Depth of cut

n, n_1, n_2, K = Constants depending on tool-work material combination

Each of these constants mentioned above is different for each of the tool and material combinations. The material removal rate in cutting operation is calculated by the following equation:

$$\text{MRR} = V*f*d \qquad \text{Eq. (5)}$$

From economic production point of view it is imperative that more material should be removed from the piece in less amount of time and cost. This means using maximum values of cutting speed, speed and depth of cut. But as we have seen previously, increasing these values means reducing tool life and thereby adding non-productive tool change cost and time. It is also found out that cutting speed has strongest impact on tool life followed by feed rate and then lastly depth of cut [25]. So, when there is a need to increase material removal rate, first depth of cut is increased to extent possible then feed rate and then lastly the emphasis is on increasing cutting speed. The effect of cutting speed on manufacturing cost per piece can be graphically shown as in Fig. 2.

Extensive work by W. W. Gilbert of General Electric Company in collecting data affecting metal cutting resulted in further extension of Taylor's equation to following complex formula for milling operation by a multiple edge cutter of diameter 'D'. This equation is a result of thirty to forty years of research publications.

$$V = \frac{K * MCF * MF * SCF * TTF * WL^{2} * TPF * TMF * CFF}{T^{n} f^{0.58} d^{0.2} * BHN^{1.72} no.teeth^{0.16}} \quad \text{Eq. (6)}$$

Where;

V = Cutting speed $= \frac{\pi DN}{12}$

K = 179,500 for HSS tool; 300,000 for Carbide tool

MCF = Material cut factor

MF = Microstructure factor

SCF = Surface condition factor

TTF = type of tool factor

WL = Wear land in inches

TPF = tool profile factor

N = Rotational speed of cutter

TMF = Tool material factor

CFF = Cutting fluid factor

T = Tool life in minutes

n = 0.125 for HSS tool; 0.25 for Carbide tool

f = Feed in inch per tooth

d = Depth of cut inches

BHN = Brinell hardness number

D = Tool diameter in inches

From this equation complexity of the cutting mechanics parameters selection issue can be easily understood. Although specific parameter selection may not be possible without some experimental basis in actual work environment; nevertheless, it issues a subjective guideline for selecting those. This understanding of cutting mechanics coupled with operations economics is used as a rational for selecting optimum operating parameters. Operation economics aspects involve identifying cost related to productive time, nonproductive time, certain overheads, etc. Again, this involves lots of specifics to be accounted for, e.g., tool change time, cost of new tool, cost per unit time of nonproductive time, etc. Its certain that it is not possible to use these kinds of specifics at conceptual design cost estimation stage. Solution to this problem can be found in Machining Data Handbook published by Machinability Data Center. Machinability Data Center (MDC) is an organization that documented, over the period of time, actual cutting conditions used in a production shop. These cutting conditions, although they may not be the best, are recommended as a good starting point for metal cutting operations when there are no previous location specific records available. For process cost estimation purpose this data becomes a standard and a starting point.

4.3 Chapter Summary:

The above analysis can be summarized as follows. Metal cutting is one of the important operations among manufacturing processes. As metal cutting is a 'reduction' or 'metal removal' type of operation, volume of the material removed from the original ingot decides the time and thereby the process cost of performing that operation. There are different types of metal cutting operations, e.g., turning, milling, drilling, etc. Each of these operations has their characteristic operating parameters that decide the material removal rate or MRR. The higher the MRR, the faster the process and more likely it would be economic. The higher the cutting forces, the stronger and sturdier the machine structure required to deal with those and consequently higher the cost of equipment. Material properties, especially the shear strength, hardness and microstructure influence the cutting forces and tool life. The analysis presented here gives a wide picture of interaction of various factors involved in metal cutting and cost of metal cutting.

Chapter 5: GENERIC COST ESTIMATION MODEL – REQUIREMENTS ANALYSIS

A Systems Analysis approach is applied to the problem of developing the cost model. This generates a lot of structured information, which is discussed in this chapter and presented below.

5.1 Goals and Objectives:

The fundamental objective of this thesis is to suggest a framework and a model based upon which the cost of a product or design can be estimated. The framework and the model should have the following characteristics:

- The model should be applicable for all the stages of product development from early design stage to detail design stage.
- Its accuracy should improve, as more details are available.
- It should apply to all manufacturing processes.
- In theory, the framework should be extendable to cost estimation of other stages of product life cycle, although the details and the factors involved in evaluation of each of them would be different and coherent with the respective stage.

In order to achieve these objectives, it should be clearly known what is the kind of information that is available for cost estimation purpose at the various stages of design.

5.2 Input to A Cost Model:

Unlike parametric estimation model, the proposed cost model is supposed to accept a CAD file of a part or assembly as an input. This is done to relate cost directly to specific physical characteristics of the product or the part itself. The kind of information extracted from Design Description and/or CAD file and other technical information sources is listed below.

- Principal shape
- Dimensions
- Material
- Manufacturing Precision
- Equipments and Tooling

- Technical Data and Information

The Design Description may vary based on the stage of product development. There are two aspects of data: Details and Accuracy. At an early design stage, data may be very sparse and inaccurate while at a later detail design stage the data may be more accurate. Same is the case with the available details about a design. But, whether it is an early design stage or detail design stage the data can be put in the same format as given above. Only the details and accuracy of the data will vary.

5.3 Expected Output from A Model:

It is important to understand what is expected as an output from the Cost Model. The information output that is expected from the model are fundamentally:

- A Cost Estimate with a certain level of confidence
- A Cost Estimate related directly to the Principal Design Parameters or Product Performance which will be used as independent variables for some of the optimization scheme

One of the main purposes is to have a reasonable cost estimate that can be used for various purposes such as design optimization, process selection or cost planning. It would be a big help from the model if it can show the effects of design specifications on cost. This information can be used for issuing general design guidelines.

5.4 Other Requirements:

It is important to understand the user context while developing any new system. This means that attention must be paid to the fact that the user need not have to change his existing systems much. These are some 'other' requirements, which are related to the current environment in which the model will work:

- The model should have capability of being seamlessly connected to other existing technical optimization programs
- It should make use of Object Technology as far as possible
- It should get connected to Product Data Management tool

Industry platforms should work as a test ground for the series of solutions desired from this cost modeling and estimation. This demands for seamless interface of the Cost Model with computer tools used regularly in Industry. Object Oriented Design of the system may solve some of its problems and help this integration.

The object technology has come a long way since it was invented in the late 60's for modeling and simulation in the form of the programming language 'Simula'. It has revolutionized the entire information technology in the last decade. There are many critical advantages of using object orientation in designing and building system. The most relevant one in this context is modularity of the programs that gives seamless connectivity and extendibility. This means the whole system can be initiated with preliminary investigative and detail work in one specific manufacturing process like milling and later can be extended to other processes. Also, cost estimation can be integrated over product life cycle.

The use of Product Data Management (PDM) tool, software that facilitates connecting various applications is becoming wide spread. The Cost Model should be designed such that PDM can be used to its full advantage in implementation. PDM facilitates communication and integration between various application programs like databases, spreadsheets, CAD programs, project management tools etc. PDM tools could become the backbone of implementation of the Cost Model in Industry.

5.5 Current work done in association with NASA, Langley Center:

In recent past attempts have been made at NASA and Boeing to develop a cost estimation model based on 'First Order Velocity Response' approximation. The programs are respectively called:

- Costaid
- Costran

The method identifies so called 'significant design parameter' of the product. Based on the experimental and historical data, the process velocities are plotted against the significant variable. The curves are fitted to evaluate various coefficients that are used to evaluate process time. Process Time is calculated using following equation.

$$T = \sqrt{\left(\frac{\lambda}{V_o}\right)^2 + \left(\frac{2\tau\lambda}{V_o}\right)} \qquad \text{Eq. (7)}$$

Where;

T = Process Time

λ = Significant Parameter

V_o= Steady State Process Velocity

τ = Dynamic System Time constant

Process time is then translated as process cost. Here in this equation, Vo and τ are constants depending on the process. The Significant Parameter is essentially a design parameter that decides process time. In the case of aircraft structure fabrication the significant parameter identified is 'Surface area of the part' where as in the case of assembly of these parts, it is the 'Perimeter of the part' [88].

Example:

A comprehensive study is carried out in calculating the cost of an aircraft wing structure fabrication and assembly using first order equation coefficients V_o and τ as mentioned in Eq. (7). Initially, individual wing part solid models and wing assembly solid model are created using SolidWorks™. These CAD models were created keeping in view their parametric nature and relations to global design parameters. Critical global design parameters from structural and aerodynamics point of view are shown in Fig. 5 and listed below.

- Chord length at wing tip and wing shoulder
- Wingspan
- Angle of wing leading edge with fuselage main axis
- Spar Cross-section geometry details

Given above details, approximate dimensions of Front Spar, Rear spar and Wing skin, etc. can be calculated using structure geometry. If we are to study the effect of these global design parameters on cost, we ought to create a Parametric Solid Model using various dependency equations. One such model is shown in Fig 6. So, given the global critical design parameters of the wing, one can identify approximate geometry details of its components. Moreover, through Parametric Solid Model, by changing these critical design parameters, one could appreciate its effect on physical properties of individual parts involved in the assembly.

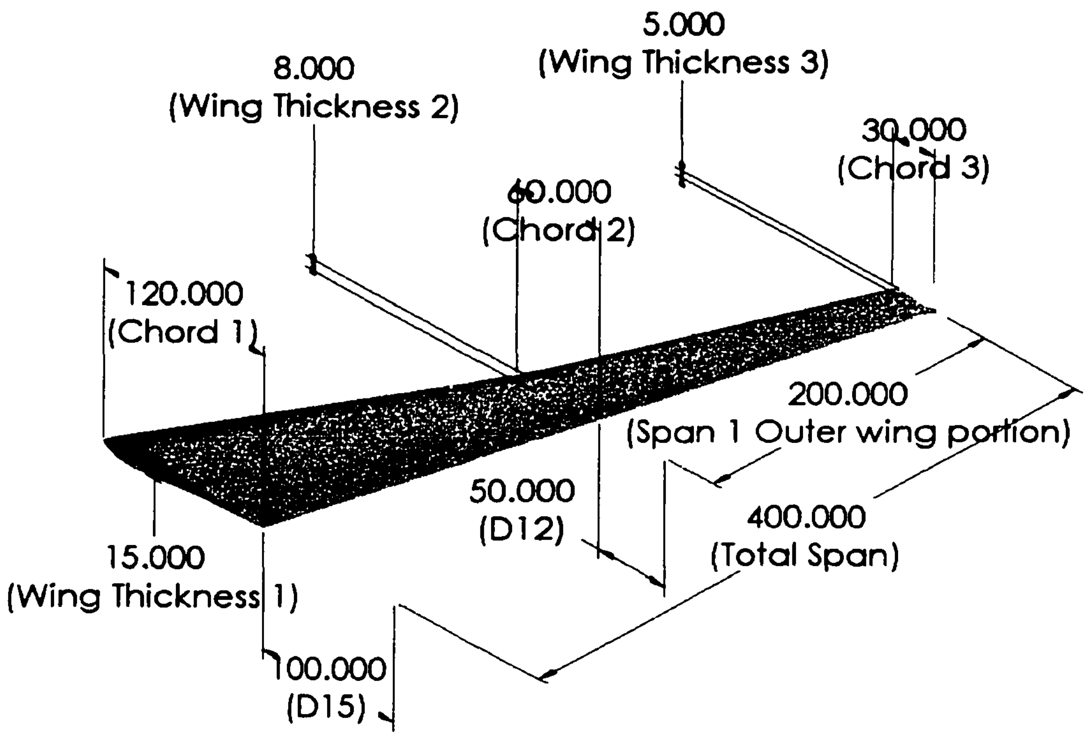


Figure 5. Critical Global Design Parameters of Aircraft Wing Structure.

Previous study at Boeing had indicated the 'wetted area' of a part as a significant parameter driving cost in the manufacture of aircraft structural components. With the input of 'wetted area' of the part provided by the CAD model and the coefficients V_o and τ appropriate for the wing fabrication and assembly process, Eq. (7) can calculate the process time required. This process time estimate is then translated to estimate costs. This method of cost estimation is implemented using Excel spreadsheet and SolidWorks® as a solid modeler. Through this setup, a designer could change any design parameters of his choice and see its physical effects in the CAD model while at the same time, the Excel program gives feedback in terms of its cost effects. This initial work in cost modeling has been demonstrated as a very successful concept.

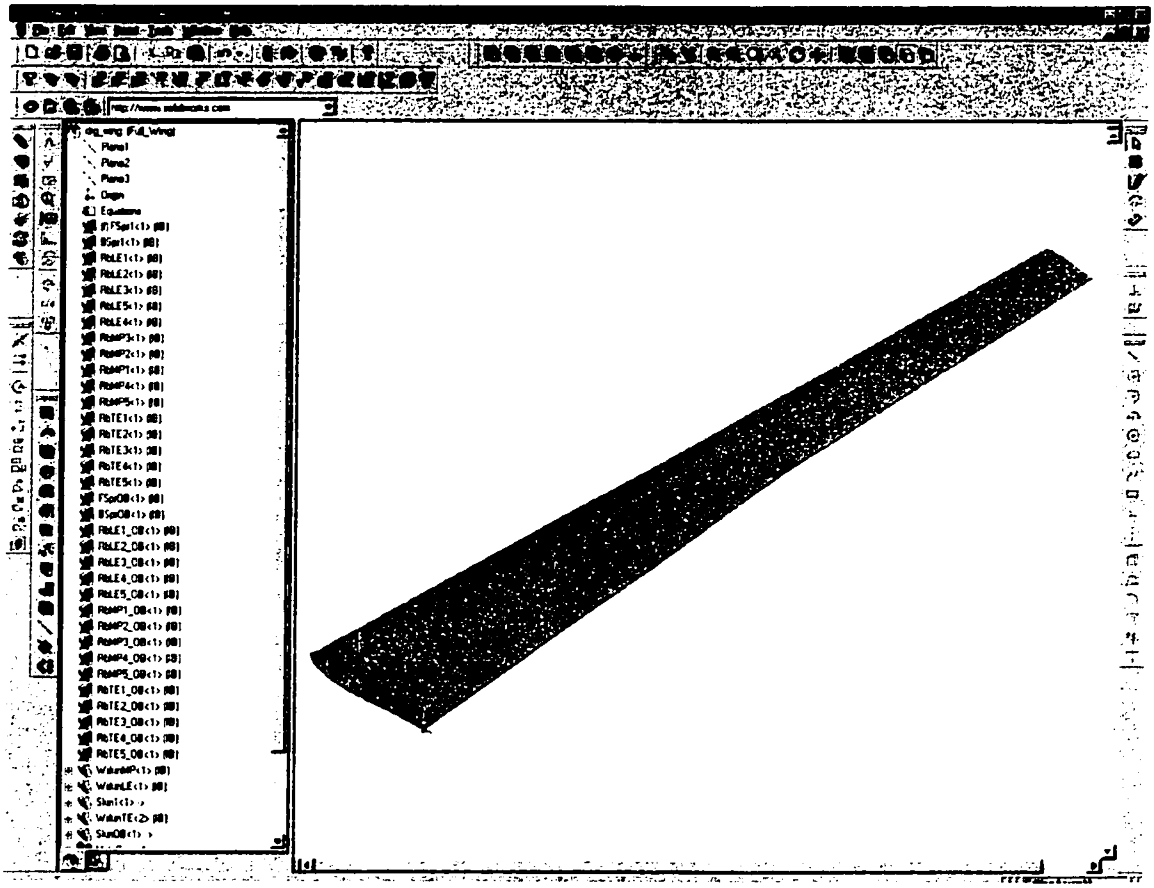


Figure 6. Parametric Computer aided model of Aircraft Wing Assembly.

The same worksheet is used in a different way to accommodate another kind of input for cost evaluation. The need is there to take care of the case when the design data is not available as a set of parameters but as numerical analysis geometry definition data like in FEA or CFD analysis. This data was essentially in the form of coordinates (x, y, z) of critical points of wing geometry. To take care of this kind of numerical input, a macro was written in Excel worksheet to transfer data from text file to worksheet and then calculate cost. The data was varied and 46 different combinations were tested for cost evaluation and effect of design parameters on cost. The results of one such case are shown in the Worksheet snapshot, Fig 7. Some of the 46 designs were studied from cost point of view with the help of this implementation in Excel worksheet. These results are shown in graphic format to study the effect of design changes on the cost. Corresponding graphs are shown in Appendix I.

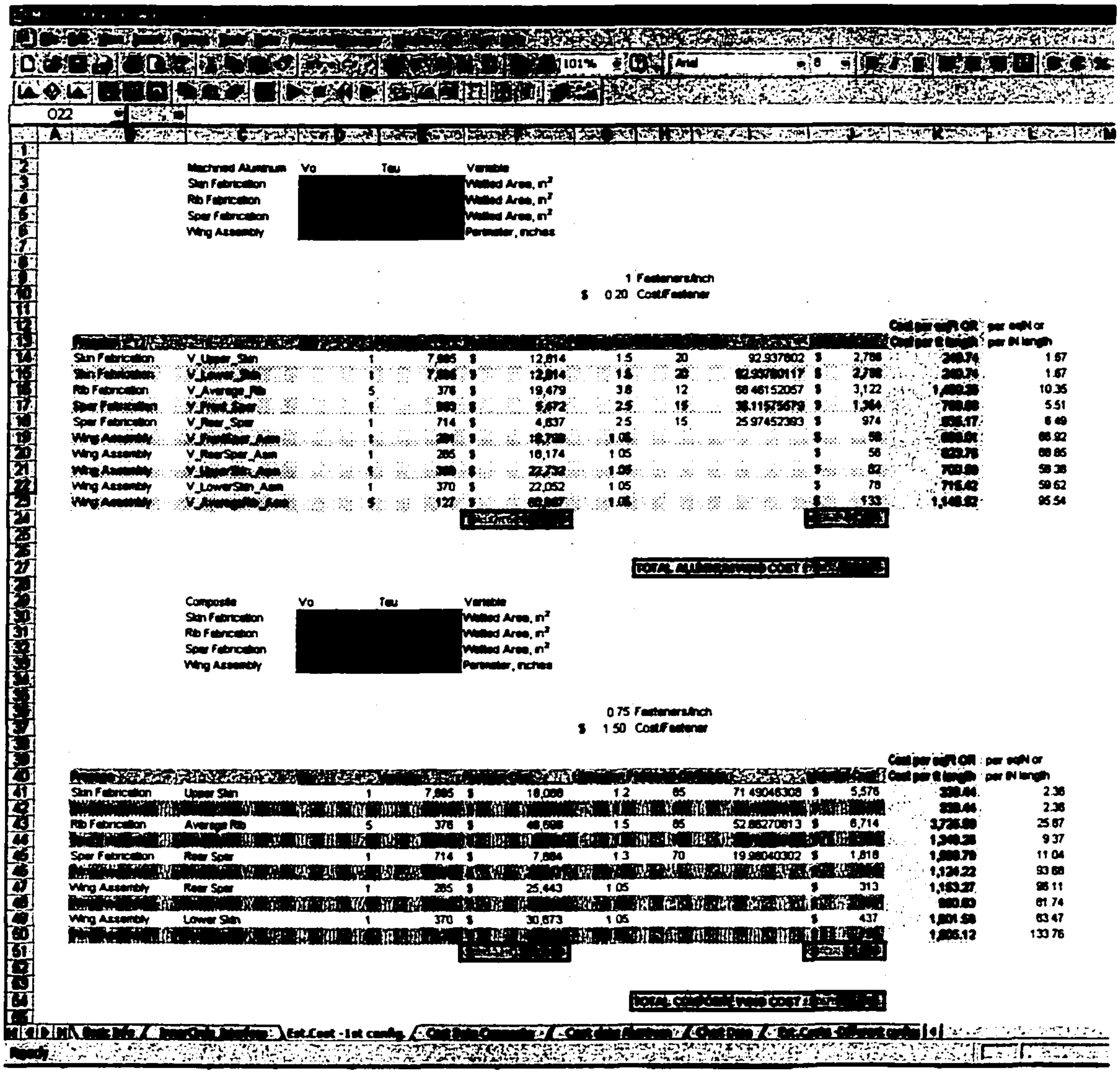


Figure 7. Wing Fabrication Cost Estimation worksheet.

5.6 Comments:

The implementation described above was very important from a learning point of view. The study showed certain strengths and drawbacks of the model. The model was easy to construct and implement, but the specific data, e.g., V_o and τ have to be identified from experimental or historic data. Firstly, this means that the model can be used only in the cases where that historic data holds good. It cannot be utilized unless validated to the actual circumstances. Secondly, the model is designed for early design stage and cannot handle detail design specifics like shape complexity, tolerance and surface finish requirements of the part. For detail design estimation, the constants data like V_o and τ have to be determined for every individual process. This is a tedious task and process based detail estimation methods would be easier to use there.

Chapter 6: GENERIC COST ESTIMATION MODEL

The 'Generic Cost Estimation System' is designed with a view to keep an open architecture to enable expansion of the system and to accommodate new elements. The primary analysis of the cost estimation problem, as detailed in Chapter 4 and 5, becomes the starting point of the design of this generic cost estimation system. This chapter details the solution framework and its elements.

Before entering in any further discussion, the extent of this research must be clarified. **Firstly, it is important to note that even though the discussion in previous chapters is mostly general and can be used to address costs at all stages of product life cycle, henceforth the treatment of the proposed cost model is strictly focused to manufacturing cost estimation, and specifics are developed only for the 'milling' process.** This is done to restrict the scope of the study. Secondly, it is also important to note that similar treatment of the model can be carried over to all other manufacturing operations and other stages of the product life cycle. In case of operations other than milling and stages other than manufacturing stage, the fundamental framework will remain the same as presented in this research but the details will differ based on the relevance.

6.1 Relative Cost Estimation:

Hypothesis - 1: Rules of Manufacturing are same everywhere, although costs may be different.

The designed generic cost estimation system relies on relative costing rather than an absolute costing. The concept of relative cost estimation was necessary and important because this allows us to skip some specific details of the costing which are not available at the early design stage. One can still proceed without those specifics and come up with a cost of a design in relation to known cost of a standard reference product or design. General manufacturing rules, principles and databases are used as a basis for comparison and evaluation of relative cost. **These rules, if they are based on scientific perspective, are same everywhere irrespective of the specific conditions of manufacturing setup.**

For example – if cutting speed of a carbide tool on 1020 steel is 180 ft/min for 60 min of tool life in turning operation, which is common and considered to be reasonable on the basis of experimental and scientific data, then this rule holds true everywhere irrespective of time and space coordinates. Using such standard practices and rules, standard designs for each manufacturing process can be evaluated for their manufacturing costs, and all such standards can be stored in system database for the comparison. Any new design then can be evaluated in relation to the standard design based on same widely accepted principles and standard rules.

The major advantage of this relative cost concept is that this introduces universality in the cost estimation technique. Cost estimation no longer depends on the specifics like burden costs, factory location, state of the technology used, currency, etc. Designs can be compared on the basis of standard, most likely conditions and then if required can be modified based on the specifics. One can expect to have some thing called 'technology index' which will speak about relative cost of standard technology and new or old technology on a time scale. Similarly there can be 'factory location index', like the living cost index for various cities, that will speak about the energy costs, transportation expenses, land and infrastructure development costs, etc. The 'Burden Cost Index' will reflect the factory operation efficiency, manpower costs, etc. These indices can then be used to modify the relative cost of a design in standard setup to actual cost in the given setup.

As the relative cost estimation is based on standard database and manufacturing science, this evaluation technique will provide a basis for standardization of the cost estimation process. Cost estimation done by different persons with different backgrounds and experience will produce same results.

6.2 Cost Modulus: A Relative Cost Index

As emphasized before, in this newly designed generic cost estimation system, cost is regarded as a Design 'consequence' and not as a result of operation decisions. When cost is considered as a property of a design or a part from a scientific perspective, this gives rise to a concept of ***'fundamental coefficient of cost'***. The coefficient is called ***'Cost Modulus'*** and it reflects the cost of the part. The Cost Modulus is an index of cost of that design compared to some standard reference design of which cost is known. If a standard part or design with known cost can be considered to have cost index or cost modulus of 1, then other non-standard designs can be compared to the standard design to identify their cost modulus. For example, in case of milling operations, manufacture of 12"x12"x12" (1 cu.ft.) of solid block, material equally removed from all six faces of a cube of 1020 steel with normal milling tolerances and one final finish cut can be regarded as a design having face milling cost modulus equal to 1. Other design with face milling cost modulus of 3.5 would then mean that this design would cost 3.5 times the cost of the previously specified reference design.

6.3 Processing Cost: a Design Consequence

Hypothesis - 2: Processing cost is a consequence of design specifications.

The process cost of a product or part in certain setup can be written as a summation of product of processing time and setup rate for individual processes.

$$C = \sum T * S \qquad \text{Eq. (8)}$$

Where;

C = Process cost

T = Process time

S = Setup rate inclusive of equipment and manpower cost in \$ per unit time

Processing time for a part is related to physical properties of a design like shape and size of the features to be manufactured, the material of construction, and the required precision. The manufacturing setup required is also a design consequence. Setup also depends on the design specifications like shape, size, type of operation, tolerance, etc. So, it is clear that design specifications affect both time and setup costs and that is how manufacturing cost is a consequence of the design specs.

Applying Eq. (8) to a standard design, we get;

$$C_{std} = \sum T_{std} * S_{std} \qquad \text{Eq. (9)}$$

Where;

C_{std} = Cost of standard part

T_{std} = Processing time for standard part

S_{std} = Setup rate for standard part

As per the definition process cost modulus is a ratio of process cost of actual design to process cost of standard design. So, taking ratio of Eq. (8) and Eq. (9) we get;

$$C_m = \sum\left[\left(\frac{T}{T_{std}}\right)*\left(\frac{S}{S_{std}}\right)\right] \quad \text{Eq. (10)}$$

Where;

C_m = Process cost modulus

This Eq. (10) is a general equation and provides the way to consolidate process time and cost.

It can be seen that, process cost modulus of a part is equal to the product of relative process time and relative setup rate. So, the cost modulus has two components, one based on relative time cost and the other based on relative setup cost. **The design affects the decision of selecting certain setup that reflects as relative setup cost and also the processing time that reflects as relative time cost.** It is critical at this point to investigate how design actually affects the processing time and setup cost components and how design specifications can be used to quantify these effects.

6.4 Relating Cost Modulus to Design Specifications:

It is clear that design specifications are responsible for process cost effects. *It is critical to note that, like other physical properties of a part such as weight, volume, surface area, moment of inertia etc., process cost modulus should be evaluated from the design specifications.* A more intense thought to the root cause of cost reveals that the cost of a part or assembly depends on the following characteristics or specifications: size, shape, precision, equipments required and material of construction.

The 'size' factor in design specification is not the physical size of the object but it is a quantification of that physical property of a part or assembly which largely governs the process time when certain process is selected to manufacture it. For Example, for a machining process, the predominant variable that governs machining time and thereby machining cost is machined volume and the 'size' is quantified by that predominant variable meaning 'volume removed by machining'. In the fabrication of an aircraft wing structure, the predominant variable could be the surface area of the wing and its subcomponents, as it is used in its complex parametric equation. The size factor in this case is 'surface area of wing'. In short, the size is a measure of or a value of the predominant variable. The bigger the process related size of part or predominant variable, the higher is the size factor and process cost associated with it. **It is to be noted that, it is not merely physical size of object that is important but the process related size.** For example, in case of aircraft wing riveting, it is the size of each rivet and number of rivets per unit length which are important. Therefore they both can be considered as predominant variables.

The Shape complexity of a part is responsible for deciding the possible manufacturing processes and the kind of equipment that could be used to produce that part. Although there may be several combinations of processes and equipments that can be used to manufacture a part, based on group technology classification a typical set of processes can be identified. Possible manufacturing processes will in turn decide the processing time and resources needed. So, in effect shape complexity affects the process time and thereby process cost. The other effect of Shape complexity is on non-productive time due to tool changes and setup time associated with them.

Precision plays a significant role in dictating process time and cost. Precision has two fundamental aspects: Tolerance and Surface Finish. Every process has a characteristic precision and, if higher precision is required then special precautions need to be taken. This means higher cost to manufacture. The higher the manufacturing precision, the higher is the cost. Moreover, it is necessary to normalize the precision with respect to the predominant variable or size of the part. For example: achieving a 2 micron precision would be easier in machining of 10.00 cm of length compared to achieving the same precision in 100.00 cm length.

The Material factor is not just the raw material of the part but also material specifications at the end of the process. They are very important in deciding cost. Raw material decides processing parameters and thereby affects time. Moreover final part specifications decide the method of manufacture. For example, when a part can be cast, machined or forged, its cost can be different depending on the method used to make it. There can be additional specifications like case hardening, antirust coating, painting, etc., that become part of final 'Material Specifications'.

Equipment and tooling needed for the manufacture is decided collectively by size, shape and precision of the design. Complexity of the equipment and tooling decides the basic cost rate or setup rate factor. The larger the size, the higher the precision, the more rigid the construction and the more flexible the operation, the higher is the setup cost for the equipment.

The discussion above can be summarized in Eq. (11):

Cost Modulus = f (Size, Shape, Precision, Material, Equipment/Tooling,) Eq. (11)

Size	-> Processing quantity
Shape	-> Possible processes, process and tooling complexity
Precision	-> Additional care/cost
Material	-> Process parameters
Equipment	-> Setup cost rate

An important thing to be noted is that, these coefficients have interaction, meaning that, they are not entirely independent. Sometimes mere 'Size' can increase tooling complexity or 'Shape' and 'Size' together can decide manufacturing process. A more detailed discussion about the dependencies and how to handle them is presented in chapters ahead. But by and large, the effects of each of these design attributes on cost can be summarized in individual coefficients or factors. Introducing five coefficients representing individual effects as mentioned above:

$$C_m = f(C_v, C_p, C_{pr}, C_e, C_{mt}) \qquad \text{Eq. (12)}$$

Where;

C_v = Predominant Variable Coefficient (Size effect)

C_p = Process or Shape Complexity Coefficient

C_{pr} = Precision Coefficient

C_e = Equipment Coefficient

C_{mt} = Material Coefficient

These factors are related to the 'Cost Modulus' of the design through some function '*f*' which is not mentioned at this point but will be defined later.

6.5 Section Summary:

A Generic Cost Model framework based on available information is created. Design attributes like Size, Shape, Precision, Material and Equipment are identified as Cost driving parameters. Each of these effects could be represented by a cost coefficient. A conceptual framework for evaluating these coefficients in case of machining or metal removing processes in general is presented in this Chapter. Further detailed discussion about the coefficients is presented in following individual chapters.

Chapter 7: COST COEFFICIENTS

Cost Modulus is intended to identify a relative measure of the manufacturing cost. Relative measure is possible only if reference is well defined. This chapter identifies these reference designs and presents the selected one that is used for the study. After the reference design is defined, the method for calculating individual Cost Coefficients of the actual design is presented.

7.1 The Reference Object (RO):

7.1.1 Shape: When we talk about comparison with Reference Object (RO), it is necessary to specify what it is and the process details for its manufacture. The specifications of the RO would decide its manufacturing process and as we intend to study 'Milling', we define the RO such that its predominant processes are of the milling category. Milling processes are used for producing flat, contoured or pocketed surfaces. These surfaces are of parts that are non-rotational in general, because other processes like turning and boring can better manufacture rotational parts. Most of the parts are box envelope type or prismatic, i.e., the raw material is likely to have flat surfaces. So, after looking at the characteristics of the milling process itself it can be seen that a simple box shaped component can serve as a standard Reference Object (RO).

7.1.2 Size: With the shape of the standard design fixed to be a box, the dimensions are fixed on the basis of other process considerations due to size of the part. In general, parts can be classified in 10 different size categories as shown in Table 1 [89].

It is clear from here that setting a single standard part for cost estimation would not be a good idea considering a wide variety of sizes of objects to be manufactured. Neither it be necessary to define standard design for each size code suggested here. For determining the number of standard box designs needed, we need to look into the effects of size on process and equipment selection. The first logical demarcation comes from the fact that certain parts can be handled manually very easily so that setup doesn't require material handling devices. The second demarcation comes from the fact that due to size and machining involved in it, sometimes a special purpose machine is needed. Consider the case of a huge aircraft wing of approximately 100 feet in length. The manufacture of this wing involves very huge custom-made machines and costs involved in there are different. With these simple and logical demarcations, complete sets of parts made by milling process can be classified into three major groups.

1. Small sized parts that can be handled manually and manufactured on standard machines.
2. Medium sized parts that can be manufactured on standard machines but having need of material handling devices.
3. Large objects that require more customized machines involving nonstandard costs.

Size Category	Maximum Dimension		Description	Examples
	English	Metric		
1	0.5"	10 mm	Sub-miniature	Capsules
2	2"	50 mm	Miniature	Paperclip box
3	4"	100 mm	Small	Large match box
4	10"	250 mm	Medium small	Shoe box
5	20"	500 mm	Medium	Bread box
6	40"	1000 mm	Medium large	Washing machine
7	100"	2500 mm	Large	Pickup truck
8	400"	10000 mm	Extra large	Moving van
9	1000"	25000 mm	Giant	Railroad box car

Table 1. Size Categories for Based on Manufacturing Characteristics.

This suggests three reference designs for milling process machined volume comparisons. Here for this study, the middle size category is chosen as most of the general objects manufactured by milling fall in this category. The other two categories can be treated in a similar way if needed. Taking into considerations this discussion on size, the final standard design is decided as **'a cube of 12" side each'**.

7.1.3 Precision: The RO is considered to have a precision that can be achieved regularly in milling operation. The tolerance on each side is the one which a milling process can produce without any special measures which is 0.010". And a standard surface finish of 125 μin Ra is adopted for it [12].

7.1.4 Material: Another important design specification needed is the material of construction for this part. It makes sense to choose a material of construction based on the industry. An aircraft industry generally uses materials that are nonferrous, high strength to weight ratio alloys whereas heavy industry uses high strength, alloyed steels. Based on this, pure aluminum 99.99%, is selected as the material for reference design for the aircraft industry while free cutting steel is considered as the reference material for other industries where ferrous machining is predominantly used. As this research is mainly intended at this stage for the aircraft industry, aluminum 99.99% pure is adopted as the material for the Reference Object.

7.1.5 RO Specifications: The complete design specifications for the RO can be summarized and specified as below.

- Shape: Box type, cube
- Size: 12"x12"x12"
- Tolerance: range 0.010" all sides, straightness and flatness
- Surface Finish: 125 μin Ra
- Material: Aluminum, cast, 99.99%

7.2 Manufacturing the Reference Object:

A typical process plan for the standard object specified above would involve the use of an appropriate milling machine to machine each of the six sides. Every time a tool would be changed for roughing and finishing of each surface. The work piece would be set six times, one time for each side. Initial cleaning and setup as well as final cleanup would be included as a part of the process. All these details plus any additional details for the process plan could be added based on the location specific conditions. The process plan details are not presented here considering the fact that the attempt here is to find relative estimate and not exact solution. As long as rules on which the details depend remain the same, costs can be compared. For example, for generating surface someone will suggest to use 4" diameter cutter and produce the surface in 4 passes over the raw surface; whereas, someone else may use 3" cutter and use 5 passes instead. Both options may be right in their own ways due to present constrains like availability of appropriate cutters. The limiting factor, however, is the ability of the machine to remove the material from the work piece. This depends on the horsepower available at the cutter, specific cutting horsepower of the material and other tool and work material combination that decides actual cutting parameters. So, leaving those location and machine specific operation decisions aside, the important fact to be considered is the amount of volume to be removed from the work piece to manufacture the Reference Object from the raw stock. Here two parameters are related, and they are the amount of volume removed and the cost incurred in doing so. Of these two, the actual cost depends on certain operating decisions but the cost-governing factor remains the same: volume to be removed from work piece.

The volume to be removed from the Reference Object can be identified by considering a 10% machining allowance on each side. This means initial raw stock dimensions of 13.2"*13.2"*13.2". The difference of final object volume to raw volume is therefore **571.968 in^3**, and the cost incurred in processing this on standard recommended machine with recommended tools is the cost of the Reference Object process cost.

7.3 Predominant Variable OR Size Coefficient, C_v:

7.3.1 Definition: As it is emphasized earlier the process cost depends on the process related size or predominant process variable of an object that determines processing time. For the 'reduction' type of manufacturing process, the predominant variable is 'the change in volume' or the 'volume removed' from parent material. Milling is a 'reduction' type of a process and therefore 'machined volume' becomes the predominant variable for milling operation cost estimation. That is to say, in case of 'Milling Processes' the time required for completing the process and thereby the process cost depends on 'Machined Volume'. So the Predominant Variable is 'Machined Volume' and;

$$V_m = (V_1 - V_2) \qquad \text{Eq. (13)}$$

Where;

V_m = Machined volume

V_1 = Volume prior to machining and;

V_2 = Volume after machining

The Predominant Variable coefficient gives the process time comparison between two milling operations; one an operation for which the cost is to be estimated and the other the predetermined reference milling operation for which the cost of a certain amount of material removal is known or established. The cost of machining is linearly proportional to the amount of volume removed in the machining process. The higher the volume to be removed, the higher is the cost in its direct proportion.

In more specific terms, the Process Size coefficient can be defined as: the ratio of V_m, the volume to be machined or milled in case of milling operation alone; to $V_{m_{RO}}$, the volume machined in case of the established Standard Reference Process or Object Manufacture. Equation 14, gives mathematical representation of the Process Size coefficient.

$$C_v = \frac{V_m}{V_{m_{RO}}} \qquad \text{Eq. (14)}$$

Where;

C_v = Predominant Variable Coefficient or Size coefficient

$V_{m_{RO}}$ = Volume machined to produce the standard part design.

This proportionality ratio is called 'Predominant Variable Coefficient' or 'Process Size Coefficient' and the process cost of any design is directly proportional to this coefficient.

7.3.2 Calculating Process Size Coefficient: Consolidating previous sections, in short, material volume to be removed in a reduction type of manufacturing process is proved to be a cost driving parameter. The range of products that can be manufactured predominantly by milling processes are mainly categorized in three categories depending on whether they can be handled manually, whether they need custom machines for the manufacture, or weather they can be produced on standard general class middle range milling centers. The simple object - a cube 12" in each side is considered as a Reference Object for relative comparison of the process cost in case of medium sized objects. An amount of material removal equal to 571.986 in^3 is associated with standard object manufacture and the cost associated with this volume removal would vary in certain limits. But considering the linear relation between process time, and thereby the process cost, and volume removal in the size range under consideration, the specific costs may be eliminated while calculating a relative cost index or Cost Modulus. The Process size coefficient for any design is calculated by identifying the raw stock volume, generally the volume of box type of envelope constructed around the design and subtracting the volume of the actual part from there. This value is the volume of material to be removed from the raw stock. Volume to be removed in actual part manufacture divided by the volume to be removed in case of manufacture of RO, i.e. 571.968 in3, gives the Process Size Coefficient.

7.4 Process or Shape Complexity Coefficients:

7.4.1 Processing Complexity of the Reference Object: Process Coefficients are supposed to represent the relative complexity of the process that reflects as an additional cost or time. The process time and cost effects are compared to the standard manufacturing process of the RO. Face milling operation is generally used to manufacture flat regular surfaces as required in case of the RO. So, the process plan of the RO manufacturing consists of mainly the facing milling operation. Other process elements attached with the manufacturing of RO are initial and final cleaning, tool setting, work loading and unloading, work setting after machining of each face and tool changing in case tool wears out. The productive time is the time spent on actual material removal. Processing times of actual parts to be manufactured are compared with this information on manufacturing of Reference Object.

7.4.2 Shape Complexity: Shape complexity increases the difficulty of manufacture of the actual design due to deviation in its shape from that of the original Reference Object design. This difficulty is due to the presence of additional geometry features. It can be measured in two ways:

- Types of Features
- Number of Features

These two sources of complexity introduce two distinctive effects to the Cost of Manufacture of the actual design. Each of them can be quantified as suggested in the next respective sub-sections. If the kind of feature present in the actual design is a very special one then special equipment for its manufacture may be needed. This effect is covered by the Equipment Cost Coefficient to be discussed later on.

7.4.3 Process Velocity Effect: If the type of feature is different than the one in original design then a different manufacturing process has to be adopted for its manufacture. For example, in case of the RO, the only feature present is 'flat' surface and the only process required to manufacture those surfaces is Face milling. If an actual design contains other features like holes, projections, pockets, etc., then processes other than just Face milling, like pocket milling, end milling, side milling, etc., need to be adopted. Each of these reduction types of operations has a limit of speed at which material can be removed. The maximum material removal rate is dependent on characteristics of the process represented by a Cutting Speed-Feed-Depth of cut combination for given tool and work material. This data is available in the form of Machining Data tables in Machinability Data Center Handbooks [31]. Using this data, processes could be related in terms of their relative processing speeds. Table 2 presents one such comparison of various types of milling processing of aluminum. The faster the process the lesser is the time required for removing a same amount of material from the stock, and the lesser is the processing cost. So, cost in cutting is determined by the type of process selected, that is, it depends on the kind of feature being manufactured. This is the Process Velocity effect due to Shape Complexity.

Based on the above discussion, a Process Velocity Cost Coefficient due to Shape complexity, C_{p_v}, for finish cutting operation is defined as the ratio of overall Process Velocity of reference operation (like Face milling in the case Reference Object considered here) to that of overall Process Velocity in selected operation, and represented by the following equation, Eq. (15).

$$C_{P_v} = \frac{1}{I_{P_v}} = \frac{(s*f*d)_{actual.process}}{(s*f*d)_{reference.process}} \qquad \text{Eq. (15)}$$

Where:

C_{P_v} = Cost Coefficient – Process Velocity

I_{P_v} = Relative Process Velocity Index

$(s*f*d)_{reference.process}$ = Process Velocity in Reference process

$(s*f*d)_{actual.process}$ = Process Velocity in actual process

s = Cutting speed

f = Feed rate

d = Depth of cut

Table 2 shows typical values for these coefficients in case of Slab milling, End milling and Side and Slot milling.

Operation	Speed (fpm)	Feed (in/ Tooth)	Depth of Cut (in)	Processing Speed (in^3/min/tooth)	Cost Coefficient – Process Velocity, C_{P_v}
Face Milling	2000	0.010	0.04	9.6	1
Slab Milling*	1000	0.012	0.04	5.76	0.6
End Milling	1000	0.005	0.02	1.2	0.125
Side and Slot Milling	2000	0.006	0.04	5.76	0.6

*Slab Milling uses only HSS Cutters.

Table 2. Relative Process Speeds

From this table it could be seen that End milling is 8 times slower than Face milling in finishing. So, for the same amount of material removal, an End mill takes 8 times more Processing Time than a Face mill. It is worth mentioning here that this statement is true in general and will vary to certain extent for a specific case but this gives a good idea about the relative time spent on an operation if the amount of volume removal is kept same.

The above equation, Eq. (15), implies that if there is only one process that removes all the material volume required, but in reality more than just one process may be required to machine the object. In that case one has to take the weighted average of all those processes involved. For example, if the actual design has two types of features that require Face milling and End milling, and 80% of volume is removed by Face milling and 20% of volume is removed by End milling, then the actual process velocity is 'the weighted average of processes Face milling and End milling with 80% and 20% weights respectively.

7.4.4 Non-Productive Time Effect: This effect is due to the number of features present in the design and where they are located in the design. There are two parts of this effect: Relative Tool setting time and Relative Work setting time.

For the manufacture of each feature, a separate tool or a set of tools is needed. Initially, these tools need to be set and setting time and related cost could be substantial. In case of manufacture of RO, only two tools are involved: Rough Facing milling and Finish Face milling. For an actual design, if there are 'n' number of features present and if each of them requires some sort of finishing operation then the number of tools required are '2n'. If the setting time is roughly same for setting each tool, then manufacturing of the actual design requires setting time 'n' times that of setting time in case of manufacture of RO. This Tool setting time is divided for a given batch size to be manufactured in one setting, but if this batch size is same as the batch size in case of RO then, it nullifies the batch size effect. If not, then it can be taken into account by multiplying the Tool setting time by the ratio of RO manufacture batch size to actual batch size. This is the Tool setting time coefficient.

If the machine has only one spindle then only one face can be manufactured in one work setting. If a part to be manufactured has features on and/or requires machining of more than one of its surfaces, then work need to be set again for as many times as equal to number of faces to be machined. The Reference Object is considered to be manufactured on a machine that has only one spindle, which is most commonly found, and it has six faces to be machined. So, it requires six changes of work. Now, in the actual design manufacture the number of work settings required are equal to the number of its faces to be machined to make it a final product. There is no effect of manufacturing batch size on Work setting time effect.

Both these effects can be consolidated in the equations given below for the Non-Productive Time effects due to Shape Complexity.

$$C_{p_n} = \frac{F_n}{F_{n_{RO}}} \frac{B_{RO}}{B} \qquad \text{Eq. (16)}$$

Where:

C_{p_n} = Cost Coefficient - Number of Features or Tool Settings

$F_{n_{RO}}$ = Number of features in Reference Object

F_n = Number of Features in actual design

B_{RO} = Manufacturing Batch Size of Reference Objects

B = Manufacturing Batch Size of Actual Design

$$C_{p_w} = \frac{W_f}{W_{f_{RO}}} \qquad \text{Eq. (17)}$$

Where:

C_{p_w} = Cost Coefficient – Number of Work Settings

$W_{f_{RO}}$ =Number of Work faces to be machined in Reference Object

W_f = Actual number of faces to be machined

7.4.5 Section Summary: The Shape of an object has a close relation with its process of manufacture. This Process-Shape complexity has two effects, one on productive time due to change in Process Velocity, and the other on non-productive time due to additional tools setting time and work setting time. These effects are quantified by three separate Cost Coefficients: C_{p_v}, Cost Coefficient – Process Velocity; C_{p_n}, Cost Coefficient -

Number of Features and C_{p_w}, Cost Coefficient – Number of Work Settings. These coefficients are calculated by Eq. (15), Eq. (16) and Eq. (17), respectively.

7.5 Precision Coefficients:

These coefficients take care of deviations in precision specifications from the precision of the Reference Object. There are two components for this coefficient: Tolerance and Surface Finish.

7.5.1 Cost Coefficient – Tolerance Factor: Manufacturing Cost has an intimate relation with specified tolerance and process capability. This relation is represented by the following equation [39].

$$C = g(\delta, C_{pc}) = \left(ae^{-b(\delta-\delta_o)} + c\right)C_{pc}^{d} \qquad \text{Eq. (18)}$$

Where:

C = Cost

δ = Dimensional Semitolerance

C_{pc} = Process Capability = $\dfrac{\delta}{3\sigma}$

a, b, c, d, δ_o = Nonnegative Constants associated with specific process

σ = Standard Deviation of the process

The constants could be obtained through experimental or empirical data. One such plot of empirical data for Face milling is presented in Fig. 8 [39]. This plot is reverse engineered to obtain following results:

$$\begin{aligned} a &= 9.0 \\ b &= 543.0 \\ c &= 1.0 \\ d &= 2.0 \\ \delta_o &= 0.008 \end{aligned} \qquad \text{Eq. (19)}$$

If tolerances and process capabilities of Reference Object and actual design are known then the relative cost can be computed by substituting the above constants into Eq. (18). The Cost Coefficient – Tolerance can then be defined as:

$$C_{pr_t} = \frac{g(\delta, C_{pc})}{g(\delta_{RO}, C_{pc_{RO}})}$$ Eq. (20)

Where:

C_{pr_t} = Cost Coefficient - Tolerance

g = Function defined by Eq. (19) and Eq. (20)

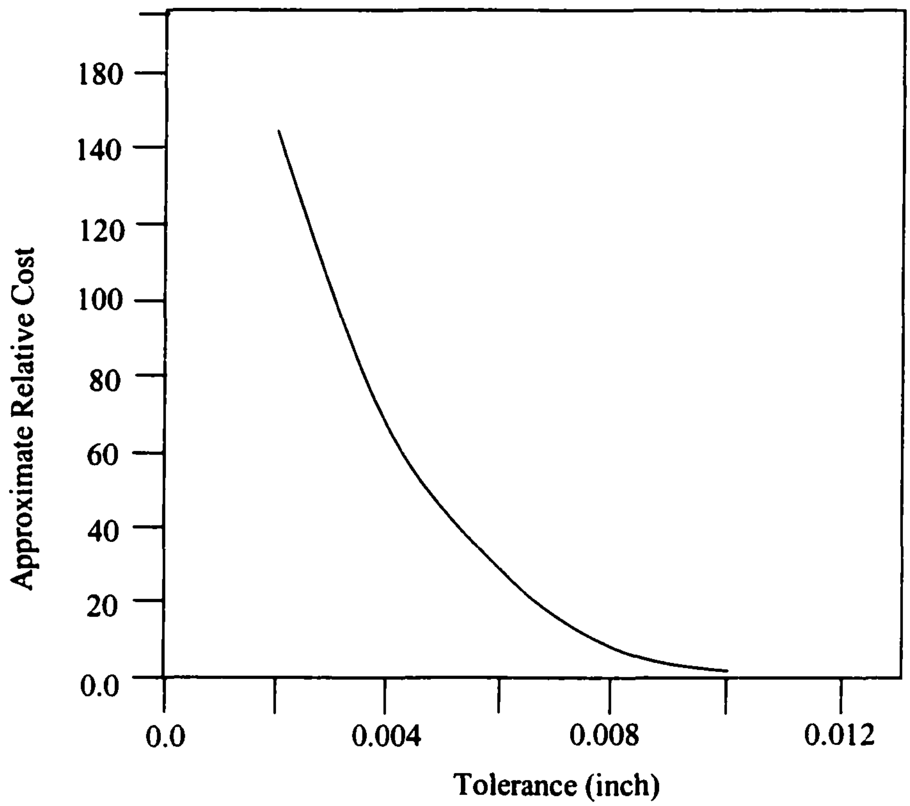


Figure 8. Tolerance effect on cost in Face Milling [39]

7.5.2 Cost Coefficient – Surface Finish Factor: Surface finish or roughness value is measured as arithmetical mean value or average deviation of points on the surface profile from its hypothetical centerline. It is generally denoted as 'R_a'. The higher the value of R_a the higher is the roughness. The predominant reason for roughness is feed marks of the tool. But, its value is compounded with other factors like built-up edge formation at tool tip, machine tool vibrations, material microstructure and inaccuracies of the machine tool motion. Equation (21) and Eq. (22) show a mathematical model calculating surface roughness due to feed marks, generally referred as ideal surface finish, for turning and slab milling respectively [26].

$$R_a = \frac{0.0321 f^2}{r_\varepsilon} \qquad \text{Eq. (21)}$$

Where:

R_a = Surface finish value in turning

f = Feed rate

r_ε = Corner radius of tool

$$R_a = \frac{0.0642}{d_t}\left(\frac{v_f}{n_t}\right)^2 \qquad \text{Eq. (22)}$$

Where:

R_a = Surface finish value in slab milling

v_f = Feed

d_t = Cutter diameter

n_t = Rotational frequency of cutter

An important point to note here is that, barring all the tool geometry specifics, surface finish or rather roughness value is proportional to squared feed rate. That means to get better finish, feed rate has to be slowed by a proportion to square root of the roughness value. Slower feed rate equals higher process time, as process time is inversely related to feed rate. This is how the surface roughness specifications of the design affect processing time in finishing operation. Comparing the surface finish specifications in Reference Object and an actual design on the basis of above equations and logic, the relative processing time in finishing operation or the Cost Coefficient due to Surface finish specifications can be defined by Eq. (23).

$$C_{pr_s} = \sqrt{\frac{R_{a_{RO}}}{R_a}} \qquad \text{Eq. (23)}$$

Where:

C_{pr_s} = Cost Coefficient – Surface Finish Factor

$R_{a_{RO}}$ = Surface Finish for Reference Object manufacture

R_a = Surface Finish of actual design

7.6 Material Coefficients:

Material selection is probably the most an important decision because it significantly affects both the manufacturing cost and the functionality of the object. From the manufacturing point of view, there are three main effects of material of construction on a part:

- Rough cutting processing time and cost
- Finish cutting processing time and cost
- Tool life and cost

The mechanism through which these effects are constituted is discussed in Chapter 4. Following sub-sections present analysis and design of Cost Coefficients designed to quantify these effects in terms of manufacturing cost.

7.6.1 Cost Coefficient – Material Effect, Rough cutting: Every material, by the virtue of its mechanical properties, requires a specific amount of energy to be put in for removal one unit amount of material by cutting. The amount of energy also depends on the type of cutting process, i.e., turning, milling, drilling, etc. By dividing both energy and amount of material removal by units of 'time', this cutting energy per unit of volume removal of material can also be represented as power per unit of volume removal rate called Specific Cutting Power. Table 3 gives typical values of specific cutting power for some of the materials [90]. In the case of rough cutting, the maximum material removal rate possible is limited by the available cutting power at the spindle and it is obtained by dividing spindle power by specific cutting power of the material. This means, considering all other conditions constant except the work material, the process velocity in rough cutting is inversely proportional to the specific cutting power of the material involved in cutting. And as process time and thereby the cost in rough cutting are inversely proportional to the process velocity, the process cost is directly proportional to the specific cutting power of the material. Using this analysis Cost Coefficient - Material Effect in Roughing is defined as in Eq. (24).

Material Name	Description	Sp. Cutting Power – Drilling (hp/in^3/min)	Sp. Cutting Power – Milling (hp/in^3/min)	Sp. Cutting Power – Turning (hp/in^3/min)
Aluminum = 7075	Sol Treated Aluminum Alloy	0.2	0.4	0.3
Brass & Copper = 314	Annealed Copper Alloy	1	1	1
Carbon Steel = 1010	Carbon Steel	1	1	1
Stainless Steel = 303	150 HB Free Machining SS	1	1	1
1018 ....Steel	126 HB Carbon Steel	0.94	1.0069	1.0113
17-4 PH ...Stainless	300 HB Hardened PH Stainless	1.1558	1.2302	1.2694
2024 .....Aluminum	Sol Treated Aluminum Alloy	0.3603	0.3989	0.3085
4140 ....Alloy Steel	205 HB Med Carbon Alloy Steel	0.9422	1.0069	1.0113
4320 ....Alloy Steel	210 HB Low Carbon Alloy Steel	1.0507	1.1203	1.1424
6061 ....Aluminum	Sol Treated Aluminum Alloy	0.3603	0.3989	0.3085
8620 ....Alloy Steel	210 HB Low Carbon Alloy Steel	0.9892	1.0561	1.0681
AMS 4350...Mag Alloy	Extrusions: Magnesium Alloy	0.2755	0.3103	0.2061
AMS 4500......Copper	Sheet,Strip,Plate:Copper Alloy	1.2228	1.3001	1.3502
Haynes Alloy 36	260 HB Cast Cobalt Hi Temp Aly	2.5024	2.6370	2.8955
Nickel 205	125 HB Nickel Alloy	1.1558	1.2302	1.2694
Nitralloy 135..Steel	240 HB Annealed Nitride Steel	1.0616	1.1317	1.1555
SRM 1107.......Brass	Copper Alloy	1.5241	1.6149	1.7141
Stellite 30	Corrosion Heat Resistance Stl	2.1174	2.2348	2.4307
Ti-8Mn .....Titanium	320 HB Wrought Titanium Alloy	1.2370	1.3150	1.3674
Zircaloy 2 (Grade32)	200 HB Zirconium Alloy	1.2516	1.3302	1.3850
Aluminum	Aluminum 99.9%	0.2	0.4	0.3

Table 3. Specific Cutting Power requirements for some of the materials.

$$C_{mt_{rv}} = \frac{E_{sp_{RO}}}{E_{sp}} \qquad \text{Eq. (24)}$$

Where:

$C_{mt_{rv}}$ = Cost Coefficient – Material Effect, Rough Cutting

$E_{sp_{RO}}$ = Specific Cutting Power for Reference Object material

E_{sp} = Specific Cutting Power for actual design material

7.6.2 Cost Coefficient – Material Effect, Finish cutting: In finish cutting, the material removal rate is dictated by cutting parameters that are in turn dictated by material – tool combination. If all conditions are kept constant except the work material, then material removal rate in finish cutting is proportional to the product of cutting speed, feed and depth of cut. Data for cutting speed, feed and depth of cut is obtained from the Machining Data Handbook [31] or similar source as mentioned before. This impact on process velocity is inversely translated in terms of cost. The Cost Coefficient – Material Effect, in finish cutting is defined by Eq. (25) as:

$$C_{mt_{fv}} = \frac{(s * f * d)_{actual.material}}{(s * f * d)_{reference.material}} \qquad \text{Eq. (25)}$$

Where:

$C_{mt_{fv}}$ = Cost Coefficient – Material Effect, Finish cutting

$(s * f * d)_{reference.material}$ = Process Velocity for Reference Object material

$(s * f * d)_{actual.material}$ = Process Velocity for actual material

s = Cutting speed

f = Feed rate

d = Depth of cut

Note: This equation may look similar to Eq. (15) but there is a critical difference between the two. The (s*f*d) values mentioned in Eq. (15) are for different processes keeping the material same whereas, here those values are for different materials keeping the process same.

7.6.3 Cost Coefficient – Material Effect, Tool Cost: Another important impact of material selection is on tool cost. Cutting tool life depends on cutting parameters and work material. Generally, the harder and stronger the work material, the shorter is the tool life while cutting on them. There are other material properties also that are important like microstructure, work hardening properties and other wear properties of tool-work material combination. The effect of work material on tool life is summarized as a machinability index of work material. Machinability index represents relative ease at which work material can be machined. Standard machinability tests are conducted to rate various materials relative to free cutting steel, B-1112, which is given machinability index of 100. Although machinability test gives relative ease at which material can be machined, it need not reflect the same proportions in tool cost. The reason is that there are too many factors of tool wear involved in machinability and machinability testing, some of them related to tool life cost, some of them not. Rather, it would be better to use tool life tests to judge tool cost effect of material selection. In this context, the recommended cutting parameters, i.e., speed-feed-depth of cut, as tabulated by the Machinability Data Center, are supposed to provide roughly 60 minutes of tool life [31]. The multiplication of speed, feed and depth of cut, which is proportional to process velocity, also represents proportionality of amount of work material removed for the same expected tool life of 60 minutes. Table 4 gives typical values of cutting parameters for various materials.

Cutting Parameters Data for various materials Operation: Face Milling, Rough cut Tool Material: Uncoated Carbide Expected Tool life: 60 min			
Material	Speed (fpm)	Feed (in/tooth)	Depth of Cut (in)
Free Machining Steel (1211)	385.0	0.016	0.3
Med. Carbon Steel (1040)	345.0	0.016	0.3
Alloy Steel (4140)	280.0	0.016	0.3
High Strength Steel (4340)	235.0	0.014	0.3
Aluminum	1200.0	0.020	0.3
Ti-6Al-4V	95.0	0.008	0.3
Titanium (99.5%)	280	0.015	0.3

Table 4. Cutting Parameters for Various Materials [31].

Using this table it can be proved that for the same expected tool life volume that can be machined for various materials is proportional to multiplication of speed, feed and depth of cut. This means, if the amount of material to be removed is the same then under recommended conditions the number of tools required is inversely proportional to the multiplication of speed, feed and depth of cut. More number of tools means more tool cost. So, the Cost Coefficient – Material Effect, Tool cost can be defined as in Eq. (26).

$$C_{mt_t} = \frac{(s * f * d)_{reference.material}}{(s * f * d)_{actual.material}} \qquad \text{Eq. (26)}$$

Where:

C_{mt_t} = Cost Coefficient – Material Effect, Tool Cost

$(s * f * d)_{reference.material}$ = Process Velocity for Reference Object material for 60 min. of Tool Life

$(s * f * d)_{actual.material}$ = Process Velocity for actual material for 60 min. of Tool Life

s = Cutting speed

f = Feed rate

d = Depth of cut

Note: This equation looks similar to the previous one but their significance and cost effects are entirely different. The impact of Cost Coefficient in Eq. (25) is on processing time while the Cost Coefficient in Eq. (26) has an impact on Tool cost.

7.7 Cost Coefficient – Equipment Factor:

The Cost of an equipment or machine tool involved in manufacturing is largely governed by its specifications. Specifications are of different types like size, capacity, precision, special attachments and technology involved. In general, the specifications for a typical metal cutting equipment or machine tool would look like the one given in Table 5.

Relation of these specifications to the base cost of machine tool can be established in following way.

- The higher the XYZ travel of the tool relative to the table, which would also imply that the higher the workload capacity and table surface, the higher the cost.

- The more accurate the machine, the more the cost.
- The faster the tool travel and positioning, the greater the cost. (e.g., production oriented machine tools.)
- The more complex the tooling and control, the more the cost. (e.g., special purpose machines.)
- The higher the spindle power, the higher the cost.

Machine Tool Specifications Machine Tool Type: Vertical Machining Center Manufacturer: Bridgeport Inc. Model: VMC 1000		
No.	Description	Specifications
1	XYZ Travel or Machine Space	40" x 20" x 24"
2	CNC Control	GE Fanuc, 18i Series Control
3	Accuracy Positioning Repeatability	 ±0.00020" ±0.00008"
4	Positioning Rapid Traverse Acceleration Minimum Increment	 1575"/min in X and Y, 1180"/min in Z, 240"/sec^2 0.00004"
5	Tooling Tool Capacity Tool Change Time	 22 number tool capacity 5.2 sec tool change time
6	Spindle Horse Power Speed Other Feature	 18 hp Spindle power 60 to 6000 rpm Spindle speeds Rapid tapping facility
7	Table Working Surface Workload (max)	 45.3" x 19.3" 1980 lbs

Table 5. Typical Machine Tool Specifications (Courtesy: Bridgeport Inc.).

Generally, higher spindle power would be coupled with faster tool travel because both of them are higher production rate oriented requirements. This would suggest four main independent variables for estimating the cost of the equipment.

- Size (XYZ Travel or Table Surface Area or Workload Handling Capacity)

- Precision (Accuracy and Repeatability)
- Intended Use (Production, non-Production, etc.)
- Tooling Complexity (Special Purpose, Additional 4th and 5th Axis, More Tooling Capacity etc.)

Based on available cost data, a regression analysis could be done to generate and equation that can estimate the cost of a machine tool.

Proper selection of above-mentioned machine tool parameters depends on Work piece and process specifications.
For example, a machine tool table should have enough space to hold the work firmly. The XYZ travel of the tool head relative to work should be enough to cover required surface of the work. Machine table should be sturdy enough to take the weight of the work without appreciable deflection that can cause problems with machining quality. It should have accuracy and repeatability of positioning so that dimensional tolerances of the work could be taken care of. If the work is supposed to be manufactured in a production quantity then machine tool should be suitable to production environment. And finally, if the work piece has some special features (Shape complexity) that require either more complex feeds and controls or additional 4th and 5th axis for intricate machining then those factors should also be considered.

To summarize, work specifications decide the machine tool specifications and machine specifications decide the base machine tool cost. If the base cost of machine tool were considered to be amortized over same period then machine hourly rate would be in same proportion as the base cost of machine tool.

The Reference Object has an overall size of 13.2" x 13.2" x 13.2" and the tool travel required is the same in the machining of each of its six sides. Each of its dimensions has a required tolerance of ±0.005". The RO is not intended to be a part of mass production setup and it does not require any special attachments for its manufacture. These details provide required specifications of the machine tool. For example, Applying appropriate allowance to above specifications, VMC 2216 of Bridgeport Inc., appears to be a reasonable choice for the manufacture of Reference Object. Any new design having its own specifications can be treated in same way to find its appropriate choice of the machine tool. The ratio of the cost of appropriate machine tool for the manufacture of actual design to the cost of machine tool for RO manufacture is the Cost Coefficient – Equipment Factor. This coefficient implies that even if the processing time is same in RO manufacture and actual design manufacture, the process cost is different because the equipment or machine tools involved are different. So, the Cost Coefficient – Equipment Factor can be mathematically defined as:

$$C_e = \frac{M_r}{M_{r_{RO}}} \qquad \text{Eq. (27)}$$

Where:

C_e = Cost Coefficient – Equipment Factor

M_r = Machine Hourly Rate for machine tool required for the manufacture of actual design

$M_{r_{RO}}$ = Machine Hourly Rate for the machine tool required for the manufacture of the Reference Object

7.8 Summary:

This chapter forms the basis of the relative cost estimation. The Reference Object in relation to which other costs to be evaluated is declared. This definition of Reference Object or RO is flexible and can be declared suitable to the environment in which the cost estimation is intended to be used. Various effects of the design specification of an actual design are examined and fundamental Cost Coefficients are defined to quantify each effect separately. These cost coefficients are to be aggregated in a specific way to arrive at a final relative cost figure. This methodology of aggregation is elaborated in the following chapter.

Chapter 8: ASSEMBLY OF COEFFICIENTS AND COST MODULUS

The previous chapter forms the basis of generic framework for 'relative cost estimation'. In Chapter 7, all the effects of design specifications on process cost are examined and Cost Coefficients related to each of them are declared and defined. This chapter suggests a methodology to aggregate those individual cost effects and put them in one single cost coefficient called Cost Modulus.

8.1 Consolidating Cost Effects:

The fundamental tenet of this thesis is indicated by following equation:

$$\text{Process Time} = \left(\frac{\text{Predominant Variable}}{\text{Process Velocity}}\right) \qquad \text{Eq. (28)}$$

As seen in the previous chapter, the defined Cost Coefficients affect Eq. (28) in various ways. Some influence the predominant variable while others influence process velocity. Table 6 summarizes the ten different Cost Coefficients and their relationships with design parameters and process parameters.

From this table, it could be seen that these scaling coefficients, which signify the relative impact of design specification over manufacturing cost in comparison to the Reference Object, are primarily applied at various levels:

- Productive Roughing Time
- Productive Finishing Time
- Non-Productive Time
- Equipment and Tooling Cost
- Total Cost before cost correction for Tolerance consideration

The following equations puts these cost contributing factors together.

$$T_p = T_{p_r} + T_{p_f} \qquad \text{Eq. (29)}$$

Where:

T_p = Total Productive Time (hr)

T_{p_r} = Total Productive Roughing Time (hr)

T_{p_f} = Total Productive Finishing Time (hr)

No	Description	Notation	Related Design Specification	Process Impact	Cost Effect Variable
1	Predominant Variable OR Size Coefficient	C_v	Change in Volume	Machined Volume	Productive Process Time - Roughing
2	Cost Coefficient - Shape, Process Velocity	C_{p_v}	Shape	Process Velocity	Productive Process Time - Roughing
3	Cost Coefficient – Shape, Tool Settings	C_{p_n}	Shape - Number of Features	Tool Setting Time	Non-Productive Time
4	Cost Coefficient – Shape, Work Settings	C_{p_w}	Shape - Faces to be Machined	Work Setting Time	Non-Productive Time
5	Cost Coefficient – Precision, Tolerance	C_{pr_t}	Precision – Dimensional Tolerance	Processing Time, and Equipment Cost	Total Cost before tolerance correction
6	Cost Coefficient – Precision, Surface Finish	C_{pr_s}	Precision – Surface Finish	Process velocity – Finish Cut	Productive Process Time - Finishing
7	Cost Coefficient – Material, Rough Cutting	$C_{mt_{rv}}$	Material	Process Velocity – Rough Cut	Productive Process Time Roughing
8	Cost Coefficient – Material, Finish cutting	$C_{mt_{fv}}$	Material	Process Velocity – Finish Cut	Productive Process Time - Finishing
9	Cost Coefficient – Material, Tool Cost	C_{mt_t}	Material	Tool Replacement	Tooling Cost
10	Cost Coefficient – Equipment Factor	C_e	Physical Size	Equipment Size	Equipment Setup Cost

Table 6. Summary of Cost Coefficients.

And

$$Cost = \left[\left(T_{p_r} + T_{p_f}\right) + T_n\right]M_r + C_{tool} \qquad \text{Eq. (30)}$$

Where:

T_n = Total Non-productive Time (hr)

M_r = Machine Hourly Rate ($/hr)

C_{tool} = Tooling Cost ($)

Cost = Total Manufacturing Cost before special Tolerance correction.

These equations and Table 6 become the basis for assembly of Cost Coefficients as presented in the sections below.

8.2 Manufacturing Cost of The Reference Object:

When design specifications of the Reference Object are known, its manufacturing cost can be found by using detailed process costing approach. The details like total productive time, roughing time, finishing time etc., as mentioned in Eq. (29) and Eq. (30), could be identified and put together.

If:

T_1 = Total productive process time in rough cutting for Reference Object manufacture

P_f = Total percentage finishing cut time for Reference Object manufacture

P_n = Non-productive process time as a percentage of productive time

P_t = Tooling cost as a percentage of all other machining costs together

$M_{r_{RO}}$ = Machine Hourly Rate for the machine tool required for the manufacture of the Reference Object

then, cost of Reference Object Manufacture is:

$$C_{RO} = T_1(1+P_f)(1+P_n)(1+P_t)M_{r_{RO}} \qquad \text{Eq. (31)}$$

All *P's* are the Percentage factors that are to be found from the detailed process plan of Reference Object.

8.3 Cost of Actual Design – Applying Cost Coefficients to Reference Object Costs: As the details of Reference Object process plan and thereby the costs are available, using Table 8.1 one can scale these costs to find the manufacturing cost of the actual design. The methodology of scaling these process times and costs is presented below.

8.3.1 Rough Cutting Time Scaling: The Cost Coefficients involved in roughing time scaling are:

- Predominant Variable or Size Coefficient, C_v
- Cost Coefficient - Shape, Process Velocity, C_{p_v}
- Cost Coefficient – Material, Rough Cutting, $C_{mt_{rv}}$

The higher the 'Predominant Variable' or 'Process related Size', the higher is the processing time. If T_l is the roughing process time for the Reference Object, then it has to be multiplied by Size coefficient to be adjusted for it. Whereas, the slower the actual process due to 'Shape Complexity' or 'Material selection', the higher is the processing time and T1 has to be scaled by dividing it by process velocity correction factors due to Shape and Material. Therefore, the adjusted process time for actual design in roughing is:

$$T_{p_r} = T_1 \frac{C_v}{C_{p_v} C_{mt_{rv}}} \qquad \text{Eq. (32)}$$

Where:

T_{p_r} = Roughing Process Time in Actual Design Manufacture.

and other coefficients are as defined before.

8.3.2 Finish Cutting Time Scaling: The effect on Finish Cutting time is primarily due to two factors:

- Surface Finish Specifications
- Material Specifications

The first effect is due to the change in Feed rate and the second effect is due to the change in overall Process Velocity. As it is defined, the finer the surface finish or lower the roughness value, Ra, the higher is the related Cost Coefficient, i.e., C_{pr_s}. In the case of Material effect on finishing process velocity, the tougher the material to be machined, the slower is the processing velocity; hence, the higher is the finishing time and related cost. For scaling Finishing process time it is multiplied by C_{pr_s} and divided by $C_{mt_{fv}}$. If P_f is the Finishing process time as a percentage of Roughing process time, and P_s is the required finishing surface area in actual design as a percentage of surface area requiring finishing in Reference Object, then the adjusted Finishing process time is:

$$T_{p_f} = T_1 \frac{P_f P_s}{C_{mt_{fv}}} C_{pr_s} \qquad \text{Eq. (33)}$$

Where:

P_s = Designed Object Surface Area requiring finishing care as a percent of Reference Object finishing area

T_{p_f}= Adjusted finishing process time in actual design

and other coefficients are as defined before.

8.3.3 Non-productive Process Time Adjustment: The non-productive process time is due to two major causes:

- Work Setting
- Tool setting

Calculation of the Cost Coefficients due to these causes is explained in the previous chapter. Originally, in the case of Reference Object manufacture the total non-productive time is found from the detail process plan. The following are the percentage factors derived from that process plan.

P_{n_t} = Non-productive process time related to tool setting as a percentage of total roughing process time

P_{n_w} = Non-productive process time related to work setting as a percentage of total roughing process time

Using Work and Tool setting time Cost Coefficients, and above percentages from Reference Object process details, the total non-productive process time for the manufacture of the actual design can be represented by the following equation.

$$T_n = T_1 (1 + P_f)(P_{n_t} C_{p_n} + P_{n_w} C_{p_w}) \qquad \text{Eq. (34)}$$

8.3.4 Total Cost of Manufacturing of Actual Design: Equations (32), (33) and (34) give roughing time, finishing time and non-productive processing time respectively. Machine tools and equipments are engaged fully during all this time. This 'process time' needs to be multiplied by equipment hourly cost to get an actual estimate of machining time cost.

$$C_{mc} = \left(T_{p_r} + T_{p_f} + T_n\right) M_r \qquad \text{Eq. (35)}$$

Where:

C_{mc} = Total Machining time cost

M_r = Equipment Hourly rate

The tooling cost can be represented as a percentage of machining time cost of the Reference Object manufacture. This percentage would remain the same if the actual design has same material as the Reference Design. If not then the tooling cost has to be compensated for the change in material of construction. This is achieved by the following equation.

$$C_{tool} = P_t C_{mc} C_{mt_t} \qquad \text{Eq. (36)}$$

Where:

P_t = Tooling cost as a percentage of machining cost in Reference Object manufacture

C_{tool} = Adjusted Tooling cost

Cost of actual design manufacture before tolerance factor adjustment is the summation of machining cost and tooling cost represented by equations (35) and (36). This is the processing cost of the actual design with tolerance specifications same as those for the Reference Object.

$$C_{act_{ref\ tol}} = \left(T_{p_r} + T_{p_f} + T_n\right)\left(1 + P_t C_{mt_t}\right) M_r \qquad \text{Eq. (37)}$$

Where:

$C_{act_{ref.tol}}$ = Cost of Actual Design with tolerances same as Reference Object

For Cost compensation for actual tolerances in the actual design, the above cost has to be multiplied by the Cost Coefficient - Tolerance factor. The total cost of an actual design is then given by the following equation.

$$C_{act} = (T_{p_r} + T_{p_f} + T_n)(1 + P_t C_{mt_t}) M_r C_{pr_t} \qquad \text{Eq. (38)}$$

Where:

C_{act} = Total Manufacturing Cost of actual design

All other terms in above expression are defined previously.

8.3.5 The Cost Modulus: Once the scaled cost of the actual design is available, the cost modulus is nothing but the ratio of actual design manufacturing cost to the Reference Object manufacturing cost. Manufacturing Cost of actual design is represented by Eq. (38) and that of Reference Object is given by Eq. (31). Taking the ratio of these equations leads to the Cost Modulus as:

$$C_m = \frac{C_{act}}{C_{RO}} = \frac{(T_{p_r} + T_{p_f} + T_n)(1 + P_t C_{mt_t}) M_r C_{pr_t}}{T_1 (1 + P_f)(1 + P_n)(1 + P_t) M_{r_{RO}}} \qquad \text{Eq. (39)}$$

Where:

C_m = Cost Modulus

Substituting for T_{p_r}, T_{p_f} and T_n, substituting $\frac{M_r}{M_{r_{RO}}}$ as C_e and readjusting the equation (38) we get the single equation that represents the Cost Modulus of the actual design as follows.

$$C_m = \left[\frac{\left(\left(\frac{C_v}{C_{p_v} C_{mt_{rv}}} + \frac{P_f P_s}{C_{mt_{fv}}} C_{pr_t} + (1 + P_f)(P_{n_t} C_{p_n} + P_{n_w} C_{p_w}) \right) (1 + P_t C_{mt_t}) C_e C_{pr_t} \right)}{(1 + P_f)(1 + P_n)(1 + P_t)} \right] \qquad \text{Eq. (40)}$$

In this equation, all P's are percentage factors that can be found from detail process plan of the Reference Object manufacturing. And all C's are the Cost Coefficients that are calculated from design specification of the actual design, engineering data and Reference Object specifications as described by various equations in the previous chapter.

8.4 Chapter Summary:

The previous chapter described the construct of individual cost coefficients. In this chapter the schema to consolidate all cost effects of the design specifications is presented. The Cost Modulus that is defined as cost of actual design relative to cost of Reference Object is expressed in a mathematical equation. The Cost Modulus equation is based totally on design specifications of actual design, engineering data related to metal cutting process and definition of Reference Object.

Chapter 9: IMPLEMENTATION, VALIDATION AND RESULTS

9.1 Implementation:

The proposed framework and model need to be implemented for testing and validation. There are three major components for this system.

- Design Data
- Material Data
- Calculations Worksheet

These three components interact with each other. At this point of time this interaction is carried out manually but if intended for the professional use, the system needs to be automated and more sophisticated. This can be done by using OLE (Object Linking and Embedding) and API (Application Programming Interface) interfaces. Each of these components is discussed in the following sub-sections.

9.1.1 Design Data: The model was tested extensively on a single components design. The component chosen was intended to be close to aircraft spar designs. Figure 9 shows the SolidWorks® solid model of a Spar. SolidWorks® was chosen as the solid modeler because of its easy interface with Excel worksheets. Care was taken while building the model so that its key parameters are governed from the excel worksheet and other parameters are calculated based on those main parameters. This is called parametric modeling, meaning that certain dependency exists between some of its parameters. The parameters that were kept independent are:

- Spar length
- Larger Cross-section Web height and
- Pitch of 'the holes' or pockets on the face

So, the entire design can be modified by varying these three parameters. The data that is collected from the SolidWorks® model is basically the physical property data like Volume, Surface Area, Weight, Moment of Inertia and location of the center of gravity. This data is transferred to the worksheet for further use. A macro was used to link these the Excel and SolidWorks® files and for the data transfer to and from. The most critical data from the Cost Modulus point of view was 'Volume' of the object.

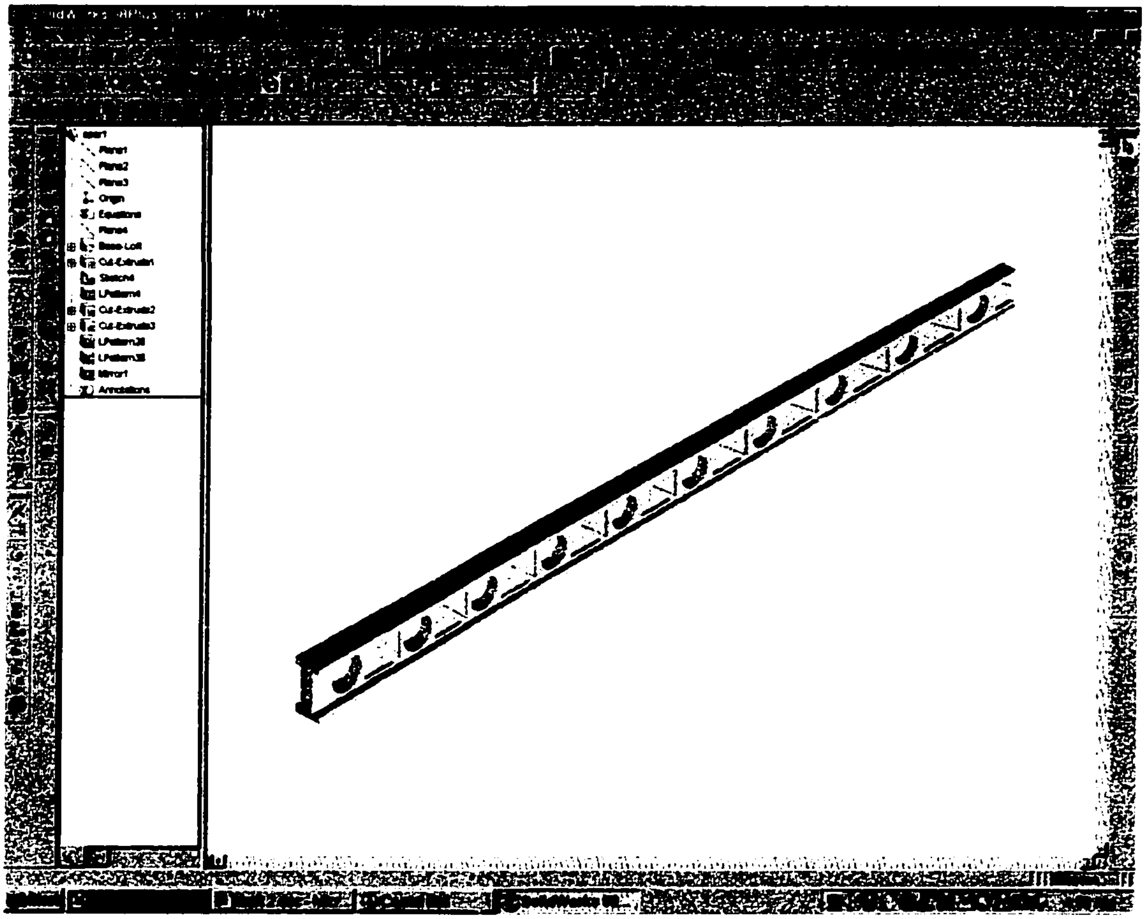


Figure 9. The 'Spar' design used for the Cost Model validation purpose.

9.1.2 Material Data: A large amount of data related to metal cutting process has been published in various sources like the Machinability Data Center handbooks, the Tool and Manufacturing Engineers Handbook. Also, commercial Cost Estimation software tool like COSTIMATOR® developed by Manufacturing Technologies, Inc., contains a large amount of metal cutting data. As the model uses this data, the required data from these sources is used for the demonstration purpose. Generally, this data would be stored in MS Office Access Database, but because only a small set of data was needed for the demo purpose, it was directly put in the same excel worksheet that was used for creating the design configurations. The material data used was:

- Metal cutting parameters

- Specific Cutting power values

Proper data was used for calculation related to the material selection.

9.1.3 Calculation Worksheet: Simple Excel worksheets were used for the required calculations based on the design data and material data. First individual Cost Coefficients and then the final Cost Modulus were calculated. Some constants, as mentioned in the previous chapter, that are based on actual process plan of Reference Object were identified from COSTIMATOR® cost estimate of Reference Object. The worksheet interfaces with Solid model and material data and finally calculates the Cost Modulus.

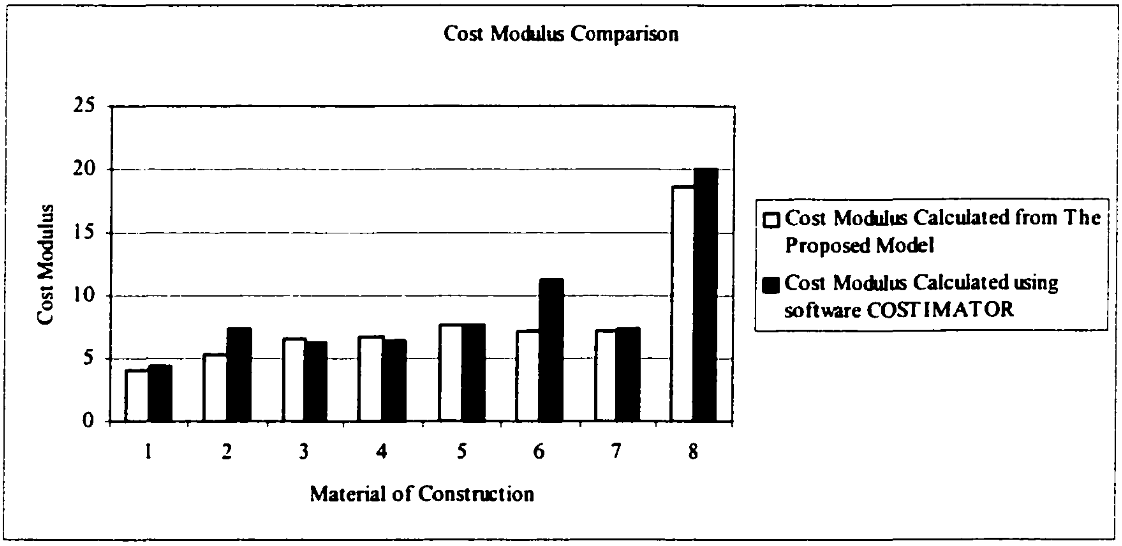
9.2 Validation:

One of the important steps for this thesis was to validate the model against realistic data. For this purpose the commercial Cost Estimation software, COSTIMATOR®, was used as a benchmarking tool. The same spar design was used for validation. It was intended to test the implemented model for various combinations of the design parameters. The design parameters that were changed for assessing the capabilities of the Cost Estimating model were:

- Material
- Shape and Size
- Surface finish area

The following are the results of the validation exercise.

9.2.1. Material Effect: The model was tested for a variety of materials on both non-ferrous and ferrous alloys. Figure 10 shows how the Cost Modulus for Spar design under consideration is affected by material selection. The graph also shows the comparison between the theoretical Cost Modulus calculated from the proposed model and the Cost Modulus obtained from the actual process based detail estimate facilitated by COSTIMATOR®. Figure 11 shows the difference in theoretical value and the one obtained from the commercial software as a percentage of the later. From both these graphs it can be seen that the model is in good agreement with the results from the process based detail estimate. The average difference was –8.87% with a standard deviation of 14.16%. Two of the readings, one with material as Copper and the other with Stainless Steel 304 were much off compared to the rest of the six readings. Average difference in Cost Modulus without these two exceptional readings was –1.52% with standard deviation of 5.49%. This is a very good agreement considering the details substituted in the model. The differences are further analyzed and put forth here.



No	Material of construction Of the Spar Design
1	Aluminum Alloy, e.g. 7075
2	Wrought Copper alloys,
3	Low Carbon Steels, e.g. 1020
4	Med Carbon Steels, e.g. 1040
5	Medium Carbon Alloy Steels, e.g. 4140
6	Austenitic SS 304 etc.
7	Grey Cast Iron
8	Ti-alloys e.g. Ti-6Al-4V

Figure 10. Comparison of Theoretical Cost Modulus and Cost Modulus obtained from commercial Cost Estimating software COSTIMATOR.

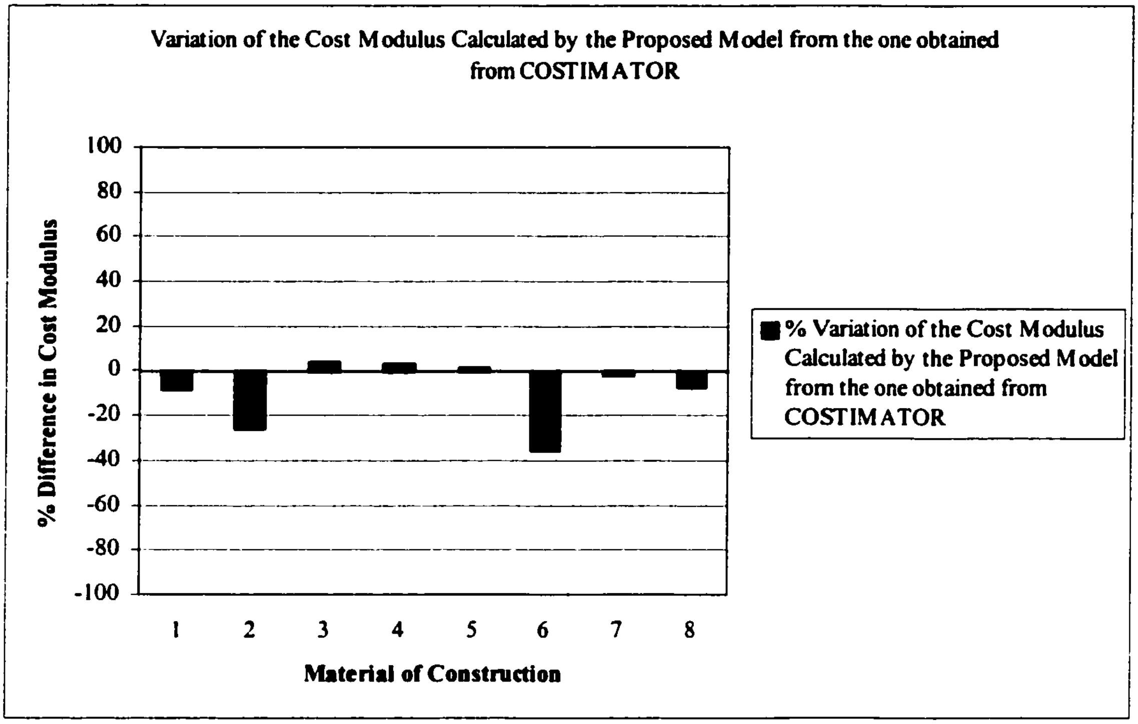


Figure 11. Difference in Cost Modulus value calculated by the Proposed Model and the one obtained from commercial software.

The average error in calculation of cost modulus is mainly due to the difference in the data sources. For the calculation of the Cost Modulus for the design with Copper as a material of construction, the speed-feed-depth of cut values used by two methods are respectively different during the validation exercise. These differences are reflected in large variation in the calculated Cost Modulus and the one obtained from Costimator software. Apparently, the one calculated by the suggested model is more accurate. The reason can be given in following way. Compared to any steel, copper is easier and faster to machine, suggesting that Cost Modulus for the copper part should be smaller compared to a same part in steel. This is well predicted by the proposed Cost Model; whereas, the Cost Modulus obtained from the software COSTIMATOR is not in line with this engineering judgment. It predicts 7.23 as a cost modulus for the copper part whereas it predicts 6.23 as a cost modulus for the same part in low-carbon Steel. The reason for this discrepancy could be that the data underneath the Costimator specifically for Copper is different from the speed-feed-depth of cut data suggested by Machinability Data Center. The same reason can be applied to the case of design with SS-304 and its variation can be explained. So, in conclusion, it is important to use proper cutting data with the model to get proper results. The proposed model uses Machinability Data Center data for cutting parameters and specific cutting power data is used from COSTIMATOR®. Which of these two data is accurate is out of the scope of this study. At the same time it can be seen that barring some exceptions, cost model agrees well with the software based cost estimate.

9.2.2 Size and Shape Variation: The spar's overall length, cross-section and other features like pockets and holes for weight reduction can be varied to determine their most optimum combination from a structural design point of view. But how this variation affects the process cost was not readily known without detailed process based estimate. This theoretical Cost Estimation model is capable of doing that. This capability of the model is tested by conducting the following study. Twelve different combinations of the overall length, cross-section parameters and pocket pattern pitch were designed and cost evaluated. The data is presented in Table 7. This comparison of the two methods of cost estimation is also graphically represented in Figure 12 and Figure 13. Figure 12 shows theoretical Cost Modulus using proposed model and software cost estimate based cost modulus side by side, and the percentage difference between the two Cost Modulus is plotted against design combination number in Figure 13.

The figures show that the Model has always under predicted the Cost Modulus in comparison with the one obtained from the Software estimate. One of the reasons that is identified is that, the commercial software - the COSTIMATOR applies 'allowance' to the manufacturing time calculated and that is added as an additional cost. The proposed model has not accounted for such allowance. The allowance applied by the Software is of the order of 10% to the total Productive or Machining time. If this allowance were added to the theoretical estimate the difference would be much smaller. The other reason is that, the Costimator estimate is for specific conditions that includes specific cutter dimensions,

Design No	Spar Length	Cross-section Web height	Pocket Pitch	Theoretical Cost Modulus	Cost Modulus from Software Estimate	% Difference
1	100	5	12	3.21	3.84	-16.4063
2	100	5	16	2.79	3.48	-19.8276
3	100	6	12	3.45	3.91	-11.7647
4	100	6	16	3.02	3.53	-14.4476
5	120	5	12	3.68	4.24	-13.2075
6	120	5	16	3.29	3.87	-14.9871
7	120	6	12	3.998	4.37	-8.51259
8	120	6	16	3.36	3.95	-14.9367
9	140	5	12	4.23	4.65	-9.03226
10	140	5	16	3.59	4.1	-12.439
11	140	6	12	4.55	4.789	-4.9906
12	140	6	16	3.9	4.21	-7.36342

* Material of construction: Aluminum

Table 7. Cost Modulus for various Shape-Size variations of the Spar.

cutter data etc., whereas, the proposed model is based on more general conditions or the average conditions. So there would be some difference expected in these two estimates. From the result however it is seen that, considering these variations the proposed model agrees fairly well with the Commercial Cost Estimation Software. Average estimation error is about –12.32 % with a standard deviation of 4.22 %, which is reasonably good.

9.2.3 Precision – Surface Finish specification:

For the spar the upper and lower surface would be required to be finish cut in normal circumstances assuming that the same surface will be used for skin and other assembly purpose. This surface approximately forms 25% of the total surface area of the spar used in this study and this figure was used for the Cost Modulus estimates. Two parameters can be varied to try and test the proposed model for its capability of handling changes in surface finish specifications. The first one is changing surface finish value and second one is the area to be finished. But the cost estimation software that would be used for validation of this effect can only assess cost effects of changes in finished surface area. It assumes that surface roughness value is the same as the one obtained in regular machining operation as its characteristics. So, only the surface finish area quantity effects

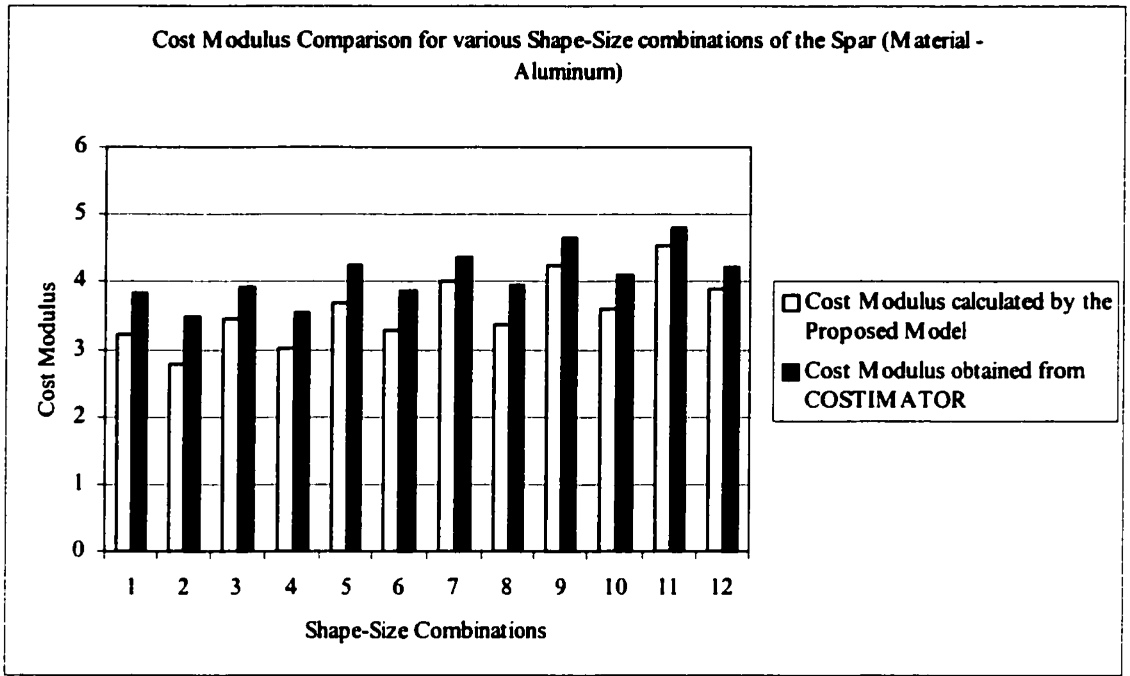


Figure 12. Cost Modulus comparisons for various Shape-Size Design combinations.

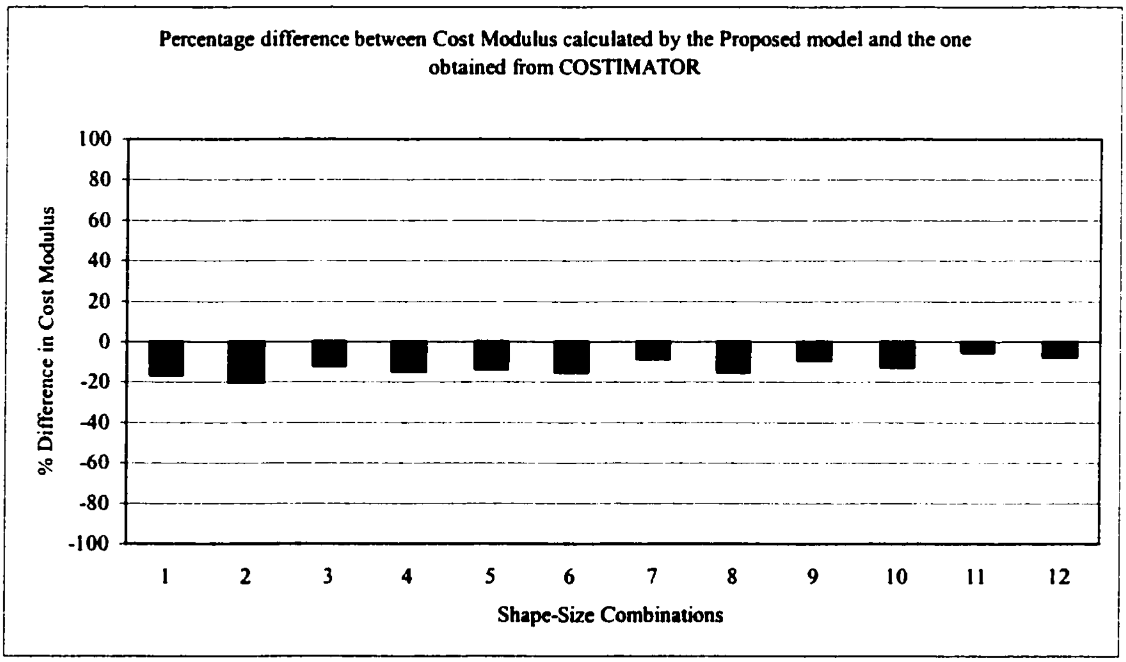


Figure 13. Percentage difference in theoretically calculated Cost Modulus and the one obtained from Software estimate.

were considered and evaluated here and surface finish specifications were assumed to be same as obtained regularly in case of finish milling.

With 25% of the total Spar area requiring finish milling, the difference in theoretical and software Cost Modulus estimation was 8.7%. In two other readings with 50% and 62% of the Spar area requiring finish-milling operation, the estimation difference was 6.17% and 5.07% respectively. This indicates that the surface finishing effects were well accounted for in the model.

9.3 Model Application and Results:

Model implementation once validated can be used to study cost behavior of the designs. This is one of the major applications of this model. Principally, as with other behavioral studies one of the concerned parameters is varied and the others kept constant to study the effect of that parameter. In this case, the design that is studied is that of an aircraft 'Spar' as shown in Fig. 9, the same that was used for validation purpose. Spar dimensions were kept same as the ones mentioned in combination number seven of the Table 7, unless otherwise specified. The following are the results of this study. One thing that should be specifically noted is that the numbers produced here are very specific to the design being studied and they are not and cannot be inferred as general conclusions. This suggests, for example, that the magnitude of the effect of material on overall machining cost would be different with different designs and they need to be evaluated separately.

9.3.1 Material Choice: Keeping all dimensions, precision and shape the same if designer varies material of construction of the spar, then the processing cost varies according to Fig. 14. It can be seen that machining Titanium alloy like Ti-6Al-4V is the costliest alloy to machine and Magnesium alloys are the cheapest to machine amongst the presented ones. The Titanium alloy was found to be 4.63 times costlier to machine compared to the Aluminum alloy. This graph could also be plotted against relative strength or strength to weight ratio, thus giving the designer a clear idea of deciding the correct material choice.

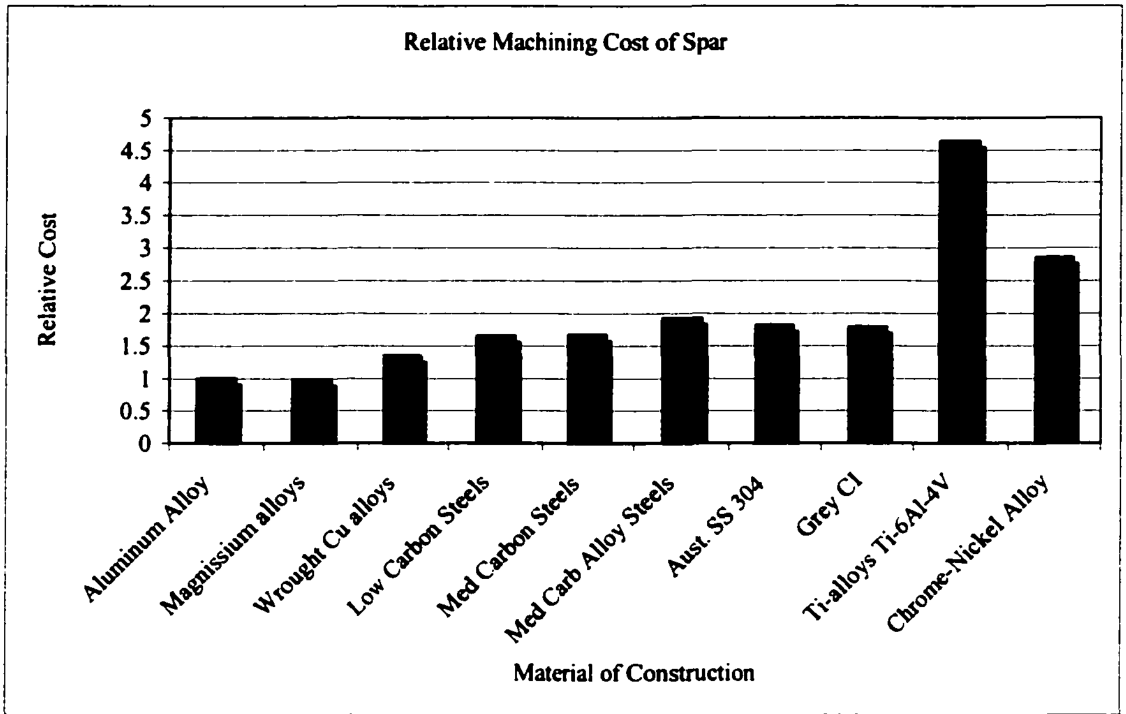


Figure 14. Effect of Material choices on total Machining Cost of a typical Spar.

9.3.2 Surface Finish Area: The finishing cost is affected by the amount of surface area to be machined by finishing operation. Figure 15 shows this effect. As the amount of finished area is increased from 0% of the total area of object to 100%, the machining cost increases by almost 5.68% in case of Aluminum as a material of construction. The same variation is of the order of 40.57% if the material is 60-40 Cr-Ni alloy. This shows that material has a significant impact on finish machining cost.

9.3.3 Tolerance: The more stringent the tolerance specifications, the higher is the manufacturing cost. Figure 16 shows the variation of machining cost against tolerance. Considering process capability equal to 0.008 in and tolerance specification of 0.008 as a reference case, the machining cost is almost 7.96 times the reference cost if the tolerance limits are halved. This information could be of much importance to designer as well as process planners while deciding the tolerance and while deciding process respectively.

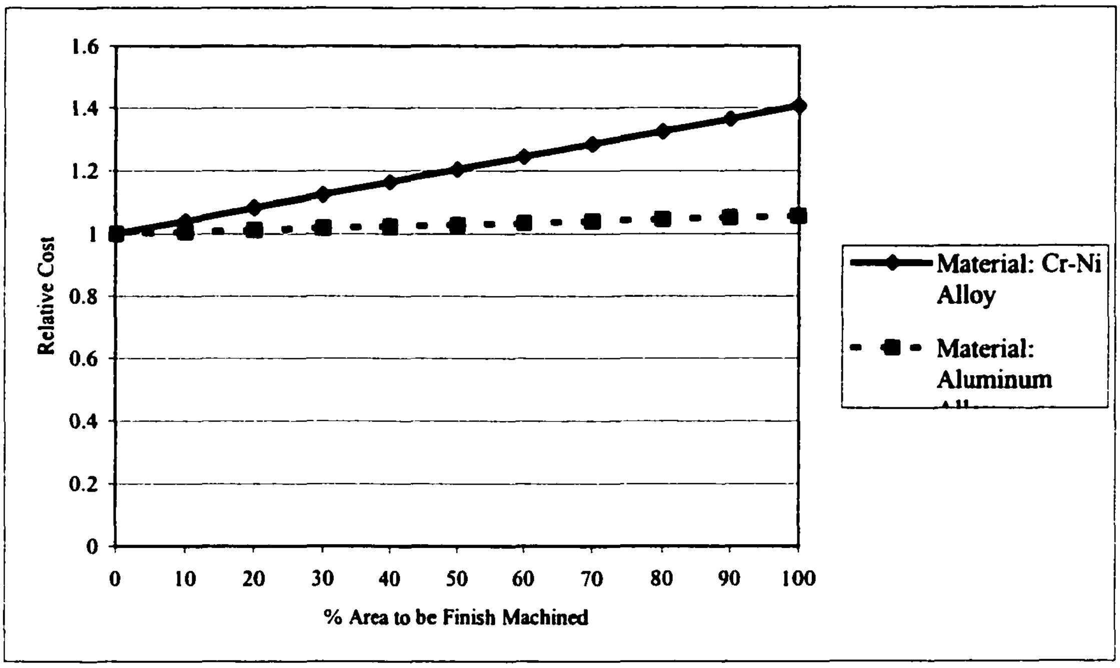


Figure 15. Effect of quantity of Surface to be finished on total Machining Cost of a typical Spar.

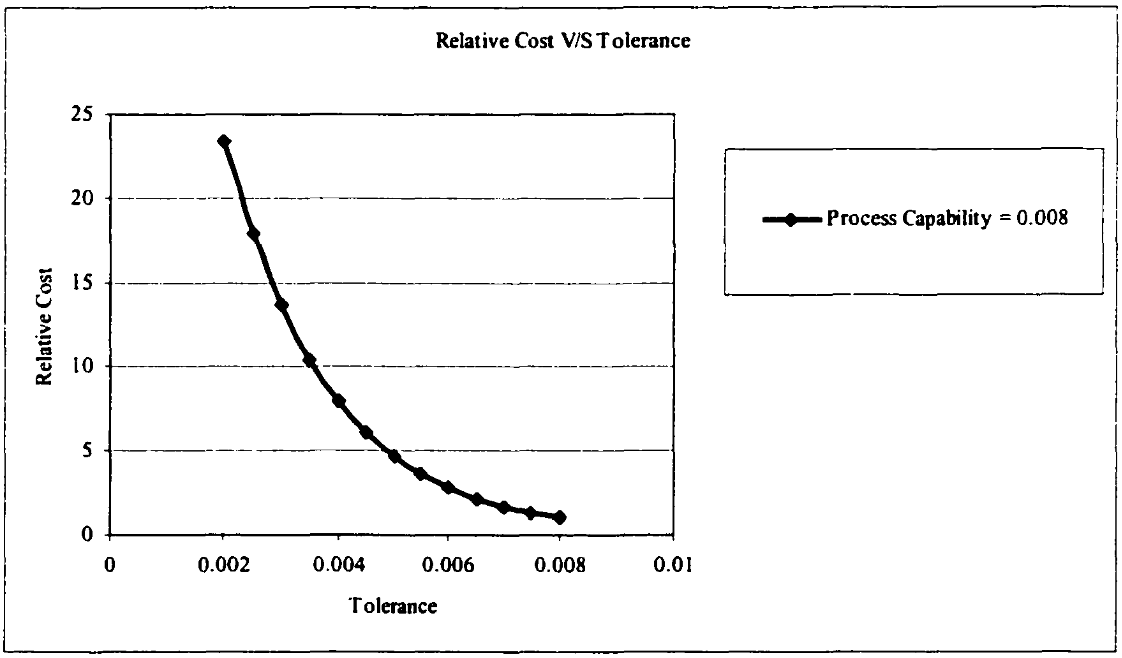


Figure 16. Effect of Tolerance specifications on total Machining Cost of a typical Spar.

9.3.4 Machined Volume: Figure 17 shows total machining cost as against the machined volume. While machining 5000 cubic inch of aluminum it takes 12.7% more cost compared to machining of 2500 cubic inch of aluminum in the case of the spar design. For other materials these results would be different.

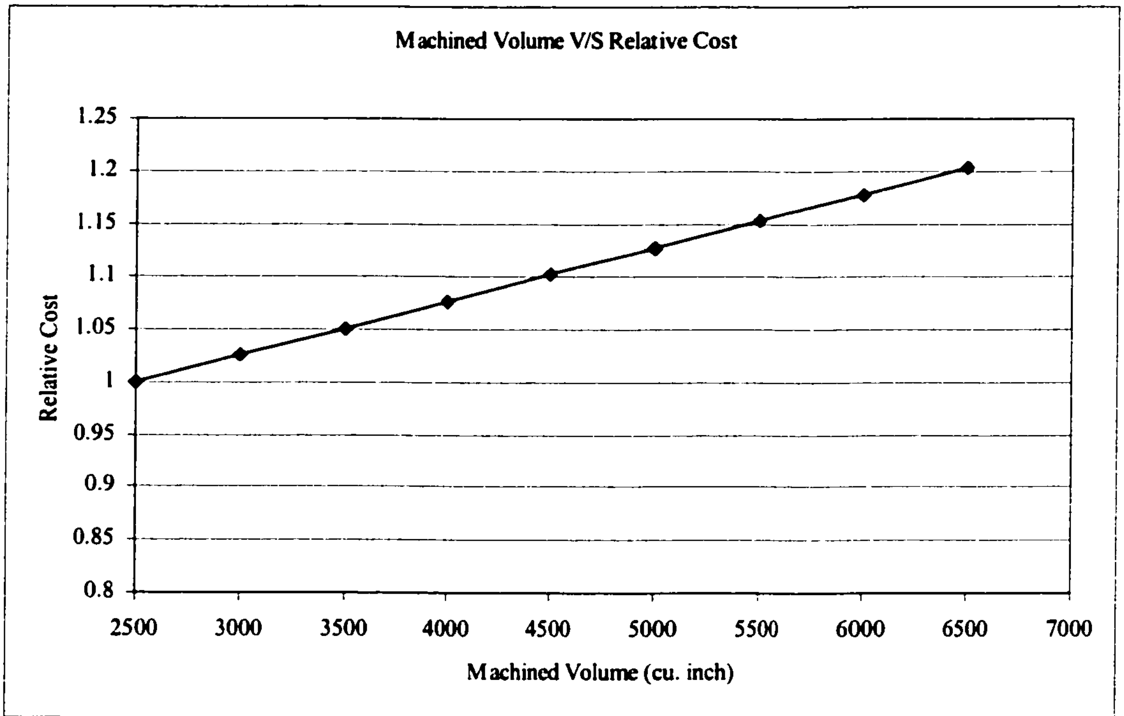


Figure 17. Effect of Volume removed in Machining on the total Machining Cost of a typical Spar Design.

9.3.5 Pocket Features: Pockets are generally difficult features to machine compared to plain surface machining. Increased material removal from pockets would significantly affect the overall cost of machining. Figure 18 shows in case of an aluminum spar how machining cost is affected by increasing pocket volume to be machined. If the volume in pockets is 60% of the total volume to be machined then the machining cost is more by 19.16% compared to the cost of the same Spar without any pockets.

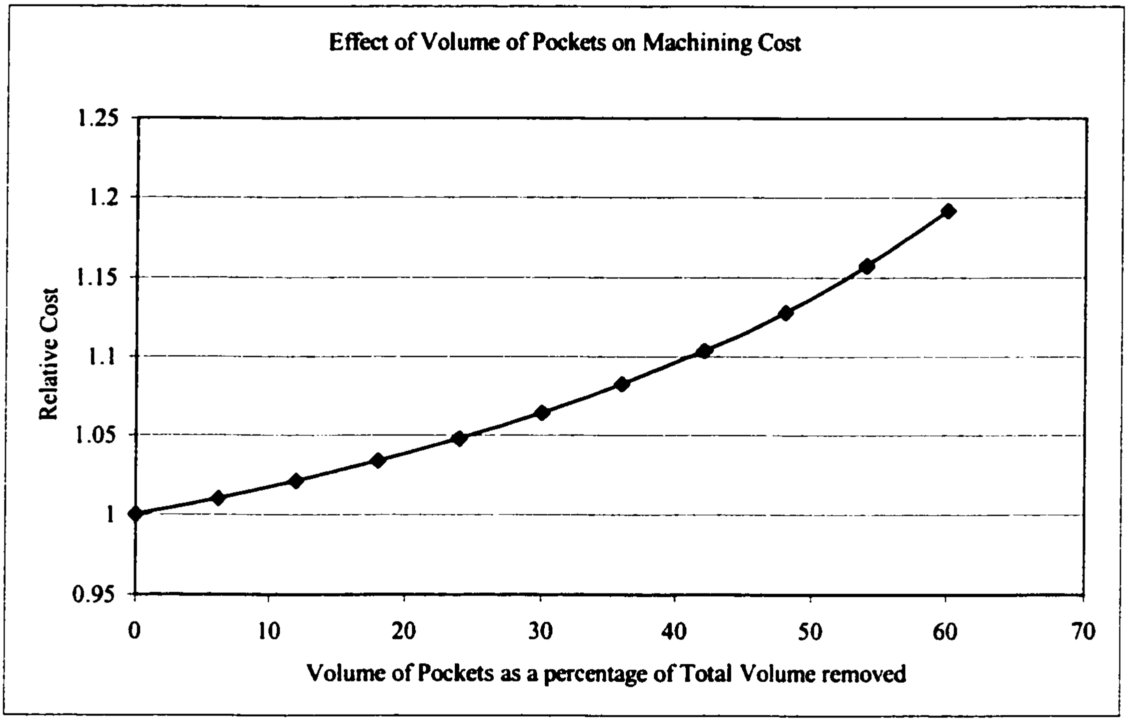


Figure 18. Effect of Volume in Pocket to be removed as a percentage of total volume removed on Machining Cost of a typical Spar Design.

9.3.6 Number of Features: A higher number of features means more tools to be used initially and certainly, additional cost is associated with that. How this fact affects the overall machining cost is shown by Fig. 19. If the number of features increases from basic 3 to 11, the cost jumps 2.4 times. This shows every additional geometric feature has a significant cost in the case of a spar manufacture.

9.4 Chapter Summary:

This chapter explains the implementation of the proposed Generic Cost Model for milling operation. The model is validated against a commercial software for machining cost estimation. The validation results were found satisfactory. The utility of the model is demonstrated by applying it to a spar design. Cost behavior is observed as against design specifications. This application of the model would of immense importance for design optimization.

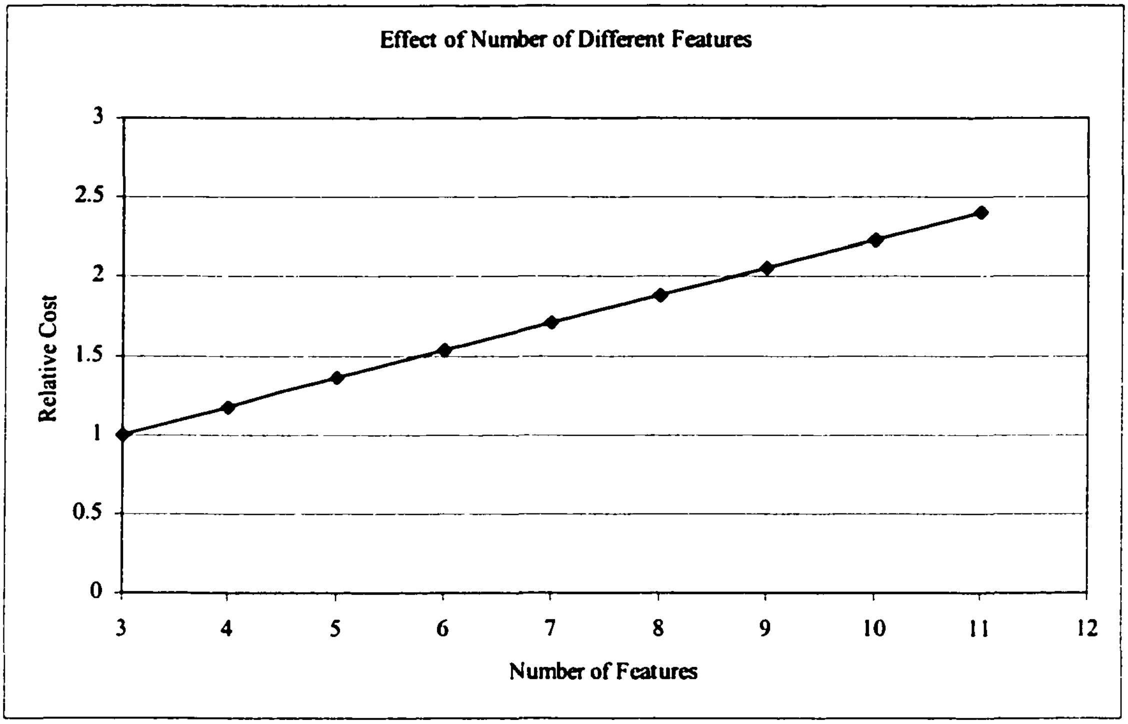


Figure 19. Effect of total number of Features present in a design on Machining Cost of a typical Spar Design

Chapter 10: CONCLUSION

10.1 Conclusion:

The complete exercise of designing a Generic Cost estimation framework based on relativistic principles was at the core of this research. The study provided a better understanding of the relationship between manufacturing cost and design specifications. The model was designed to take care of cost resulting from general design specifications. The use of 'relative estimation logic' helped eliminate many operation specifics from the estimation exercise. The model was validated against a commercial cost estimation software, and it showed good agreement with it. The variation in estimation compared to the commercial software was of the order of 10%. Some of the readings showed exceptional disagreement wherein engineering judgment was used to reason out the difference. This is essential because that brings engineering meaning to the estimate and it does not just remain mathematics. The model was successfully implemented using Excel worksheet, Access database and SolidWorks CAD software. Although complete automation of the estimation process was not intended at this point of time, the system was good enough for model validation and general use. The model can be used effectively to study the effect of design specifications on manufacturing cost. The results discussed previously show how material choice, size, surface finish, tolerance, etc., affect manufacturing cost of the object. This study can be used to generate guidelines for better designs. Finally, manufacturing cost estimation essentially consists of computing manufacturing time and resources and then converting them in terms of dollars. 'Time' as a resource forms the major part of estimation. It is perfectly said that 'Time is Money'.

10.2 Summary:

One of the major drawbacks of present cost estimation models is their incapability of embracing effectively complete product development stage. Parametric estimation works well in the early design stage but, when it comes to detail design stage, a more complete estimation is provided by process model based and detail estimation techniques. A major paradigm shift is suggested in this research work, and that is to consider 'Cost' as a design consequence rather than as an outcome of operation decisions. It also suggests studying the 'Cost' from a scientific and engineering perspective rather than just an accounting practice. A comprehensive framework using System Analysis fundamentals has been designed to study the process 'Cost' aspects of a part or a design. A successful implementation of this new approach has been demonstrated in this thesis. It has also promised integration of 'Cost' with other disciplines in Multidisciplinary Optimization and Collaborative Engineering. The integration is achievable through new technologies like API, OLE, CORBA and similar interface tools.

10.3 Future Work:

This work is a small part of the larger manufacturing domain. It is therefore essential to experiment this model in different situations and on all types of manufacturing processes. Based on the nature of the process the specifics in the model may be varied but the general philosophy could remain the same. So, from that point of view, the next immediate work would be to design estimation for other categories of manufacturing processes like casting, joining, forging, assembly, non-traditional machining, etc. Once individual modules prove to be functional, it is essential to weave them together because a product is hardly manufactured using just a single process. Information technology would be of utmost importance at that point of time, and that is the reason why one should establish certain standards for documentation and implementation of individual modules. Apart from just the manufacturing domain, to achieve the higher goal of 'Life Cycle Cost Estimation and Optimization' one can imagine that the system required would be highly complex. Systematic efforts in this direction would one day achieve this goal. Design specifications are a major source of product characteristics apart from the fact that how that design is executed and managed throughout its life. There are other characteristics like operating cost, maintaining cost, reliability, safety, cost of failure etc. that can be related to design specifications. Establishing these relations would be a major step in ultimately realizing the goal of 'Total Product Optimization'.

Time is Money!

There is no fun wasting Time!

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APPENDIX I

Aluminum Wing Manufacture --

Skin Fabrication - Top	$	12,814	$	12,814	$	12,814	$	12,814	$	12,814
Skin Fabrication - Bottom	$	12,814	$	12,814	$	12,814	$	12,814	$	12,814
Rib Fabrication	$	19,479	$	19,479	$	19,479	$	19,479	$	19,479
Spar Fabrication - Front	$	5,472	$	5,472	$	5,472	$	5,472	$	5,472
Spar Fabrication - Rear	$	4,637	$	4,637	$	4,637	$	4,637	$	4,637
Wing Assembly - Front Spar	$	18,798	$	18,798	$	18,798	$	18,798	$	18,798
Wing Assembly - Rear Spar	$	18,174	$	18,174	$	18,174	$	18,174	$	18,174
Wing Assembly - Top Skin	$	22,732	$	22,732	$	22,732	$	22,732	$	22,732
Wing Assembly - Bottom Skin	$	22,052	$	22,052	$	22,052	$	22,052	$	22,052
Wing Assembly - Rib	$	60,687	$	60,687	$	60,687	$	60,687	$	60,687
Total Process Cost	$	55,217	$	55,217	$	55,217	$	55,217	$	55,217
Total Assembly Cost	$	142,443	$	142,443	$	142,443	$	142,443	$	142,443
Total pro + Asmbly Cost	$	197,660	$	197,660	$	197,660	$	197,660	$	197,660

Material Cost Data

SkinTop	$	2,788	$	2,788	$	2,788	$	2,788	$	2,788
Skin Bottom	$	2,788	$	2,788	$	2,788	$	2,788	$	2,788
Rib	$	6,244	$	6,244	$	6,244	$	6,244	$	6,244
Spar Front	$	1,354	$	1,354	$	1,354	$	1,354	$	1,354
Spar Rear	$	974	$	974	$	974	$	974	$	974
Rivets - Front Spar	$	59	$	59	$	59	$	59	$	59
Rivets - Rear Spar	$	56	$	56	$	56	$	56	$	56
Rivets - Top Skin	$	82	$	82	$	82	$	82	$	82
Rivets - Bottom Skin	$	78	$	78	$	78	$	78	$	78
Rivets - Rib	$	133	$	133	$	133	$	133	$	133
Total Material Cost	$	14,556	$	14,556	$	14,556	$	14,556	$	14,556
Total Cost Of Al - Wing	**$**	**212,216**	**$**	**212,216**	**$**	**212,216**	**$**	**212,216**	**$**	**212,216**

Process Cost Data - Per sq FT of relevant Area

Skin Fabrication - Top	240.74	240.74	240.74	240.74	240.74
Skin Fabrication - Bottom	240.74	240.74	240.74	240.74	240.74
Rib Fabrication	1,490.36	1,490.36	1,490.36	1,490.36	1,490.36
Spar Fabrication - Front	793.68	793.68	793.68	793.68	793.68
Spar Fabrication - Rear	935.17	935.17	935.17	935.17	935.17
Wing Assembly - Front Spar	803.01	803.01	803.01	803.01	803.01
Wing Assembly - Rear Spar	823.76	823.76	823.76	823.76	823.76
Wing Assembly - Top Skin	700.59	700.59	700.59	700.59	700.59
Wing Assembly - Bottom Skin	715.42	715.42	715.42	715.42	715.42
Wing Assembly - Rib	1,146.52	1,146.52	1,146.52	1,146.52	1,146.52
Percent Change WRT config. "0"	-0.0587	-0.0587	-0.0587	-0.0587	-0.0587

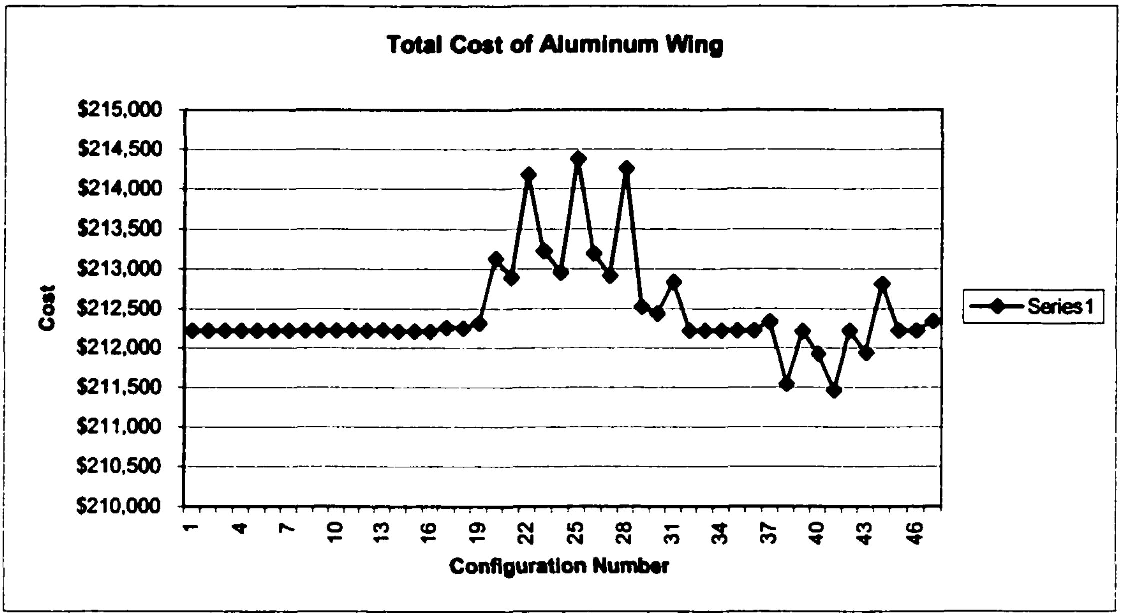
Process Cost Data - Per sq IN of relevant Area

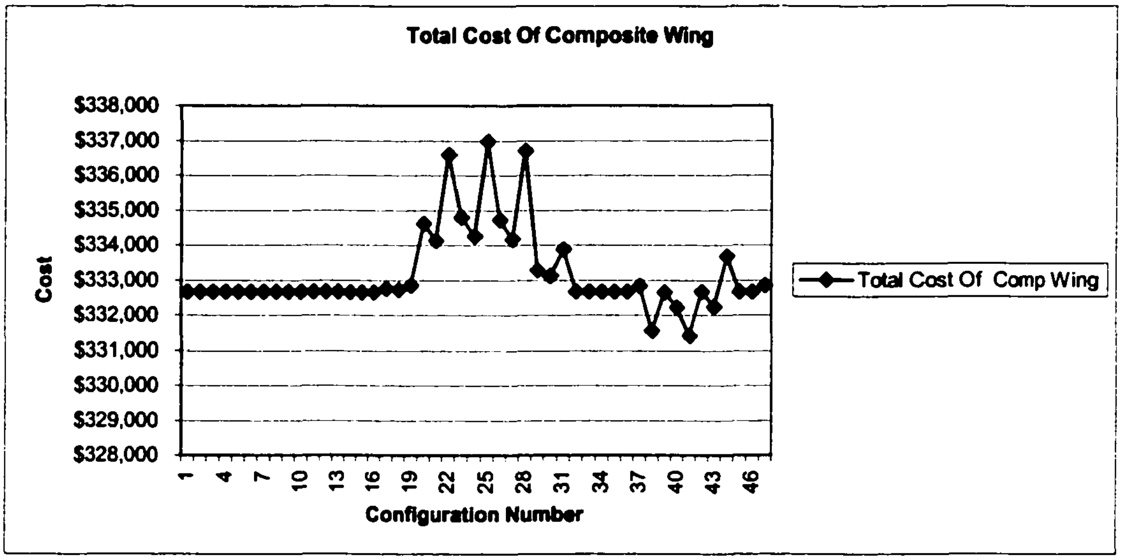
Skin Fabrication - Top	1.67	1.67	1.67	1.67	1.67
Skin Fabrication - Bottom	1.67	1.67	1.67	1.67	1.67
Rib Fabrication	10.35	10.35	10.35	10.35	10.35
Spar Fabrication - Front	5.51	5.51	5.51	5.51	5.51
Spar Fabrication - Rear	6.49	6.49	6.49	6.49	6.49
Wing Assembly - Front Spar	66.92	66.92	66.92	66.92	66.92
Wing Assembly - Rear Spar	68.65	68.65	68.65	68.65	68.65
Wing Assembly - Top Skin	58.38	58.38	58.38	58.38	58.38
Wing Assembly - Bottom Skin	59.62	59.62	59.62	59.62	59.62
Wing Assembly - Rib	95.54	95.54	95.54	95.54	95.54

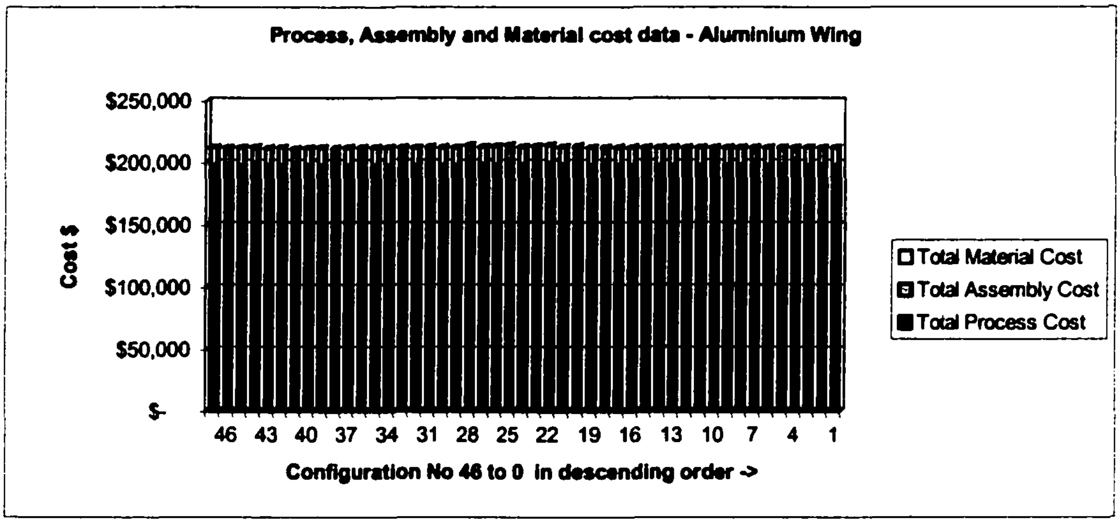
Composite Wing Manufacture --

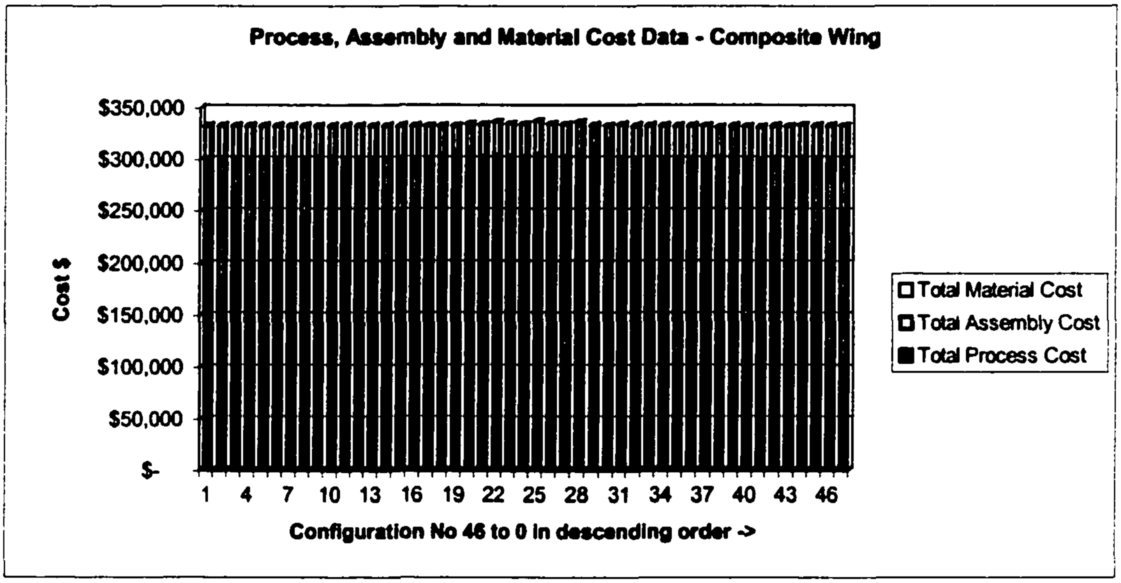
Process Cost Data					
Skin Fabrication - Top	$ 18,068	$ 18,068	$ 18,068	$ 18,068	$ 18,068
Skin Fabrication - Bottom	$ 18,068	$ 18,068	$ 18,068	$ 18,068	$ 18,068
Rib Fabrication	$ 48,698	$ 48,698	$ 48,698	$ 48,698	$ 48,698
Spar Fabrication - Front	$ 9,303	$ 9,303	$ 9,303	$ 9,303	$ 9,303
Spar Fabrication - Rear	$ 7,884	$ 7,884	$ 7,884	$ 7,884	$ 7,884
Wing Assembly - Front Spar	$ 26,317	$ 26,317	$ 26,317	$ 26,317	$ 26,317
Wing Assembly - Rear Spar	$ 25,443	$ 25,443	$ 25,443	$ 25,443	$ 25,443
Wing Assembly - Top Skin	$ 31,825	$ 31,825	$ 31,825	$ 31,825	$ 31,825
Wing Assembly - Bottom Skin	$ 30,873	$ 30,873	$ 30,873	$ 30,873	$ 30,873
Wing Assembly - Rib	$ 84,962	$ 84,962	$ 84,962	$ 84,962	$ 84,962
Total Process Cost	$ 102,020	$ 102,020	$ 102,020	$ 102,020	$ 102,020
Total Assembly Cost	$ 199,420	$ 199,420	$ 199,420	$ 199,420	$ 199,420
Total pro + Asmbly Cost	$ 301,440	$ 301,440	$ 301,440	$ 301,440	$ 301,440
Material Cost Data					
SkinTop	$ 5,576	$ 5,576	$ 5,576	$ 5,576	$ 5,576
Skin Bottom	$ 5,576	$ 5,576	$ 5,576	$ 5,576	$ 5,576
Rib	$ 13,429	$ 13,429	$ 13,429	$ 13,429	$ 13,429
Spar Front	$ 2,528	$ 2,528	$ 2,528	$ 2,528	$ 2,528
Spar Rear	$ 1,818	$ 1,818	$ 1,818	$ 1,818	$ 1,818
Rivets - Front Spar	$ 332	$ 332	$ 332	$ 332	$ 332
Rivets - Rear Spar	$ 313	$ 313	$ 313	$ 313	$ 313
Rivets - Top Skin	$ 460	$ 460	$ 460	$ 460	$ 460
Rivets - Bottom Skin	$ 437	$ 437	$ 437	$ 437	$ 437
Rivets - Rib	$ 750	$ 750	$ 750	$ 750	$ 750
Total Material Cost	$ 31,220	$ 31,220	$ 31,220	$ 31,220	$ 31,220
Total Cost Of Comp Wing	**$ 332,660**	**$ 332,660**	**$ 332,660**	**$ 332,660**	**$ 332,660**

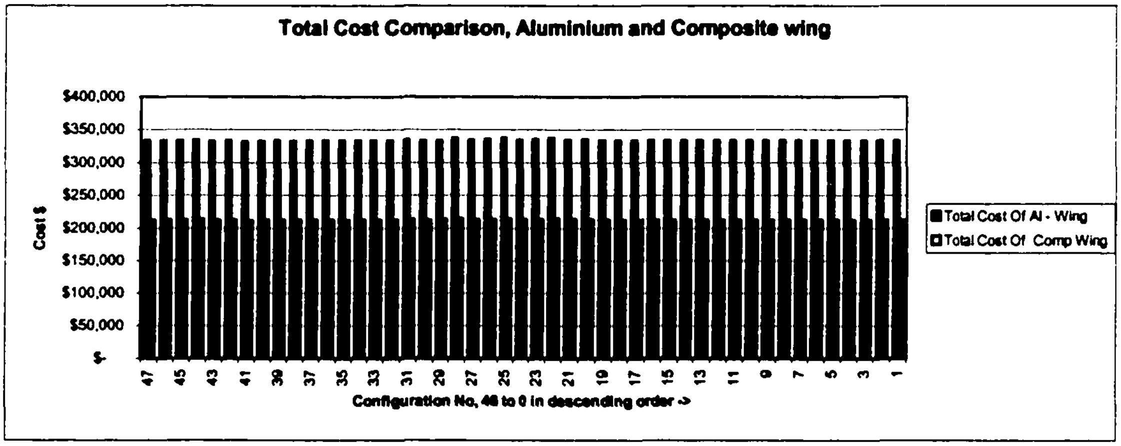
Process Cost Data - Per sq FT of relevant Area					
Skin Fabrication - Top	339.44	339.44	339.44	339.44	339.44
Skin Fabrication - Bottom	339.44	339.44	339.44	339.44	339.44
Rib Fabrication	3,725.90	3,725.90	3,725.90	3,725.90	3,725.90
Spar Fabrication - Front	1,349.26	1,349.26	1,349.26	1,349.26	1,349.26
Spar Fabrication - Rear	1,589.79	1,589.79	1,589.79	1,589.79	1,589.79
Wing Assembly - Front Spar	1,124.22	1,124.22	1,124.22	1,124.22	1,124.22
Wing Assembly - Rear Spar	1,153.27	1,153.27	1,153.27	1,153.27	1,153.27
Wing Assembly - Top Skin	980.83	980.83	980.83	980.83	980.83
Wing Assembly - Bottom Skin	1,001.59	1,001.59	1,001.59	1,001.59	1,001.59
Wing Assembly - Rib	1,605.12	1,605.12	1,605.12	1,605.12	1,605.12
Percent Change WRT config. "0"	-0.055575791	-0.055575844	-0.055575844	-0.05557585	-0.055575149
Process Cost Data - Per sq IN of relevant Area					
Skin Fabrication - Top	2.36	2.36	2.36	2.36	2.36
Skin Fabrication - Bottom	2.36	2.36	2.36	2.36	2.36
Rib Fabrication	25.87	25.87	25.87	25.87	25.87
Spar Fabrication - Front	9.37	9.37	9.37	9.37	9.37
Spar Fabrication - Rear	11.04	11.04	11.04	11.04	11.04
Wing Assembly - Front Spar	93.68	93.68	93.68	93.68	93.68
Wing Assembly - Rear Spar	96.11	96.11	96.11	96.11	96.11
Wing Assembly - Top Skin	81.74	81.74	81.74	81.74	81.74
Wing Assembly - Bottom Skin	83.47	83.47	83.47	83.47	83.47
Wing Assembly - Rib	133.76	133.76	133.76	133.76	133.76

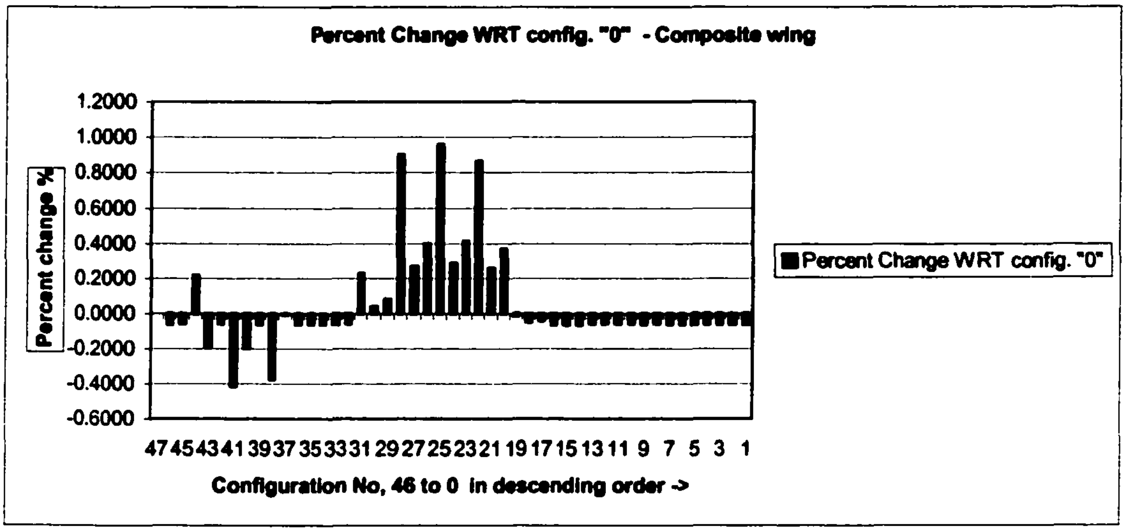

Total Cost of Aluminum Wing
Cost
$215,000
$214,500
$214,000
$213,500
$213,000
$212,500
$212,000
$211,500
$211,000
$210,500
$210,000
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46
Configuration Number
Series1

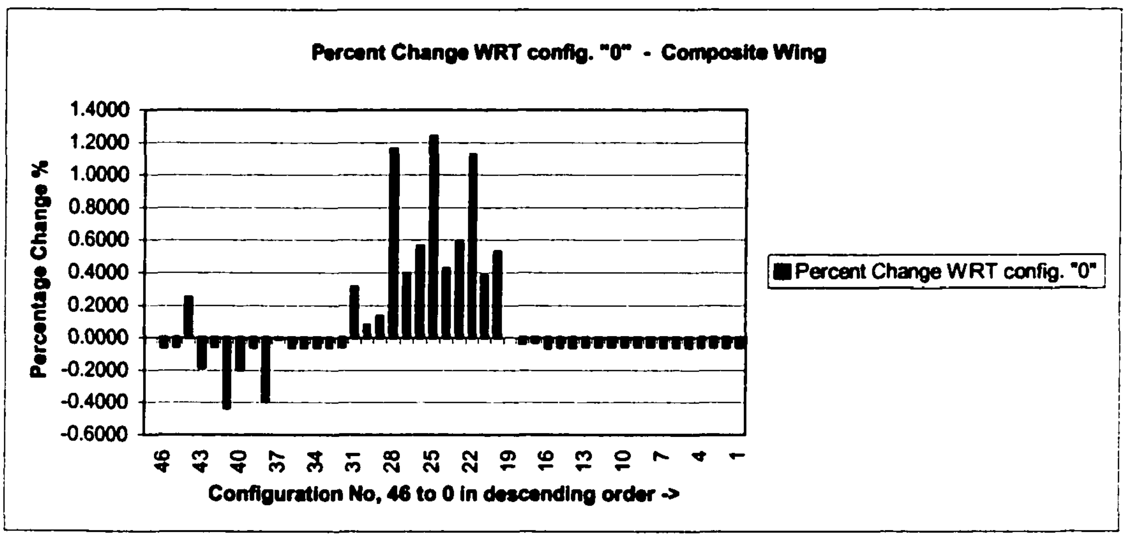

Total Cost Of Composite Wing
Cost
$338,000
$337,000
$336,000
$335,000
$334,000
$333,000
$332,000
$331,000
$330,000
$329,000
$328,000
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46
Configuration Number
Total Cost Of Comp Wing


Process, Assembly and Material cost data - Aluminium Wing
$250,000
$200,000
$150,000
$100,000
$50,000
$-
Cost $
46 43 40 37 34 31 28 25 22 19 16 13 10 7 4 1
Configuration No 46 to 0 in descending order ->
Total Material Cost
Total Assembly Cost
Total Process Cost


Process, Assembly and Material Cost Data - Composite Wing
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$-
Cost $
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46
Configuration No 46 to 0 in descending order ->
Total Material Cost
Total Assembly Cost
Total Process Cost


Total Cost Comparison, Aluminium and Composite wing
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$-
Cost $
47 45 43 41 39 37 35 33 31 29 27 25 23 21 19 17 15 13 11 9 7 5 3 1
Configuration No, 46 to 0 in descending order ->
Total Cost Of Al - Wing
Total Cost Of Comp Wing


Percent Change WRT config. "0" - Composite wing
Percent change %
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
-0.2000
-0.4000
-0.6000
47 45 43 41 39 37 35 33 31 29 27 25 23 21 19 17 15 13 11 9 7 5 3 1
Configuration No, 46 to 0 in descending order ->
Percent Change WRT config. "0"


Percent Change WRT config. "0" - Composite Wing
Percentage Change %
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
-0.2000
-0.4000
-0.6000
46 43 40 37 34 31 28 25 22 19 16 13 10 7 4 1
Configuration No, 46 to 0 in descending order ->
Percent Change WRT config. "0"

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PATENTS, LICENSES, OR COPYRIGHTS:

Ph.D. Dissertation: Generic Cost Estimation Framework for Design and Manufacturing Evaluation, Patent application in process.