2. Literature review

In this chapter, the literature pertinent to the objectives of present research is briefly reviewed. The cost issues in product life cycle design and work carried out related to the specific product life cycle phases is first reviewed. The discussion primarily looks at the cost issues in design, production and construction, operation and support and disposal phases of product life cycle. The cost estimation approaches are also reviewed along with the classification of LCC models. A detailed review of life cycle cost models developed over the years is then carried out and finally, the formulation of problem for the current research is discussed.

2.1 Cost issues in product life cycle design

The concept of life cycle cost originated in defense equipment procurement in the US department of defense (DOD) in early 1960s to increase the effectiveness of government procurement (Shields and Young, 1991). The DOD was primarily interested in improving their ability to set design-to-cost targets and for competitive source selection. Metzler (1974), Dixon and Anderson (1976), Caver (1979) and Dighton (1980) discussed some of the procedures and policies of DOD during this time. Prior to the 1970s the concept of integrating product design and economic modeling had received very little attention. Pugh (1974) was first to make the mention of providing economic information to product designers. The importance of cost modeling in design stage has also been discussed by Boothroyd and Dewhurst (1983), Ehrleinspiel (1987), Weirda (1988) and Alting (1993). Noble and Tanchoco (1990) developed a conceptual framework for concurrent design and economic justification of the system. A prototype implementation was developed to explore the usefulness of the design justification concept. Actual data from the design of an electromagnetic/radio frequency shield, a component in electrical metering equipment, was used to demonstrate the model. Early implementation of cost analysis not only influences the final design by providing relevant cost information to designers but also contributes to cost reduction by identifying cost drivers and how changes in design parameters affect cost.

A multistage integrated decision model in which decisions on product and process design are simultaneously made and supported by economic evaluation at each stage of the manufacturing process is presented in Oh and Park (1993). This paper
reclassified the total manufacturing cost into four categories namely, productivity cost, quality cost, flexibility cost and inventory cost. For each classified cost element the cost function for a unit of product for each significant process in the manufacturing operation is derived for a set of alternatives for that particular process. As a solution procedure a dynamic programming method is used to obtain the optimal design decision which minimizes total product costs. The costing concept employed is very similar to ABC. The most significant aspect of the work is the use of an optimization procedure to derive the solution to the design problem. Yang and Lin (1997) developed a cost estimate model to predict manufacturing cost in the early design stage. In this model, it was regarded that the total product manufacturing cost was the sum of the costs of machining all the form features of the product. In this case, a method was developed to automatically choose the manufacturing processes for each feature and a group of suitable machines for the processes. The machining cost for each feature was calculated by multiplying the machining time with the unit time cost of a machine selected for the operation.

The cost in production and construction phase consists of cost of manufacturing, assembly, test, facility construction, process development, production operations, quality control and initial logistic support requirements (Fabrycky and Blanchard, 1991). Most of the work done in product LCC deals with the production and construction phase of product life cycle. The most successful methodologies are the design for assembly principles developed by Boothroyd and Dewhurst (Dewhurst and Boothroyd, 1984) and the Hitachi assembly evaluation method developed by Hitachi (Miyakawa and Ohashi, 1986). These methods evaluate an assembly based on a number of DFA criteria and compute a numerical score which is intended to predict the ease of assembly and suggest ways to improve the design to reduce the cost of the assembly.

In a series of papers, Boothroyd and Dewhurst (Boothroyd and Dewhurst 1983a, b; Dewhurst and Boothroyd 1984a,b) presented models for calculating the cost of assembly of products using robots, automatic machines and manually. These have been formalized into computer programs. The programs can show whether a particular product is likely to cost less if assembled manually, automatically or by a robot. The cost in all cases is based on determining the time needed to assemble the products by the particular method and a cost rate plus the cost of the equipment used.
As part of a design for manufacture research program at the University of Rhode Island a number of computer based models for estimating the cost of fabricating parts have been developed (Dewhurst 1988). The object of these studies was to provide methods with which the designer or design team can quickly obtain information on costs before detailed design has taken place (Boothroyd 1994). Studies have been completed for machined parts (Dewhurst and Boothroyd 1988, Boothroyd and Radovanovic 1989), injection-moulded parts (Dewhurst 1988, Dewhurst and Boothroyd 1988), die-cast parts (Dewhurst and Blum 1989) and sheet-metal stampings (Zenger and Dewhurst 1988). Luong and Spedding (1995) described the development and implementation of a generic knowledge-based system for process planning and cost estimation for hole making processes. A major feature of this system is that it unifies process sequence, machinability, and cost estimation into an integrated system, which caters to the requirements of small and medium-sized companies.

Models for the estimation of the cost of fabrication have also been developed by others. Knight (1991) has developed a methodology for determining the cost for processing parts manufactured by sintering from powder metals, Dixon and Poli (1995) have developed methodologies for injection moulding, stamping and die casting and Mahmoud and Pugh (1979) developed models for turned parts. Most of these models for early cost estimating result from a detailed study of each process to identify the main cost drivers. From these studies, simplified but realistic cost estimating procedures are developed which can then be used to quantify the effects of early design decision on manufacturing cost (Knight 1991). Nicolaou et al. (2002) presented a general method for cost, quality and environmental attribute estimation for machining processes focusing on end milling and drilling. Activity based costing approach is employed to estimate costs. The quality estimation model, cost estimation model and environmental estimation models are described.

The cost model developed by Son (1991) included labor, machining, tool, setup, space-occupied, computer software and material costs. The model also separated the raw material cost and labor cost into different categories. The proposed model included insurance, utility, maintenance, repair and property costs. Ostwald (1992) estimated product cost as the summation of material cost, manufacturing cost, labor cost, and overhead expenses based on hourly usage of machinery or direct labor. Yang et. al.
(1998) proposed a manufacturing cost estimate system using an activity based costing method. In their system, feature recognition and process generation techniques were used to transfer design information into manufacturing features and generate process plans. The estimated cost was then calculated based on the activities in these processes. Wei and Egbelu (2000) used geometric design data and developed a method based on a tree representation of alternate processes to estimate the product manufacturing cost. Although the approach focused on obtaining the optimum results, it did not consider direct labor cost. Kiritsis et al. (1999) proposed a method for the cost estimation of the machining of parts based on the description of given features and associated alternative manufacturing operations. The proposed methodology was based on Petri nets to determine overall costs, including machining, moving, setup and tool-change costs.

The costs in operation and support stage of a product comprises operation of the product in the field, and sustaining maintenance and logistics support throughout the system or product life cycle. Operating and support costs are the most significant portion of the LCC and the cost of operating and supporting an item may exceed the initial purchase price of that item as much as ten times (Wilson, 1986). A product which is reliable and easily serviceable leads to maximum availability and maximum customer satisfaction. To improve customer satisfaction, companies have started to address the issue of developing products that are more maintainable at the least cost and with a minimum expenditure of support resources. The time to carry the maintenance actions is made of active and passive repair times. The components of active repair time include localization of the fault, isolation/diagnosis and actual hands on repair time (disassembly, interchange and reassembly) and verification/checkout (Smith and Babb, 1973). The diagnosis forms about 30-50% of the repair time for some systems (Ruff and Paasch, 1993). The concept of service model analysis (SMA) as an evaluation method of design for serviceability was developed by Gershenson and Ishii (1993). Its use in design evaluation is discussed in Marks et al. (1993) and Ishii (1995). SMA focuses on any form of service needs in estimating life cycle ownership cost. Computer software infers the labour operations necessary for various service operations, identifies cost drivers and indicates areas for improvement. Service modes include regular maintenance, repair of failed components of systems, or service for undesirable side effects. The current implementation utilizes a semantic network representation known as ‘linker’ for the design layout.
At the end of useful life period of products, there are various options available such as recycling, remanufacturing, reusing and disposal. The impacts caused by the product usage and disposal are difficult to assess quantitatively as they depend on factors that are difficult to predict. At present, a complete model which contains all the necessary parameters and relevant data doesn’t exist (Weule, 1993). Technical cost modeling (TCM) is presented in Automotive Engineering (1993). This is an approach to determine the best ways to recover materials from automobiles. The TCM approach has been implemented using a spreadsheet. The model tracks material flow through the various recycling stages beginning with the scrapped vehicle to determine the net cost of recycling. TCM focuses only on direct cost. However, as stated in Shields and Young (1991) the significant opportunities for cost reduction occur not with direct labour but with indirect labour. Recycling consists of using waste or waste-derived material as a raw material for products which may or may not be similar to the original product. When this process is selected for the unserviceable product, the product will be disassembled for recycling operations (Yan and Gu, 1995). Remanufacturing refers to use of certain refurbishing or restoration processes that allow unserviceable products to regain the functions and performances of products which are similar to new ones (Yan and Gu, 1995). Reusing comprises of further use of waste product in its original form, such as the refilling of a previously discarded container (Yan and Gu, 1995). Disposal refers to the elimination of the waste product without recovering any intrinsic value (Ishii et al., 1994). Since it is not possible to completely recycle a product, the aim should be to maximize the recycled resources while minimizing the effort that has to be invested (Kriwet et al., 1995).

Disassembly is a key factor in the analysis for product retirement (Ishii et al., 1994). The role of product disassembly on product retirement and service for that matter is discussed in detail in Jovane et al., (1993), and Scheuring et al., (1994). Das et al. (2000) developed a model to estimate the cost required for the end of life product disassembly. The aim of this model is to support and facilitate the economic analysis of the disassembly activity. In this model, it did not use the traditional costing method for cost calculation. Instead, it used a multifactor model to compute the disassembly effort index score, which is representative of the total operating cost to disassemble a product through a general conversion formula. The model consists of the following seven factors: time, tools, fixture, instruction, hazard, and force requirement.
2.2 Cost estimating approaches

Depending on the stage of analysis and level of details required, a LCC model may be a simple series of cost estimation relationships (CERs) or a set of computer subroutines. LCC analysis during the conceptual or preliminary design phases may require the use of basic accounting techniques and model may be rather simple in construction. On the other hand, life cycle cost analysis done during the detail design stage may be more elaborate. Just as design process produces lower level functional requirements through functional decomposition to enable design solutions to be easily developed, it is imperative to perform cost decomposition in LCC analysis. Such decomposition is known as a cost breakdown structure. This is based on the principle that many functions can be quantified and the costs associated with a function are often simply related to the quantity or quality. Cost estimating approaches used in industry can be broadly classified as parametric models, analogous models (estimating by analogy) and detailed models (Asiedu and Gu, 1998). These cost estimating approaches are discussed in the following sections.

2.2.1 Parametric cost estimation

Parametric models are derived by applying the statistical methodologies and by expressing cost as a function of its constituent variables. These techniques could be effective in those situations where the parameters, sometimes known as cost drivers, could be easily identified. Parametric models are generally used to quantify the unit cost of a given product. Parametric models involve generation and application of equations that describe relationships between cost schedules and measurable attributes of a system that must be brought forth, sustained and retired (Dean, 1995). Cost estimation with a parametric model is based on predicting a product’s cost either in total or for various activities such as design or manufacture, by the use of regression analysis based on historical cost and technical information. The statistical methods correlate costs and technical information with parameters describing the system and results in a set of formulae, called CERs. The parameters typically include manufacturing complexity, design familiarity, weight and performance. Most of the cost estimating relationships for airborne military systems relate the cost to the parameters such as weight, cruise speed, etc. of the system. Parametric estimating can involve considerable effort because of the systematic collection and revision process required to keep the CERs updated, but once this data is available estimates can be produced fairly rapidly (Greves and Schreiber, 1993). There are several commercial models available now. The most widely used is the
Lockheed Martin’s PRICE system. Establishments such as British Aerospace Corporation (Daschbach and Apgar, 1988), the European Space Agency (Greves and Schreiber, 1993) and NASA (Dean, 1989) use PRICE system. An illustration of its use is given in Burmeister (1980).

Cavalieri et al. (2004) developed a parametric model for the estimation of unit manufacturing cost of a new type of brake disk using the weight of the raw disk, unit cost of raw material, and the number of cores as parameters in their model. A wide range of parametric models can be found in the literature. For example, Hajare (1998) modeled parametric costing of components using the product specifications. Roberts and Hermosillo (2000) used approximate tool paths and process parameters from available factory resources to estimate time and cost for small surface units. Boothroyd and Reynolds (1989) adopted a parametric costing approach using the volume of typical turned parts as a parameter to estimate the cost in the early design stages. Unlike the detailed-breakdown approach, the method adopted by them could be used in the early design stage without the need of a process plan. The drawback of parametric estimating is that it is not very good for estimating the cost of products that utilize new technologies. Parametric estimation is often referred to as a ‘top-down’ estimating technique.

2.2.2 Cost estimation by analogy

These techniques employ similarity criteria based on historical cost data for products with known cost, such as regression analysis models or back propagation methods. Regression analysis models make use of the historical cost data to establish a linear relationship between the product costs for the past design cases and the values of certain selected variables so that the relationship can be used to forecast the cost of a new product. Cost estimating made by analogy identifies a similar product or component and adjusts for differences between it and the target product (Shields and Young, 1991). The effectiveness of this method depends heavily on an ability to identify correctly the differences between the case on hand and those deemed to be comparable (Greves and Schreiber, 1993). The regression analysis approach based on the similarity principle was adopted by Hundal (1993) and Poli et al. (1988). They used a basic cost value and considered the effects of variable cost factors by assuming linear relationships between the final product cost and the cost factors. Lewis (2000) further used existing designs to provide cost estimates for similar new designs, whereas Pahl and Beitz (1996) provided more general costing approaches based on similarity. Back-Propagation Neural-Network
(BPNN) models use a neural network that can be trained to store knowledge to infer the answers to questions that even may not have been seen by them before. This means that such models are particularly useful in uncertain conditions and are adaptable to deal with nonlinearity issues as well. McKim (1993) discussed the application of neural network in cost engineering. Shtub and Zimerman (1993) compared the cost results obtained with the regression model and the BPNN model and observed the superiority of the latter in many ways. The main disadvantage of estimating by analogy is the high degree of judgment required. Expert judgment and complete familiarity with the products and processes are required to identify and deal with similarities and make adjustments for perceived differences. This approach tends to be very good for new products.

2.2.3 Detailed cost estimation

This approach requires decomposing a product into elementary units, operations and activities that represent different resources consumed during the production cycle and expressing the cost as a summation of all these components. Detailed models use estimates of labor times and rates and also material quantities and prices to estimate the direct costs of a product or activity (Shields and Young, 1991). An allocation rate is then used to allow for indirect/overhead costs. This is known as bottom-up estimating and is widely used by organizations to build up estimates from task or work-package level (Greves and Schreiber, 1993). It is the most time consuming and costly approach and requires a very detailed knowledge of the product and processes. However, the most accurate cost estimates can be made using this approach. The method involves estimation of the time needed to perform an activity and the hourly rates for the man and machine, and then multiply times and rates to get costs. Time standards can be industry standards, in-house standards or based on expert guesses. In-house standards are the best but most difficult to develop. Industrial time standards for production operations exist for many common tasks. This approach is flexible. The information used is basic information and can therefore be used on numerous occasions. The other estimating techniques demand one or more existing products that resemble the new product in some way. The main difficulties of this method include (Weirda, 1988):

- Determining or collecting the basic standard times
- Determining the hourly rates and keeping them up-to-date
- Management of large amount of information
- A large number of simple but tedious calculations
- The skill and experience required to use the basic information properly
2.2.4 Activity based cost estimation

Activity based costing (ABC) has emerged as one of the several innovative and more accurate costing methods in recent years. It is based on the principle that products or services consume activities and activities consume resources that generate costs. Thus, the ABC system focuses on calculating the costs incurred on performing the activities to manufacture a product. Greenwood and Reeve (1992) presented a comprehensive activity based framework for supporting operational decision making which allows managers to predict activity and process costs under alternative product design and production. The architecture described supports process analysis, product costing and simulation. The framework presented in not easy to understand and as the authors noted at the end of the article, the framework offered in this article is not simple. Indeed, this framework is likely unworkable except in advanced manufacturing environment. Though the authors indicated that it is intended to be used for predictive purposes, it does not deal with uncertainties. However uncertainty is always associated with predictions and it is a predominant factor in design.

An object-oriented approach to activity based cost estimation which is capable of supporting the engineer in the early phases of design was presented in Fischer et al. (1994). This method combines a product model and a resource model. In the first step of the design process the engineer fixes the main attributes of the new product. The system checks all products in the knowledge database for objects like form-features and components with similar attributes. These objects are matched to those used for the new product to predict activities and the resulting production costs. Through the combined consideration of the product characteristics, the target costs and the available resources, a product structure with optimum production processes is deduced (Fisher et al. 1994). Emblemsvag and Bras (1994) illustrated how an ABC based deterministic cost model can be used in the decision making process to obtain an overall cost efficient design. They considered the recycling of the product at the end of its useful life. The recycling phase is broken down into a hierarchy of activities. Then for a particular design, a determination is made of the activities that it will require and the cost calculated. Though this model is supposed to help designers make decisions, the models as presented in this paper can only be used to make decisions at the product level.

Bras and Emblemsvag (1995) extended their work in Emblemsvag and Bras (1994) further to include uncertainties. The crux in developing an ABC model is to identify the activities that will be present in the life cycle of a product and assign reliable
cost drivers and associated consumption intensities to the activities. Uncertainty distributions are assigned to the numbers used in the calculations, representing the inherent uncertainty in the model. The effects of the uncertainty on the cost model behavior are found by employing a numerical simulation technique, the Monte Carlo simulation technique. The additional use of detailed process action charts and sensitivity charts allows the influence of the uncertainty to be traced through the cost model to specific product and process parameters. Ong (1995) presented the development of an activity based cost estimating system to help designers in estimating the manufacturing cost of a printed circuit board assembly at the early concept stage of design. Activities are identified, quantified and the costs are allocated based on the quantum of activities used by the printed circuit board (PCB). A spreadsheet PCB tool is used for the calculation of the manufacturing cost based on the input data, cost build-up table and activity charts. The data required as input includes the batch size, life value, number of boards per panel, length dimension of the panel and unskilled and skilled workers rates. Though the author claims the model is meant to be used at the conceptual phase of design, the data needed for the evaluation will not be generally available till the preliminary design stage.

Cagwin and Bouwman (2002) investigated the improvement in financial performance that is associated with the use of activity based costing, and the conditions under which such improvement is achieved. Results showed that there exists a positive association between ABC and improvement in financial performance when ABC is used concurrently with other strategic initiatives such as in complex and diverse firms, in environments where costs are relatively important, and when there is limited number of intra-company transactions. Kee (2003) modified ABC to reflect separate flexible and committed cost driver rates for an activity. This enables the model to reflect the difference in the behavior of an activity’s flexible and committed costs needed for operational planning decisions. The modified ABC determined the resources required to produce the product mix developed from the firm’s strategic plan and the excess capacity that will result. The modifications made to ABC aided in determining an optimal product mix when the firm has excess capacity, while the traditional ABC may not. Gosselin (2006) reviewed the evolution of ABC from its emergence around 1985 to its most recent development, in addition to the consequences of ABC on the evolution of management accounting. A more detailed review of literature on activity based costing is also provided in chapter 8.
2.3 Classification of LCC models

Sherif and Kolarik (1981) classify LCC models into three general forms such as conceptual, analytical and heuristic models. Conceptual models consist of a set of hypothetical relationships expressed in a qualitative framework. Conceptual models are generally constructed at macro level. Analytic models consist of a set of mathematical relationships, which are used to describe a certain aspect of the system. Such models range from models covering very specific aspects of a system to models, which address total system life cycle cost. Heuristic models are not as general as analytical models and can normally only be used for the specific situation for which they are intended.

Gupta (1983) identifies three types of analytical models namely design trade-off models, total cost models and logistic support models. Design trade-off models relate to the design phase of the life cycle cost and attempt to minimize cost to meet a given value of design parameters such as reliability and availability to maximize the value of design parameters for given cost constraints. Total cost models are termed true life cycle cost models and usually encompass the total life of the system. They attempt to minimize the total life cycle cost of the system while maximizing its performance and effectiveness by evaluating various parameters such as reliability, maintainability, availability etc, which affect life cycle cost. Logistic support models are concerned with the operations phase of the life cycle. Usually the objective of such models is to determine costs for alternative support plans and effect on the system’s effectiveness. They reflect operations cost parameters as variable costs and research, development, test and evaluation and acquisitions costs as fixed costs. These models are inconsistent in that design parameters such as reliability and maintainability heavily influence operations costs and therefore fall short of determining optimal life cycle cost.

Dhillon (1989) simply classifies life cycle cost models as general life cycle cost models, and specific life cycle cost models. General life cycle cost models are not related to any specific equipment or system whereas specific life cycle cost models have been developed for particular types of equipment or system. Given the specific interrelationships and interactions of a particular system, the application of general models is clearly limited. Daniel (1991) has classified life cycle cost models into two broad categories mainly accounting models which attempt to assemble and distribute costs, determined elsewhere so as to describe the total cost of a system and predictive models which are used to forecast the values of the various cost elements required as input to the accounting models.
2.4 Review of life cycle cost models

In general, product life cycle cost is estimated by using one or a combination of the following two methods (Shields and Young, 1991):

- **Analogy**: A product cost estimate is made by comparing with the cost of a similar product or a similar component that was made in the past.
- **Cost accounting models**: They estimate the labor times and rates, material quantities and prices to calculate the direct costs of a product. An allocation rate is used to allow for indirect costs.

LCC model can be a simple series of cost estimation relationships (CERs). LCC analysis during the conceptual or preliminary design phases may require the use of basic accounting techniques (Fabrycky and Blanchard, 1991). The most important task in LCC modeling is the construction of cost breakdown structure (CBS), which shows various cost categories that combine to provide the total cost. Cost breakdown structure should exhibit the following basic characteristics:

- All system cost elements must be considered.
- Cost categories are generally identified with a significant level of activity or some major item of hardware.
- The cost structure and categories should be coded in such a manner as to allow for the analysis of certain specific areas of interest (e.g., system operation, energy consumption, equipment design, spares, maintenance personnel and support, maintenance equipment and facilities). In some instances, the analyst may wish to pursue a designated area in depth while covering other areas with gross top-level estimates. This will certainly occur from time to time as a system evolves through the different phases of its life cycle.
- When related to a specific program, the cost structure should be compatible (through cross indexing, coding etc.) with the contract work breakdown structure and with management accounting procedures used in collecting costs.
- For program, where subcontracting is prevalent, it is often desirable and necessary to separate supplier costs (i.e., initial bid price and follow-on program costs) from other costs. The cost structure should allow for the identification of specific work packages that require close monitoring and control.

There are few LCC models that are popular among practitioners that can be used for estimation of life cycle cost of airborne military equipment. Taylor (1981) proposed a
LCC model focused on the capital and revenue costs. Taylor claims that in any discussion of trade-offs between initial and subsequent costs, a point that is frequently made is that there is a major distinction between initial capital costs and revenue costs. It is claimed that companies and public bodies faced with limited capital budget or cost limits do not have the facility to increase initial capital costs on the chance that there will be future revenue gains. However, Taylor claims that the distinction between revenue expenditure and capital is an accounting one which doesn’t affect the life cycle cost concept based on the cash flows throughout the life of the asset. Taylor’s costs of owning physical asset fall into three groups, first the initial capital costs secondly the revenue costs of operating and maintaining the asset during its operational life and thirdly the cost of asset disposal, which may be revenue of capital if it is substantial. The initial costs for an organization which designs and constructs physical assets for its own use or for resale would be research and development, design and specification, manufacturing, quality control and testing and monitoring performance. The second group of costs is incurred during the operational life of the asset and this would include the costs of operating the assets including the labor, materials, tools, fixtures and overheads, maintenance including spares and labor. Finally, there are disposal costs which include costs of demolition and removal, dislocation of existing production capacity and may be any disposal value of the physical asset.

Stump (1988) developed a LCC model based on Markov chains and illustrated the model for a hypothetical remotely piloted vehicle (RPV). The Markov chain is used to estimate the operation, maintenance and support costs. The model assumes that the system goes through a number of states. For any state, the number of visits per cycle multiplied by the cost per visit and the expected life of the RPV in cycles will yield a life cost for that state. Summing over all states will yield a total life cost. Dhillon (1989) discussed twenty-three different types of life cycle cost models. Some of these are general and others are specific life cycle cost models. The models presented under general category are not very general as they consider either major cost elements or are based on some assumptions. This book also covers various cost estimation techniques and estimation of manufacturing, quality and maintenance costs. The methodology presented in Johnson (1990) consists of an LCC model composed of elements to calculate RDT&E (Research, development, testing and evaluation) cost, production cost, DOC (Direct operation cost), IOC (Indirect operating cost) and an existing conceptual design and analysis code, the flight optimization systems (FLOPS). This paper did not
discuss the development of any particular cost model but rather discusses the use of models already being used by other firms for life cycle cost analysis in aircraft design.

Riggs and Jones (1990) presented a new technique for performing life cycle cost analysis. The technique is based on graph theoretic representation of interrelationships among the variables and functions making up a given methodology; learning, cost parameters, cost factors and quantities. Roskam (1990) divided the LCC into four major categories such as research and development, test and evaluation, program acquisition cost that includes manufacturing cost and manufacturer’s profit, operating cost, and disposal cost. R&D cost is further broken into cost elements such as airframe engineering and design, test flight aircraft and flight test operations, test & simulation facilities and cost to finance. Each of these cost elements is estimated using parametric methods using aircraft weight, maximum design speed and number of aircrafts built. Similarly, acquisition cost is calculated using parameters such as the number of aircrafts manufactured, manufacturing cost, take-off weight, design cruise speed etc. Operation costs are broken into the material costs, direct and in-direct personnel cost and logistic support costs. The disposal cost is taken as 1% of the life cycle cost.

Fabrycky and Blanchard (1991) developed the detailed LCC model. The most important task in their model is to develop the cost breakdown structure. There is no method set for breaking down the costs as long as the method used can be tailored to the specific application. Primarily the cost is divided into the following four categories such as research and development, production and construction costs, operation and maintenance costs, retirement and disposal costs. Research and development cost includes all costs associated with conceptual feasibility studies, basic and advanced research and development, engineering design, fabrication and testing of engineering prototype models (hardware) and associated documentation. It also covers all related program management functions. Operations and maintenance cost includes all costs associated with the operation and maintenance support of the system throughout the life cycle subsequent to the equipment delivery in the field. Specific categories cover the cost of system operation, maintenance, logistic support and equipment modifications.

Raymer (1992) developed a life cycle costing model based on the development and procurement costs of aircraft (DAPCA IV model) developed by the Rand Corporation. The Rand Corporation developed several cost estimation relationships for estimating various costs for all departments including engineering, tooling, manufacturing and quality control groups. DAPCA assumes a ten-year product life,
which also is an industry standard. Rand Corporation claims that DAPCA, coupled with appropriate factors is accurate to within +/- 5% of actual costs. Burns (1994) developed a cost estimation relationship for predicting life cycle cost of aircraft based on its weight. Burns model is a simple extension of Roskam’s life cycle cost model. The model also includes judgment factor for computing airframe-engineering hours for development and production. Warren and Weitz (1994) developed a life cycle cost assessment technique that considers the various cost components of LCC such as material, manufacturing, packaging, maintenance and repairs, disposal and environmental costs. Bodsberg and Hokstad (1995) presented an analytical method of estimating reliability and life cycle cost of process safety system. Ishii (1995) surveyed the life cycle design methodologies and identified key research issues in developing an integrated life cycle design tool. The paper further elaborates on estimating life cycle service cost and total retirement cost associated with a product.

Woodward (1997) presented a case on total cost of ownership on South Yorkshire Passenger Transport (SYPT). SYPT’s main activity is the provision of passenger transport services by road. The company purchases vehicles that form a major part of the capital expenditure on a regular basis and the decision to purchase them is based on the LCC technique. The estimated life cycle costs are discounted at an assumed monetary cost of capital of 15%, after including a standard inflation rate assumed over the life of the asset. If the two alternatives have similar discounted costs, then a choice will be made by the financial director taking into account non-financial factors such as the credibility, reliability etc. of the suppliers. Although, the case was on passenger transport by road, the concept is valid for any system, including airborne defense equipment. Karlsson et al. (1997) provided life cycle cost estimates of 400 kV substation layouts. The paper presents the reliability and life cycle cost analysis of two different schemes; a single bus bar in two sections and a double circuit breaker system with double bus bar. The presented LCC model considers investment, operation, maintenance and outage costs.

Asiedu and Gu (1998) presented a state of the art review of product life cycle cost analysis models until 1997. The cost estimation models are divided into three types namely analogous, parametric and detailed. It is concluded that the reviewed models are restricted to simple operations or one phase of life cycle, often the design and manufacturing stage. This explains the necessity to develop models that include more parts of the product life cycle. Foster and Hanley (1998) presented life cycle cost
analysis of photovoltaic water pumping systems. Degraeve and Roodhooft (1999) developed a mathematical programming model that uses total cost of ownership information to select suppliers and determine order quantities over a multi-period time horizon. The total cost of ownership quantifies all costs associated with purchasing process and is based on the activities and cost drivers determined by an activity based costing system. They have also discussed a case on the purchasing problem of heating electrodes at Cockerill Sambre, a Belgian multinational steel producer. In this case, quality issues accounted for more than 70% of the total cost of ownership making the quality of the supplier a critical success factor in the supplier selection process.

Baaren and Smit (1999) presented the results of SMARD (Safety, Maintainability, Availability and Reliability in Design) model development phase. The proposed model incorporates reliability, availability, maintainability, supportability and LCC aspects in the design and development process of large scale complex technical systems. Widiyanto et al. (2002) discussed on selecting a power system using life cycle assessment (LCA) and life cycle cost. The paper describes a LCC model to estimate the cost and performance of coal fired power plant with and without pollution control. Ebling (2002) discussed three different LCC models. These models tried to capture the effects of MTBF and MTTR on product LCC. Holden (2003) addressed the key issues in rolling stock asset management at lowest life cycle cost in view of the success of all railway operations. The use of a detailed LCC model is advocated as a decision tool. The LCC model presented has nine different cost elements. Davis et al. (2003) presented a framework for documenting and analyzing life cycle costs using a simple network based representation. The LCC-NET model seeks to document casual factors that lead to costs, identifies the effect of each technology factor and analyses the total cost implications in introducing a technology factor.

Sandberg et al. (2005) presented a model for life cycle cost prediction in the conceptual development of the hardware part of functional (total care) products. The discussed design support model can be used to assess life cycle cost and create a view of how decisions between a number of design, performance, and manufacturing and maintenance activities affect each other in conceptual design. Hwang (2005) developed a static model to find an initial system configuration to meet the required performance based on reliability, availability, maintainability (RAM) and life cycle cost. They also developed a time and failure truncated model for system RAM test. The costing model is applied to a production facility wherein the acquisition, support and maintenance costs
are taken into account. Lapasinskaite and Boguslauskas (2005) discussed maintenance cost allocation in product life cycle within the context of LCC. The four different ways of performing LCC have been presented. These include analogy models, parametric models, engineering cost models and cost accounting models. The paper further illustrates use of regression analysis to estimate maintenance costs.

Xu et al. (2006) proposed a framework of product life cycle costing system that helps a product designer to obtain the life cycle cost of a product at early product development stage. The framework consists of three subsystems: design aid subsystem, product LCC estimate and optimization subsystem and product life cycle cost information reference subsystem. It is a dynamic system in which the cost information is modeled and upgraded as the product development process progresses. The framework makes use of case based reasoning method to build a new product model; the activity based costing method to calculate product life cycle costs and dynamic programming to optimize the overall product life cycle cost. The paper also comments on the limitations of the cost models developed so far such as, the costing models only focus on estimating product costs for a particular stage of product life cycle, e.g. manufacturing cost. They cannot be applied to other stages of product life cycle to calculate entire product life cycle cost. Niazi et al. (2006) presented a detailed review of the state of the art product cost estimation (PCE) covering various techniques and methodologies developed over the years. The paper categorizes the PCE techniques as qualitative and quantitative. The qualitative PCE techniques are based on comparison of new product with the products that have been manufactured previously to identify the similarities in new one. Quantitative PCE techniques rely on detailed analysis of a product design, its features and corresponding manufacturing processes.

Enparantz et al. (2006) discussed a life cycle cost calculation and management system for machine tools to provide life cycle cost data prediction at offer phase and to support the design phase decisions by managing real machine tool behavior data. The LCC model takes care of acquisition cost, operation cost, maintenance cost and turnover/scrap cost. Carpentieri and Papariello (2006) presented a LCC calculation model for automotive production line. The model is composed of different operative environments such as cost analysis, LCC calculation and NPV calculation. The model has two supporting databases for maintenance analysis namely, preventive maintenance database and corrective maintenance database. Nilsson and Bertling (2007) carried out life cycle cost analysis of wind power systems using condition monitoring systems.
(CMS) to gain an understanding of whether a CMS is profitable for the separate wind turbine onshore and the wind farm offshore. The LCC model used comprises of acquisition, downtime, support and maintenance and disposal costs. Hwang et al. (2007) presented a performance model for manufacturing facility design considering systems configuration, RAM design and the system life cycle cost. A four step approach is used considering the system performance factors such as system configuration, system reliability, availability and maintainability (RAM), life cycle cost and system optimization. The life cycle cost model presented takes into account acquisition cost, maintenance cost, breakdown repair cost and logistic support cost.

Wang et al. (2007) discussed a decision support model that enables better decision making in product family configuration and part changes based on LCC rather than part procurement costs. The developed LCC model considers the dynamic cost due to design and customer change. Major cost elements at the design, procurement and production inventory and product service inventory stage of a product life cycle are considered. The paper also briefly comments on a life cycle cost model presented by Fabrycky and Blanchard and Woodward’s life cycle cost analysis (LCCA) model. Castagne et al. (2008) developed a model on hierarchical basis to analyze the manufacturing cost of aircraft fuselage panels. The manufacturing cost modeling relies on the genetic-causal method where the drivers of each element of cost are identified relative to the process capability. The cost model is then extended to life cycle costing by computing the direct operating cost as a function of acquisition cost and fuel burn. This model considers the material, manufacturing, assembly, operation and maintenance and repair cost only.

Kleyner and Sandborn (2008) proposed a methodology that incorporates several dependability-related activities into a comprehensive probabilistic cost model that enables minimization of the product's life cycle cost. They provided a quantitative solution that minimizes the life cycle cost of a product by developing an optimal product validation plan. The model utilizes the inverse relationship between the cost of product validation activities and the expected cost of repair and warranty returns. The developed model is demonstrated on an automotive electronics application that considers design, validation, manufacturing, warranty and overhead costs.
2.5 Formulation of the problem

In general, the life cycle cost of products is estimated using a variety of life cycle cost models. A LCC model basically identifies the various cost components associated with the life cycle of a product and represents them in the form of an equation. There are different approaches to developing cost models for LCC analysis (Asiedu and Gu, 1998). Most LCC models are structured along three general lines such as conceptual, analytical and heuristic. Conceptual models consist of a set of hypothesized relationships expressed in a qualitative framework. They are generally very flexible and can accommodate a wide range of systems. These models are generally constructed at macro level. They allow a minimum of details and little ability to quantify cost characteristics of a system. Analytical models are usually based on mathematical relationships which are designed to describe a certain aspect of a system/product under certain conditions/assumptions. Heuristic models are not as general as analytical models and can normally only be used for the specific situation for which they are intended. Thus, the LCC modeling approaches can be classified into specific life cycle cost models and non-specific life cycle cost models. The specific life cycle cost models are developed for a particular product or system. The non-specific models are not tied to any specific product or system.

By now, a number of cost estimate models for various kinds of products have been developed. A review of number of such models (M1, M2, M3,...., and M30) developed over the years with regard to the life cycle phases and the life cycle cost components identified by these models is shown in Table 2.1. A close study of such models with regard to the life cycle phases and the life cycle cost components identified by these models reveals that the LCC modeling practices have certain limitations. Most of the models are product specific, consider only major cost elements and are based on certain assumptions such as there is no preventive maintenance, no failures occur in standby and perfect switching occurs with negligible down-time, the annual operating requirements are constant and all the units are identical and acquired at the same time. The costing models only focus on estimating product costs for a particular stage of a product life cycle, e.g., manufacturing cost. They cannot be applied to other stages of product life cycle to calculate the entire product life cycle cost (Xu et al., 2006). The LCC modeling practices are more often concentrated on limited phases of the product’s life cycle. A bulk of work is centered on and around the product manufacturing phase and thus lacks the broader life cycle perspective.
| Product Life Cycle Components | Concept and definition | Research and development | Design and development | Product validation | Intellectual property cost | Raw material acquisition | Inspection and storage | Manufacturing | Recurring functional testing | Cost of diagnosis and rework | Assembly | Quality control | Qualification and certification | Profit charged | Product modification | Packaging and warehousing | Transportation and distribution | Installation and commissioning | Acquisition / Capital/Investment | Training and documentation | Operation | Warranty | Downtime/Production loss | Support | Maintenance and repairs | Disposal | Environmental |
|------------------------------|------------------------|--------------------------|------------------------|-------------------|------------------------|---------------------------|------------------------|----------------|-----------------------------|-----------------------------|---------|----------------|----------------------------|----------------|--------------------------|-----------------------------|-----------------------------|-----------------------------|----------------|---------|----------------|---------|----------------------|---------|----------------|
| M1 (Stordahl and Short, 1968)| ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M2 (US DOD, 1976)           | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M3 (Blanchard, 1978)        | ✓                      | ✓                        |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M4 (Monteith and Shaw, 1979) | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M5 (Bhuyan, 1982)           |                        |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M6 (Ganapathy, 1983)        | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M7 (Dhillon, 1989)          | ✓                      | ✓                        |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M8 (Dhillon, 1989)          | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M9 (Snyder, 1990)           | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M10 (Cardullo, 1993)        | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M11 (Curry, 1993)           | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M12 (Warren and Weitz, 1994)| ✓                      | ✓                        |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M13 (Ahmed, 1995)           | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M14 (UNIFE, 1997)           | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M15 (Karlsson et al., 1997) | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M16 (Karyagina et al., 1998)| ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M17 (Hyd. Institute, 2001)  | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M18 (Kopscick, 2003)        | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
| M19 (Davis et al., 2003)    | ✓                      |                          |                        |                   |                        |                           |                        |                |                             |                             |         |               |                             |                |                          |                             |                             |                             |                         |       |           |                |        |                     |         |               |
Thus, it is apparent that there is a need to develop a model and a framework that will consider all aspects of the product life cycle. Therefore, a comprehensive life cycle cost model (M31) based on the broader life cycle perspective is proposed. The model is comprehensive in that it considers almost all aspects of product’s life cycle. As the literature reveals and as stated above, it has been recognized that the design process needs cost models that take into account the complete life cycle of products, can be used at very early stages of design and can provide information to designers in timely manner and in a form that can be used. Some efforts have been made towards providing the designer with cost information during the design process. While most of these authors recognize the need for a LCC model, the models developed are however restricted to specific processes, simple operations or one phase of the life cycle. A large number of these efforts have been for the production and construction phase of the product life cycle. On the other hand, the models that treat the product at the system level seldom treat the end-of-life of the product and more importantly, such models are more useful for procedural purposes than for design. Thus, there is a need for a comprehensive LCC model which is attempted in the current work.