Advanced Cost Models for Application in Composite Aero-Engine Components

Nikhil Thakur

PhD

2018

BIRMINGHAM CITY University

Advanced Cost Models for Application in Composite Aero-Engine Components

Nikhil Thakur

A thesis submitted to Birmingham City University for the degree of

Doctor of Philosophy

2018

In loving memory of my 'father'

Shri. Kashmir Singh Thakur

Those we love never leave, but are always near, helping us with their hidden presence, loved and missed even more and the care always felt.

Abstract

Composites have been used all over the world when it comes to developing advanced light weight and highly efficient components. Companies like Boeing and Airbus have successfully used more than 50% composites by weight in their aircraft's structural and non-structural parts, which has been found to increase efficiency, cut down weight by 30% and absorbed vibrations. This triggered a need to develop new and advanced engines that are both light in weight and efficient and can support these aircrafts. Hence, to cope with this new engineering requirement, companies like Rolls-Royce and General Electric are developing advanced engines using composite materials. The use of composites in aero-engines has brought forth certain challenges. One of the main challenge is to predict cost of the composite part very early in the decision making phase so as to improve design efficiency.

The current methods/techniques of Cost Estimation (CE) have been designed taking a product or a manufacturing process as the basis and hence, show drawbacks, which include, (i) lack of knowledge regarding composite technology, (ii) platform dependent architecture, (iii) complex in its structure and implementation, (iv) knowledge less flexible and (v) not easy to maintain. Most of the drawbacks that the current methods/techniques have may be overcome by using Knowledge-based Engineering (KBE) techniques, whose benefits can be directly applied to the composite CE problem. However, to increase the flexibility and applicability of KBE along with an easy to use system, a more logical method is needed. It has also been seen and understood that the percentage cost share of carbon footprint in the overall cost of a product is of the order of $\leq$ 20%. Thus, the inclusion of carbon footprint knowledge in terms of cost in the overall product life-cycle is very important and will increase the current capability of CE.

This work is the presentation of application of a mathematical set theory-based logical knowledge management system, which utilises the KBE's principles for knowledge creation and integrates the same to the mixed CE approach. The basis for the knowledge creation is a novel way of using generic composite life-cycle which includes carbon footprint knowledge in terms of its cost impact from all the phases of the life-cycle. This way, a more logical and manageable system is created which can handle composite material based complexity and generate an advanced capability in cost estimation of an aero-engine component. The research is conducted in a systematic step-by step fashion in 3 parts. The first part covers literature review in the fields of composite technology knowledge, KBE, CE and carbon footprint. The second part covers the formulation of a logical set theory-based cost estimation methodology along with development of an advanced CE tool. The final part covers validation of the methodology and the tool on four aero-engine based component case studies along with an industry expert validation.

From this research, the results revealed that the methodology developed is, (i) very good at handling complex information, (ii) reliable in estimating cost, (iii) platform independent, (iv) logical in knowledge management for composites and (v) easy to maintain and model. Further, the cost estimates generated are under a variance of less than 15%, which is an industry allowed limit. It has been seen that the developed advanced system increases the current cost capability and can also predict carbon footprint as a cost impact, which is a further advancement in the current system. Overall, it can be said that utilising the developed method, an advanced system can be created which is capable of, generating reliable cost estimates for composite aero-engine components, adds to the existing knowledge base and increases the existing capability in cost, proving to be more efficient and effective.

Acknowledgement

My very first thanks is to god who has always been a support system and merciful towards me in all the difficult times in my life.

I would like to express my sincere gratitude towards my main supervisors, **Prof Michal Krzyzanowski, Prof Ilias Orifige** at Birmingham City University, **Dr Pathmeswaran Raju** at Cranfield University and **Prof Craig B. Chapman** for encouraging, supporting, guiding and advising me in all respects to help me achieve my goals smoothly and successfully. Their help and support has been extraordinary and has pursued me to complete this task with diligence. I would like to extend my gratitude towards **Dr Phani Chinchapatnam** and **Dr Stuart Jinks**, cost managers at Rolls-Royce plc, Derby for giving me the opportunity and environment to pursue the research topic I was interested into. I deeply appreciate the help extended by my colleagues both at the University and Rolls Royce Plc. They have invested their valuable time in reading and supporting my work. I would like to extend my deep gratitude towards my family who has always been very supportive, encouraging and patient throughout this time and has always backed me in stressful situations.

I am also thankful to Vanguard Systems Inc. for providing me student license for their cost modelling software. I am also thankful to NASA and other government organizations whose composite material component knowledge has been very useful in this study.

Lastly, I would like to express my sincere thanks to Birmingham City University, UK and Rolls Royce Plc., Derby, UK for funding my studies through SIOLET grant funding and providing me bursary to support other expenses.

Contents

List of Publications

As an outcome of the PhD research, some part of the work has been presented and published in international academic/industrial research conferences and peer reviewed journals. The details of which are given below:-

Thakur, N., Chapman C. B., Raju, P. and Chinchapatnam, P. (2016) Using Knowledge-Based Engineering (KBE) in Cost Estimation for a Composite Material Part: A Review. In: *IVth International Conference on Production and Industrial Engineering*. Jalandhar, India, 19-21 December 2016. India: NIT, pp. 1-12.

Abstract: Cost estimation is a technique wherein the cost related to a product or a project is predicted well in advance to make planning easy and simple. For composite components, stakeholders' requirements and technical requirements are complex. Large number of cost drivers with very little knowledge of composite technology makes cost estimation a difficult task. Uncertainty in information is another problem in cost estimation. Proper KM and automation are necessary for making cost estimation models simple and flexible. KBE is a cyclic process where knowledge is captured, assimilated, refined, coded, automated and reused in a desired format to save time. This paper presents a review of the current knowledge about composite materials, their cost estimation techniques and use of KBE in cost modeling. This paper also shows the drawbacks of the current system which can be overcome by applying the benefits of KBE.

Thakur, N., Raju, P. and Chinchapatnam, P. (2017) Knowledge-Based Engineering (KBE) for Cost Estimation of an Aero-Engine Part. *as abstract in University Conference RESCON-2017*. Birmingham, UK, 05 April 2017. UK: BCU, pp. 1-1.

Abstract: Cost estimation is a technique wherein the cost related to a product or a project is predicted well in advance to make planning easy and simple. For composite components, stakeholders' requirements and technical requirements are complex. Uncertainty in information is another problem in cost estimation. This work is the presentation of application of knowledge based engineering techniques in the realm of composite part cost estimation. Here a set theory based mixed approach coupled with knowledge based engineering is proposed and applied on a Titanium Metal Matrix Composite (MMC) part. The methodology applied results in an advanced cost modelling system for composite aero-engine parts, capable of, (i) making the cost models flexible; (ii) keeping the composite knowledge in a systematic and unified format; and (iii) predicting product unit, factory and life-cycle cost. Application of the methodology in MMC is done as a test case. Here after application dummy cost models are prepared. An advanced cost model thus obtained is presented in the Vanguard StudioTM, a cost modelling software, in a tree format along with the output chart. The benefit of this research would be (i) to show the wide application of knowledge based engineering in the fields of cost estimation and composite knowledge management; (ii) to show how knowledge based engineering can manage uncertain knowledge in a unified system; and (iv) to have a unified system of cost modelling so as to have a wider application in all fields. As the system developed is on a generic model, the scope of this research is wide and can be applied in all the fields requiring project, product or process cost estimate in advance.

Thakur, N., Raju, P., Krzyzanowski, M. and Chinchapatnam, P. (2017) Combined Life-Cycle Including Carbon Footprint for Composite Materials. *International Journal of Research in Mechanical Engineering & Technology*, 7(2), pp. 157-161.

Abstract: Cost estimation for a composite material part requires cost driver information from various activities just like any other material part. Every process involved to convert the product from raw material to finished state requires the consumption of certain cost value. The activities that are responsible for these cost changes are termed as cost drivers. Process cycle or life-cycle is a way to represent the processes necessary in a products complete journey. It is important to map different phases in a processes and include them in the life-cycle for proper analysis and management. The present work reviews the importance of different phases in a processes and quantifies the contribution of various processes in the composite material part overall cost. This contribution is represented in a tabular form and then compared to conventional method of life-cycle. The importance of including carbon footprint in the life-cycle is also reviewed and finally a generic process/project life-cycle for composite material part is defined. This contain processes that are contributing the most to the overall cost of the product and form a basis for process/project analysis, optimization and management.

Thakur, N., Raju, P., Krzyzanowski, M. and Chinchapatnam, P. (2018) Logical knowledge-based Advanced Cost Estimation Methodology (LKACEM) Applied to Metal Matrix Composite Aero-Engine Blisk. *International Journal of Computer Science and Technology*, 9(2), pp. 53-65.

Abstract: Cost estimation is an important activity for advanced understanding of product/process knowledge that is used to plan activities accordingly. For composite material parts, choices of materials and their methods of manufacturing are broad and thus complexity is high. Design is complex too involving tight tolerances leading to need of a new and advanced costing system. Proper knowledge management followed by improving the current cost estimation methods is a viable solution. This paper proposes a logical knowledge-based advanced cost estimation methodology that uses a mathematical set theory-based knowledge management system designed by utilising a generic product life-cycle for Knowledge Information & Data collection. This acquired KID is represented as parent sets, subsets and elements. The knowledge structure so created is coupled to a mixed method of cost estimation for developing logical advanced cost estimation system that can be used for both composite and conventional costing. Standard rules governing the parameters of cost and their relationships with the knowledge base is included in this methodology as a part of logical layer which interacts with other layers to form a reliable cost estimate. This methodology is then applied to develop a factory cost model for an aero-engine blisk design made up of metal matrix composite. This is done by using both simple and advanced software tools. Finally the outcome from these softwares are analysed by comparison study. The comparison is shown graphically for machining, material and overall cost parameters as a difference in their output cost values. As an outcome it is proved that the methodology is flexible for use with different softwares, is capable of reliable estimates, is less complex and thus can be used for cost estimation.

List of Figures

List of Tables

Abbreviations

1.	ABC	:	Activity Based Costing
2.	AFC	:	Aramid Fiber Composite
3.	ALC	:	Abstraction Layer Concept
4.	AML	:	Adaptive Modeling Language
5.	AS/RS	:	Automated Storage and Retrieval System
6.	BIM	:	Building Information Modeling
7.	BIW	:	Body-In-White
8.	CAD	:	Computer Aided Design
9.	CAE	:	Computer Aided Engineering
10.	CAM	:	Computer Aided Manufacturing
11.	CBS	:	Cost Breakdown Structure
12.	CER	:	Cost Estimation Relationship
13.	CFRP	:	Carbon Fiber Reinforced Polymer
14.	CM	:	Cost Model
15.	CMC	:	Ceramic Matrix Composite
16.	CNC	:	Computerised Numerical Control
17.	COCOMO	:	Constructive Cost Model
18.	CO_2	:	Carbon Di-Oxide
19.	DART	:	Design Analysis and Response Tool
20.	DESCEM	:	Decision Support for the Selection of Cost Estimation Method

21.	FE	:	Finite Element
22.	FRP	:	Fiber Reinforced Polymer
23.	GFRP	:	Glass Fiber Reinforced Polymer
24.	IFC	:	Industry Foundation Classes
25.	IP	:	Intellectual Property
26.	IT	:	Information Technology
27.	KBE	:	Knowledge Based Engineering
28.	KBES	:	Knowledge Based Engineering System
29.	KBS	:	Knowledge Based System
30.	KID	:	Knowledge Information and Data
31.	KM	:	Knowledge Management
32.	KMS	:	Knowledge Management System
33.	KNOMAD	:	Knowledge Optimized Manufacture and Design
34.	KOMPRESSA	:	Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications
35.	LCA	:	Life-cycle Assessment
36.	LCC	:	Life-cycle Cost
37.	LCCA	:	Life-cycle Cost Analysis
38.	LCLS	:	Linac Coherent Light Source
39.	MDE	:	Model-Driven Engineering
40.	MHED	:	Material Handling Engineering Division
41.	MMC	:	Metal Matrix Composite

42.	MMeMeR	:	Min-Mean-Mean-Roughness
43.	MOKA	:	Methodology and tools Oriented to Knowledge-based Applications
44.	MOM	:	Method of Manufacturing
45.	MP	:	Methodology Packages
46.	MS	:	Microsoft
47.	MTM	:	Method Time Measurement
48.	MIST	:	Multi-attribute Interview Software Tool
49.	NO_X	:	Nitrogen Oxide
50.	PACKS	:	Parametric Composite Knowledge System
51.	PBS	:	Product Breakdown Structure
52.	PDL	:	Parametric Design Language
53.	PLA	:	Poly-Lactic Acid
54.	PLM	:	Product Lifecycle Management
55.	PMC	:	Polymer Matrix Composite
56.	RBS	:	Resource Breakdown Structure
57.	SCADS	:	Steered Composite Analysis and Design System
58.	SEER-DFM	:	Software Evaluation and Estimation of Resources Design for Manufacture
59.	SiC	:	Silicon Carbide
60.	VA/VE	:	Value Analysis and Value Engineering
61.	VHDL	:	Very High-speed Hardware Description Language

62.	VR	:	Virtual Reality
63.	WBS	:	Work Breakdown Structure
64.	3D	:	Three Dimension

1 Introduction

1.1 Research Background

As the technology is advancing and the use of advanced materials is increasing for manufacturing of components in the field of aerospace engineering, there is a strong need to understand the cost impact of the same. Another important need which has gained momentum from the past 10 years, is to make the aircrafts economical and environmentally friendly. As the major source of emission in the aircrafts is the aero-engine, therefore, it is important to reduce the overall weight of the engine itself and increase its efficiency. To achieve this, aero-engines have seen use of composite materials in most of their components. These components range from compressors and turbine parts to auxiliary parts. The composites from all categories namely, Polymer Matrix, Metal Matrix and Ceramic Matrix are used in these parts, also, automated, semi-automated and fully-automated methods are used for their manufacturing. This vast combination of material as well as manufacturing choice increase the complexity in estimating cost of the same. As the composite technology is still under development, capturing the complete knowledge becomes difficult, increasing uncertainty in design and manufacturing information.

Cost estimation has always been an integral part of the industry and helps the engineers and project planners to design and plan the activities in such a way that these become economically viable. It has been discussed in many researches that for any engineering application, besides meeting technical requirements, it is important to meet financial requirements as well, which can sometimes be even more important in the final decision making. The techniques of cost estimation range from manual to automatic and from mathematical to Artificial Intelligence (AI) based. Methods like Activity Based Costing (ABC), Parametric Costing, Bottom-up approach and Expert Judgement have been long used and found to be beneficial in early estimation. Advanced methods like Neural Network, Fuzzy-logic and AI have been very good in handling uncertainty but are complex in their structuring. The problem with these methods are that they have been applied to conventional materials and the application is either project specific or product specific. Knowledge Based Engineering (KBE) has been found to be helpful in solving some of the problems of the conventional costing methods. There has been considerable work done in the field of KBE based costing in conventional materials and composite materials. Computer Aided Design (CAD) to Cost, Model-based and rule-based cost modelling is an example of KBE based cost estimation. These have found application in both conventional and composite products, however, the application was limited to a particular manufacturing process and was not comprehensive enough to be used directly into composite cost estimation problem.

The present research proposes a mathematical approach for KBE. Here, a logical set theory-based knowledge management technique has been developed which utilizes the principles of KBE integrated with a mixed approach for cost estimation to develop advanced costing system that can be used for cost evaluation of a composite material part. The system developed uses a generic life-cycle which includes carbon footprint for development of knowledge sets. These knowledge sets are then kept in a three layer structure. This allows the knowledge to be kept as mathematical sets where the interactions between them takes place by using a logical set running separate to the knowledge database. This keeps the knowledge logical, flexible, platform independent and maintainable. As no work has been carried out in terms of carbon footprint into cost estimation and into the composite technology, its knowledge into the cost realm is introduced in this study thereby increasing the current cost capabilities and achieving an advanced costing system. This methodology is later used to develop an advanced cost estimation tool in Microsoft (MS) Excel, which can have multiple selection parameters working parallel to the input parameters, thereby providing the capability to achieve cost estimation for composite aero-engine components. The data and knowledge contained in the previous literature and industrial case studies are used to benchmark the methodology design and structuring. Also, the Method of Manufacturing (MOM) and the Bill of Materials documents are used to verify the design, process and parameters used for designing the advanced cost estimation tool. Machining formulas and parametric relationships that are available as open source as well as in the industry documents are used to check the logical consistency of the methodology and the tool. Outputs which are generated as part of the validation process in this research are compared against previous cost evaluations that have been carried out in similar components and the market price of identified components. This technique, allows validation of the research and its outcome under a predictable range of variance. As the variance range should lie between 0 - 15%, which is an industrial acceptable range, the quantification of the validation is achieved.

1.2 Research Motivation

Engineers all round the world look for ways of competitive design which forms the basis of any new or existing technology. Project optimization which includes both product and process optimization requires design and manufacturing to be cost effective. Cost estimation has always played a very important role in predicting and analysing processes and products information. It has been seen that most of the research done in the field of cost estimation is focused towards a particular product or a particular process. The methods developed for cost estimation cannot be used interchangeably, but are suitable for a particular kind of problem. Moreover, the main problem lies with the choice of the cost estimation system which is highly dependent upon the kind of problem and the ability to utilize a particular method or a technique (Simion-Melinte, 2016). Another important inclusion in the latest aero-engine manufacturing field is the conversion of old designs into new composite technology based engine designs, which are lighter and stronger, thereby, providing the best trade-offs in terms of efficiency and price. The focus of attention has always been conventional materials but not many methods have been developed that can easily estimate cost for composites. New material inclusions with newer manufacturing techniques and very little knowledge of a product design or process, leaves a wide gap in the area of aerospace composite material part cost estimation (Nagavally, 2017). Although, composites were in use in the automotive industries, cost estimation of the same were not developed as most of the parts were purchased directly from suppliers. Also, energy and environment have become the center of attention for future designs. Future designs are developed keeping in view their environmental impact, therefore, understanding carbon footprint and that too in terms of cost earlier in the product's life is very important (Radu et al., 2013). This work has not been carried out till now. This wide gap along with the industries' need to be future proof in developing new products is what drives this research. The knowledge that I have gained so far working as a design and a production engineer along with the experience that I have gained by supervising many projects have made me realize the actual importance of cost estimation. Also, I have myself seen the importance and a shift of industries and governments towards greener technology development for which composite materials are going to be the choice of designers and engineers all over the world in their future designs. This has also led me to gain a liking towards this research. The benefits that early estimation has to the industry is immense. Not only does it help in estimating the product's cost but also gives a complete analysis which can be used for proper planning and developing an environmentally friendly design which is sustainable in its entire life-cycle. The impact factor of this research will be on any new or existing composite material product for which a project or process or cost capability is required.

1.3 Aims & Objectives

The aim of this research is to develop a logical set-based knowledge management technique to serve as a Knowledge Based Engineering (KBE) method and couple it to knowledge from composite technology, cost estimation methods and carbon footprint to come up with an advanced methodology, capable of (i) making flexible cost models, (ii) unifying the composite knowledge in a systematic format, (iii) handling composite technology complexity, (iv) having a platform independent structure, (v) expanding the scope of current cost estimation and (vi) increasing the maintainability of the system developed. These aims are further broken down into individual objectives which are defined for smooth conduct of this research. These objectives are defined in a step-by-step manner as outlined below:-

1. Step 1: Conduct extensive literature review in the fields of composite material technology, KBE, cost estimation techniques and carbon footprint to understand the current state of the art with benefits and drawbacks.
2. Step 2: Identify the methods/techniques that can be used in the development of a more logical KBE system which can be used for composite cost estimation.
3. Step 3: Capture carbon footprint knowledge and convert that knowledge into cost format so that it can become a part of the cost estimation system.
4. Step 4: Utilise the identified methods/techniques and integrate them with a logical KBE system to develop an advanced costing methodology that can effectively achieve cost estimations for composite material aero-engine parts.
5. Step 5: Develop a cost estimation tool and simulate 4 realistic aero-engine composite component based case studies so as to validate the methodology and tool developed.
6. Step 6: Analyse the results and find out the benefits and drawbacks the developed system brings for future study in this area.

1.4 Research Method

This research was conducted by utilizing a standard step by step model of research processes. This model is utilized to break the entire research into phases or steps. These steps or phases identify and distinguish a category of work and then define a standard flow which the problem steps would follow to bring that whole work into a conclusion. The flow of these phases/steps for this research is represented in a flowchart manner as shown in Figure 1.

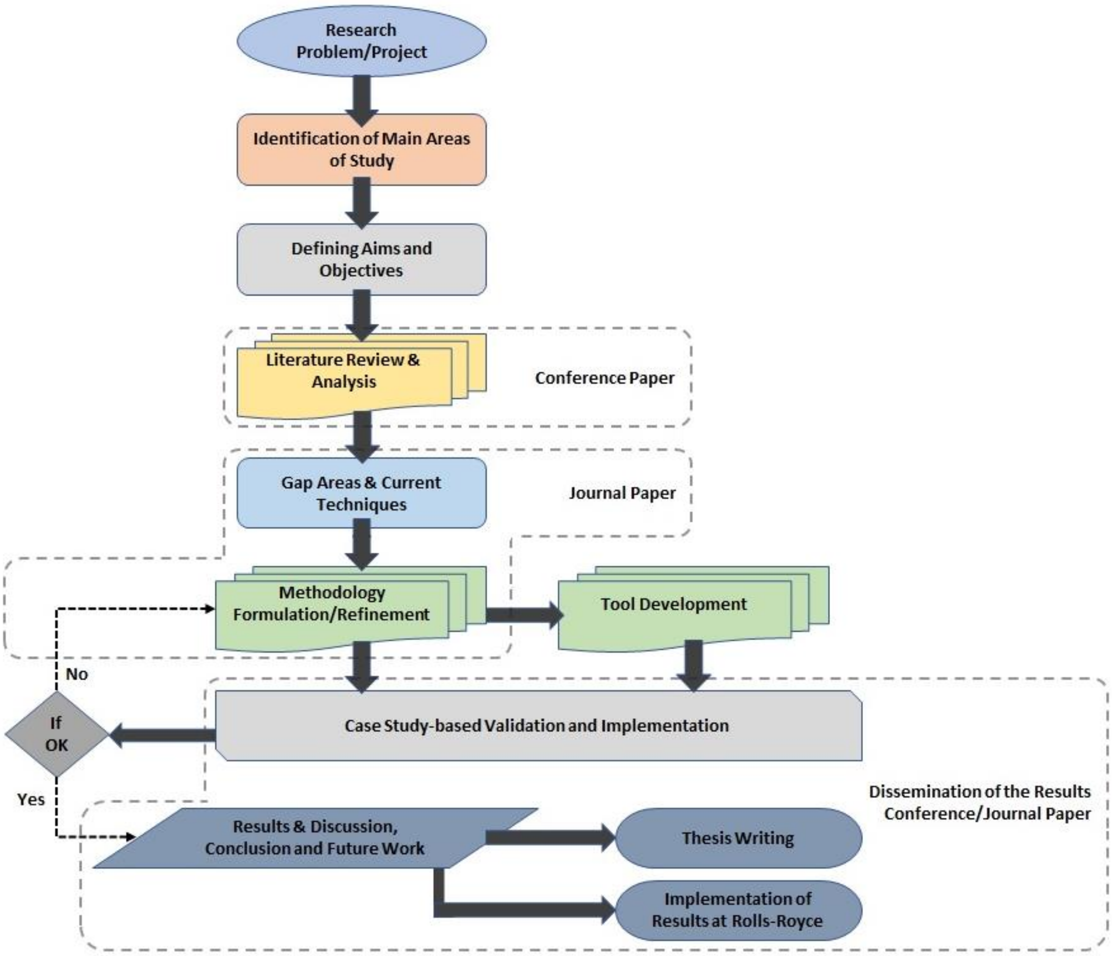


Figure 1: Schematic Representation of Research Outline & Design

From understanding the industrial requirements and some initial understanding of the subject, the research interest is represented in a form of a research problem. This is followed by breaking the research problem into main areas of study, which are further divided into smaller sections. Previous literatures, documents, journals, conference papers, databases, reports, electronic media is searched taking into account these main areas and thus a proper literature search is carried out. The aims & objectives play a very important role in keeping the study on track and also help in constant upgradation of the literature review process.

The next process is analysing and understanding the gap areas that have been identified in the process. This helps in understanding the current methods/techniques, their benefits and drawbacks and the areas which have not been explored. After an understanding has been developed, the system is utilised in developing an advanced methodology which is used to form advanced costing system. The gap areas are again checked with the latest research to validate and confirm that the area categorised as gap area is still existent or not. Once this has been identified a simplistic but effective system is searched which can be used for addressing the research problem in hand. A cost estimation tool is designed in the same phase in a simple but effective excel based design format. Open source data and industrial used cases and information from different parts in an aero-engine technology design, specifically from the composite realm, are chosen to validate the methodology and the tool design.

In the last phase of the study, results are systematically laid down and discussed in the most scientific manner and future study areas are highlighted. The entire work is then represented in a book form for easy understanding and utilization. The results from each step is intended to be presented as journal and conference papers and are represented in Figure 1. The presentation of these papers in peer reviewed journals and conferences ensures that the areas identified exist in a much wider environment.

For achieving the aims and the objectives of this research, each process has been well defined and followed systematically for this research. The process is in-line with the general outline of the research and follows the same step-by-step model. This model for the entire thesis can be further elaborated from Table 1.

Table 1: Schematic Representation of Research Method

Process	Description	Method Used	Objectives Achieved
Review of Current Methods/Techniques	A thorough study of the current technology and methods that have been previously used or applied to the conventional system is done	• Strategic Study • Qualitative Analysis • Quantitative Analysis • Critical Evaluation	Objectives 1 and 2 have been achieved. (Refer: Chapter 1.3)
Methodology Development	Study for development of a system that is capable of handling composite complexity to achieve advanced cost estimation is done	• Mathematical Set Theory-based knowledge management • Mixed Cost Estimation Approach • Inclusion of Carbon Footprint Knowledge	Objectives 3 and 4 have been achieved. (Refer: Chapter 1.3)
Tool Development	Application of the developed methodology is done so as to come up with an advanced tool capable of predicting composite aero-engine part costs	• Worksheet-based knowledge base • MS Excel for knowledge and logic representation • MS Excel Macro functions for creating interface	Objective 4 has been achieved. (Refer: Chapter 1.3)
Validation	A proper working and application of the methodology and the tool is checked	• Used Case Study Analysis • Open Market Product Comparison Analysis • Expert Feedback Analysis	Objectives 5 and 6 have been achieved. (Refer: Chapter 1.3)

This way the entire research is conducted in a process based manner which clearly defines the task that needs to be handled, the method that is planned to be used and the intended outcome that has been defined to be achieved. An early thinking in the method of research makes the research systematic and achievable in realistic time frame which is very important for any research work.

1.5 Scope of Research

This research has been conducted keeping in view a future need of the industry and thereby of the designers, engineers and project planners. The scoping of the research lies in the main areas of study and has been kept in a reasonable frame i.e. between very specific to very generic. This way the research although applicable to one part of engineering keeps doors open for future research. The scoping can be understood by understanding Table 2.

Table 2: Field-wise Scope Description & Distribution

Field	Description	In-Scope	Out-of-Scope
Technology Selection	The initial stage of the research which defines the technology that will be evaluated for study	• Composite material technology finding use in aero-engines	Conventional materials and composite materials finding use in other areas
Cost Estimation	This defines the methods that will be used in the research work and will form a part of the advanced system	• ABC • Parametric Costing • Bottom-up Approach • Mixed Approach	Other advanced artificial learning, neural network, fuzzy logic and computational techniques that require special systems
Knowledge Management	This is used to develop advanced methodology and define the knowledge sets. It is also used to capture knowledge and categorize the same	• Cost driver elements from generic processes • Carbon Footprint Knowledge • Composite materials knowledge	Other information related to composite material composition, strength and mechanical or chemical properties. Manufacturing Technologies in composites that are still under research and have not fully developed like 3-D Printing and robotic fabrication
Tool Development	This is used to represent the knowledge and convert it into a usable form. This also includes the interface and languages that are used to code the knowledge. Cost models are also a part of this field	• Vanguard cost model • MS Excel • Mathematical set theory • CER	Advanced programming languages, programmable interfaces and complex structures and databases
Cost Output	This is the final stage where cost is finally calculated, represented and displayed	• Life-cycle cost • Factory cost • Unit cost • Carbon footprint cost	Other costs related to the product, like should costs and could costs etc. that are used in cost benefit analysis

It has been thus defined that the scope of this research lies in the aero-engine realm and chooses composite technology as the main technology for study and analysis. This is where the major part of the knowledge is extracted from. The knowledge that is extracted is only related to the cost and not any other parameter. Another area of knowledge capture is the carbon footprint which is kept parallel to the generic product life-cycle that has been developed from analysing the use of composite technology in other conventional applications. This knowledge is then represented by using the principles of Knowledge Based Engineering (KBE) and applying those principles to a mathematical set theory-based structure. This structure forms a logical knowledge management that can easily categorize, represent, store and flow Knowledge Information and Data (KID). This knowledge base becomes logical and can be very easily coded using any existing techniques. As advanced methods and programming is out of scope of the research, hence, a very simple excel worksheet based method is employed for representation and reusing of the knowledge created. This is the design chosen for tool development and is used for advanced cost estimation. The major scope lies in the knowledge capture, knowledge addition and knowledge management, however, for the representation and result verification a very simple method using Microsoft (MS) Excel has been chosen.

1.6 Thesis Roadmap

A very important part of the research is the presentation of the thesis. In this research, the thesis is written parallel to the research and is structured in a very systematic order so as to make the work easy to understand and logical in flow. Parallel writing of the thesis ensured the thesis to be completed on time and also to make it easy to manage. As this research has many elements that form part of the method as well as the tool, therefore, it is very important to understand each section in a detailed fashion. Even though there are various knowledge elements from various phases, the representation is categorised and presented in a simpler and systematic manner. To represent the flow of the thesis and the flow of the work as such a roadmap has been designed. This roadmap is the structuring of the thesis in a systematic order, which is represented as shown in Figure 2.

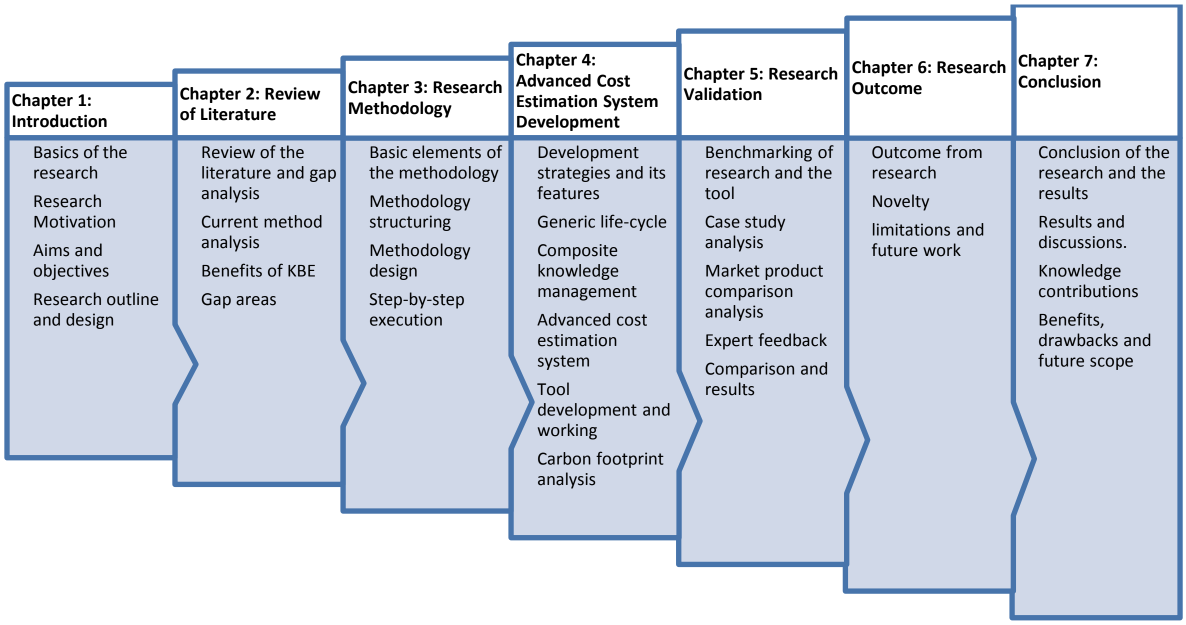


Figure 2: Schematic Representation of Thesis Roadmap

From the thesis roadmap it has been clearly represented how each chapter in the thesis is designed and what is being discussed in each chapter. This makes the chapters easily accessible and targets specific audience interested for the same to simply go to the relevant chapter that interests them the most, thereby saving time and energy. The chapters are discussed in detail in the sections to follow.

2 A Review of Literature

2.1 Chapter Introduction

This research aims to develop the approach for modelling cost and related processes for composite aero-engine components and increase the current capability of cost estimation. Hence, the area of research is focused on a combination of four main important fields, namely, composite materials technology, cost modelling, an engineering design automation method called Knowledge Based Engineering (KBE) and carbon footprint. KBE is a very useful tool when it comes to modelling and utilization of Knowledge Information and Data (KID) and the subsequent reuse for product/process knowledge for automation. As the development of a cost estimation method requires accurate and complete representation of knowledge of all the processes, an in depth study of KBE and its techniques becomes important. Accordingly, the literature has been divided into topics and sub-topics relevant to these four fields and in line with the research context in hand. The division of these topics and the sub-topics are shown in Table 3.

Table 3: Topics & Sub-topics for Literature Review Analysis

Literature Review Topics / Sub-Topics			
Elements of Composite Technology	**Knowledge based engineering**	**Cost Estimation and Modelling**	**Carbon Footprint**
Basics of Composites	Basics of Knowledge Based Engineering	Basics & Types of Cost Modelling	Basics of Carbon Footprint
Types of composite Materials	Knowledge Based Engineering Approaches	Composite Product Life Cycle	Importance of Carbon Footprint
Cost Modelling in Composites	Benefits of Knowledge Based Engineering	Cost Drivers in Composite Technology	
Manufacturing Techniques in Composites		Cost Modelling Tools and Techniques	

The subject of data collection is wide and is not limited to the topic division as shown in Table 3. This was done to smoothen the literature review process and track the progress from time to time. Some important sources of data collection being Birmingham City University (BCU) KBE lab's previous thesis and/or research papers, BCU Curzon library, Rolls-Royce database, Institute of Materials, ELSEVIER, IEEE, CHEMIK, NASA repository, Science Direct and Google Scholar. Besides these, other sources from different parts in the world have been explored and have not been ignored. Some key-words or phrases used for the search are: "Composite Materials", "KBE", "Cost Modelling Methods", "Manufacturing Techniques in Composites", "Cost Drivers", "Product Life-Cycle" and "Carbon Footprint". Other words or phrases specific to the process and/or technologies under review are also used. To further help with the process of literature review, a systematic strategy was developed and followed. This systematic strategy involved; identifying knowledge, sources, capturing KID, refining KID, revising for other areas or left out areas and categorizing knowledge into a usable form. The search strategy utilized in this research is shown in Figure 3.

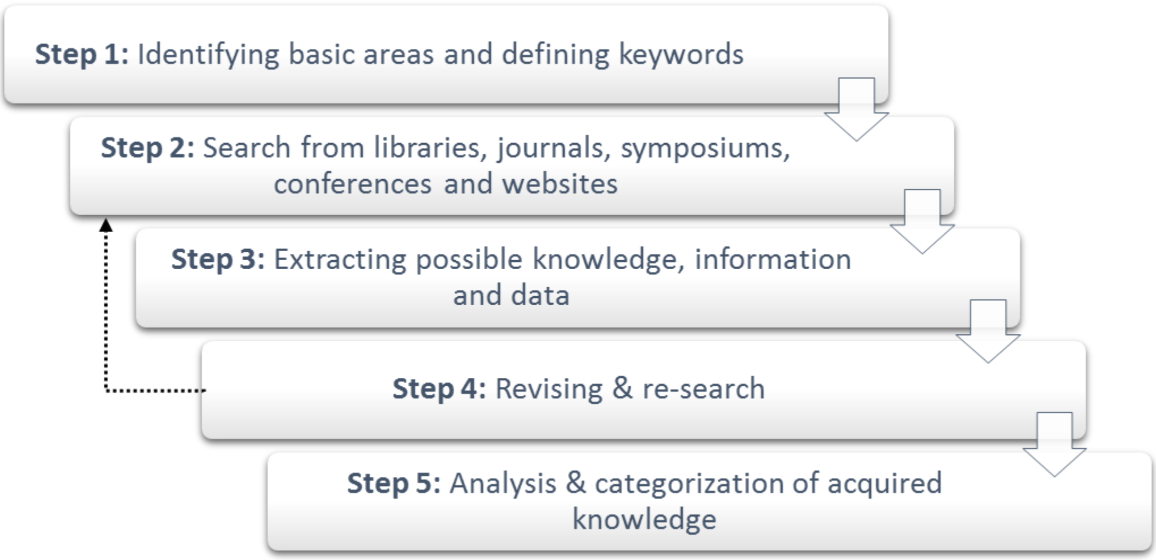


Figure 3: Search Strategy for Research Analysis

The strategy, as shown in figure 3 is utilized to conduct the research further. As the strategy has some steps to be systematically followed, the research is made even more organised. The main areas that have been identified to be studied further are presented as a review in the sections to follow.

2.2 Composite Technology Knowledge

2.2.1 History of Composite Materials

Composite Materials are a mixture of two or more materials having different chemical and mechanical properties, physically mixed together to form a third kind of material having different properties to those of the parent materials (Harris, 1999). This material is made up of two basic elements namely, (i) matrix: responsible for acting as a binding agent and providing dimensional stability and (ii) reinforcement: acting as the main load bearing agent (Chawla, 2012). The use of man-made composites dates back to 3400 BC, when Mesopotamians used glue and wooden strips to make boards. Later, in 1500 BC, Egyptians and Mesopotamians used straw reinforced in mud to make bricks, pottery etc. With the advent of science and technology, composites started replacing traditional materials (Mar-Bal Inc., 2016). The construction industry was the first to use composites in many forms to replace and sometimes strengthen structures. Composites in construction are categorised based upon the usage, namely (i) Intermediate use: fence posts, signposts, ladders, small pipes, light posts, sewer pipes and roof sheets; (ii) short-term use: frames, concrete repair plates, reinforcement and gate parts; and (iii) long-term use: load bearing parts, reinforcement tensioners and loaded pipes (Department of Army, 1997). Polymer composites have also been used in pipes, roofs and tank liners which gives almost 30% increase in lightness, corrosion resistance and ease of processing. In some of the building designs, side panels and roof panels were found to be made up of Glass Fiber

Reinforced Polymer (GFRP) which proved to be very successful. Most of the swimming pools in luxury building designs have been made using GFRP. This use allows innovation in designs such as roof mounted swimming pools (Halliwell, 2000). Composite use in construction brought many advantages, such as, prefabricated parts that can be joined together to form a big section, innovative designs that allow intricate ideas to become reality, speedy completion of the construction projects and design freedom that allows artistic construction (Reinforced Plastics, 2010). Military construction has used composites in many innovative ways to bring about advantages to the field. Bridge construction and structural parts of static and dynamic equipment's were made using sandwich design fiber reinforced polymer. New manufacturing techniques and design possibilities were explored in these applications successfully. Even cost savings were observed in parts made by using composites over conventional materials (Bakis et al., 2002). The use of composites in construction industry showcased that the basic usage of composites in mostly structural parts for both new and old designs is more economical and lighter in weight. It was clearly seen that composites are useful and provides overall benefits but at the same time requires a study to understand the long term impact of this use on performance and cost impact of a product (Deng et al., 2017). The benefits that composites showcased were utilized by automotive industry for their structural and non-structural parts. Carbon fiber was chosen to be the material for making Body-In-White (BIW) structural panels, high impact parts and visual components. New processes and techniques were evolved around this material to make fast production possible. Automation is one such evolution for composite technology (Cytec Industries, 2014). With the need to develop higher fuel efficient and low emission automobiles, weight reduction became important. To keep the same strength and still fulfil these requirements, composites were used in most of the body parts of the vehicle. Not only this, certain engine parts were also being made by different varieties of composites. Glass fibers, natural fibers and carbon fibers coupled to thermosetting plastics were the first to be used in automobiles. Now most of the vehicles have 30-40% use of composites (Komornicki et al., 2017). Another study confirmed that use of hybrid composites which are a mixture of composite with conventional materials prove to provide a feasibility of 20%-30% in the overall light weighting of the automobiles. It was seen that composites, specifically from polymer family, are found to be useful in such hybrid applications. Also, most of the industries around the world are looking for methods to further improve design which will require more use of composite materials (Pervaiz et al, 2016). After the successful use of composites in automobiles, a need to apply these into aerospace sector started happening. The use of composites in commercial aircrafts were put forward by Airbus in its A380 program (Pora, 2001). For achieving attributes such as high strength to weight ratio and developing a robust design, different composites were chosen for different parts. A technology-down selection process was adopted where the required characteristics were divided in the entire fuselage and material selection pattern was developed based on that. The distribution of composites in some of the parts of A 380 were; (i) J-Nose: Glass fiber thermoplastic, (ii) Wings, Central Wing Box, Vertical Tail, Fuselage: CFRP and (iii) Bulkhead: Non-crimped fabrics (Pora, 2001). From here it was understood that to achieve competitive design and low cost carrier capabilities more and more use of composites was required. Companies such as Rolls-Royce Plc. have also adapted to the changing demand for using advanced materials for developing their new families of engines. UltraFan is an example of one such advanced engine. This advanced engine features the use of composite materials in its components such as fan, casing, discs and blades etc. (Rolls-Royce Plc., 2016). It will not be wrong to say that composites have now become a material of choice for many industries and its in-depth knowledge including cost is very necessary for its effective use. This knowledge is necessary for project/process evaluations in engineering and hence, requires to be captured and used logically for the benefit of humanity.

2.2.2 Basics of Composite Materials

Composite materials are made up of two or more similar or dissimilar materials that are mixed under different mechanical and chemical states, which are physically or chemically bonded together to form a third kind of material. This material possesses a fine blend of properties of its parent materials or constituent materials and reflects its own advanced properties over them (Hussain et al., 2006). Composites can be classified into many types depending upon their constituent elements, fiber orientation, joining methods and manufacturing processes etc. A basic form of classification which used some of these properties is shown in Figure 4 (Hussain et al., 2006).

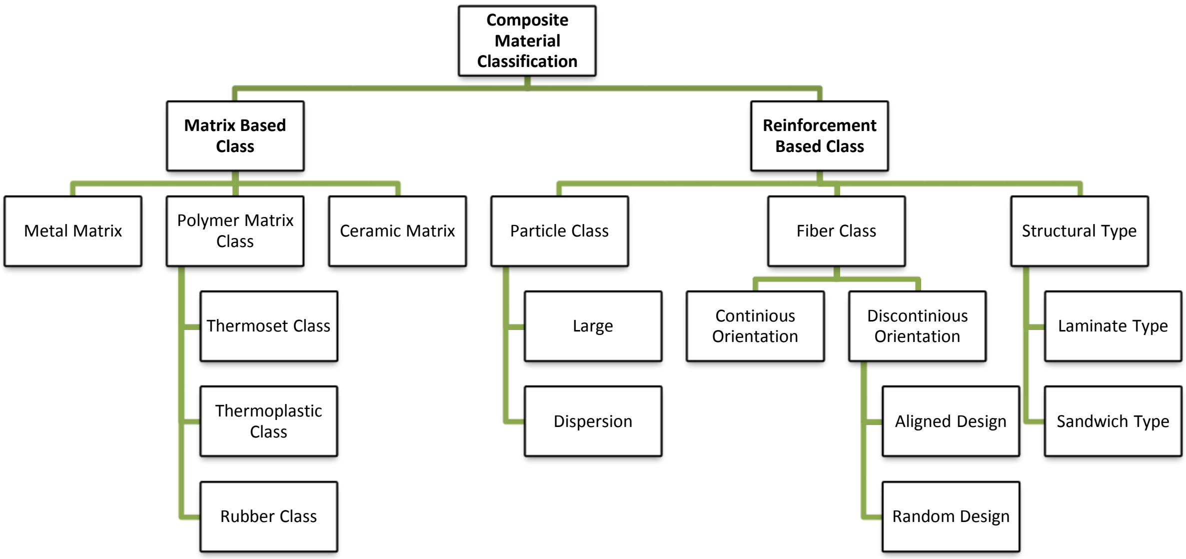


Figure 4: Classification of Composite Materials (Hussain et al., 2006)

Fiber orientation, as shown in Figure 4, can also be classified into different forms namely, continuous filament, short fiber, platelet, sphere and irregular (Smith and Yeomans, 2011). Composites used in industrial applications have fibers in the form of particulate, flake, long and nano scale, which, come under the category of particle orientation. Another classification of composites from the polymer matrix class is thermoplastics and thermosetting composites, which vary with the kind of fabrication process (Thori et al., 2013). A new class of composites namely, Glass Fiber Reinforced Polymer Composite (GFRPC) and Carbon Fiber Reinforced Polymer Composite (CFRPC) from the fiber class are the most widely used in industrial applications (Goodwinds Composites, 2011). These are mostly used in combination with plastics in the form of fibers reinforced in polymer resins and can be manufactured manually as well as by using automated machinery (American Chemistry Council, 2015). For the suitability of aerospace needs, E-Glass & S-Glass fiber, Aramid and Carbon composites are modified and used. These are specifically modified to work for aerospace industry and can work under extreme environmental conditions such as high temperature and pressures (Nayak, 2014).

A new class of intelligent composites finding use in the industry are, (i) Bio-composites: capable of bio degradability; and (ii) Nano-composites: capable of modifying material properties as per user requirements and environmental conditions. The materials are sometimes termed as intelligent materials as they have the capability to change or react to an external trigger (Barton et al., 2014). Carbon nanotubes are being looked forward as the next generation of advanced materials finding application in electronics and shielding for aircrafts. The use of Metal Matrix Composite (MMC) in shape memory metals and core materials for the aero parts show a great potential in the composite technology (Mrazova, 2013). Companies such as GE Aviation, Hexcel and Blackhawk have pioneered in the use of composites in the aerospace technology (Mrazova, 2013). A developmental study has been conducted for the development of composite fan case and guide vanes for the next generation light weight aircraft engines. A combination of 3D preform and epoxy matrix with autoclave and filament winding techniques have been used to produce components lighter in weight and higher in strength. The results here have shown a considerable improvement in performance of composite components (Tsutomu et al., 2014). The development of aero-engine components from Ceramic Matrix Composite (CMC) has been tested in fatigue and spin test for turbine nozzles and blades. In this study Silicon Carbide fibers were used as the matrix material and introduced in a semi molten state. A Melt Infiltration Method was employed for the development of turbine vanes and blades as a test object. Using spin tests and fatigue tests the test objects were tested thoroughly. From this study it had been verified that the vanes and blades maintained their functional integrity under all test conditions without any change in their overall efficiency. This study confirmed that CMC can be a viable alternative for a turbine blade material (Takeshi et al., 2014). Various materials are used for the manufacturing of gas turbine engines. The basic requirements for these materials are, high tensile strength, low cycle fatigue and ability to withstand creep. Titanium and aluminium based composites are found to be more suitable for the internal components in aero-engines such as compressor and turbine parts. Ceramic based composites are found to be more suitable for combustion chambers and linings (Muktinutalapati and Rao, 2011). From this study it can be concluded that when high engine thrust and fuel efficiency are important, advanced composites find their place in engine parts.

Another aspect in the use of composites is the environmental impact, which has become an important engineering requirement for the development of lighter and fuel efficient aircraft engines (Lacombe et al., 2009). CMC has been found to be very effective and efficient in the manufacturing of complex aircraft engine components. Advanced Silicon Carbide fibers have self-sealing properties in a composite, thereby increasing its build performance. New and advanced self-sealing fibers have been developed which are from the family of CMC and are becoming the future for composite aircraft engines. These have proved to be competitive in all respects with conventional metallic materials and also have improved engine life even under high temperature and pressure conditions (Lacombe et al., 2009). Alloys and super-alloys such as titanium and aluminium alloys were the material of choice for the advanced engine manufacturing. As the aircraft engine requires high performance under stressful operating conditions, many materials were tested for their light weight and superior performance. As the requirement of timely delivery, growth, manufacturing, sustainability and global competition increased, conventional materials got replaced by composites which were found to be more suitable not only in the outer casing parts, but, also in the intricate and high performance parts (Backman et al., 1992). The use of advanced composites in engine technology has been investigated in the General Electric (GE) Aircraft Engines in the realm of rotating and non-rotating pars. Here, the use of Titanium Metal Matrix Composite has been investigated for its processing cost and manufacturing feasibility. It was observed with flight data from GE in its various different engines and parts that, Titanium Metal Matrix Composite is quite feasible in manufacturing and also provides better operational performance besides being lighter in weight, about 30% lighter than conventional alloys (Singerman et al., 1996). A careful study of this research showed that, if, end users and suppliers can generate sufficient demands, the use of this advanced material will be even more feasible. Also if, the cost prediction models become more and more complete with knowledge, implementation of this material will be widespread.

The Romanian Research & Development Institute for Gas Turbines has conducted a study on composite materials for gas turbine manufacturing. Here, a stator blade was manufactured by using CFRP composite targeting the aircraft engine as its component design source. Autoclave technology was used for manufacturing the component and its active noise vibrations were monitored for different running conditions. The study revealed that CFRP composites can be used in the stator blades for compressor section of the engine but needs some improvement to be fully made commercial (Raluca, 2012). Oxide CMC is an advanced form of ceramic composite which finds use in highly demanding thermal and mechanical applications. Different manufacturing innovations such as vacuum assisted lamination have been developed to suit the material. A careful selection of the material property with industrial application such as flame tube, lift gate, hot gas distributer, charging racks and thermal lining in aero engines have shown a great potential in this highly advanced material (Pritzkow et al., 2015). From the study conducted and the research done, this material has been developed with properties such as high stability in high temperatures, low weight with low density, high strength and superior corrosion resistance (Pritzkow et al., 2015). Thus, it can be said that this material can suit aero-engine requirements for combustion linings and turbine casings, which are extremely sensitive components.

The use of composites in aerospace brought expansion options and development of new composite products with higher performance. The underlining problem with its wide acceptability is the less feasible and cost effective manufacturing system. Also incomplete knowledge of the process and its implementation techniques coupled with ineffective cost estimates, result in less usage of the advanced materials in aircraft engine manufacturing.

2.2.3 Cost Modelling in Composite Technology

Despite having superior mechanical properties, composites are not as cheap to buy and produce as conventional materials. If the cost of carbon fiber is reduced by around 50%, a considerable cost saving in the overall life-cycle would be obtained (Oak Ridge National Laboratory, 2001). Not only this, it has been seen that there is a vast majority of composite usage in countries such as China as compared to other countries. This difference is driven by cost forces, which in turn refer to manufacturing and market driven costs. It was clearly shown in this study that for a product to be highly successful, a complete knowledge of the cost factors needs to be developed. Understanding cost and its distribution is very important to make critical engineering decisions, which are sometimes even more important than mechanical or engineering requirements (Fuchs, 2003). To find out the cost burden, a precise knowledge management of composite process is required. Designers working on composite structures need accurate cost estimates well in advance to finalize their design attributes. One of the reliable sources of information is from the use of Finite Element (FE) models. New costing procedures have been adopted using Ansys FE software and the Ansys Parametric Design Language (PDL) (Barlow et al., 2002). A drawback with this system is that the cost estimate does not precisely utilize the knowledge potential and hence is incomplete. Different techniques for modelling short fiber composites depend on the method of assigning material property. Some involve assigning the properties to the whole element while others assign them to the quadrature points (Wilmers and Lenhof, 2014). If the traditional method is replaced by a macroscopic approach, computational costs relating to modelling and simulation can be lowered.

There is a lack of knowledge of composites in the conventional cost models which needs improvement. Hence, a survey-based approach is used to establish new relationships between part count and tooling for composite technology application (Lambert, 2011). If these relationships are put into Life-cycle Cost (LCC) model, flexibility of cost models can be increased. Another cost measurement method is Method Time Measurement (MTM) where time associated with each motion for manufacturing the composite part is mapped. These motion patterns are associated with a time which in turn is associated with a resource and then finally converted to cost. This methodology when applied on a manual process of manufacturing shows a high acceptability rate and seem to be a viable solution (Kumar and

Kendall, 1999). By improving the knowledge base, it can be made applicable to other processes with a high degree of acceptability.

A data management method for composite materials was brought forward in data management systems for conventional materials in GRANTA MI^{TM} in collaboration with material data management consortium (Marsden and Warde, 2010). This method involves leading industries in aerospace such as Boeing, Airbus, Rolls-Royce and NASA to present data and information for overall development and improvement of the technique. It was observed during the development of composite data that, as the properties of composite materials differ in different planes, which means anisotropic, the properties become more dependent upon the geometry and thus difficult to capture (Marsden and Warde, 2010). A process-based parametric cost model SEER-DFM has been applied for calculating the real time costs for composite and metallic component design in the modification phase. Statistical relationships using attributes associated with previous products were applied and same analogy was then applied to predict cost of new designs. Specific-process based cost drivers were identified and embodied into the software framework for better association (Rush et al., 2003). This method can be used to predict costs by considering it as a design variable. It is also observed that data necessary for developing cost driver information is incomplete and inconsistent, hence it needs to be improved and enriched. An advanced cost model for composite automobile design using carbon fiber as the material, used information functions to capture and automate the manufacturing process. Here, a main function which is the cost function collects information from plant, material and machines and utilizes the same into its sub-functions which act as secondary operators breaking down the information to a much detailed form (Karlsson, 2013). A drawback with this system is that it is useful for a particular material and process type and cannot handle changes in any of these. The application is also limited due to its overall concentration towards the manufacturing aspect ignoring other main areas that contribute a lot to cost. The total life-cycle cost model for a composite train structure was inspected using autoclave manufacturing technique (Jolliet, 2007). In this technique a coupled method using data source from the cost parameters and life-cycle inventory was used with a hybrid system. It was found that the coupled system proved to be an efficient way of capturing production data. It was also found that the product weight accounts for the major share of the total cost followed by material purchase and resin cost (Jolliet, 2007). A unified approach for cost prediction and reporting in the Advanced Composite Technology Program defines a detailed flowchart containing basic elements to be included while comparing costs of composite structures to that of metallic ones. Here, different techniques for the estimation of costs are also inspected along with their use in the different phases of the product. It was observed that computer software techniques used in the cost estimation and reporting, reduced the effort and cost for the project management by utilizing previous knowledge. This has clearly shown that the Knowledge Management System (KMS) can be used in cost estimation and reporting which proves to be easy to use and cost effective (Freeman et al., 1990).

The design and analysis data have been used to determine the life-cycle cost for an inter-stage element of space launch vehicle. Here, a sizing software Hypersizer® has been used to specify parameters of the components both metallic and composite and the output from both were compared. Multiple failure calculations have been made using the detailed model. The detailed analysis provided the baseline data for cost estimation. In-depth parameter sets were used for the life-cycle cost estimates both for manufacturing and fabrication (Mann et al., 2012). It was observed that complexity of the cost estimation is reduced by eliminating efforts made in knowledge extraction of the processes. As this is a low knowledge process, expert judgement is the best suitable method, hence seems to represent a good approach for cost estimation of fabricated parts (Mann et al., 2012). A new approach named as the Quantitative Cost Modelling which could process cost analysis by using the physical-mathematical models relating process conditions to the quality affecting features has been developed (Elzey and Wadley, 1995). This approach uses the following features; (i) factors which affect conversion of raw materials to useful items, (ii) numerical simulations to observe the amount of change when a process parameter changes, (iii) critical cost drivers for the measurement of quality and cost and (iv) finding the cost/benefit ratio to predict the affordability of different approaches. It was shown that detailed models are not required for the application of Quantitative Cost Modelling to manufacturing and predicting cost (Elzey and Wadley, 1995). The major shortcoming found was that the method considered the models to be based on physical principles, which are sometimes good in a particular product, but may behave differently when changes in features such as design parameters or material choices are observed. A very recent study has been conducted on the recycling of carbon fiber polymer composite cost effectiveness (Meng, 2017). Here, for the first time both recycling cost and energy cost has been modelled using mathematical formulas instead of assumptions. The focus of information collection and method development has been on the fluidized bed carbon fiber recycling process. Energy demand, emission and recycling process data are utilized to be converted to a mathematical relationship, which is directly used to calculate the results. These results are in a simplistic mathematical form and hence are very crude in nature. To quantify the critical areas a detailed thermodynamic study is included in the formulation. This gives a result very much near to an actual value (Meng, 2017). The major shortcoming of this study is that it is focused on one particular process and material type which is not always the case and hence, a wider generic model may be required. Moreover, composite is not always used in its pure form but, is used with many materials in combination and such combinations are not taken into consideration.

2.2.4 Manufacturing Techniques in Composites

Manufacturing techniques involve time and resources which affect the cost estimation. To effectively develop cost models, it is important to understand various manufacturing techniques. In the case of composite materials, manufacturing usually means fabrication. However, as new families of composites have been developed, the term manufacturing in composites has acquired a wider scoping (Gardner Business Media Inc., 2014). Manufacturing in composites can be classified in many types depending upon the category they fall into. There can be both mechanical and automated techniques in each of these categories. The techniques used for composite manufacturing from various categories are shown in Table 4 (Gardner Business Media Inc., 2014).

Table 4: Category-wise Composite Manufacturing Techniques

Composite Manufacturing Techniques		
Polymer Matrix Composite (PMC) Technique	**Metal Matrix Composite (MMC) Technique**	**Ceramic Matrix Composite (CMC) Technique**
• Hand lay Up • Spray Moulding • Vacuum Bagging • Compression Moulding • Resin Transfer Moulding • Computerised Numeric Control (CNC) Lay Up • 3-D Printing	• Stir Casting • Infiltration • Diffusion Bonding • Powder Processing • Spray Forming • Electroplating • Chemical Vapour Deposition	• Ionic Bonding • Porous Preform Infiltration • Liquid Infiltration • Gas Infiltration • Reaction Bonding • Cold Pressing

The categories of manufacturing processes correspond to the categories of composites and are sometimes unique for a different type of composite. For polymer based composites, hand Lay-up is the simplest process wherein the composite reinforcement and resin are applied manually. Spray moulding on the other hand uses a spray gun or a semi-automated spray machine to spray reinforcement fibers into the mould. Vacuum bagging is a process involving use of silicon or plastic bag to cover the mould and apply resin under vacuum pressure (Gardner Business Media Inc., 2014). Compression moulding is somewhat similar to vacuum bagging but involves the use of compression machinery to compress the mould and have dimensional stability. Resin transfer process involves transfer of resin under pressure in the mould containing reinforcement fibers (Georgia Institute of Technology, 2011). These processes are easy and good for manufacturing auto body parts. For manufacturing metal matrix composite, stir casting process is economical and suitable. In this method fiber reinforcements are introduced in the matrix which is in molten state and the whole mixture is stirred regularly to achieve consistency of the composite composition (Jokhio et al., 2011). For manufacturing large composite structures for aerospace, tape laying process is used, which uses manual and semi-automated machines for laying up of tapes of the fiber that are pre-treated with resin. These pre-treated composite tapes are layed up as defined by the Computer Aided Design (CAD) geometry information of the part. This way a component is manufactured (Grimshaw et al., 2001). If fully-automated tape laying machine is used, mass production can be achieved besides reducing cost per hour of the process. To reduce lead time for fiber reinforced plastics, automated manufacturing is a more suitable alternative for economical and fast manufacturing (Chaple et al., 2013).

The latest innovation in the field of composite manufacturing is 3D printing. In this technique, Poly-Lactic Acid (PLA) is used as a matrix material and filaments of carbon fiber are supplied continuously. A Commercially available 3D printer modified to work with carbon fiber is used to print the part. The results show that this technology is acceptable in making small parts but become non-useful when it comes to structural components (Matsuzaki Laboratory, 2011). By using Knowledge Based Engineering (KBE) techniques, 3D printing can be made industrially applicable and cost effective. A mathematical model to study the mechanical behaviour of a single layer composite made from S-Glass and E-Glass composites, revealed a high level of complexity in the composite material properties. Here, various parameters affecting the mechanical behaviour were identified and mathematically modelled (Al-Mukhtar, 2012). This study being concentrated on a single layer, proved to give uncertain outputs and showed that to model a composite part made up of multiple layers, complexity increases making process study difficult (Al-Mukhtar, 2012).

A vacuum assisted resin infusion moulding method is used for the manufacturing of PMC. Here, dry preform material in the form of fabric is placed in an open mould where a vacuum bag is used to cover the open mould and apply atmospheric pressure for transferring resin. The mould is then heated to complete the bonding process. A programmable logic controller is used in this process which ensures proper control over the entire process (Goren and Atas, 2008). As this process develops void free and high quality composite parts, it seems quite a promising method for manufacturing PMC’s. A review of the modern pultrusion process has been conducted showing different processes and their uses including the types of resins used. The three different zones of the pultrusion process; heat transfer, pressure and pulling are discussed (Fairuz et al., 2014). Here, it is observed that a pneumatic puller is better than a hydraulic one in terms of production rates and manufacturing of high quality composite parts. It is also seen that thermosetting resins play a very important role in the manufacturing quality, and, resins such as; polyester, vinyl, phenolic and epoxy are widely accepted ones for their better bonding abilities (Fairuz et al., 2014). This method for manufacturing is good for manufacturing high fiber content composite materials but needs improvement so as to increase the manufacturing capacity and reduce overall cost. A project for development of an efficient and affordable method to develop large aerospace composite parts reducing cycle times illustrates that, slow material lay-up methods and the increased thermal times are a major cause of high energy consumption (Department of Energy, 2015). Here, a smart system using computerized control of the autoclave and smart susceptors is used. This system precisely controls the temperature in the autoclave and utilizes laser assisted fiber placement technique (Department of Energy, 2015). It is quite evidently observed that advanced automated methods followed by logic control can reduce the manufacturing cycle times, energy consumption and thereby the overall cost.

Some of the advanced manufacturing techniques used in the manufacturing of ceramic matrix composites include infiltration, bonding and pressing. In manufacturing of high density and high performance auto parts such as brake discs and pressure plates, advanced infiltration methods like porous and chemical are used (Garcia, 2017). Here, fiber preform is placed in a chamber and a pressurized liquid or gas infiltrant is supplied. This causes the infiltrant to form an equal coating on the entire fiber mesh creating a very dense structure (Garcia, 2017). This is a very costly process and new automation methods needs to be developed for making this process less time-consuming and cost-effective. Ceramic matrix composites require three basic steps for their manufacturing, namely (i) deposition phase, (ii) infiltration phase and (iii) coating of sealant phase. The infiltration method depends upon the procedure utilized, namely (i) gas method, (ii) liquid method, (iii) powder method and (iv) hybrid method (Naslain and Zamawiany, 2005). All these methods find applications in aerospace which make them very important. Manufacturing processes form a very important part of the cost estimation process, thus proper knowledge of the process along with their cost contributing factors need to be thoroughly understood.

Components manufactured from composites require perfect balance of mechanical properties in all directions of fiber alignment (Anno et al., 2012). To achieve this, automation of some of the tasks is inevitable. Flat charge laminator machine is one such machine modified for the purpose of applying skin on aerospace structures. For manufacturing intricate profiles CNC lay-up machine is used (Anno et al., 2012). Knowledge related to these processes is incomplete and hence the cost effectiveness could not be ascertained. Dry fiber placement technique is adopted using 6 degrees of freedom ‘poly articulated robot’ for the laying-up procedure. Long range movements of the robot are achieved by having a fiber feeding system comprising of flexible pipes. This setup has 120^0 of arm movements which can be used in various orientations to lay fibers as per part geometry (IIT Delhi, 2006). Manufacturing is always a complex activity having a multitude of constraints. The term ‘’Process Planning’’ can be defined as a method of formulating manufacturing tasks in a manner to have cost effective results. Today products need to have a blend of financial, economic, manufacturing and appearance viability. Process planning parameters that are important to a product are listed in Table 5.

Table 5: Process Planning Parameters (Feng and Song, 2005)

Parameter	**Process Planning Requirement**
Requirements	The plan should meet the design, material, manufacturing and stakeholder requirements
Utilization	Manufacturing should be planned to use the full capacity of production facility
Flexibility	The process should accommodate the changes in requirements or technology
Economy	The process should combine as many operations as it can into a single activity
Cost	Process should be designed taking into account the minimum cost of the final product

These parameters play an important role in cost estimation and process planning. Process planning is used to predict cost of a product, process or a factory. An automated process plan could be achieved by using a multi-agent technique (Feng and Song, 2005). An information management model where meaningful relations of information, current state of the system and manufacturing capability knowledge are represented, can be used to achieve a good process plan (Kals, 1999). As the information management system controls the accessibility, availability and the relationships of information, it could be employed in logic generation for cost evaluation. If the manufacturing information in the composite realm is captured, categorised and accurately related to the process parameters, a generic cost estimation can be achieved which can increase the estimate's effectiveness.

2.2.5 Composites in Aero-Engines

Composites have found use in aircraft engines after a need to develop lightweight aircrafts arose. Every different part in an aero-engine has a different type of composite material used for its manufacturing. For example, the fan section of a turbofan engine uses fiber based composites in fan blades, cones, bypass ducts, stator vanes and guiding vanes. Metal Matrix Composite (MMC) are used in compressor and turbine sections of the turbofan engine, comprising of, namely, compressor blades, stator blades, turbine blades and discs. Ceramic Matrix Composite (CMC) are mainly used in the combustion and exhaust sections of the turbofan engines usually in areas like combustion linings and exhaust nozzle (Bohar et al., 2016). A study has revealed that using SiC composites in the high temperature sections of an aero-engine not only helps in the weight reduction of the overall engine but also improves the heat transfer ability, thereby improving overall efficiency. Parts like combustion chamber and turbine blades are coated with a lining of CMC. This coating helps in resisting heat and the engine can extract maximum possible work from hot exhaust gases. The durability of the parts also improves to a great extent by the use of CMC coatings. These mechanical and thermal benefits makes the use of CMC in future light weight and high efficiency engines inevitable (Zok, 2016). Aerospace industry has started using composites in areas which require both high performance and safety. The use of composites have been made from all the three basic classes. Polymer Matrix Composite (PMC) are used in structural and load bearing parts of the aircraft including certain tertiary parts. MMC are used as replacement to conventional materials in parts requiring special properties. The ease with which a material property may be engineered in composites makes it a right choice for use in complex and challenging environments. Properties like heat resistance, electrical conductivity, weight, density, thermal resistance and magnetic property are some of the examples. Different metal based composites show different benefits. Al-MMC show a benefit of light weight and high strength and finds use in mechanical components requiring strength. Ti-MMC, however, provides great heat resistance coupled to light weight and thus is mostly used in high temperature applications. For high corrosion resistance, acidic resistance and high temperature coating applications CMC is found very useful. These coatings have also been used in space applications (Toozandehjani et al., 2018). Although these materials are beneficial a thorough understanding of the properties and application is required for improving their performance and increase their applications.

As the use of composites in commercial aircrafts and space industry increased, so has the need for development of advanced engines. Composites are chosen for many parts of these engines. Fan blade uses PMC which is coupled to the exoskeleton design of the blade. The skeleton is made by using conventional material and the skin is made by PMC. This way a hybrid blade is manufactured which is light in weight but is more efficient. The natural frequencies are lower even in subsonic speeds thereby reducing noise vibrations (Abumeri et al., 2004). It has been seen that these types of designs prove to be highly reliable. The only drawback is that analysis similar to cost, mechanical and design cannot be done in advance which makes it costly in manufacturing. There has been use of CMC in turbine parts of jet engines. This application includes a coating applied on the conventional turbine parts, thereby increasing their thermal resistance. This, in turn, is useful in increasing thermal efficiency of the turbines. There is a reduction in the hydrogen attack observed with turbine parts coated with CMC. These composites are mostly used in the inner linings of the turbines and their blades (Herbell and Eckel, 1992). CMC have also been used in the gas turbine engines. Parts like cover plates, shrouds, combustion liners, seals, tailcone, augmenter liners and nozzles are made up of different categories within CMC. Some parts are manufactured using fiber reinforced or metal reinforced CMC and others are coated with Silicon Carbide (SiC) based CMC (Schmid, 1992). These parts perform both primary and secondary functions in an engine and are an integral part for the functioning of an engine. Various design configurations have been developed, namely (i) 3D Cylindrical, (ii) 3D Orthogonal, (iii) 3D Interlock, (iv) 3D Interply and (v) 4D Layup. These configurations helps in increasing the stability and performance of the parts using composites (Schmid, 1992).

Application of composites are also found in the turbo machines specifically used with aerospace engines. These machinery have impeller blades that are manufactured using CMC. These include a category of CMC where metal fibers are reinforced into the SiC based CMC. This is helpful in absorbing vibrations and increasing damping characteristics. Even the blisks made up of the same material showcases an increase in the damping characteristics, thereby reducing vibration triggered cracks (Min et al., 2011). All these applications of different composites in various parts of the aero-engine confirm that composites are beneficial in the manufacturing of these parts and to predict the performance of these parts it is very necessary to develop cost estimation methods for composites.

2.2.6 Discussion

Composites have long been used by man and its history spreads to uses from simple household items to more complex modern engineering applications. The vast majority of composites are from polymer class which find applications in many different areas from automotive to aerospace. Metal Matrix Composite (MMC) and Ceramic Matrix Composite (CMC) have been used with specific features so as to develop advanced machines. These composites provide the desired features and still reduce the overall weight of the component. Composite manufacturing has been done by both manual as well as automated methods. These techniques have proven to be very effective, but have showcased a problem of being very costly. To reduce the cost of design and manufacturing, productivity needs to be increased which requires, mass manufacturing in less time and proper cost analysis, well in advance. Manual manufacturing methods are time consuming but less costly. Automated methods on the other hand provide a better production rate but are costly in the first place. There is a trade-off between quality and cost. To precisely utilize the potential of composites, it is important to understand the categories, manufacturing, application and cost impact of composites. This section has discussed all these areas in detail. Here, it has been observed that besides the usual benefits, cost evaluation is an area which has not been looked into in the level of detail as required. This has led to very less understanding of the areas contributing more to the overall cost which is very important while making an engineering decision or developing a project plan. Specifically, for the applications in the aerospace sector, very less work has been carried out to understand the cost impact of changing material choices for manufacturing various parts. The cost estimation methods developed are more concentrated towards simple parts and that too from automotive sector. Moreover, only a particular manufacturing process has been chosen for such a study. This study is thus incomplete and requires more in-depth knowledge management.

2.3 Knowledge Based Engineering (KBE)

2.3.1 Basics of KBE

Knowledge Based Engineering (KBE) is an innovative way of capturing, categorising, coding then modelling and reusing tacit, explicit and implicit Knowledge Information and Data (KID) relating to processes and/or products, thereby giving industries the capability to rapidly develop new products (Birmingham City University, 2011). KBE has Knowledge management (KM) and Knowledge Management System (KMS) as integral parts, which capture, then reuse methods to make such knowledge automatic. There are three basic types of categories of knowledge that are shown in detail in Figure 5.

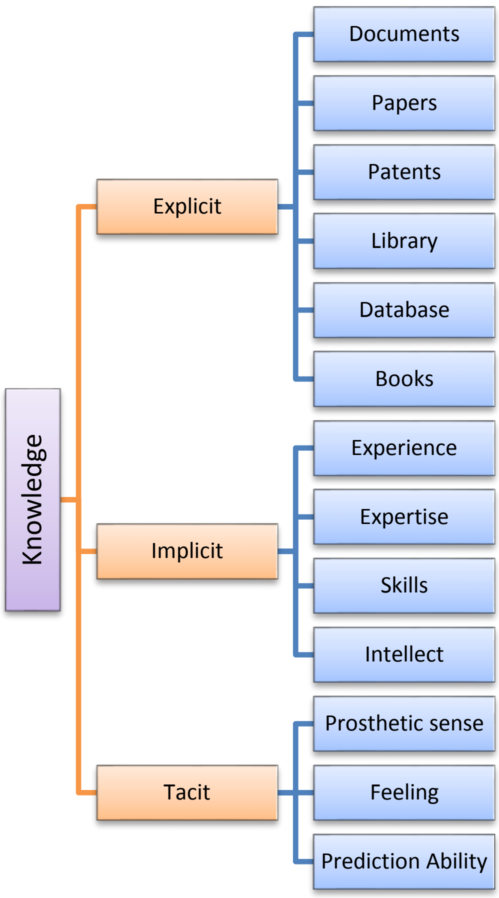


Figure 5: Categorization of Knowledge

Explicit knowledge is the documented or physical form of knowledge which can be physically understood or experienced. Implicit is the knowledge inside the head of a person or something related to practical knowledge gained by a person over time and can be documented if recorded in a proper format. Tacit is a knowledge of sense and relates to a person's own ability to sense an outcome, may be due to his own knowledge or experience, and is, therefore, difficult to document (Massachusetts Institute of Technology, 2011; King, 2009).

KM is an integral part of KBE. In KM, knowledge, which is defined as the ability to understand problems gained through experience and study, is coupled to management, which is defined as systematically arranging, distributing and using something to its maximum possible efficiency. Information and data, though being an important part of knowledge, have different meanings and applications when taken separately. Data is something which is very rough and has no utility on its own. When a relationship of this data or another data is made to form a meaning, the data gets converted into information. A database is a usable form of information which is physically stored for reuse. KM is the creation of an information platform to create a system of knowledge acquisition, categorization, keeping and reuse. The application of KM has been seen in many areas inside of an organization. Some of the key areas include research & development, human resources, operations, marketing and Information Technology (IT) (Tutorials Point Pvt. Ltd., 2015).

KMS employs computer based architectures to capture, refine, categorize and automate knowledge for reuse. KM process follows a life-cycle which defines a steps that KM has to follow or can be called as the building blocks, as shown in Figure 6.

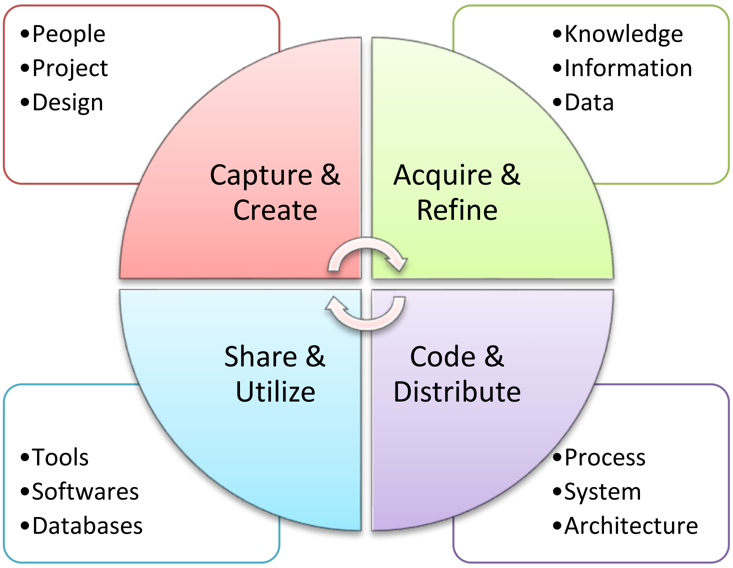


Figure 6: Knowledge Management Life-cycle

The different phases contributing to the whole process starts by capturing knowledge in a crude form which is then refined and categorized in three basic forms knowledge, information and data. After a relevant refinement has taken place, a process of codification is carried out which converts the human understandable knowledge into machine understandable form. From here, the final phase of utilization is reached where the entire knowledge base created is used for doing specified work. People, Knowledge, Process and Tools form the four most important pillars of KM process (King, 2009; Tutorials Point Pvt. Ltd., 2015; Mohammed et al., 2008). Most organizations use two basic KM strategies – (i) codification: the method of coding knowledge in computer codes and making it easy to use; and (ii) personalization: the way of creating knowledge by discussions, maps, intranets and posters etc. and works on the social aspects of knowledge (Mohammed et al., 2008). Applying knowledge-based reasoning to the design process can reduce the need of redesigns and rework. Design rules are coded in 'if-then' format using 'and-or' Boolean algebra. Case-based reasoning can be applied to the rule-based reasoning to achieve a high level of automation (Scacchi and Mi, 1997). The KM process is useful in distribution and reuse of knowledge in a systematic fashion to people requiring it in different stages of the process. There is substantial information embedded into the KM system. This includes, relevance, customer requirements, engineering principles, operations and investment. As the knowledge flows from level 1 which is the user tools and moves to the mature state of knowledge systems, the knowledge growth is much higher. It has been seen that in the near future, for organizations to grow in business size, knowledge management will be extremely necessary (Gerami, 2010). In a study it has been seen that KM has wide application in organizations but, proper understanding of the need and importance needs to be made (Gonzalez and Martins 2017). Here, it has been observed that KM processes are helpful in increasing the efficiency of an organization on a whole but, needs a lot of storage capital. This is a fact as KM strategy needs a strong database which is created while knowledge is acquired, refined and coded and it needs a significant amount of storage space to accommodate such knowledge. Knowledge keeping is another aspect which needs a thorough study (Gonzalez and Martins 2017).

Knowledge Based Information System (KBIS) is another domain of KBE where model-driven information system is coupled to knowledge-driven system. Model-Driven Engineering (MDE) forms the basis of this system by utilizing enterprise and transformation models together to come up with a knowledge-based intelligent model. Main driving elements of the model are, user, system engineer, subsystem, tool and developer. Different models are created for catering to the different phases of the process. Case models, functional model, activity model and requirement model all are included in this method to come up with the final consolidated result (Lopata et al., 2012). It is observed that KBE based information system acts as an intelligent object-oriented database which can be utilized for complex problems. One of the drawback with such a system is that it is useful under specific engineering applications and is not generic in application to other problems. KBE is very important in strategic planning for big companies. It has been found that 67% of the big companies agree that KBE and KM has helped them achieve their goals successfully. It has also been observed that if companies need to remain competitive in the market, design time, operations time, cycle time and development time must be reduced. To achieve this KBE is found to be very effective and necessary (Bhojaraju, 2005). KMS has been very successful in controlling and managing knowledge across systems and also maintaining higher efficiency in terms of its reuse. However, KMS works on two types of models, namely, (i) model 1: utilizing information from predetermined attributes in a system and (ii) model 2: utilizing experience and intellect of persons involved in that system. Every business needs a flexible and agile KMS which can be achieved by completely understanding and coding knowledge and keeping it in cost effective and flexible way. One of the main reasons of the failure of KMS is that it cannot adapt to the changes of business requirements (Malhotra, 2002). It has been seen that KBE is a very useful tool but it needs improvement specifically in its flexibility and robustness so as to be more applicable to vide fields.

2.3.2 KBE Approaches & Techniques

Every product has a life-cycle which is a summation of all stages a product has to go through to reach its finished state. Meta-modelling and modelling construct the organizational process model, which contains relations of tools, tasks and resources (Massachusetts Institute of Technology, 2002). If Knowledge Based Engineering (KBE) is used to simulate the model, a high degree of effectiveness can be achieved. Knowledge-based design management helps in solving engineering problems by acquiring, assimilating and formalizing the stakeholder's requirements into a knowledge base (Chapman and Pinfold, 2001). If Multi-attribute Interview Software Tool (MIST) is applied to incorporate the stakeholder's requirements into the design process, a single unified system of knowledge-based engineering design can be achieved. Knowledge Based Engineering System (KBES) has seen application in Body-In-White (BIW) structural design and analysis. BIW is an empty shell of a vehicle without paint and accessories. The problems encountered by BIW designers are solved by capturing design and constraint knowledge. Design Analysis and Response Tool (DART) omits the need to create a separate model for analysis, thereby, reducing duplication of Computer Aided Design (CAD) model and design time. This system has been successfully applied in the automotive sector (Singer and Borrmann, 2015). The potential of such a system is quite significant and with some modifications it may be applied to other fields of engineering.

KBE has also been applied to infrastructure design and planning where the technique combines a knowledge-based system with Building Information Modeling (BIM). Abstraction Layer Concept (ALC) for hierarchical structuring is used which opens door to cost effective and high quality planning (The Pennsylvania State University, 2000). This methodology has shown a great potential in KBE approach for cutting down time and cost. Using Methodology and tools Oriented to Knowledge-based Applications (MOKA) and Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications (KOMPRESSA), product knowledge of an enterprise can be managed to ensure quality and value as the product follows a life-cycle. The framework made by using various programming languages can be applied to standalone applications, linked applications in the company and linked applications between companies to make knowledge manageable (Petter et al., 2011). KBE gives an ability to reuse manufacturing experience and implement it into the design system. This introduction of experience automates repetitive tasks, hence reduces effort (Van Der Laan and Van Tooren, 2008).

A method to incorporate cost in the design phase has been developed using knowledge-based techniques. Here, manufacturing and assembly data are extracted from the parametric movable model which is used in combination with bottom-up approach to make reliable Cost Estimation Relationship (CER)'s, which is further utilized in cost estimation with reliable outcomes (Hale and Schueler, 2002). A knowledge-based software tool for manufacturing, design and analysis has been developed using object-oriented knowledge representation from Parametric Composite Knowledge System (PACKS) and Steered Composite Analysis and Design System (SCADS). An "IS-A" relationship is used to represent inheritance and "HAS-A" to represent structure in Adaptive Modeling Language (AML) environment. Thus, a developer is able to define any object or sub-object and its attributes which automatically supports collaborative design. The benefits of such a system include, reduction in cycle time, higher clarity earlier in the process and saving in engineering labour time (Marino and Chemaly, 2002). Another use of AML is in the object-oriented modeling framework. Communication of design followed by implementing specifications using organized knowledge is done on different attributes of the model. Design parameters, part specifications and object features define the cost dependency of each attribute. Different activities are mapped using Activity Based Costing (ABC) approach. The overall cost of a system is the addition of all the module costs (Lee and Lee, 2007). This method is good for having 'what-if' analysis quite early and have a reasonable cost estimate.

Knowledge Management (KM) being an integral part of KBE, has been applied to many problems relating to organizational management from human resource planning and activities to software tool generation and from manufacturing planning to process planning (Rasula et al., 2012). With the use of Information Technology (IT), it could be applied to customer and financial planning to reduce time. Organizational performance can be enhanced by the use of

KBE techniques. Capturing the precise data combined with organizational culture gives information related to 'how' and 'why' of the knowledge which could enhance organizational management (Sainter et al., 2000). KBE and KM tools can be used in the same manner to capture the composite knowledge, put it into a single unified system and make it reusable. A new system comprising of different KBE approaches has been used in the material handling equipment design (landschuetzer et al., 2011). Here, input parameters are taken as design constraints and rules are applied on top of it using constraint classes. These are applied using fuzzy logic which controls the shape, design and size to be handled. As all the material handling equipment's work on the principle of the amount of load to be put on them, hence, design features are directly used to calculate the weight (landschuetzer et al., 2011). Now, the design features drive the selection of material handling equipment and in this way the entire Material Handling Engineering Division (MHED) is automated. Storage and retrieval is very important in the material handling realm. This is automated by using CAD-KBE model and incorporated into the Automated Storage and Retrieval System (AS/RS) model. New constraints are added in this system which include customer requirements, design specifications and manufacturing/production requirements. The whole process now becomes an advanced MHED, which has three basic phases, (i) classes of rules phase, (ii) functions of features and reliability phase and (iii) outcome benefits phase. This whole system is then integrated into CAD which brings it into the design phase (landschuetzer et al., 2011). The drawback with such a system is that it does not handle live feeds from the system which are necessary if there is a design change or a machining change that changes the requirements altogether.

A KBE based system is employed in the new product development of an aerospace industry. Here, Activity Based Performance Measurement Methodology is applied to a product development scenario for an Italian firm. Knowledge capturing is done using a method of interviews done by interviewing people from different backgrounds namely, (i) design, (ii) Research and Development (R&D), (iii) product engineering and (iv) production. CAD and Computer Aided Engineering (CAE) are incorporated together with Design Measure Analyse Improve Control Methods and Six Sigma approach (Corallo et al., 2010). KBE based tools were mainly developed as an outcome of this research, namely, (i) CTX Vane Creater: which utilized the design constraints and rules to create a design model and (ii) Gear Generator: which utilized information exchange between different platforms to come up with a parasolid format. The use of this system has showcased 90% reduction in modeling time and 60% saving in the overall cost (Corallo et al., 2010). The drawback in such a system is that it is based upon design constraints as the main driving force, however, there are many factors like, capital investment, customer requirements, legal obligations and production facility that have not been considered.

KBE has an important part which is key to the effective use of the services. This part is called knowledge sharing. A study has revealed three approaches that can be used in a KBE system. The three services can be understood as (i) point-to-point service sharing: two systems dependent upon each other solve a problem by logics which call for functions from each other to come to a solution, (ii) neural interchange: two systems exchange knowledge via an intermediate function that is controlled by neural logics making it dynamic and more accurate and (iii) neural authoring: a form of translation which keeps the knowledge in one neural language and sends it to the target output requirement in the same language reducing the number of exchanges or intermediate functions required to handle the same amount of data (Uschold et al., 2000). All these can translate between different ontologies and can create a universal language like Very High-speed Hardware Description Language (VHDL) for knowledge sharing. There is a drawback of excessive use of power in the form of computational requirements hence, this needs modification. A knowledge-based software system has been developed for space explorations (Narayan and Pandey, 2014). This Knowledge Based System (KBS) is capable of understanding features of space objects and can carry out space explorations based on previous knowledge and live feeds from a mission. In this system, a selection-based sampling of asteroids is done and a knowledge based software compares it with previously collected data. This is then fed to the robotic system which can perform qualitative and quantitative analysis. A combination of neural networks and fuzzy logic is used to process the information and select between various functions based upon the geometric model of the asteroid (Narayan and Pandey, 2014). This system, being still under study, lacks validation and is constantly upgraded for better performance. KBE has now become a part of many organizations, but one of the big problems with KBE is the lack of standardization. Retaining the value and usefulness of knowledge in a KBE system needs to be maintained. Some of the issues like knowledge loss, knowledge misuse and improper utilization of knowledge needs improvement (Resatsch and Faisst, 2004).

2.3.3 Benefits of KBE

The benefits of Knowledge Based Engineering (KBE) are wide and have been highlighted in several previous research works. A measurement approach for performance measurement of the Knowledge Management Initiative has been proposed in one such research at SGL CARBON. Here, it has been observed that the initiative has a considerable impact on the decision making at early stages and can highlight the problems much earlier in the decision making phases itself. Cost monitoring and tracking of the process is another benefit that the initiatives provides (Kumar et al., 2014). An application of KBE is seen in Computer Aided Design (CAD) where previous knowledge related to the product, process and manufacturing experience is coded in the CAD software itself to provide a helping tool for the designers and project planners. KBE is used to merge three attributes necessary for design automation, namely (i) artificial intelligence, (ii) object-oriented programming and (iii) design automation. Major companies have benefitted from the use of KBE and have developed advanced systems. These are namely, (i) Lotus Engineering: Integrated Car Engineer System, (ii) Jaguar Cars: KBE System for time reduction in bonnet manufacturing and (iii) The Boeing Commercial Airplane Group: KBE Airplane Knowledge System (Voss and Overend, 2012). The use of KBE is not only limited to automotive design and manufacturing, but has been found to be equally beneficial to other realms. In the design of buildings, it has been seen that Building Information Modeling (BIM) plays a very important role. KBE is applied to the BIM to make it flexible and more re-usable. A study conducted on the application of KBE for tool building in the BIM was seen using rule-based knowledge management technique (Joshi et al., 2009). Here, for the façade design manufacturing, constraint knowledge is captured using the geometric design information which is stored in Industry Foundation Classes (IFC) format. The design outcome map is coupled with the manufacturing information and a tool is made capable of live capture and reuse of expert knowledge (Joshi et al., 2009). This has helped the façade designer to be more innovative in design and has reduced his/her efforts. Another important application of KBE has been seen in the conceptual design for an airship. The design information from the Unigraphics NX™ software is extracted and combined with the material and process information. This is coupled to the basic airship hull design and assembly. The information which the Unigraphics NX™ files generate is assembled as per the principles of KBE. This way a Three Dimension (3D) airship model is specified using the volume information (Shehab et al., 2002).

KBE is found to be useful in both increasing the productivity and decreasing the design time bringing about complete design automation. Software tools such as Product Engineering Optimizer Workbench utilizes the KBE techniques in keeping the information as a master document, which enables part information, assembly information, design rules and production rules to be used in the KBE system. These master files are then interrelated to come up to an optimization trade off. Design automation is thus one of the widely accepted KBE benefits (Biahmou et al., 2007). Another application of KBE is seen in the design and manufacturing of an aircraft nacelle model for wind tunnel tests. The tool used to achieve this was ICAD which used object oriented programming for codification purposes. The design tasks were divided into functional units and then these functional units were broken down to smaller problems for reasoning to come up with a solution. Later this solution was passed on to the ICAD which combined the geometrical information to the solution in a reliable fashion (García and Fan, 2002). This has been a very good solution, but due to its bulky nature and complex architecture, other powerful methods cannot be ignored like ontology, machine learning and artificial intelligence.

KBE has also been applied to aircraft structural maintenance, repair and overhaul. This is one of the major applications specifically in the after sales service phase of the product life-cycle. These are highly labour intensive jobs which includes working in critical areas like, line, airframe, engine and components (Infosys Limited, 2017). A KBE system is applied to this problem and major activities are distributed based on Work Breakdown Structure (WBS). The entire procedure is coded coupling the component CAD design to KBE system which enables easy location of problems and necessary repairs. Later the problem is divided into activities namely, (i) damage location, (ii) damage categorization, (iii) repair requirement, (iv) repair design and (v) repair execution. Previous history of the repairs are included for validation and cross checking. All this is automated using an object-oriented programming language platform thus reducing cycle times and increasing efficiency (Infosys Limited, 2017). This method of using KBE for aircraft maintenance is state of the art and is now being used as standard among the industry. There has been wide use of knowledge-driven technologies that have gained their pace in the recent years specifically in the aerospace sectors (Kortbeek et al., 2018). The areas where most of the development in terms of applications of KBE and KBE-based system has been taken place includes, (i) aircraft structures: wings, wing boxes, movable parts, fiber-based structural parts and laminates, (ii) engines system and components: compressors, power units, casings, seals, turbines, shrouds, blades and starter motors, (iii) after sales: overhaul, service, corrosion monitoring, health monitoring, complete system checks and part handling, (iv) aircraft systems: internal and external systems and interactions and (v) concepts: design, prototyping, analysis and manufacturing. These applications make the KBE system very important in both new and old aircraft structures (Kortbeek et al., 2018). For reducing the product development time in a landing gear design KBE is used in the CAD/ Computer Aided Manufacturing (CAM)/ Computer Aided Engineering (CAE) phase (Infosys Limited, 2017). The design models are evaluated for mechanical, financial, machining and aerodynamic behaviours by coupling the CAD/CAM/CAE model information to the rule-based information from respective subsystems. Health and maintenance systems developed using KBE techniques for the aircraft's landing gear helps in diagnosing and correcting any problems faster than usual, saving time and money. Information like tire wear, tire pressure, ground floatation, brake size and load estimates are fed by the KBE system direct into dynamic simulation resulting in speedy health monitoring and virtual system checking (Infosys Limited, 2017).

Another important use of KBE is seen in the virtual reality applications that are custom designed for various industries. These include applications such as training simulators, Virtual Reality (VR) design & prototyping tools, 3D design studios and sales & service simulators (Gorski, 2017). All these applications demand high amount of computational power and a bulky system. The knowledge hierarchy followed here is planning, preparing and programming. Such kind of virtual systems are also used for knowledge sharing and reuse among the industry specifically to train using virtual teacher, a tool prepared using KBE methodology 'Methodology and Tools Oriented to Knowledge-based Applications' (MOKA) (Gorski, 2017). It can be said that benefits of KBE are immense and the applications can be in any fields. In cost estimation, however, this system needs to be less bulky and maintainable.

2.3.4 Cost Applications of KBE

An intelligent approach of cost estimation utilizing Knowledge Based System (KBS) has been used for product cost model. Hybrid knowledge representation and object-oriented framework are employed. Fuzzy logic is used to deal with the uncertainty in information (Shehab et al., 2002). This system, besides estimating costs, can also be used for process planning. Integration of design and Knowledge Based Engineering (KBE) techniques are used to develop design for automation. The integration of KBS with the material and Computer Aided Design (CAD) database is used to develop reliable cost estimation. This system unifies cost modelling with process planning and design automation (Choi and Woo, 2009). It can generate cost estimates taking feature as the basis and provide flexible outcomes. An architecture using KBE techniques for cost estimation of the composite airplane structures has been proposed. This system extracts data from CATIA V5^{TM} geometric model. The knowledge so extracted includes design, process, manufacturing and fabrication details of a component. A component level knowledge acquisition is done which is used for estimating weight and cost (Zhao et al., 2015). The knowledge base created and the inference engine of CATIA V5^{TM} cannot only automate the design process but can also be used for cost estimations. An integration of the Cost Breakdown Structure (CBS) with the Product Breakdown Structure (PBS) is used to obtain a cost estimation tool for aircraft component. This cost tool is integrated to the KBE application having design information. Breakdown of activities in a product life-cycle is used to assign geometry parameters which are assigned with cost values. Aggregating the entire life-cycle estimates gives a cost estimate of a part (Verhagen and Wim, 2012). Use of Knowledge management (KM) tools for aircraft programs have shown a huge potential in KBE system. A knowledge-based cost estimation of a composite part has been developed. KM principles are utilized for this purpose. Exploitation, visibility and life-cycle management of the knowledge are applied. This type of approach has shown great potential of KBE in composite part cost estimation (Hale and Vasey-Glandon, 2001). Besides having benefits, there are certain drawbacks, namely, (i) not fully automated, (ii) improper and incomplete knowledge base for composites and (iii) incomplete utilization of KBE's full potential. Parametric Composite Knowledge System developed through "The Boeing Corporation" for its composite parts utilizes embedded knowledge captured from design, analysis and manufacturing. This system works like a "design for manufacturing system" and utilizes input data in the form of geometry parameters. Analysis is conducted based upon the refined data and process outputs are generated which are used for manufacturing purposes (The World Bank Group, 2011). The benefits of this system are: (i) it is robust, (ii) it reduces cycle time and (iii) it has higher clarity in decision making. Lack of being flexible and dependent on geometry parameters make its application difficult in fabrication type manufacturing processes.

A design to cost system for injection moulding uses the object-oriented knowledge representation and utilization. Here, CAD, material selection module, KBS, process optimization and cost estimation module are integrated together to function as a unified system. Design information is used to develop a model which is then passed on to material selection and process optimization through KBS. Cost estimation is done based upon the machining process selection and geometric complexity (Wim et al., 2010). As the system is designed for a particular process, it does not cover the entire manufacturing possibilities for a composite part. A research method to develop knowledge-based environment with a process-based cost estimation tool encoded in spreadsheet format was proposed and analysed in an aero system (Van Der Lan, 2008). Here, the complexity of the process was dealt with by breaking down the process into smaller components and then applying KBE tools and techniques to manage life-cycle, exploitation and visibility of the components. Validation was achieved by applying the proposed method on a wing top (Van Der Lan, 2008). The limitation of this research method was that it worked on incomplete data which was used for development of the cost modelling tool and as a result gave uncertain outputs. KBE has been used in cost estimation of the aircraft design (Van Der Lan, 2008). Here, parametric cost modeling, analogous costing, bottom-up approach and top down costing all are independently used based upon the design requirements. A multi-model generator is utilized to describe the data files and a design and engineering engine is utilized to form closed loop in the optimization process. This is useful in the transfer of data and interchange of data between different modules of the KBE system. Later multi-functional CAD is added to the optimization and manufacturing specifications developing a movable Design and Engineering Engine, enabling cost estimation selection in the very design phase ensuring "design to cost" capabilities (Van Der Lan, 2008). The drawback with such a system is its bulky design and dependency on the design and manufacturing constraints. The dependency of a model to understand only design and manufacturing constraint does not include other processes which may contribute even more to the overall cost.

A capability benchmarking tool utilizes KBE for cost estimation and cost monitoring (Shermon and Gilmour, 2013). This tool is useful in understanding the cost capabilities and engineering design capabilities inside an organization. This helps in understanding cost impacts and identifying areas of improvement for better efficiency and higher competitiveness. A QinetiQ's KBE method is employed to develop a cost capability inside an objective assessment framework that assesses outcomes against industry standards. The building blocks of this process remain people, knowledge, process and tools which are standard KBE building blocks. Historical data coupled with statistical tools then evaluate a cost estimate which is then verified against company standards. This way the outcomes become traceable and reduce assumptions (Shermon and Gilmour, 2013). This method is very crude in form and does not discuss about its automation process. Two KBE methodologies namely, Methodology and tools Oriented to Knowledge-based Applications (MOKA) and Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications (KNOMAD) are applied to the façade sector and cost attributes are coupled to the methodology to bring about complete optimization (Montali et al., 2017). The bigger problem is first divided into smaller problems of design, material, requirements and location. All the relevant information is captured and designated to the relevant attribute in the façade design. This way every aspect of the façade has its set of information tagged to it which is managed using KBE methodologies, either MOKA or KNOMAD. Cost functions are applied as rules on top of the information class and an outcome can be predicted along with façade design process (Montali et al., 2017). This is a unique system of utilizing KBE in façade deign and cost but is not verified thoroughly and lacks proper knowledge thereby needing vast improvement.

Knowledge sharing is used in many companies by employing KBE taxonomy so as to reduce costs by adapting a first-time-right theory (Curran et al., 2009). This is done by implementing KBE techniques and capturing tacit and explicit knowledge from various phases of the product development and refining that into cases, methods, rules, algorithms and parameters. This then becomes a more usable form of knowledge that can be fed to KBE based applications and expert systems for automation and multi-disciplinary conceptualization. This methodology is further utilized to visualize manufacturing and production costs by using Cost Estimation

Relationship (CER)'s in the KBE system. Uncertainty analysis is also a part of the model, hence accuracy of the estimate can be enhanced. This method has been applied to aircraft fuselage where manufacturing and assembly costs are predicted (Curran et al., 2009). This method is good for early cost predictions, but due to a complex structure and high computational power requirement, is not widely acceptable. Another use of the KBE based costing is in the aircraft box structures (Dijk et al., 2012). Here, different modules relating to different aspects of the design optimization are considered. NASTRAN 105 Solver has been used for validation of sizing which contributes to the design related information necessary for other related actions in the modules. This information is related to the cost information using advanced KBE feature via a design engineering engine framework. Material cost is derived from the material database and the labour cost is derived from manufacturing times. The manufacturing cost is derived from the parent classes containing production information as subclasses (Dijk et al., 2012). This way a cost estimation module is reached. This module follows a series of steps to automate the entire process namely, (i) geometry division: categorization of manufacturing and assembly steps, (ii) defining properties: giving property attributes to a category, (iii) assign a code: define a code for the related process and (iv) generate estimate: transformation of knowledge into a value for use. This way an estimate is prepared which can be used for optimization (Dijk et al., 2012). One of the drawbacks with this system is its dependency on a particular type of part or material.

In the value chain KBE has been utilized to estimate cost. This is done by utilizing the KBE's potential of design automation and incorporate it into the Value Analysis and Value Engineering (VA/VE) framework for value chain. The design and redesign loops are controlled by the KBE system, which interacts between the design and the production modules within the system. Besides the usual constraints from the design and manufacturing phases, customer requirements and analysis phases are added using VA/VE framework. This increases effectiveness of the whole system and is knowledge-based itself. Cost reporting is added as a feature to represent the cost as per company standards (Unde and Krishna, 2016). This method enables a standardized system of cost evaluation and representation, but as it consumes a lot of time in iterations and lacks complete information, it still needs improvements. In the construction cost estimation, KBE is used to automate the process of cost evaluation by using a feature-based design pull system that is coupled to Activity Based Costing (ABC) platform. The feature-based design pull system converts the design into various features like, walls, windows, beams, circular arches etc. These features contribute to the amount of complexity involved in a design and drives the process of defining activities that become associated to the design features. These activities are then further associated with the resources they consume. Combining different activities depending upon the feature of a particular design, an overall estimate is made (French et al., 2003). This system is one of the simplest systems of cost evaluation and is easy to use and apply. The major drawback with such a system is that it requires precise information of the activities and resources which sometimes become difficult especially for new designs which have not been developed earlier.

A hybrid KBE-based cost estimation method utilizes concurrent engineering and lean manufacturing coupled to KBE technique for cost evaluation and optimization (Wasim et al., 2013). Object-oriented and rule-based methods are utilized for knowledge representation and management. Different processes such as material selection, manufacturing, machine selection and tool selection are assigned parametric values. Process parameters are grouped together based upon the output and requirements to evaluate cost. This is represented in a neutral format for easy access and reuse (Wasim et al., 2013). This system, although being useful, is very complex in its structure and requires special training to be effectively utilized.

2.3.5 Discussion

Knowledge Based Engineering (KBE) is a process of capturing, refining, categorizing, coding and reusing Knowledge Information and Data (KID). This process involves utilization of four important pillars, (i) people, (ii) process, (iii) knowledge and (iv) tools. The interaction of knowledge constantly circles between these pillars. Methodology and tools Oriented to Knowledge-based Applications (MOKA) and Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications (KOMPRESSA) are the simplest ones in terms of its structuring but not that practically acceptable. Feature-based, rule-based and model-based are some of the newly developed methods and techniques which have been used in many industries but are bulky and complex in their design. Advanced methods include use of fuzzy logics and neural network. These methods though very useful in automation of knowledge are very bulky and highly complex. They also require special tools and techniques to maintain and is something for which highly skilled labour is required. The use of KBE has been put forward by many companies ranging from automotive to aerospace and construction to education. These companies have shown that KBE can be used to improve productivity, decrease cycle time, increase innovation and increase profitability by around 60%. One of the major drawbacks with a KBE system is that it is complex in architecture for big enterprises. Another drawback is that there is a serious dependency on the quality of knowledge captured. It is a well-known fact that to develop KBE systems, high capital investment is needed. This is sometimes even higher when large database requirements and complex features are to be handled, which require high computational power. Developing and maintaining KBE systems require special skills and the tool although is easy to use, the KBE system itself is complex to understand. The benefits like object-oriented structuring, standardization of knowledge and vast applicability overpowers some of its drawbacks. This system is highly beneficial but some improvements need to be made to make the system easy to use and easy to maintain.

2.4 Cost Estimation & Modelling

2.4.1 Basics of Cost Estimation

To understand cost estimation it is important to understand three main important constituents of it, namely, cost, cost drivers and Cost Estimation Relationship (CER)'s (The Institute of Cost Accountants, 2014). Cost may be defined as the ability to evaluate resources consumed by an activity or a process in terms of a monetary value for delivering a service or a product. Sometimes a work cost centre is used to define cost in industries. This refers to an accumulation of all the costs incurred for a particular resource or an activity such as a product, service, plant, machine or a factory. Cost can be classified in many ways which depend upon the activity or a resource consumed. For this research an intense classification is represented in Figure 7 which includes all the identified methods of classification (The Institute of Cost Accountants, 2014).

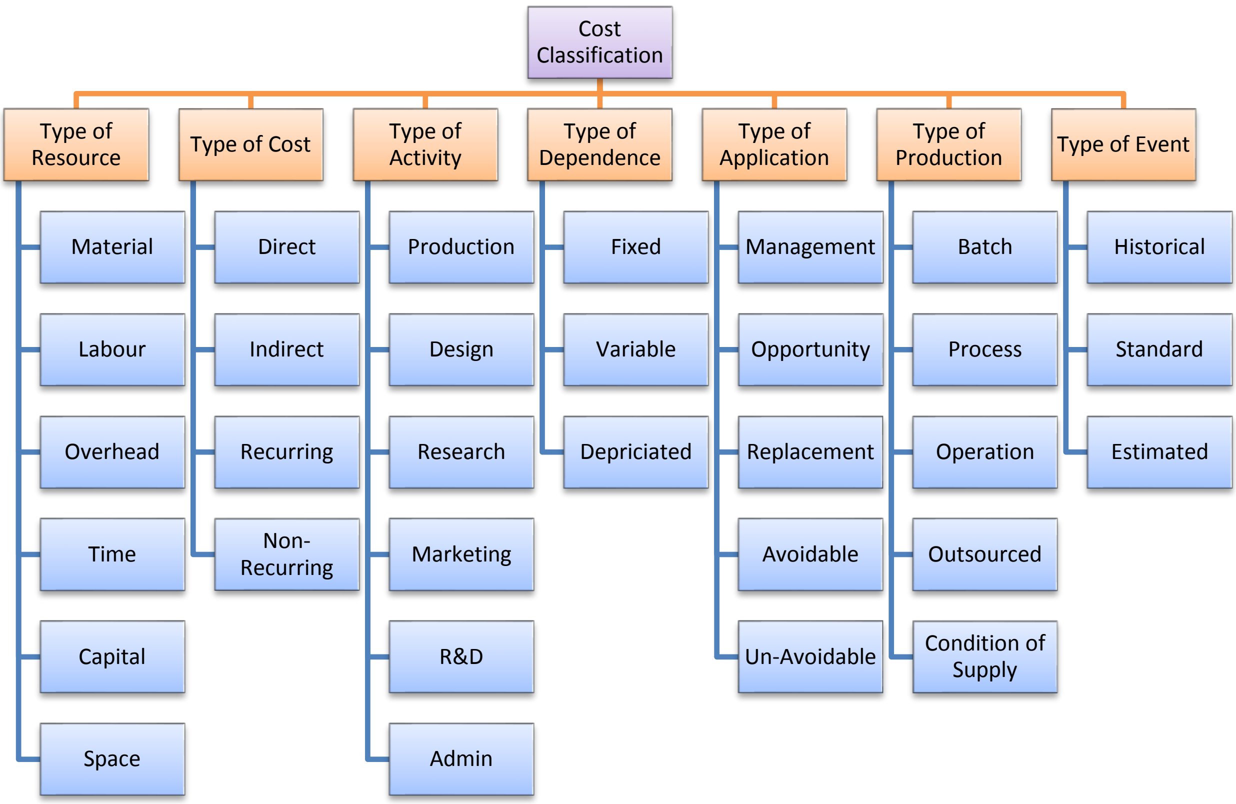


Figure 7: Classification of Cost (The Institute of Cost Accountants, 2014)

`

Material cost can be defined as the amount incurred in acquiring a particular amount of a specific material type for a related design by weight, volume, area or number. Labour cost is the direct monetary investment in human capital required for a particular process/activity. This human capital investment can be time-based, activity-based, resource-based or experience based. Overhead cost is the amount incurred on interdependent activities or resources which are necessary for carrying out a particular project (Oluwagbemiga et al., 2014). Direct costs are the costs directly incurred for carrying out a particular activity, or in terms of production, the cost incurred for manufacturing a unit of a product. This includes a direct material, direct labour, direct manufacturing and direct overhead costs. Indirect costs are the costs incurred on support activities which are required to be carried out along with direct cost activities. This includes cost of R&D, machine, inventory, marketing and technology (Aurora, 2013). A cost classification based on the type of cost dependence is represented in Table 6.

Table 6: Dependence-based Cost Classification (Aurora, 2013)

Fixed Cost

- Asset Cost
- Machine Purchase Cost
- Insurance Cost
- Salaries
- Taxes
- Rents

Variable Cost

- Material Cost
- Machining Cost
- Operating Cost
- Labour Cost
- Storage Cost

Depriciated Cost

- Resale Cost
- Scrap Cost
- Process Loss

Fixed cost is a value which is not dependent upon the production capacity of a plant, but will also be incurred irrespective of any production at all. Variable costs on the other hand are the costs that depend upon the production capacity. Depreciated cost is a value of a product/activity/process/item which reduces with time. These costs are negative in contribution, but are not always taken as negative value for mathematical applications (Novak and Popesko, 2014). The costs depending upon a task such as production process, activity or event are sometimes included in other categories and represent as a direct value of cost incurred during a related task. This may or may not be dependent upon production volumes, but upon the activity contributing these costs (The Institute of Cost Accountants, 2014). Cost drivers on the other hand are the elements which drive a positive or negative change in the cost of a product or a process. These elements vary depending upon the resources or activities involved in the overall life-cycle of a product. Cost drivers are categorised as shown in Figure 8 (Cheong and Steve, 2012).

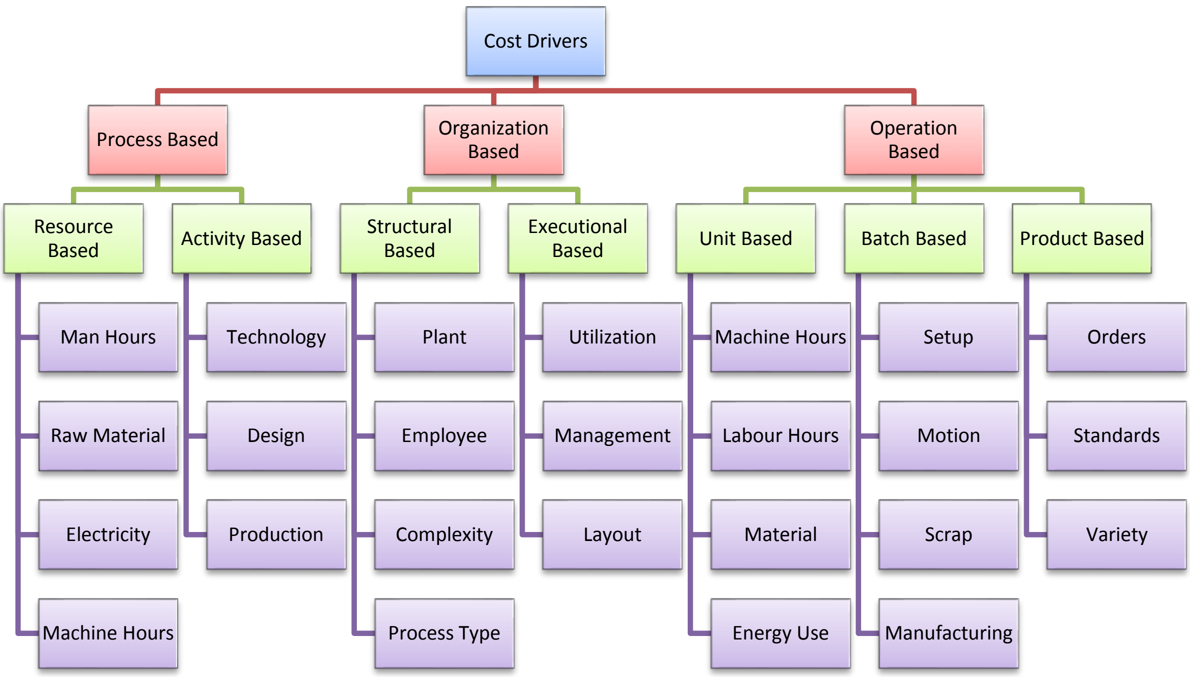


Figure 8: Cost Driver Classification (Cheong and Steve, 2012)

All these cost drivers can be used to estimate cost of a process or a product under various circumstances. For a more elaborate cost estimation a life-cycle based cost driver analysis can also be done. In this type of analysis various drivers from different processes in a life-cycle are used to estimate total cost of an activity. This can be understood from an application of this method in cost estimation of Additive Manufacturing (Lindemann et al., 2012). Here, the process of additive manufacturing is divided into activities and then a cost breakdown is carried out based on the additive manufacturing life-cycle. Design, manufacturing, post-processing and quality are taken as key processes in this life-cycle. Aggregate of these cost drivers will give a cost estimate (Lindemann et al., 2012). The drawback in this system is that it is not precise and as it is applied to only one type of manufacturing process, it lacks a more generic applicability. Conversion of cost drivers into a logical or mathematical or relational and usable form is done so as to come up to an estimate. For a particular problem, the conversion process goes through some steps. These steps include, (i) collecting cost driver information, (ii) understand the cost drivers, (iii) develop the entire cost picture, (iv) develop CER's and (v) compile a solution. There are certain steps like, analysing situations, scaling of information and result formulation that are sometimes kept inherent to the main steps of conversion (SAS Institute Inc., 2012). For the purpose of cost estimation the conversion of cost drivers is very necessary and one of the main elements remain the CER's. CER is defined as a relationship between a function variable to the cost driver elements or the relationship between variables in the form of cost driver elements which can be utilized to calculate the output (Dragos et al., 2009). In simple words CER relates cost to other variables in a product or a process that are not exhibiting cost as a property, but may represent some other property altogether. A CER has two basic elements embedded into it, (i) rational link between the independent variable which is the cost driver to the dependent function usually cost and (ii) a statistical representation with a fair degree of precision. The precision of a CER will, however, depend upon the method used for developing a CER (Dragos et al., 2009). Applications of CER has been done in many component cost estimations. One such application is the use of CER to calculate the compressor rotor blade design cost of an aero-engine (Salam et al., 2013). Here, parametric CER's are developed by utilizing very few key design information as cost drivers. Design effort is chosen to be a variable function and a parametric relationship is developed which states that CER function is directly proportional to variable function. Linear regression is carried out against a set of historical data containing design details from previous used cases. By carrying out 6 iterations and incorporating multiple data points a regression curve is fitted to the data which then defines a CER for that particular problem. This way a more reliable and authentic CER is prepared (Salam et al., 2013). This way using a CER for estimating cost of an aero-engine component is one of the best methods when historical data is available.

Cost estimation is an integrated framework of predicting product or project cost. Computer based estimation is a form of cost modelling besides manual methods. The framework of cost estimation follows three basic steps, namely, Work Breakdown Structure (WBS), cost revenue structure classification and estimating model generation (Iowa State University, 2007). Various cost estimation approaches are:-

(A) Bottom-UP Costing: This is applicable in bigger projects with higher amount of data and starts from the basic foundation of the project. Here WBS is utilized to break a problem into steps starting from the very first right up to the final stage. All the cost elements are then added to have a final estimate (CEDIA, 2015).

(B) Top-Down Costing: This is applicable to projects that have some historical data that can be utilized. Here an assumption has to be made of the final product utilizing the historical data and rest of the elements are worked around it moving reverse into the process. The information so gathered is captured and added to find the final estimate (CEDIA, 2015).

(C) Parametric Costing: Parametric Costing can be used where key cost drivers or parameters from different phases of a product's life-cycle like design, condition of supply, manufacturing and service can be utilized to form CER's which will give a mathematical value of cost. The cost from all the phases can then be summed up to find the overall estimate (Dysert, 2008).

(D) Analogy Costing: Also known as analogues costing can be used where existing cost models for an existing technology which closely relates to the new technology can be extrapolated. This means the historical data can be incremented or decremented based upon the technology in question and an estimate can be done (Torp and Klakegg, 2016).

(E) Expert Judgement: Expert judgement can be adopted where knowledge and experience of an engineer or designer or any expert is taken into consideration and a prediction for the cost of that project is made. This type of method will be predictive method and will not give a true cost, hence, is more useful in initial stages of a project that only requires an assumptive cost estimation (Torp and Klakegg, 2016).

(F) Activity Based Costing (ABC): When some activities have been defined for manufacturing of a product or some process activities are defined, ABC can be used to connect activities to resources and then the resources to cost and then calculating the cost of a product or a project activity-by-activity. A total of all the activities cost will give an estimate of the total technology cost. This is one of the most precise methods of cost estimation and is very time consuming because it requires a lot of information and data that needs to be refined and coded (Al-Qudah and Al-Hroot, 2017).

Different cost attributes such as product unit cost, life-cycle cost, factory cost and design cost have various cost driver activities contributing to cost. Cost driver relationships coded in the computer-based models can be used to predict cost well in advance in an automated form (Dysert, 2008). Every product made from any material has to follow a life-cycle which starts with the architectural decision and goes until the disposal phase. The complete Life-cycle of a product can be visualized as per Figure 9 (Dysert, 2008).

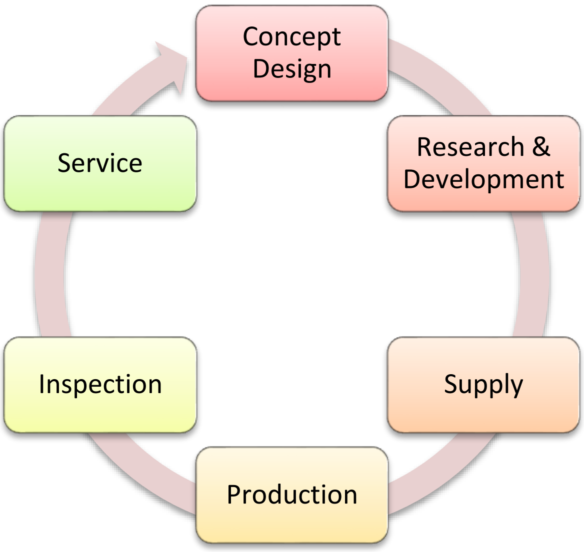


Figure 9: Product Life-cycle

Inspection, packing & dispatch and the maintenance phases play important roles in cost estimation of a composite part and hence, should be included in a product's life-cycle. Even the sale aspect of the product has a life-cycle having different stages namely, introduction, growth, maturity and decline (Leterrier, 2000). These stages in the product life-cycle contribute to cost and the overall cost is summation of all these costs. These processes that contribute to the overall cost of a product cannot be ignored and have to be either included in a life-cycle phase or showcased separately for proper understanding and proper knowledge acquisition.

2.4.2 Methods of Cost Estimation

After considering the composite life-cycle, many areas have been identified contributing to cost which were otherwise not given importance like durability and quality. Maintenance, reuse and recycle are some of the additional elements in the life-cycle analysis of composites (Sreekanth and Lokesh, 2014). Effective cost analysis for passenger cars using composites can be done by Life-cycle Cost Analysis (LCCA) method. Recurring and non-recurring costs are included in the analysis by evaluating various properties of the vehicle (Khoonsari, 2009). It is observed that manufacturing parts with composites alone is costly but can be economical when used in combination with conventional materials. Cost estimation can also be done by Activity Based Costing (ABC). According to it, products consume activities and activities consume resources. It is one of the simplest methods, forming a basis for cost estimation (Cokins, 2010). ABC can calculate both activity as well as overhead costs. Inventory requires more complex activities to be incurred which can be modelled with existing ABC model to predict the overhead costs (Ahn, 1998). Raw material availability and complex combinations make the selection of composites even more difficult. Fabrication of material poses another problem with tight tolerance. All these activities add to cost and are taken into account as a cost driver (Schreve and Basson, 2004). ABC has wide applications but is not flexible enough to be directly applied to composite cost estimation. Other methods used to make cost models are allowance budgeting and strategic budgeting. Knowledge Management (KM) and knowledge reuse form the basis of cost estimating model (Owens, 2007). Most of the software tools used for cost estimation are made for a specific use with little manufacturing knowledge, but some of the open source softwares are available for cost estimation (Vector Infomatik GmbH, 2011). Proper use of Knowledge Based Engineering (KBE) techniques and cost driver selection can make cost models flexible and suitable for composites.

An agile Cost CENTRE-ing approach has been developed that has the capability of using in-house engineering experience of an aerospace company, procurement knowledge, product specification and the knowledge of the procurement market and then integrate it into a generic methodology (Accudyne Systems Inc., 2015). This methodology has proved to be more rational, agile and responsive in negotiating price reductions, as it is based on categorization of product families and casual cost estimation. The drawback of this approach is its less knowledge both quantitative and qualitative which has not been used for effective integration. Also, identification and control of suppliers needs to be fully developed in this approach (Accudyne Systems Inc., 2015). A study has proposed unit cost modelling methodology which was applied to the Rolls-Royce Plc. aero-engine fan blade (Curran et al., 2011). The methodology proposed presented an approach to model the design, manufacturing and material costs by using a discrete event simulation factory model. Two softwares were used to model the data namely; (i) Vanguard Studio: acting as the interface and (ii) Extend Sim: running in the background. The methodology was achieved by breaking down the factory model into blocks and then analysing each for cost drivers (Curran et al., 2011). Major advantage found was the gain in the credibility of the cost estimation. However, it showed that a further fine tuning is required in the Vanguard Cost Model to accurately integrate the cost information, make a model robust and increase its reusability (Curran et al., 2011).

A study conducted by Cheung et al. presents two different tools for cost estimation, namely, (i) Generic Factory Cost Model: An activity based model which can predict cost of each activity of manufacturing and later sum up the cost of each activity and (ii) Scalable Cost model: A model which estimates the unit cost of future Blisk designs (Cheung et al., 2009). In the factory cost model depreciation costs and the indirect costs were added in the model with the help of automation in manufacturing. ABC is implemented for calculating the cost of different activities and converting indirect costs to machine hours. Cost Estimation Relationship (CER)'s are used for regression analysis at various stages. The blisk design variables that affect unit cost are identified and a Trial and Error approach is used to find the combination of variables in operation times. The Monte Carlo Simulation is used along with Vanguard Studio which even models Gaussian-type-Probability Density Function and S-shaped Cumulative Distribution Function (Cheung et al., 2009). It has been shown that the Factory Cost Model could aid the manufacturing engineers to optimize their methods. It is also shown that the factory cost model and the scalable cost model when used together could give designers a better way to come up with optimized feasible design. As this research is concentrated only on the blisk design, therefore, it is not suitable for catering to design changes (Cheung et al., 2009). A research conducted to validate the cost study conducted by Rolls-Royce Plc. showed that, a casual model to estimate cost taking into account the design features rather than the attributes like weight, volume or material properties, is better, easy to use and a useful tool in predicting overall cost. It was also shown that the weight, volume and material properties currently used to predict cost, prove to give faulty predictions and lower the cost estimates, which would be otherwise higher (Langmaaka et al., 2013).

A thorough study of the current methods used for cost prediction in the aerospace supply chain was done which was followed by proposed Pro-COST model (Paul et al., 2001). Here, analogous classification of parts was done followed by the development of parametric relations to link part attributes to production cycle times and finally ratio estimates were made to determine manufacturing and treatment costs. The major drawback with this technique was the lack of flexibility of the model with varying information and the lack to capture uncertain information (Paul et al., 2001). A new mechanism for selection of cost estimation method appropriate for a particular problem has been proposed. The advantages and disadvantages were highlighted for various cost estimation methods, like; (i) parametric, (ii) neural network, (iii) expert judgement, (iv) function costing, (v) feature-based costing, (vi) group technology, (vii) case-based reasoning, (viii) knowledge-based systems, (ix) generative costing and (x) activity based costing (Watson et al., 2006). Classification of the different Cost Estimation (CE) methods was done using Web Grid III and for the method selection set of rules were established. These were embedded into a decision tree named as Decision Support for the Selection of Cost Estimation Method (DESCEM) using Vanguard Decision Pro. Although the proposed method seems advantageous, but due to lack of order evaluation and quantitative comparison of various methods, it cannot be authenticated (Watson et al., 2006). A study linking engine component deterioration with the business led estimation requirements has been analysed (Evans et al., 2006). It has been found that a component deterioration can be used as the basis for life-cycle cost estimation for engine life-cycle. Different cost estimation methods and component life estimation techniques were reviewed. A deterioration mechanism for key components of the engine were studied and a link between the deterioration and the life-cycle was generated. The major drawback with this system was lack of data availability. It was also observed that a more accurate and efficient cost estimate could have been generated if historical data would have been possible to capture (Evans et al., 2006).

A study was conducted to establish the benefits of unit cost modelling in the design phase of an aero-engine part (Zhao et al., 2011). Here, a value driven design was outlined to understand the impact on cost that the design decisions make at a very early stage. A case study on the turbine disc was made as a part of the research and design. Parameters were changed to see the effectiveness of the parametric unit cost model. The benefits found were; (i) graphical representation of results, (ii) collaborative modelling, (iii) reusable model library, (iv) feature to roll up or drill down, (v) web reporting and (vi) integration with existing business systems.

This research has discussed the importance of understanding the cost drivers very early in the design phase so as to reduce the life-cycle cost of the component and the lead time (Zhao et al., 2011). A novel methodology for cost estimation using the shrinking technique on a multi-layer feed-forward neural network and auto assistive clustering revealed that the technique of shrinking is capable of reducing the mismatch between the estimated and the actual cost (Waghmode and Kohle, 2014). It was shown in the research that the Kernel component analysis can improve the estimation efficiency by shrinking the input variables based on the Constructive Cost Model (COCOMO) II data set. By doing this data sets become small and manageable thereby easing the estimation process. The down side of this methodology was that the benchmarking and results obtained could not be relied upon as these were not tested. This methodology was not qualitative enough to obtained good quality of results (Waghmode and Kohle, 2014).

2.4.3 Types of Cost Models

Cost models are computer generated codes or software tools or applications or mathematical representations that utilize a combination of cost driver information, Cost Estimation Relationship (CER)'s and cost estimation methods to represent a cost output (Rajkumar and Alagarsamy, 2013). Different models are utilized for different problems. Based on the estimation methods that are used for generating a cost output, cost models are named. This way of categorization is the most simplest and the easiest way as it directly assigns a particular model to a related problem (Rajkumar and Alagarsamy, 2013).

The classification of cost models can be made in many ways based upon various parameters which govern the category they belong to. This is shown in Figure 10 (Rajkumar and Alagarsamy, 2013).

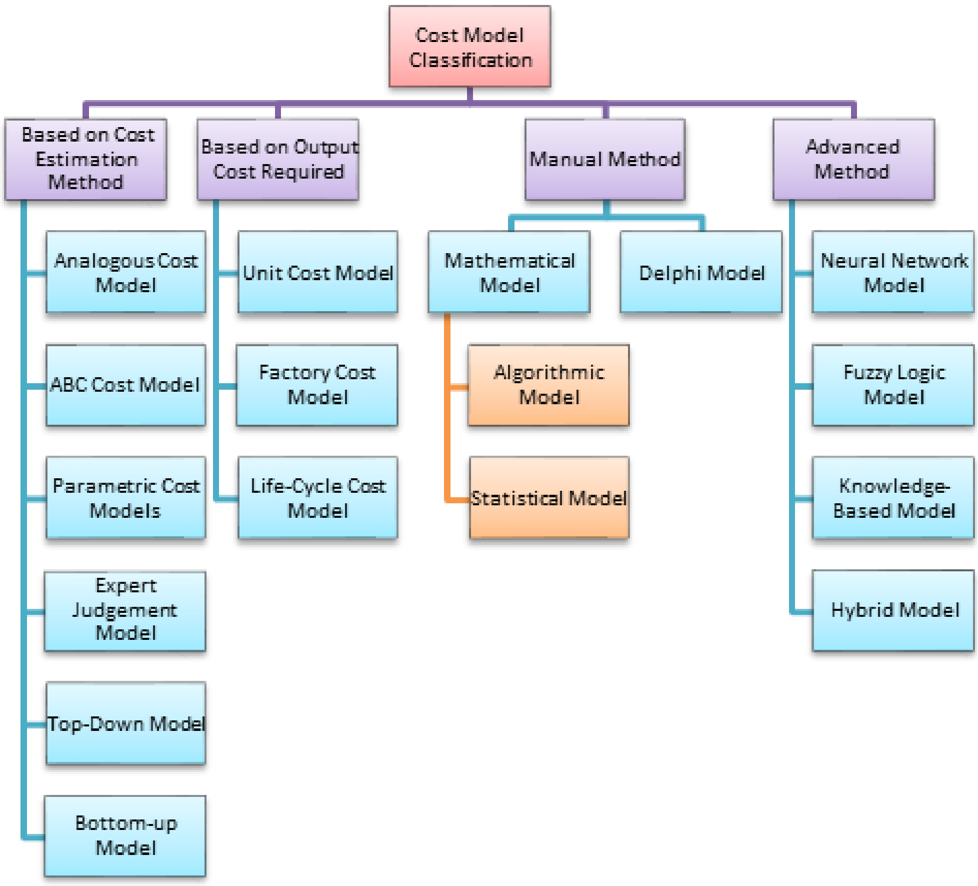


Figure 10: Cost Model Classification

Analogues cost model is a mathematical representation of past information or historical data that can be utilized with certain modifications or without modifications directly to the problem in hand (Doloi, 2011). This way an analogy is defined which relates the past information with the problem, which allows relation to be created, which in turn can be utilized for other models. This way a representation model is made which has input and output functions involving a higher uncertainty in cost estimation. This uncertainty in outputs can be mapped by ranging the historical data to achieve a more accurate result (Doloi, 2011). There are wide applications of Activity Based Costing (ABC) cost model as it is a model directly relating activities in a process or project to the resources. The resources can be in the form of time, amount, value or human capital. The generation of ABC model follows a generic step-by-step method. There are six steps in this method, namely (i) identification of activities, (ii) allocation of resources, (iii) defining cost drivers, (iv) calculation of cost value of an activity, (v) adding activity costs and (vi) conducting product cost estimation. This way a cost driver-based model is made which utilises these steps (Kabinlapat and Sutthachai, 2017). The ABC model has also been utilized for product storage management (Gill, 2017). The method of model generation again follows generic step by step method. Activities in the storage process follows a normal distribution and hence, is directly assigned with a cost value utilizing normal distribution formulae. Under-utilization cost is added to the normal distribution function so as to include activities which contribute in a loss in process efficiency. The mathematical functions of current orders, reorders and total demand forms the ABC model (Gill, 2017). Parametric cost models on the other hand require some form of detail in designing a relationship between the cost drivers of a particular project or a process. This type of model finds application where some kind of detailed information in the form of design, process, manufacturing, machining and complexity are available (Alexander, 2017). The process of developing this cost model starts by understanding the design details and the process details. These details are then utilized to break down the overall problem also known as Work Breakdown Structure (WBS). From this WBS cost driver information is captured which gets converted to Cost Breakdown Structure (CBS). A relation in the form of CER is made between these cost drivers which forms the main basis of a parametric cost model. A parametric model is therefore a more detailed model and is also used for both predictive and analytical cost estimation (Alexander, 2017).

Expert judgement model is in reality predicting an estimate using a probability of the outcome and understanding the uncertainty of that outcome around the problem (Colson and Cooke, 2017). The model uses two types of methods, namely (i) classical model and (ii) information pooling. In the classical model experts are utilized to provide an extra validation when the data is insufficient to predict any outcome. Quantification of uncertainty is done by choosing a target data and evaluating it against some previous prediction. This way moving from one data point to another an overall uncertainty value is obtained. The expert's confidence for a predicted value very crudely defines the overall accuracy of this model (Colson and Cooke, 2017). In the information pooling method more than one expert is involved to predict an outcome and an expert distribution is prepared. This distribution is a list of ranges that have been predicted by the experts. Mathematical averaging of the predictions or a weighted average of the predictions is made to come to a final outcome. An in-sample validation is conducted to choose the best possible outcome for a particular problem. As the accuracy of this model is as good as the model itself, therefore, this method has highest uncertainties and limited use (Colson and Cooke, 2017). The Top-down and the bottom-up approaches are not a model themselves, but are used to define a precise structure of CBS and WBS. These methods help in the breakdown of a problem which is very essential for the development of cost model. These methods are usually responsible for data acquisition, usage of data and flow of data in a cost estimation process. Sometimes these methods can directly yield a predictive cost model which can be used to make an early estimate (Mendez et al., 2017). Top-down approach is considered to work based upon the technical requirements and predefined framework at a high level by experts. Bottom-up on the other hand is stakeholder driven and conforms to the requirements put forward by the stakeholders and hence the framework is more useful (Saidani et al., 2017). However, this method is unable to handle large data sets from different markets or stakeholders resulting in a haphazard prediction if used alone.

Based on the output cost requirement, cost models can be made, utilizing existing information. There are many cost outputs and many models as such, but in engineering design problems the main three cost models are (i) unit cost model, (ii) factory cost model and (iii) life-cycle cost model (Thompson, 2012). Unit cost model is a mathematical representation of the value obtained by a cost function which is dependent upon an averaged total cost as one variable and total units produced as another variable. The output cost is defined as the cost of one unit of a particular item. Unit cost model includes both fixed and variable costs combined with direct and indirect costs. This type of model is useful in providing, (i) pricing plan, (ii) optimization analysis, (iii) break-even analysis and (iv) technology costing (Thompson, 2012). A factory cost model is defined as a cost function representing the cost that is incurred in manufacturing goods/items. These costs include direct materials, direct labour and manufacturing overheads (CPE Courses, 2018). Direct materials include the cost of materials required to be incurred for manufacturing of goods. This also includes the cost of material wasted during a manufacturing process. Direct labour is the cost that is incurred on the labour required for manufacturing of these goods. Manufacturing overheads are related to production rate and include the cost needed for running a manufacturing facility. The factory cost model is thus useful in predicting the cost of a facility that is needed to manufacture a good/item and is very important in decision making especially if a new product, process or a facility is being introduced (CPE Courses, 2018).

Life-cycle cost model is a function of elements from all the phases of a usable life-cycle of a product. This type of model takes into account the entire life-cycle of a product right from its design phase till the maintenance phase (Abu-Rumman et al., 2017). From these phases CER's are drawn utilizing various cost drivers from these phases. The CER's once created form a function or a set of functions which are capable of predicting the entire cost of that product, thereby allowing process, project and product's optimization (Abu-Rumman et al., 2017). These methods being mathematical or statistical in nature can be used for computer modeling. Another type of cost model is based on the manual method, which includes both mathematical and non-mathematical models (Shekhar and Kumar, 2016). In this category of mathematical model, first comes the algorithmic model which utilizes the use of equations and mathematical relationships to estimate cost. The derivation of the equations and relationships are carried out by research and user inputs from various sources ranging from, design rules, risk analysis, cost driver information and source codes etc. Models such as, Constructive Cost Model (COCOMO), Software Evaluation and Estimation of Resources - Design for Manufacture (SEER-DFM), Parametric model and Putnam's model fall under these categories (Shekhar and Kumar, 2016). The statistical model is mostly used in combination of these models to further understand the outputs and/or perform the optimization task. These models perform additional functions like, regression analysis, break-even analysis, cost dependency analysis, uncertainty analysis etc. In the early days of cost estimation statistical model was the simplest way of cost evaluation (Shekhar and Kumar, 2016). In this model raw data or information was represented in a dependent and independent variable format, which was further converted from one form of output to another in steps. This was then finally converted to the required form after a number of steps of pre-evaluation stages. Sometimes graphical representation of the data was also used for cost evaluation (Shekhar and Kumar, 2016).

Delphi cost model is based on the Delphi approach which is a manual method where a group is formed and an opinion is taken from that group (Rajkumar and Alagarsamy, 2013). It is an extended form of expert judgement method which follows structured steps. Selection of group plays a very important role in this method. Thus, a group comprising of experts from all the areas of engineering are involved in performing this method. A specially designed format is distributed among the group formed and an estimation is taken from the group. The steps involved in this process are represented in Figure 11 (Rajkumar and Alagarsamy, 2013).

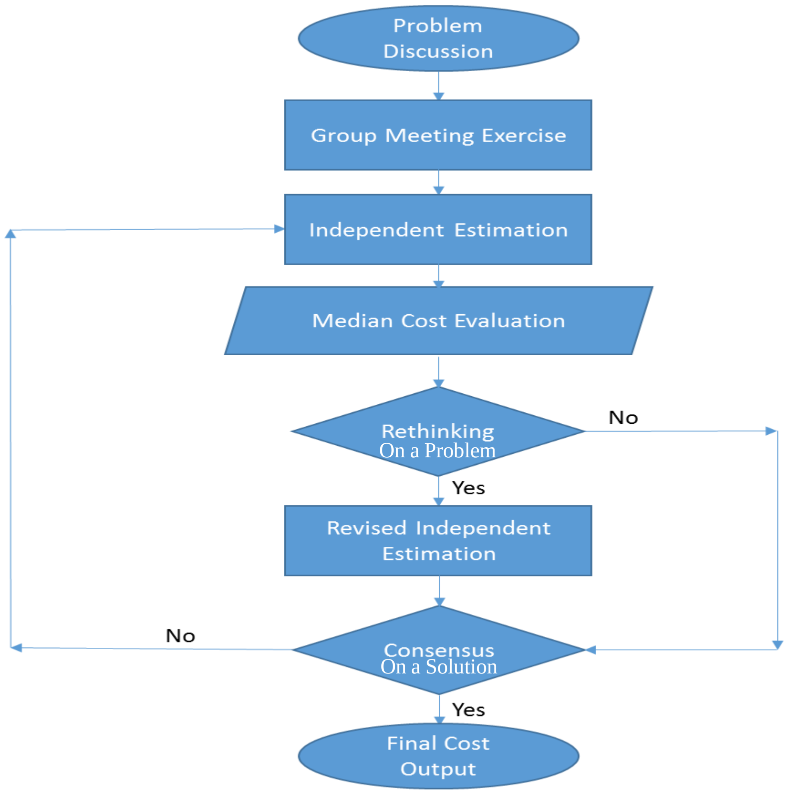


Figure 11: Steps in Delphi Cost Model

The Delphi model brings about certain advantages of knowledge sharing, independent thinking and broad perspective of understanding the problem. This way of deriving an estimation is an advancement over traditional manual method and brings about a better chance of the estimate to be less uncertain. There are however certain disadvantages embedded in this method some of them being, more time consuming, accuracy dependent upon the competency of the group selected and requirement of skilled personnel for estimation to happen (Rajkumar and Alagarsamy, 2013). Some of the advanced methods of cost modeling are the ones which make use of computer codes to convert raw information into machine understandable format (Darla, 2017). Neural network-based cost models use a back propagation neural network which is composed of an inner layer, outer layer and hidden intermediate layers. Each layer has its own neurons or a function and computing related inputs, which passes the outputs to the next set of neurons in the adjacent layer with the help of a transfer function. A feature-based neural network is obtained by utilizing historical data for developing relationships between cost drivers and output cost. This way the back propagation of errors ensures a continuous learning which enables artificial intelligence in the cost estimation process (Darla, 2017). Fuzzy logic modeling is usually used to handle uncertainty in the system. This model is capable of providing more reliable estimates by handling fuzziness in the data points (Darla, 2017). A decision table generates a set of rules and constraints which when applied to a tabular set of data points generates the required output cost estimation. These system require high computing power, but are good for early estimates in the design process. Another advanced method is knowledge-based cost model, which utilizes the Knowledge Based Engineering (KBE) techniques to achieve process planning (Darla, 2017). These models utilize the knowledge database to capture and refine cost driver information for a particular system and then integrate it with the costing sub-system to finally come up with an overall estimate of the process. These methods have been mostly utilized in the design and the manufacturing processes and have been found to be very effective in automating repetitive tasks (Darla, 2017). A hybrid cost model is the combination of different models together to form an advanced system which has the benefits of parent models (Darla, 2017). Usually, the algorithmic method and the neural network are combined to form a hybrid system. Another hybrid system uses parametric model and fuzzy logic coupled to ABC. Framework development for a hybrid system depends upon the type of estimate to be made and the type of problem to be handled. Unique combination of data can be handled by such a system, thus it is finding applications in complex situations like the one found in aerospace sector (Darla, 2017). All the cost models are good in one way or the other, but the dependency lies in the process or in the product, hence they are specific to a problem. There is no such method or technique which can be used for all the combination of problems. Due to this fact, cost methods, techniques and models need further improvement.

2.4.4 Discussion

Cost estimation is a very important task in design optimization and process planning. The technique of cost estimation involves various steps, namely, (i) understanding of design and process knowledge, (ii) understanding the activities involved in these processes, (iii) finding out the cost driver information from these activities and (iv) later convert that cost driver information to Cost Estimation Relationship (CER) for making a cost estimate. Rule-based, process-based, model-based, design-based and function-based are some of the examples of the cost estimation processes from the first step. Cost models are the computer based or manual based functions or a set of functions performing a task of complex cost estimation in a much simpler and user friendly manner. The models are also classified in many ways but the best cost model depends upon the problem in hand and the type of output required. It has been seen that Activity Based Costing (ABC) and parametric cost models are the best ones in terms of a less uncertain estimate. Expert judgement and manual methods are found to be good in early prediction of a new technology. No method is a best method and no method is a worst method, each of the methods have their own applications and benefits. For some of the applications demanding less precision and fast estimate, manual methods seem to be more viable, whereas, in applications demanding greater precision with higher complexity computer-based methods are more useful. All of these methods can be very well used for composite material-based product's cost estimations. However, a drawback of these models are that they are either product dependent or process dependent and hence if there is a problem containing multiple combinations of processes of a number of different products, there is no one model which can handle this. Also, when there is a new technology like composite material introduced into an existing product like aero-engine, complexity increases and there is no cost model which can straight away handle this. Hence, there is a need for new advanced cost estimation method that can be used for composite technology in aero-engine realm.

2.5 Carbon Footprint & Costing

2.5.1 Basics of Carbon Footprint

As the green revolution and the environmental laws became strict, the need for a revolutionary design arose which posed a new challenge. The challenge was to design and develop low emission and high efficiency machines (The Edinburgh Centre for Carbon Management, 2008). A term carbon footprint was later introduced to understand the environmental impact of any activity. Earlier it was defined as a measure of greenhouse gases emitted by an activity, process or a product. It was considered to be a direct effect of an activity back then, but, now both direct and indirect influences are taken as carbon footprint, and hence, it is now defined as a measure of energy consumed in any form for carrying out an activity (The Edinburgh Centre for Carbon Management, 2008). Global warming was the trigger for studying the effects of any activity on the environment. With the increase in environmental awareness and taxes introduced by various governments, carbon emissions have become a major cost contributor and a factor to be considered by the designers/engineers and project planners (The Edinburgh Centre for Carbon Management, 2008). A report on the emission of carbon and thus the foot-printing associated with the activities in the industry suggests that energy utilized and wasted in an organization is quite high and also distributed among various phases in a product's manufacturing. Production of materials, distribution, consumption and recycling are the major contributors of these emissions and thus add up into the cost of a product indirectly (Carbon Trust, 2017). As the need for analysis of carbon footprint became important in manufacturing as well, composite manufacturing was also analysed. Life-cycle analysis technique was used to access environmental aspects associated with a project or a process (Song et al., 2009). In this study four stages were taken into account in a Fiber Reinforced Polymer (FRP) using pultrusion method. Energy use over the entire life-cycle was calculated and it was found that lighter materials are more favourable for saving life-cycle energy (Song et al., 2009). A drawback was that as the study used only four processes, which were considered as life-cycle over one manufacturing technique, it was not comprehensive enough to cover other processes which are equally important in a life-cycle. With the use of advanced materials in more and more applications, its viability both economically and environmentally are in question. A detailed analysis is done on the different applications and the 'green effect' composites have on the overall usage of a product (Dobbins, 2015). It has been found that after the sales activity has been carried out, use of composites in most of the applications is greener than conventional materials because of their light weight and increased overall efficiency. This helps in lesser energy consumption and emissions from a product. Another ironical discovery is that manufacturing, processing and maintenance are contributing more to the greenhouse gases for composites and thus making it inefficient (Dobbins, 2015). It has been observed that composite recycling is economically and environmentally viable than using a new manufactured composite raw material (European Composites Industry Association, 2017). Specifically, thermosetting composites, glass fiber as well as the carbon fiber reinforcements are recyclable. 16% reduction in carbon footprint is observed when using recycled composite cementing technique. In this technique a perused part is partially of fully grated and reinforced by applying some new fibers grafted onto the weak area and fixed in place using a polymer resin (European Composites Industry Association, 2017).

A study has been conducted for carrying out the carbon footprint Life-cycle Assessment (LCA) of an aero-wing skin design. This study utilized life-cycle analysis of the wing design and involved the use of carbon fiber for upper wing skin (Chua et al., 2015). Carbon footprint information was taken from electrical usage and emissions from the manufacturing process of this part. The study revealed that electricity consumption was the major contributor in the overall emission for both part and carbon fiber manufacturing. One of the drawbacks with this study was that it was carried out assuming the United Kingdom (UK) to be the major source of all the production activity, however other options for manufacturing were not considered (Chua et al., 2015). Another study for calculating the carbon footprint has been done for fiber optic manufacturing. In this study the analysis uses a life-cycle approach from gate-to-gate manufacturing of an optical fiber (Inakollu et al., 2017). Although the scoping has been done taking life-cycle, but for the study only two phases of this life-cycle are considered which are material processing and optical fiber production. The elements that are taken for this analysis are the emissions from different processes of manufacturing. This includes voluntary emissions, used fuel emissions, machining emissions, electricity and raw material emissions. The mathematical relationship calculates the Co2 emissions from all these categories and aggregates it to get the total Co2 emission of the process (Inakollu et al., 2017). This way a complete analysis was conducted and it was observed that with the use of automation process and advanced composite material combinations, emission factor has decreased from the year 2013 to 2016 (Inakollu et al., 2017). The major drawback with this study was that it did not quantify carbon footprint as a cost burden, also there was only one type of problem and one type of manufacturing chosen, which could not be accepted for generalization of the results.

For the assessment of carbon footprint, a standard has been introduced which defines how, when and where the carbon footprint can be calculated and represented (Carbon Footprint Ltd, 2017). This standard allows organizations to calculate greenhouse gas emissions, which has to be defined by the organization itself. The organization also needs to describe the type of greenhouse gas emission taken for consideration and evaluation. Some other factors like production factors, national laws and international environmental enforcements are also included in this standard. This standard can be used to understand the different ways of doing a carbon analysis (Carbon Footprint Ltd, 2017). The Fifth Carbon Budget was introduced in the UK on 20th July, 2016 which showcased many areas contributing to emissions. It was decided that by the year 2030 the emissions needed to be reduced by almost 57% of the emissions value in the year 1990. These targets covered the government sector and started getting into the private sector as well. Manufacturing companies were also taken for consideration (Committee on Climate Change, 2017). This was later modified and introduced as second UK Climate Change Risk Assessment in the year 2017 where importance of scientific understanding of environmental impacts were emphasized. It was clearly shown that production, manufacturing, business and household were the main contributors of pollution in the form of emissions or energy usage (Committee on Climate Change, 2017). This way a norm that has been discussed as a political discussion has triggered a need for engineers to find out a way of developing efficient and cleaner aero-engines. For proper understanding of this, cost contribution of environmental factor in the overall life-cycle of an aero-engine needs to be clearly understood. If the carbon footprint is quantified as a cost value with the life-cycle of a product a decent analysis of the process/project could be done. Thus, including carbon footprint in the life-cycle is viable and is necessary for future design and manufacturing.

2.5.2 Importance of Carbon Footprint

With the need to develop advanced machines came a need to make them efficient. Green revolution and global warming raised issues of concern about environmental impact of engineering products and innovations. There has been many environmental restrictions put on certain products like automotive and aerospace which restricts the amount of emissions they make and the energy they use (Cao et al., 2017). Environmental certifications have become necessary for certain products which forces the designers and engineers to innovate and manufacture these products in such a way that they can get the requisite certification and be environmentally safe. Many industries have seen growth in their sales when they have designed their products based on the environmental standards and have involved environmental innovation into their product range (Cao et al., 2017). Different countries have different norms for emissions and energy use that the companies have to follow so as to make their products saleable in those respective countries (Naimoli et al., 2017). Certifications like Euro-I, Euro-II, Euro-III, Euro-IV and Euro-V (used in most of Europe as an emission certification for automobiles) and BIS-I, BIS-II, BIS-III and BIS-IV (used in India as an emission standard for automobiles) is an example of country specific laws and certifications. Certain countries are still not following any norms on their products due to which they have seen a global impact in their product acceptance among customers. Countries like China, who have become a global supplier of electronics goods and other items introducing environment laws, is now set to introduce new laws to govern manufacturing of environmentally friendly vehicles (Naimoli et al., 2017).

The aero-industry has seen the impact of these global emission standards that have led them to design and manufacture environmentally friendly aircrafts and space vehicles. As the emissions are directly thrown into the outer layers of the atmosphere, these cross boundaries and are international cause of concern (Civil Aviation Authority, 2017). Aircrafts emit lots of global warming causing gases through the fossil fuels they burn in their engines. Carbon Di-Oxide (CO_2), Nitrogen Oxide (NOx), soot and aerosols are the major constituents in the aircraft emissions. A study conducted in the year 2012 revealed that 6% of the overall United Kingdom (UK) emissions were from aircrafts. It has been predicted that if such a trend continues by the year 2030 the aircraft emissions will constitute almost 20% of the overall emissions (Civil Aviation Authority, 2017). International flights contribute to 90% of emissions and domestic flights 10% of the aircraft share in emissions. Similarly light weight aircrafts contribute to a much less emission percentage (Civil Aviation Authority, 2017). In order to have sustainable aviation, new innovations needs to be made. The UK aviation industry has responded to this increasing demand of sustainable aviation. There has been use of efficient engines in the new fleet of aircrafts. From the year 2006 till 2016, more than 450 fleets have been replaced by new and advanced aircrafts and by the next 10 years there will be around 400 new fleet of aircrafts to replace the old high emission aircrafts (Airlines UK, 2017). The new aircraft fleet offers at least 13% saving in the fuel and offers a reduction in the CO2 emissions. There is still, however, a need to make the engines more efficient and environmentally friendly and a strong need to understand the behaviour of the engine during flight. There is a mission of the aviation industries to reduce the greenhouse gas emissions by more than 30% by the year 2030 and around 50% by 2050 (Airlines UK, 2017). Aero-engine's play a very important role in this mission as they are the main source of these emissions. Hence, it is very important to understand the environmental effects of these engines right from the design stage.

Customers have changed their way of looking into products and making a choice. The products that are marketed under a green label are found to be more in demand as compared to the products without this label (Ferraz et al., 2017). The behaviour of the customer has been mapped by doing a survey and it is found that more customers get attracted towards purchasing or using a green product than a non-green alternative. A 7-point structured model has showcased that 82.7% Canadian families like greener products for their daily use (Ferraz et al., 2017). These trends reflect a change in the general perception of customers that has changed for conventional products and showcases their interest that has grown towards use of green products. Many industries have moved from conventional methods of manufacturing to greener and more efficient manufacturing methods. Understanding the carbon footprint in manufacturing process itself has become important to reduce environmental impact (U.S. Department of Energy, 2018). Like many countries, the United States (US) manufacturing sector depends upon conventional energy resources. The effective and efficient use of these energy resources and the cost that is spent on this energy is very important in the competitiveness and economic stability of the US manufacturers. In the manufacturing of products a lot of energy is utilized and this energy is what contributes to the carbon footprint as shown in Figure 12 (U.S. Department of Energy, 2018).

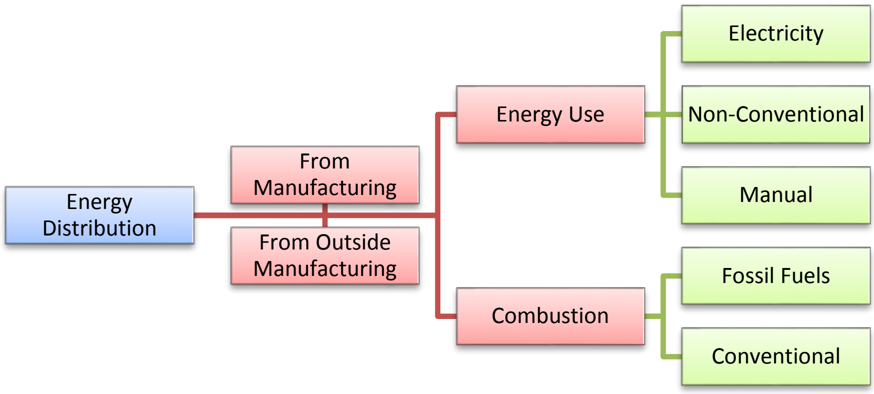


Figure 12: Energy Distribution in Manufacturing (U.S. Department of Energy, 2018)

Most of the carbon footprint share comes from the manufacturing industries and the major part of this share is in-process carbon footprint. In-process means the activities that are required to be carried out in order to achieve a process completion in a product design and manufacturing. This in-process carbon footprint gets reflected in the overall product's cost and hence is important to be analysed (U.S. Department of Energy, 2018). Not only in the manufacturing process, but carbon footprint has been found to be evident in supply chain as well. The analysis in the supply chain has shown that the amount of outsourced manufacturing cost is directly related to the carbon footprint of a particular product (Cordero, 2013). The major contributors of the carbon footprint in the supply chain are from the use of fuels, transportation and extraction of materials from earth. The initial trials showcased a successful use of carbon footprint assessment to form a sustainable supply chain, but as the methods are not as effective and in a very initial stage, improvements needs to be made (Cordero, 2013). Also carbon footprint is only considered to be a part of some processes which directly consume energy. Other processes which can or which do consume energy in a qualitative form needs to be quantified. Overall it can be said that carbon footprint analysis is very necessary to completely understand carbon footprint in the entire life-cycle and include it in the cost estimation for composites. This is a new field in engineering as no work has been carried out to incorporate carbon footprint analysis as part of the cost analysis over the entire product's life-cycle which can make it highly usable information for conducting analysis and carrying out engineering innovation making the system future proof.

2.5.3 Discussion

With the need to develop advanced, highly efficient and environmental friendly products, the need to have carbon footprint analysis arose. It was really very important to understand the emissions that increase greenhouse gas production. This was later linked to global warming and temperature change. This led to a need to have a global strategy to reduce emissions and pollution as a whole. Aerospace, automotive and general industries were among the major contributors to the overall carbon footprint. Countries formed environmental protection laws, emission standards and pollution norms which controlled the way products were designed, manufactured, supplied and serviced. Many new and advanced materials like composites have been developed to replace traditional materials in some of the automotive and aerospace parts. This has proved to be useful in reducing the overall weight and increasing the efficiency, thereby achieving lesser emissions and a greener solution. Customers have also shifted their liking from traditional products to a greener alternative. Customers are willing to pay more for a greener product than a cheaper more pollution causing product. As the government has imposed taxes on high emission products, the overall cost has been affected. There is a need to understand the carbon footprint distribution and carbon cost impact in a product's life-cycle. To do this carbon footprint needs to be included in cost estimation. If carbon footprint is made to be an integral part of the cost analysis, the overall products effectiveness and competitiveness can be drastically improved. Hence, the importance of carbon footprint in cost estimation cannot be ignored.

2.6 Literature Synthesis

2.6.1 Overall Literature Analysis

The research study has been conducted in a systematic by way taking important areas of study as the foundation for literature review and analysis. The overall summarization of the study can be visualised in Figure 13.

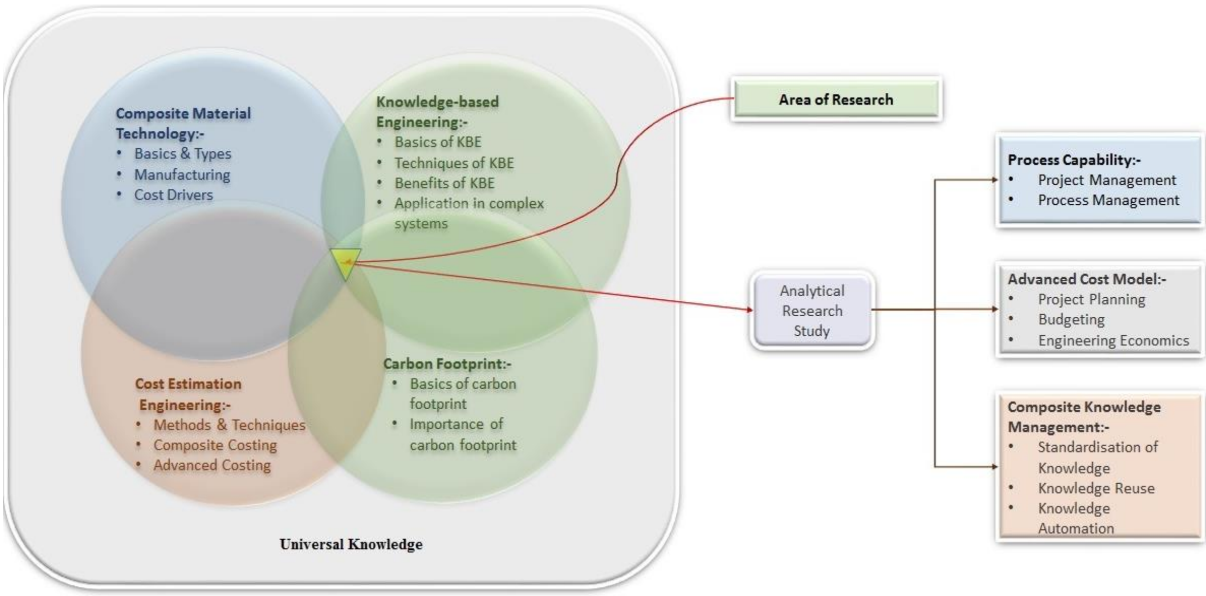


Figure 13: Literature Review Summary

The area of this research lies in the intersection of four basic fields. These include Composite Technology Knowledge, Knowledge Based Engineering (KBE), Cost Estimation and Carbon Footprint. From the literature study it has been seen that, composites are not as cost effective as conventional materials and despite the fact that 50% reduction in carbon fibre purchase can reduce the overall Life-cycle Cost (LCC), no considerable work has been carried out to map the same. Precise knowledge management of composite process is required for early prediction of cost. Finite element models are taken as a reliable source of information and costing procedures utilizing Ansys Finite Element (FE) software and Ansys Parametric Design Language (PDL). A drawback with this method is that it does not utilize the complete knowledge potential and concentrates more on the design attributes. There is lack of composite knowledge in the conventional cost models. Methods like the survey-based approach and the Method Time Measurement (MTM) method for cost estimation have been applied to the manual processes, but have not been improved to cope with the complexity involved in composites. Parametric cost model Software Evaluation and Estimation of Resources-Design for Manufacture (SEER-DFM) has been applied in the composite cost estimation but due to lack of proper data necessary for developing cost driver information, the cost models are incomplete and inconsistent.

Cost estimation is a framework of predicting product, process or project cost in advance. The techniques used for conventional cost estimation include Activity Based Costing (ABC), top-down approach, bottom-up approach, analogy costing and parametric costing. All these methods require precise manufacturing knowledge and cost driver information over the entire life-cycle. LCC analysis is an effective method used in composite cost estimation but requires effort and is time consuming. Simplest form of costing is ABC which can calculate activity, overhead and inventory costs. Its application is wide but is not flexible enough to be directly applied to composites. Proper use of KBE techniques and cost driver selection can make cost models suitable for composites. New automated manufacturing techniques have been adopted by the aerospace industry. Computerised Numerical Control (CNC) lay-up and Three Dimension (3D) printing are some of the new techniques which require complex attributes and are very difficult to map. Process planning techniques such as multi-agent technique is used to automate manufacturing data which can be used to generate logics for cost estimation of such processes. Meta-modelling and modelling are used for organizational modelling. KBE based design management can be used for automation of these processes. Multi-attribute Interview Software Tool (MIST) approach is an example of KBE used in capturing stakeholder's requirements. Using Abstraction Layer Concept (ALC) for hierarchical structuring, effective cost planning in the Building Information Modeling (BIM) is observed. KBE gives the ability to reuse manufacturing experience and automate repetitive tasks, thereby reducing effort. There are many uses of KBE including development of reliable Cost Estimation Relationship (CER)'s.

Carbon footprint is another important aspect of this study that has been done to understand its importance in project/process management. It has been seen that emission standards, environmental laws and customer liking have forced industries to move into the direction of green revolution and develop more efficient and environmentally friendly products. Carbon footprint has been seen to contribute towards the product's overall cost and thus its analysis needs to be conducted parallel to the manufacturing analysis and process analysis. Although, the study has many drawbacks but the basic essence has showcased a major need of carbon footprint analysis to be a part of the whole project/process management where cost estimation plays a very important role. Need for understanding of carbon footprint as a part of cost evaluation can be considered to be a need of the hour for future product development.

2.6.2 Gap Analysis

There has been some use of Knowledge Based Engineering (KBE) in composite part cost estimation. Hybrid knowledge representation with use of fuzzy logic has been applied for cost estimation of composites. Knowledge Based System (KBS) and Computer Aided Design (CAD) database is used to develop cost models. An integration of cost breakdown structure and product breakdown has been developed using KBE for estimating cost in the entire life-cycle. The benefits of the current system include (i) robust design, (ii) reduction in cycle time and (iii) higher clarity in early stages. There are however certain drawbacks namely, (i) inaccurate knowledge base, (ii) not fully automated, (iii) incomplete utilization of KBE, and (iv) designed for a particular product or process. An analytical study of some of the methods and approaches of cost estimation has also been conducted as part of the literature review. These methods/approaches have been identified to be applied in various technologies both from conventional material types to the advanced composite material types. These cost estimation methods/approaches are found to be very effective in some cases and non-preferable in others due to a major fact, that they are designed taking a process or a project or a part as the basis and become very specific in application. Another major fact in the current cost estimation approaches is that the methods used for their development are based upon the problem which has to be taken care of. This is not good when a system is required to function as a unified or generic model as all the information taken for its development is from a particular problem. This not only creates a system with uncertain results but a model which can work only with one type of problems and requires re-modelling for others.

This study has highlighted some major benefits and drawbacks in the current methods/approaches which can be modified or utilised in combination as per user requirements and the problem in hand for a better cost estimation. These are represented in Table 7.

Table 7: Benefits & Drawbacks in Current Cost Estimation System

Cost Estimation Methods/Techniques	Positives	Negatives
Activity Based Costing (ABC)	• Easy to use and reliable • Activity mapping can be done	• Non-flexible • Needs lot of effort
Top-Down Approach	• Fast and easy • Works with less information	• Unreliable • Non-flexible • Uncertain outputs
Parametric Costing	• Used for developing Reliable CERs • Capable of early estimations	• Complex • Dependent upon parameters
Process Control Estimating Program (PROCEP)	• Uses old estimation methods and thus reliable	• Difficult to handle complexity
Regression Analysis	• Efficient • Reliable • Less Uncertainty	• Complexity is high • Difficult to implement
Neural Network	• Handles uncertain information • Can handle complexity	• Complex architecture • High dependence on other systems
Expert Judgement	• Uses historical knowledge • Implicit knowledge can be included • Previous cases are used	• Vey difficult to code • Reliability is questionable • Time consuming
Project Management Estimating Software	• Customised spreadsheet generated • Uses cost estimating software applications • Rapid analysis of different scenarios	• Costly to implement and develop • Needs very precise information • Dependent on the availability of software databases for cost

Activity Based Costing (ABC) is a method which includes converting of a process or a project into activities and sub-activities and relating these to resources. This method allows the relationship of resources to be built for a particular project or a process which can be quantified by estimating the value of the resources consumed. Summation of these resources generates the overall estimate. This method is very accurate and is highly elaborate which can estimate cost with less uncertainty, however, the process of building an estimate is time consuming in itself. Also the application is dependent upon the maturity of the previous information. Top-down approach and the bottom-up approach are not a direct way of cost estimation, however, they are needed for building the Process Breakdown Structure (PBS) which is further utilised for development of the Cost Breakdown Structure (CBS). This allows a complete cost driver information pack to be built for a problem that can be used for developing a perfect Cost Estimation Relationship (CER). These methods are very good in early predictions as they are mostly developed with very less information but at the same time are unreliable and develop uncertain results, if used for cost predictions. A good way of cost estimation is the Parametric Costing which builds parameters from processes and links these parameters with the help of CER's. These relationships are highly mathematical and, therefore, the results can be used for sensitivity analysis and uncertainty analysis. The accuracy of the estimate is high, but the requirement of precise information makes the use of this method limited to projects which are rich in historical data. Another method which has been used for generating bill of material is the Process Control Estimating Program (PROCEP). This method utilises physical counting of similar parts in an assembly drawing and then generating a spreadsheet with a list of parts, their total counts and their respective dimensions. This information is then linked to the purchase method to come up with an estimate of the cost. The method is simple but tedious. Also, if the design is complex with many components, physical counting becomes difficult. Another manual method of estimating cost is the Regression Analysis. This method has now been coded into some estimation models to reduce the time needed for the tough job of doing the regression. This is a statistical method to use historical data of a similar technology and populate the data by plotting it against a two variable system. The two variables usually are time and cost. A trend line is plotted which shows the historical trend of that technology with changes to the input data. To estimate the technology in question, minimum r^2 point is used and time-cost values are taken from the regression fit curve. This method is highly time consuming and very difficult to implement if the data points are more than two or if the dependency cannot be converted to a two variable format. A way of quick estimation which is usually used in the early stages of the projects is the Expert Judgement method. Here, the experience and expertise of the estimators are used to develop an estimate of the technology in question. This is done only when there is very less information available and it is very difficult to clearly identify the parameters that influence cost in a problem. As it is based upon a person's own ability to predict values, it is not reliable and has highly uncertain outputs. The biggest benefit is that it is fast and can work with very less to no information. Computer based advanced techniques such as Neural Network, Artificial Intelligence (AI) and Fuzzy Logic are the methods that are used separately or in combination as a program to train the system and make it learn to develop estimates and calculate uncertainty. By including sensitivity analysis the system can be made intelligent to make its own decisions and change the input values to get a reliable output. Although these methods are the best, the time and resource it consumes for its development is very high. Also for the development of these methods the knowledge and information should be very high and complete. These methods coupled to software programming are used to develop software tools which are used for cost estimation. No matter how beneficial a method may be, its use is limited by the maturity level of the knowledge, the kind of application and the outcome which is intended. Hence, no method is complete enough to be directly used in composite problem.

From the literature review, some of the drawbacks in current methods/approaches are identified. These relate to the inaccurate Knowledge management (KM), lack of composite knowledge, complex structure, lack of generalization of knowledge and lack of utilization of KBE's full potential in costing. For eliminating most of the drawbacks, KBE seems to be a viable alternative. The benefits of KBE include precise knowledge capture from explicit, implicit and tacit knowledge, generalized structuring, object-oriented approach and ease of knowledge reuse. These could be used with certain modifications to the existing approaches to make them even more flexible and applicable to complex situations like composite technology.

KBE could also be used for development of advanced cost models for composite parts that are even more reliable and flexible than before. The benefits of KBE as applied to overcome the drawbacks in current methods/approaches are shown in Figure 14.

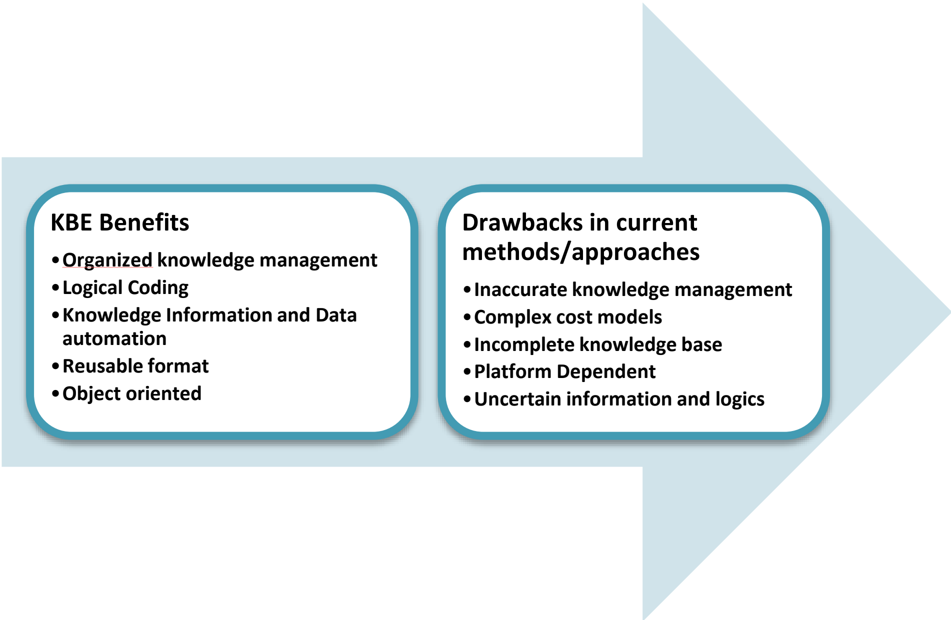


Figure 14: Benefits of KBE v/s Drawbacks in Current Costing System

For composite materials, the material knowledge is vast and varying. Manufacturing complexity is geometry dependent and involves a lot of uncertain information which can be quantified by using KBE. It is clear from the study conducted so far that knowledge related to composites needs to be improved and codified in a manner that can be effectively utilised by cost models. For this, KBE can be applied in knowledge capture itself and could be utilised for knowledge automation in a very early stage. Also the current cost capability involves scoping from a process involving certain knowledge areas. These knowledge areas include design, manufacturing, supply, quality and overheads. This is a very old approach as it does not talk about some key areas which play a very important role in driving the cost of a product or a process. Also, for effective and sustainable process or project management, besides cost estimation, environmental effects need to be included in the cost study. From the literature review conducted in this research, gap areas have been identified. These gap areas have been represented in Figure 15.

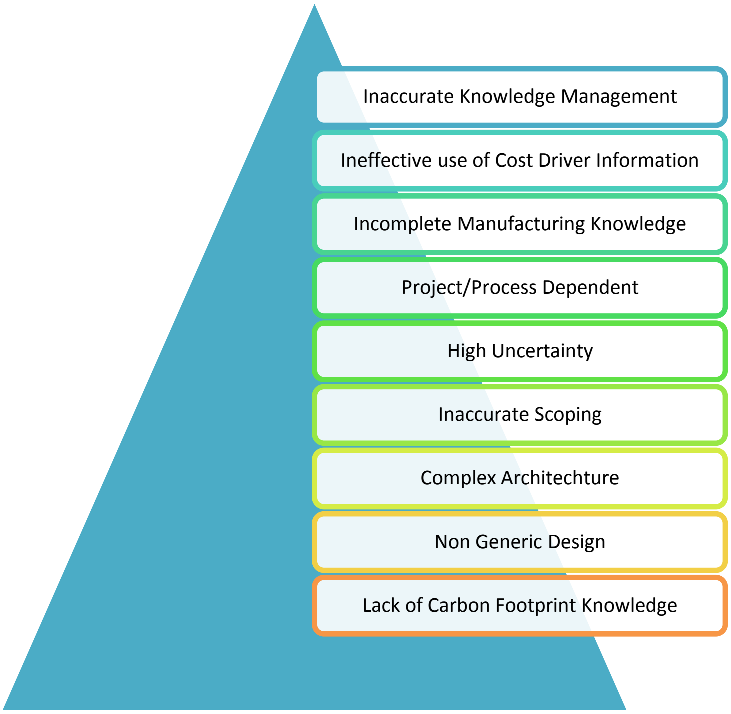


Figure 15: Identified Gap Areas

These gap areas are further elaborated and discussed below:-

(a) Carbon footprint which has been identified as the new area in the field of composite cost estimation has not been included in the cost analysis and has not been modelled. This is extremely important for increasing the applicability of the cost models, making them advanced and future proof.

(b) Cost estimation methods and models have a non-generic design which is found to be applicable to a particular situation or a problem but fails when there is a change of circumstances. The current system is not managed accurately into a single unified and systematic format that can be generalised to apply to a wide range of problems.

(c) The architectural design of cost models is very complex and cannot be understood by designers and engineers to a higher flexibility as it should be. Due to this fact there is a separate cost team which works in line with the other departments to do the hard work for them. This makes the cost models difficult to maintain.

(d) The current scoping is outdated and has not been revised, which needs addition of knowledge from different phases of the life-cycle of a product and also needs to include carbon footprint knowledge looking forward for a futuristic design and manufacturing outcome.

(e) The methods and techniques that are employed in developing a cost model or a cost estimation depends upon the cost driver information. However, this information brings a lot of uncertainty which has not been quantified especially in terms of composite technology.

(f) The overall process of costing is either project or manufacturing dependent which makes the models applicable to only one type of design or technology and the cross-applicability of these models become difficult.

(g) Lack of logics and lack of effective knowledge capture in composite technology makes the information highly uncertain and even unusable. This in turn causes inaccurate knowledge of manufacturing processes resulting in inconsistent estimations.

(h) The platform dependent structure of current methods/techniques makes it difficult to be used in cross platform applications and causes further problems of compatibility.

(i) The major area of concern is the inaccurate knowledge management which triggers most of the other problems. The inherent weaknesses of many other areas could be resolved by effective use of KM strategies.

The present research concentrates on some key areas of concern. These include, improving knowledge management for costing, cost estimation applicability, scoping of knowledge in costing, structuring and designing of cost estimation techniques. This study concentrates on composite technology and tries to improve composite knowledge and include carbon footprint knowledge into costing for future proof system design. The other attributes that this research addresses is the use of mathematical method for development of advanced cost estimation system which is flexible in operation, easy to maintain, comprises of composite knowledge relevant to aero-engine component design, platform independent and has increased capability of conducting carbon footprint analysis as a cost burden. This research uses a mixed cost estimation approach which utilizes the positive attributes of the existing cost estimation techniques. This way a problem will be resolved using different methods for different parts based upon the knowledge available, output required, design complexity and nature of estimate maturity. For improving the KBE approach, a mathematical set theory-based knowledge acquisition, keeping, coding and reusing is used. This way a more logical basis will be formed for achieving advanced cost estimation for composites.

2.7 Chapter Summary

This chapter concentrates upon the study of the literature from four basic fields of engineering namely, Composite Technology Knowledge, Knowledge Based Engineering (KBE), Cost estimation and Carbon Footprint, and further, scoping it down to the intersection of these fields. The literature review is conducted in a step-by-step manner and all the explicit, implicit and tacit knowledge is captured for the study. From here gap areas have been identified which relate to inaccurate Knowledge Management (KM) of composites that lead to complex attributes requiring a separate cost estimation methodology. Different cost estimation approaches have been studied and their applications and benefits identified. It has also been highlighted that the selection of the cost estimation methods and the application of the same depends upon many factors, out of which, complexity of technology, maturity of the technology and the outcome required are the major parameters. Cost estimation methods have also been seen to be dependent upon either a process or a component leading to a specific nature of the estimation models. This not only makes a model to work for a particular problem or a component but also leads to ineffective use of the same in a problem involving multiple parts having mixed complexity levels. Another problem is the platform dependent design which makes the system more complex and less maintainable. The analysis revealed that benefits of KBE could be directly applied to overcome drawbacks in the current cost estimation methods, however, as KBE has its own problems, there is a need to use a more logical and simple system of KM. This chapter has discussed all these problems and current state of the art in detail which has led to identification of gap areas and development of problem to be handled. The next chapter discusses about the methodology design and structure that would be followed to answer the identified problem keeping in view the outcomes of the literature review. Also in the next chapter a basic outline is presented which guides the research further and streamlines the milestones for achieving aims and objectives of this research.

3 Research Methodology

3.1 Chapter Introduction

This research follows various identified methods and integrates them to form a logical and advanced system which is capable of handling complex data and knowledge together with achieving a composite aero-engine component cost estimation. The focus of this research is kept within the realm of composite cost estimation and into aero-engine components. Another reason for choosing composites is the need that has been developed after new and advanced engines are required that are capable of high efficiency offering lower weight. To carry out the research smoothly certain identified methods/techniques have been used adopted from three main areas, namely, (i) Cost Estimation, (ii) Knowledge Management (KM) and (iii) Carbon Footprint, taking composite technology as the basis. These areas form the basic building blocks for this research. A more detailed discussion of the methods used for conducting research are made below:-

(i) Cost Estimation: It has been seen that Activity Based Costing (ABC), parametric costing, bottom-up and expert judgement approach are having good combination of the advantages that are needed for the development of an advanced system for composites. Simple in their design and association of cost drivers with the output, makes these methods very useful for the complexity that aero-engine composite components have in their design and manufacturing. Also, these methods can give early as well as detailed cost estimates with a good degree of acceptability and variance. In this present research the advantages of one method is used to cancel out the disadvantages of the other and hence a mixed costing approach using these identified methods is used for developing reliable Cost Estimation Relationship (CER)'s. Bottom-up approach is used to breakdown a problem into processes starting from the first till the last.

(ii) Knowledge Management: From the literature study and analysis it has been seen that Knowledge Based Engineering (KBE) benefits can be applied to overcome the drawbacks in the current methods/techniques. Also the basic principles of KBE are very useful in composite knowledge management and helps in developing advanced costing methods. There are methods such as Computer Aided Design (CAD)-to-cost, Building Information Modeling (BIM), rule-based costing and model-based costing which have used KBE techniques successfully. The application of all these processes have not been made fully into composite aero-engine realm. The complexity with an aero-engine design is high followed by the material selection parameters and manufacturing complexity which further makes the KM difficult. To overcome this, the present research uses a mathematical system of collecting, categorizing, coding and reusing knowledge. This is a logical set theory which has the capability to present the knowledge into elemental form, which can then be further reused as it is or can be modified before use. Also, the generic structure being logical and mathematical, makes it platform independent and easy to maintain. For this research the logical set based composite KM is developed which is then integrated with the cost estimation methods to form an advanced costing system.

(iii) Carbon Footprint: It has been identified in the previous studies that carbon footprint is extremely important to be included in the life-cycle of a product. As the world is moving towards a greener future all the industries whether from construction background or that of aerospace background are looking into ways to cut down the carbon signatures of their products. With a change in the environmental laws and additional taxation, it has become even more important to include carbon footprint knowledge into cost. This is because in the near future carbon signature of a product will influence its overall cost to the customer and for a company to remain competitive, it will be important to design products that have less carbon signature and cost impact. In the present system, knowledge capabilities of the cost estimation structure does not have carbon footprint as its integral part. Also, there is no model which can predict the carbon footprint as cost burden for a product or a design well in advance. This research has included the carbon footprint knowledge as part of the cost knowledge and have taken a generic life-cycle approach which includes carbon footprint as part of the life-cycle starting from the very first phase of decision making till the last phase of disposing off. This inclusion of this knowledge increases the current cost capability and further advances the cost estimation system for composites.

The final application of the developed methodology into a tool has been done in MS Excel and Vanguard-based cost software. The academic license for the vanguard software was obtained for one year, however, it did not have all the advanced modeling features unlocked for use. Therefore, the application was also made in MS Excel which did not require any special licenses for use. Finally, MS Excel was chosen to be the basis for designing an advanced cost estimation tool.

3.2 Methodology Overview

For the fulfilment of the aim and objectives of this research and conducting the research smoothly, the methodology has been split into different phases. These phases in the methodology structure define a step-by-step method which is used as a basis for conducting research work along with other tools/techniques/methods. This way a systematic and logical plan is followed for conducting research further and finally designing an advanced cost estimation system. This methodology structure can be visualized from Figure 16.

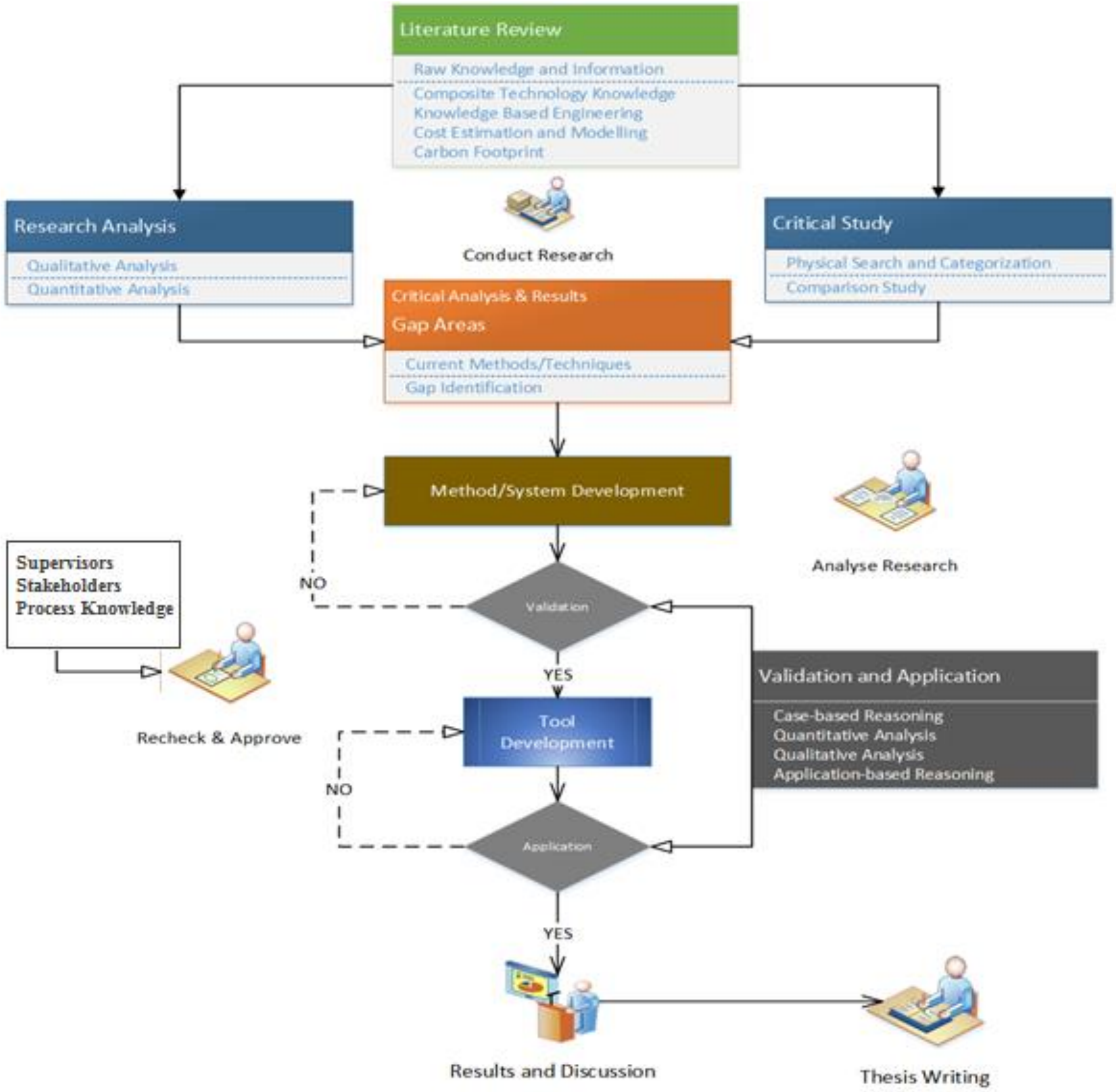


Figure 16: Schematic Representation of the Methodology Structure

From the methodology structure it can be understood that a systematic flow of events takes place. The literature is divided into major areas of study which are taken in a broader fashion to suit the needs of this research. These areas of study are thoroughly analysed using both mathematical and non-mathematical methods to scope it down to cost estimation in composite technology from aero-engine realm. Another field is included in this step which is carbon footprint. This field is analysed parallel to other fields so as to find a proper co-relation of this area of technology with the main stream technology. From current methods/techniques which are comparatively analysed, gap areas are identified that are taken as a problem statement for further research work. After this is done an analysis report is structured which gives an insight of the main objectives, aims and gap areas which are combined together so as to define a proper basis for further research. A new method for development of an advanced costing system is visualized, studied and defined. This method is systematically structured and designed to suit the problem in hand. The design of this method is kept as wide and generic as possible so as to increase its applicability from one technology to another and also make the system thus obtained to be platform independent. This method is then tested using case studies that have been collected by conducting industrial visits. These case studies are chosen to be from aero-engine components manufactured using composite materials. A tool is prepared using the developed method simultaneously. This tool is made in MS Excel using its advanced features to structure, keep, model and reuse knowledge in an advanced way so as to have a multi-use cost estimation tool. This tool is also validated using open market available aero-engine components from composite technology realm. Once this is complete the final outcomes are presented in a result and discussion document whereby the results are critically discussed with the stakeholders, supervisors and process engineers and a feedback is taken.

As the methodology has been outlined taking into account the generic structure, phases in the same play a very important role in the overall breaking of the research problem into much smaller and manageable steps. These steps can be further broken down into objectives and outcomes for easy and trackable movement of the research. A second level of detail of the methodology structure can be understood by analysing Table 8.

Table 8: Methodology Phases & Intended Outcomes

METHODOLOGY PHASES: OUTCOME & OBJECTIVES		
Methodology Steps	**Proposed Outcome**	**Objectives**
*MP 1 – Literature Review and Analysis Time: 12 months	• Problem definition • Aims and objectives • Gap areas in current technology • Literature Review document • Publication in a Conference	To find out the gap areas and understand the benefits and drawbacks of current methods/approaches
*MP 2 – Industrial Visits and Data Collection Time: 9 months	• Detailed definition of the research focus • Detailed analysis of current logic • Report on data evaluation	Understand the industry practice and collect data for study
*MP 3 – Developing Advanced Cost Modelling System Time: 9 months	• Conceptual design of KM methodology • Conceptual design of advanced cost model for a composite part • Journal paper	Develop a concept for the development of the advanced cost estimation system which is knowledge-based
*MP 4 – Benchmarking and Case Study Time: 6 months	• Analysis report of the developed prototype version of the advanced cost modelling system. • Journal paper	Validate the method/technique developed with the data collected and simulate results
*MP 5 – Thesis Preparation Time: 35 months	• PhD thesis • Advanced Composite Cost Estimation Tool V 2.0 • Advanced cost modelling system	Writing thesis and developing advanced cost estimation tool's working version

*MP: Methodology Phases

The steps in this table are further understood in detail in the subsections to follow. Here each step is discussed in a more detailed fashion including the manner in which these steps are completed. These steps are very important for the smooth functioning of the overall research and are represented by the letters 'MP' followed by a number representing the step. All the information and findings from these steps are duly reported from time to time.

3.2.1 MP 1: Literature Review & Analysis

Literature review and analysis are intended to understand the existing state of four major areas namely, Composite Technology Knowledge, Knowledge Based Engineering (KBE), Cost Estimation and Carbon Footprint. One of the main aspects is to analyse the various methods and techniques used to predict the cost of composite part. The understanding of the current knowledge based approaches used for developing cost models and the current method of knowledge capture for composites needs to be studied. First of all, it is important to understand the background and definitions of the core subjects starting with composite materials and continuing with KBE, cost modelling and carbon footprint. This would lead to a basic information of the advances in these fields. For understanding the aero-engine composite material part manufacturing, various manufacturing techniques have been identified and studied. Manual, automatic and semi-automatic processes have been studied in detail to understand their applicability and complexity levels. Cost estimation techniques from judgmental to predictive and from manual to automated are analysed and benefits and drawbacks discussed. KBE based techniques/approaches are also discussed and a rationale of using KBE to overcome the drawbacks in the current system is showcased. Later, the carbon footprint field is studied in detail and its definition, use, need and application is discussed. Later, a need to bring this knowledge in terms of cost to the existing system is theorized. Finally, all this study and analysis is presented in the form of gap areas which are then utilized to formulate the research problem and conduct further research.

3.2.2 MP 2: Industrial Visit & Data Collection

As composite technology is a new field in relation to the aero-engines, the data are either covered under proprietary rights or available in a limited number of industries. As this project is carried out in collaboration with Rolls Royce Plc, the data collection has been carried out with help from Rolls Royce facilities for some of the part of this research. Also, as most of the data cannot be included in the representation or evaluation purposes, additional knowledge has been captured from open sources to support the research further. Initially, data was collected from papers, previous theses, used business cases and patented information. In the next step, data collection was done by conducting visits to Rolls Royce facilities and working on composite technology products. This included, (i) meeting senior officials to seek their permission in regard to gathering knowledge in composite technology from the relevant engineers; (ii) capture explicit as well as implicit knowledge of the current composite technology and costing methods from the concerned engineers; and (iii) visiting various departments such as design, procurement, manufacturing, quality, packing & dispatch and after sales, etc. in order to gather information relating to the composite technology. Most of the data were taken from open source materials and the used cases that could be taken from the industry was included as the part of the validation. This part has been very important in utilizing the knowledge and converting it into an advanced methodology for further research.

3.2.3 MP 3: Developing Advanced Cost Modelling System

After collecting all the data, the information was refined into a meaningful form and the knowledge so gathered was first classified as explicit, implicit and tacit. This explicit, implicit and tacit knowledge was used to generate a logic for Cost Estimation Relationship (CER)'s and scoping knowledge capturing for making advanced knowledge sets that were capable of Knowledge Management (KM) of composite technology. This knowledge was used for generating a composite KM methodology which is logical and highly flexible. This was prepared by applying the principles of Knowledge Based Engineering (KBE) into mathematical set-based theory and integrating it to mixed cost estimation methods. The approach used was to refine, codify, simulate and automate the composite knowledge in a mathematical set form.

The most important part of this step was the acquisition of knowledge from all the possible areas available. The first part of the knowledge acquisition was from tacit category of the knowledge which is related to the intuition of a person and is understood in the manner in which the complexity of a problem is defined. The second part of the acquisition process was implicit knowledge which was taken from the experience of the engineers and/or project planners. This involved understanding of the relationships that are developed for a particular design by experts and the key attributes that are needed for making a reliable cost prediction. The final step involved acquiring explicit knowledge which was much simpler as it contained documented form of knowledge. This was done by analysing previous knowledge bases and studying previous research documents. All the relevant information was captured and converted to an understandable form. Later, it was converted into a mathematical and statistical form by conducting analytical analysis. This way, the entire knowledge was generalised and categorised for ease of use with the cost estimation system. This process of knowledge conversion can be visualized from Figure 17.

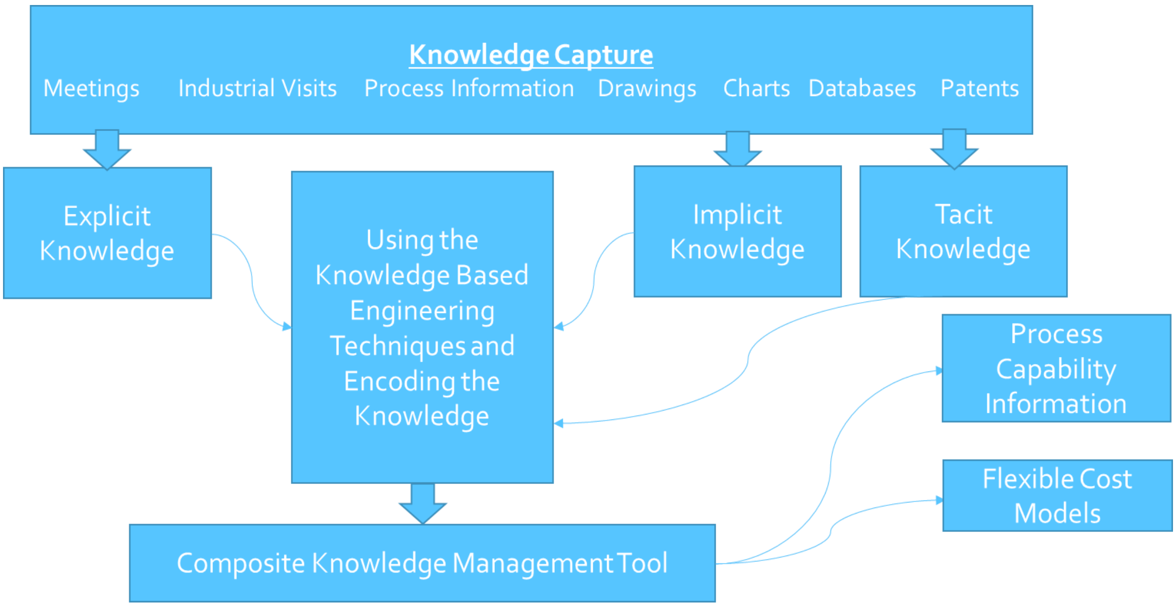


Figure 17: MP 3 Step Visualization

The composite knowledge management system is utilized for improving the process capability information and/or making flexible cost models. As soon as the task reaches its finishing stage, necessary corrections and/or changes are carried out with regard to the aim of the research.

3.2.4 MP 4: Benchmarking & Case Study

Validation and benchmarking form the most important stages of this research as they show how the developed technique actually works on a real life business case. First of all, the developed methodology is evaluated and examined thoroughly to see how the represented technique interacts with the different cost models. Here, computer based simulation is carried out by taking the used business case study, which is generic in nature, from the Metal Matrix Composite (MMC) composite and the Polymer Matrix Composite (PMC) aero-engine component. The case studies are elaborate in their design and attributes and are very intricate parts of the aero-engine. After analysing the developed technique with the business case, all the drawbacks and shortcomings, if any, are thoroughly recorded and improvements with the models, logics, composite Knowledge Management (KM) system and Cost Estimation Relationship (CER)'s are carried out. After this, an advanced cost estimation tool is made using the developed methodology and validated using open market source knowledge of generic composite based piping products that find application in aero-engines and can be used elsewhere in an environment which has high pressure and temperatures. The information which is covered under IP has not been included in this research in any form. Whatever has been presented has been passed through the company's internal clearance process. Even the papers presented as part of the research have been duly cleared and copyright still remains with Rolls Royce Plc. Some of the logics, drawings, processes and parameters have not been included due to an IP protocol which is the part of the agreement with Rolls Royce. Proper care has been taken to modify/normalize/change the data and then include in this research.

3.3 Methodology Design

Once the stage of scoping down has been reached, it has been seen that, this research includes multiple parameters relating to the composite technology, hence, the composite technology selection plays a very important role in this research. This is followed by a mapping of the life-cycle and data collection. The next step is the identification of key cost drivers based upon the generic process flow for which refinement of information is done using Knowledge Based Engineering (KBE) techniques. This is then followed by developing a cost modelling system using a mixed approach of cost estimation coupled to KBE technique, specifically designed to work with composite cost estimation. The approach uses Activity Based Costing (ABC), parametric costing, bottom-up approach and expert judgement for developing process models and the generic rules. After using the mixed approach, for the validation part, two case studies are used. These case studies are specifically chosen to be aero-engine components of different materials in the composite domain. This is followed by the development of an advanced costing system which is capable of advanced cost estimation, process and design optimization. Second stage validation is carried out using two case studies from open market composite products which are used in aero-engines. These case studies are applied directly to the tool and the outcome is observed which is compared to the actual cost of the product.

The methodology follows a standard design; this design relates the basic building blocks together in a functional form which are very necessary to complete this research smoothly. This is done so as to make the process run in a desired fashion and keep the knowledge traceable. Another reason of a methodology design is to utilise the maximum possible knowledge in a systematic order keeping undesired knowledge out of the system. The methodology design that is used for further research could be understood from Figure 18.

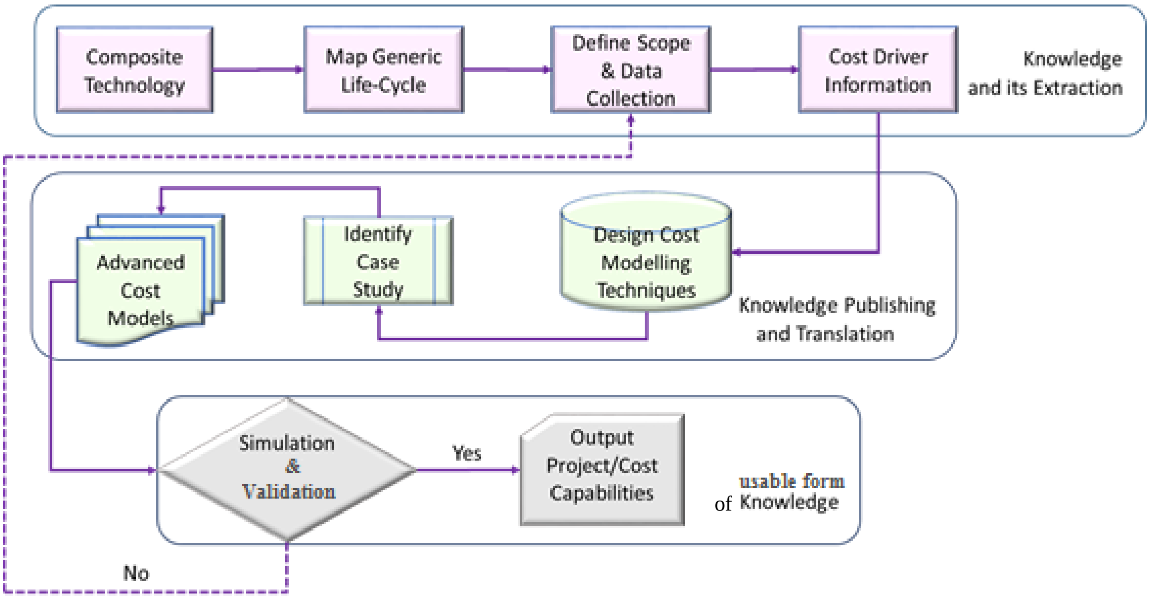


Figure 18: Schematic Representation of the Methodology Design

The design follows a flowchart where different areas of study have been identified, such as technology selection, generic life-cycle definition, Knowledge Information and Data (KID) extraction, KID representation/modelling, evaluation and validation. Composite technology has been seen to be a dominating selection for development of advanced aero-engines for the light weight and highly efficient aerospace designs. Thus, composite material technology has been chosen for the development and representation of advanced cost estimation system. It has also been seen that the choice of cost estimation methods depend upon the technology maturity and the problem in hand. For early design problems and new technology problems, predictive methods are easier to apply and more relevant. As the technology becomes more and more packed with knowledge and information, a more precise and complete method of cost estimation can be utilized. In the present selection, some of the areas of composite technology has been developed whereas other areas are still in the initial phases. Thus, no one method can be fully modified to be useful in composite cost estimation. It is due to this fact that the present methodology utilizes a mixed approach of cost estimation wherein, predictive and quantitative methods are coupled together to form a cost estimation relationship that can be used directly into the advanced system. To utilize the full potential of both the composite technology and the cost estimation, KBE plays a very important role. There are several KBE approaches that can be utilized for the problem in hand, but it has been identified that a more logical and manageable format is required that can be directly applied to costing without disturbing the process parameters. Also, as the application of this logical system involves use of complex composite knowledge, there should be a system that can be generalized for future use. To achieve this, a mathematical set-theory based Knowledge Management (KM) system is developed which couples the related KID into mathematical sets with subsets and elements that can be interlinked to each other following a mathematical logic that can be converted into machine understandable language. This way knowledge becomes easily codable, accessible and maintainable. Even the logics can be kept as a separate entity, so that they do not interfere with the design of the primary knowledge sets or their inter-working with secondary knowledge sets or with each other. To systematically execute the entire research, methodology is divided into steps which are precisely scheduled for easy tracking of the progress and define a particular time limit for completion of the sub tasks associated with that step.

3.4 Chapter Summary

For smooth conduct of the research, the structuring and design of the methodology has been made in a step-by-step manner with defined work packages scheduled within the time frame of three years, the intended completion time. Initially, methods/techniques are identified that are utilized for the conduct of this research. Later, work packages are defined which divide the entire research into steps that are carried out one by one. These steps start by an initial literature study where current technology is understood and gap areas are identified. From here a methodology design is developed which is used for an advanced knowledge management system. Knowledge from all the three main knowledge types is captured and converted into a usable form. Explicit, implicit and tacit knowledge which has been captured is converted into a mathematical or logical format so as to make the knowledge codable. This knowledge representation is further utilized for the development of an advanced cost estimation system, which is represented in a worksheet format of MS Excel. This way, a complete system is created and utilized.

This chapter discusses the structuring and design that has been utilised for the methodology and describes the steps that are followed for the system development. The methodology design that has been described in this chapter forms the basis of the composite cost estimation system and is further utilised for the advanced cost estimation system development. The next chapter discusses the advanced cost estimation system development in detail. The chapter discusses about the cost estimation approach used, Knowledge Management (KM) technique developed, carbon footprint knowledge inclusion as well as the advanced costing tool that is developed as part of this research. Architecture, design and application of the advanced system are all part of the next chapter and are discussed in detail.

4 Advanced Cost Estimation System Development

4.1 Combined Life-cycle & Carbon Footprint

4.1.1 Introduction

With the advancement in design and requirement of more and more environmentally friendly machines, advanced materials became the choice for manufacturing of structural as well as non-structural parts. Light weight and higher strength with superior mechanical properties made composite materials a unanimous choice (Mar-Bal Inc., 2016). To make complete use of these materials and to plan the project activities, designers, engineers and project planners needed to make cost estimates related to these materials in advance and with a certain degree of acceptability. Developing a perfect Cost estimation Relationship (CER) is challenging keeping in view the complexity involved in the composite material itself and the wide range of manufacturing choices available. Not only this, as every product has to go through a life-cycle, and based upon that, elements contributing to cost are to be mapped, establishing a relationship becomes difficult without actually knowing their importance in the overall life-cycle. These elements also termed as cost drivers need to be accurately mapped so as to have a considerable amount of accuracy in the overall estimate of the cost. If the processes and the activities are correctly included in the life-cycle a real time model mapping the activities may be used for the process analysis or in other words process optimization may be achieved.

This section reviews the importance of cost driver analysis followed by cost estimation procedures and later present the requirement to map phases in a process for a life-cycle analysis. This is done by analysing a process flow of a product journey from raw material to the finished product and then calculate the contribution of each phase in a process in relation to the overall cost. This contribution is then represented in a tabular form and compared to the conventional method of life-cycle designing. Another review conducted is in the importance of including carbon footprint as a cost driver early in the life-cycle definition itself, so as to have a thorough analysis both financially and environmentally. Finally, based on the comparison and a pie distribution, generic project/process life-cycle for composite material part is defined and proposed. Thus, by carrying out this study, an elaborate and well defined life-cycle is developed including carbon footprint forming a basis for Work Breakdown Structure (WBS), Cost Breakdown Structure (CBS) and project/process management for use in developing composite cost estimation system later in this research.

4.1.2 Importance of Life-cycle in Cost

Every product has to undergo a life-cycle and thus consume resources while transiting from raw material to finished product. Any activity which drives a change in the cost is termed as a cost driver. Consumption view, allocation base, activity base and traditional approach are some of the selection methods for cost drivers. The main criteria for the selection depends upon, (i) ease of identification, (ii) existence of relationship, (iii) positive or negative value change, (iv) degree of accuracy and (v) degree of usefulness (Cokins and Capusneanu, 2010). A theoretical analysis for choosing cost drivers in Activity Based Costing (ABC) in a Chinese well company showed that contributors to cost can be other activities which were otherwise considered unimportant (Wang et al., 2010). Data from the company was analysed against all the processes in operation of the oil well and a number of mathematical analysis was carried out to find out the cost value for each activity. It was shown that the major cost drivers for ABC would be, (i) number of wells, (ii) distance of wells, (iii) weight, (iv) depth and (v) ton-kilometres and thus, were later included as cost drivers in the overall cost analysis of the plant (Wang et al., 2010). A study was conducted for the analysis of parameters to be included as cost drivers for the manufacturing overhead (Ahn, 1998). In this study inter-relationships of different levels of cost drivers in manufacturing of automobile were analysed. Data were collected from 74 companies and an empirical study was conducted on that data. The study showed that manufacturing overhead was twice as that of the direct labour. Volume and activity formed a positive share in the overhead cost (Ahn, 1998). To have a precise cost estimate it is important to know the activities that influence cost. An experimental design study has been conducted to show time as a cost driver (Cardinaels and Labro, 2008). In this experiment a subset of 20 tasks was assigned to participants and time for each activity was measured. To keep the coherence of the tasks they were simply aggregated in a group of three major tasks. The results showed that errors related to aggregation and measurement in the overall cost estimate may be reduced if time is taken as a cost driver (Cardinaels and Labro, 2008). Cost estimation methods and approaches are complex in their design and structuring, similarly the tools required for costing, hence, a thorough knowledge of the cost parameters or cost drivers play a very important role. System requirements, functional hierarchy and physical hierarchy plays an important role in cost parameter information (John, 2012). Thus, it can be concluded that for attaining a precise cost estimate, cost driver analysis is necessary and important so that the cost drivers which contribute the most to the overall cost are not left out from inclusion in the overall cost analysis. A very important inference from the above study made is the real knowledge of the cost estimation procedures. For developing a cost model or a cost estimate, a scope and a schedule development is the first step. This is carried out with the help of a Work Breakdown Structure (WBS) which gives a complete decomposition of the process needed for a project.

The purpose of a cost model is to establish a process plan quantitatively well in advance with calculative risk factors for which life-cycle processes needs to be well established. This can be understood from Figure 19 (U.S. Department of Energy, 2015).

Figure 19: Cost Estimation Knowledge Flow (U.S. Department of Energy, 2015)

From the figure it can be seen that the first part of the cost knowledge is the introduction of parameters and values that are important in the cost estimate. The second part is the estimation which takes place only if a thorough scope is defined and a schedule is created. The third part is the risk analysis which is used to identify areas that may influence the performance of the estimate. Finally, the last step is the representation of the estimate which is usually done through graphs. The two major types of procedures such as, (i) performance based and (ii) project based, may be used for development of cost estimation and its final representation (U.S. Department of Energy, 2015). For any type of estimate, precise knowledge of the process cycle needs to be maintained. Aerospace is one of the most complex places of project as well as process planning (NASA, 2015). A procedure adopted for costing by NASA reveals the same steps of WBS, but now in the aerospace realm. Here, the cost estimation is done for both the agency and the stakeholders. Before even starting to develop a cost estimation plan, a project life-cycle is defined which identifies points for cost estimation. The cost estimation starts with inputs from the customer, WBS and technical descriptions, followed by development of cost methodology and finally cost estimation and assessment. Project management is achieved by integration of both WBS and Cost Breakdown Structure (CBS) in the life-cycle (NASA, 2015). The cost estimation procedure followed in another tough situation is in the Linac Coherent Light Source (LCLS) project management (Stanford University, 2006). Here, cost estimate is conducted for the intention of execution plan, process plan and value management. For the detailed cost estimate Resource Breakdown Structure (RBS) is used. The resources associated with the process/project life-cycle are calculated and aggregated for achieving an overall estimate. Design, management and judgement factors are all considered as cost drivers and thus included in the life-cycle (Stanford University, 2006). Even for cost estimation of transport projects, precise management of knowledge related to the process breakdown and the associated tasks needs to be carried out. After having a baseline estimate of the tasks a risk assessment is conducted and then applied to the process life-cycle. It has been observed here that for true estimation, planning, scoping and designing needs to be carried out, which is only possible with a detailed life-cycle breakdown and analysis (Washington State Department of Transportation, 2015). Even in the realm of software project planning and cost estimation, the basic structure remains the same. Project size, duration and effort are quantified. Precise process knowledge and WBS are the techniques used to make a cost estimate plan (IIT Kharagpur, 2009). From this discussion it is clear that life-cycle processes plays an important role in cost estimation and thus needs to be fully defined for a clear and precise estimate. Also, as the life-cycle may be defined in many ways based upon applications, a generic understanding needs to be developed which can completely define the life cycle and its phases which would be an advancement.

4.1.3 Carbon Footprint & Life-cycle

A measure of the greenhouse gases emitted by an activity, process or a product is termed as carbon footprint. Earlier it was considered to be a direct effect but now both direct and indirect influences are taken as carbon footprint. Global warming was the trigger for studying the effects of any activity on the environment. With the increase in environmental awareness and taxes introduced by various governments, carbon emissions have become a major cost contributor and a factor to be considered by the designers (The Edinburgh Centre for Carbon Management, 2008). A report on the emission of carbon and thus the foot-printing associated with the activities in the industry suggests, that the energy utilized and wasted in an organization is high and also distributed among various sections. The production of materials, distribution, consumption and recycling are the major contributors of these emissions and thus add up into the cost of a product indirectly (Carbon Trust, 2017). As the need for analysis of carbon footprint became important in manufacturing as well, composite based product's manufacturing was also analysed. Life-cycle analysis technique was used to access environmental aspects associated with a project or a process. In this study four stages were taken into account in a Fiber Reinforced Polymer (FRP) using pultrusion method. The energy use over the entire life-cycle was calculated and it was found that lighter materials are more favourable for saving life-cycle energy. A drawback was that as the study used only four processes and also one manufacturing technique, it was not comprehensive and also could not be quantified (Song et al., 2009). With the use of advanced materials in more and more applications, its viability both economically and environmentally are in question. A detailed analysis is done on different applications and the green effect composites have on the overall use. It has been found that after-sales the use of composites in most of the applications is greener than conventional materials because of their light weight and increased overall efficiency. Another discovery made is that manufacturing, processing and maintenance are contributing more to the greenhouse gases and thus inefficient (Dobbins, 2015). It has been observed that composite recycling is economically and environmentally viable than using a new manufactured composite raw material. Specifically, thermosetting type composites and the glass fiber as well as carbon fiber reinforcements are recyclable. 16% reduction in carbon footprint is observed when using recycled composite cementing technique (European Composites Industry Association, 2017). From the study it is observed that different processes have different impacts in emissions and also contribute to cost significantly. If the carbon footprint is quantified as a cost value with the life-cycle of a product a decent analysis of the process/project could be done. Thus, including carbon footprint in the life-cycle is important.

4.1.4 Combined Life-cycle for Cost Estimation

For the use of composites in various fields it is necessary to understand the generic life-cycle that has to be followed. Not only this, but for having a good process and product management, understanding of the cost drivers is important for which proper life-cycle plays a very important role. A detailed analysis is conducted considering five different composite materials. Different phases in the overall process are analysed based upon the overall cost contribution and a comparison is made with the current processes. After analysing, a generic life-cycle is defined for use in the composite material parts cost estimation. Data sets for the different material parts along-with the proposed processes are shown in Table 9. These data sets are derived from composite reports by governmental organizations and NASA files (Mann et al., 2012; Tenney et al., 2009; Xudong, 2009). Another table averaging out values of the processes is shown in Table 10. Table 11, however, shows Cost Breakdown Structure (CBS) as per conventional Life-Cycle method. The processes which are not considered in the conventional method, are given a value '0' in the related column, so that an analysis of the data can be carried out. Table 11 values are compared to that of table 10 and a rationale of defining a comprehensive life-cycle for composite material is arrived. The comparison is shown in Figure 20 as a combined graphical representation.

Table 9: Detailed Process Breakdown & Cost

Composite Material	Life-Cycle Processes										
	Decision	Procurement	Manufacturing	Design	Assembly	Testing	Inspection	Packing	Material Handling	Storage	Maintenance & Disposal
	Overall Cost Distribution in % of a product made by these materials										
CFRP	7	11	44	8	12	3	2	2	1	1	9
GFRP	6	12	40	8	6	6	4	6	1	3	8
MMC	8	11	42	9	6	4	4	4	3	2	7
CMC	8	9	44	9	4	8	2	2	4	2	8
AFC	11	9	37	7	8	9	3	2	1	1	12

Table 10: Averaged Cost against Process Breakdown

Composite Material Cumulative Average Score	Life-Cycle Processes										
	Decision	Procurement	Manufacturing	Design	Assembly	Testing	Inspection	Packing	Material Handling	Storage	Maintenance & Disposal
	Cumulative Average Cost Distribution in % using detailed processes in a life-cycle										
	8	10	41	8.2	7.2	6	3	3.2	2	1.8	8.8

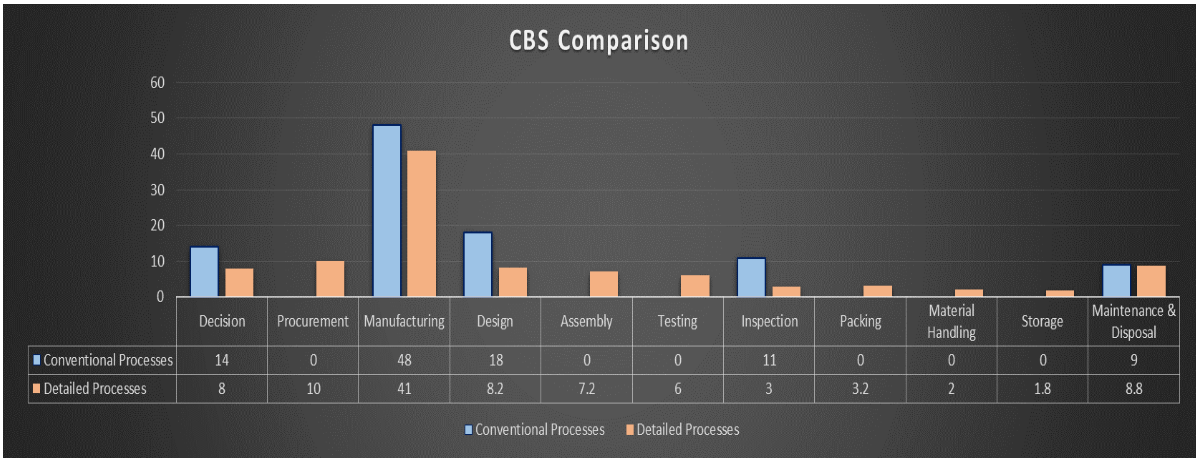
Table 11: Averaged CBS in Conventional Life-cycle Method

Conventional Material Cumulative Average Score	Life-Cycle Processes										
	Decision	Procurement	Manufacturing	Design	Assembly	Testing	Inspection	Packing	Material Handling	Storage	Maintenance & Disposal
	Cumulative Average Cost Distribution in % using conventional processes in a life-cycle										
	14	0	48	18	0	0	11	0	0	0	9

*Note: ‘0’ indicates non-inclusion of a process in the conventional system and does not represent cost share.

`

The values represented in the tables are the percentage contribution of each and every phase in a product's overall cast. It can be seen from Table 11 that only major processes are considered in conventional life-cycle method and rest all are coupled into those major processes. The value '0' does not mean that the related processes do not consume any cost, but, it indicates that the processes are not considered separately in the conventional method. A value '0' has been used so that a comparison can be made between a detailed and conventional method. This comparison is represented as a graph in Figure 20.



*Note: '0' indicates non-inclusion of the related process in the conventional system and not the cost share.

Figure 20: Combined Analysis Representation

It can be seen clearly that for detailed analysis and process optimization, conventional method is not correct and concise. It is good for early and fast estimate but not for a detailed analysis like Life-cycle Cost Analysis (LCCA) and process optimization. This strongly suggests a new life-cycle process for cost estimation. Also, the aspect of time utilized in analysis for process optimization is based upon how the division of activities have been done. Once a detailed process life-cycle is outlined, the activities become noticeable and much easier to locate in the overall process, making them easy to analyse, reducing time.

From the above study and analysis conducted, it can be well rationalized that a new life-cycle has to be developed for composite part cost estimation. Another aspect of the study involves the implementation of carbon footprint. From the study conducted and the data analysis derived from different research papers related to carbon footprint, a combined pie chart showing contribution of different phases of a life-cycle including carbon footprint in the overall cost of a product is derived. This is shown in Figure 21 (The Edinburgh Centre for Carbon Management, 2008; Carbon Trust, 2017; Song et al., 2009; Dobbins, 2015; European Composites Industry Association, 2017).

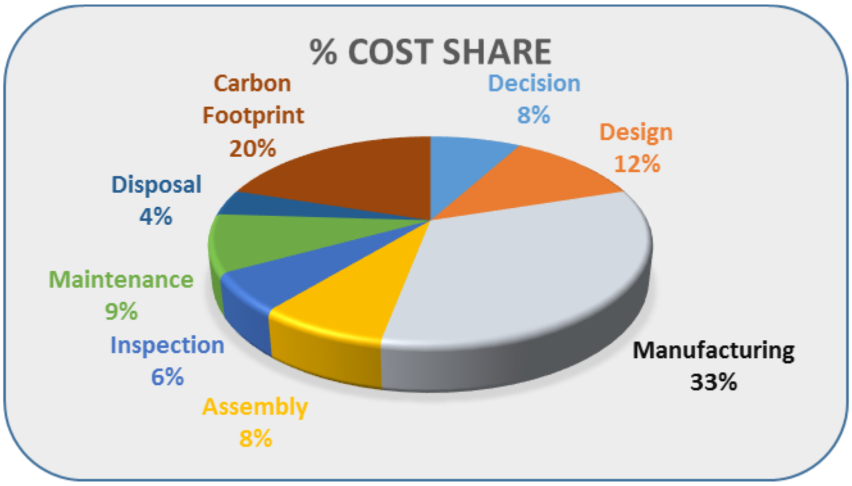


Figure 21: Process-wise Overall Cost Share

Here, phases such as after sales and environmental clearance are also included which form a part of the product use and contribute to the product's running cost. This cost was not very important in the previous studies, but as some companies have started leasing their products, keeping the load of after sales on themselves, have made these costs important for a product study. Also, new taxation policies on environmental emissions have led to the inclusion of the carbon footprint as a monetary burden in the cost analysis inside a company or an organization. To quantify the carbon footprint, both direct and indirect aspects of an activity contributing to energy use are mapped. This energy use is then distributed among the processes and multiplied with the energy prices using an open source web based tool, named as "Carbon Calculator." Based upon the pie chart it is seen that the carbon footprint cannot be excluded from the life-cycle being a major contributor of the overall cost. This pie chart has taken the overall aggregate of the carbon footprint contribution from all the different phases. Some phases have more contribution of carbon footprint others have less, but as in this particular representation distribution of carbon footprint per phase is not important, hence, it has been taken as an overall aggregate. This is not one of the best methods of representation, but can very well represent the need of including carbon footprint in the cost estimation studies or a study involving product and process evaluation. Based on the results from this analysis, a new life-cycle is proposed which will be used for conducting further research. Also, the conversion of carbon footprint as cost has been made for the first time, hence, the results may later vary. For the purpose of a good project and process evaluation/optimization, a proposed combined life-cycle is designed and represented as shown in Figure 22 which will be treated as a base line for composite material part cost evaluation and analysis in this research.

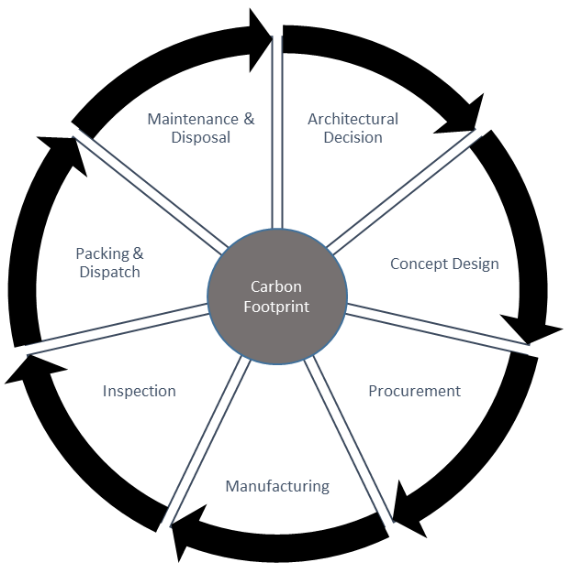


Figure 22: Combined Life-cycle Including the Carbon Footprint

The Combined life-cycle is made by coupling those activities together which have minimal effect on cost and thus they become significant when coupled together. This way all the activities are covered but in a generic form. Carbon footprint is kept in the center of this life-cycle signifying that it is being shared by all the phases in some way or the other and their overall summation leads to an overall carbon footprint phase. This can now be used for any analysis and can be used to form the basis of Work Breakdown Structure (WBS) which can provide a detailed CBS that can be used for both process/project management and cost estimation. Process optimization and business structuring can also be carried out with the help of this chart and thus can be used as a basis for all composite material parts study. As this study has taken data for composites from open source material, the scope of modification still lies for application in conventional materials. The discrepancy in data cannot be ignored, but as the representation has been made in a percentage share basis, the result still remains valid.

4.1.5 Discussion

Cost estimation is an important aspect of process and product management. To achieve a precise cost estimate it is important to understand the process activities in detail and their corresponding cost drivers. Conventional methods and life-cycle are not able to fully utilize the Work Breakdown Structure (WBS) because all the activities are not included in the life-cycle. In case of composites due to high level of complexity and vast mixture of manufacturing techniques involved, it is important to have a generic life-cycle where Cost Breakdown Structure (CBS) can be implemented with a considerable amount of precision. Carbon footprint is an area which was not included in the overall cost, but being a considerable contributor especially in case of composites, needs to be included in the Life-cycle Cost Analysis (LCCA). This study has presented a review of CBS, conventional method of life-cycle and carbon footprint and has thus presented a rationale for developing a detailed life-cycle. Here, detailed life-cycle for composite material based products with carbon footprint as an integral part through the life-cycle has been proposed. The application of this generic life-cycle can be made in knowledge management, costing and business planning/management. As the data is an open source material, the possibility of it being not precise cannot be denied. Because the proposed life-cycle takes percentage contribution of the phases in the overall cost and not the actual value, this life-cycle does not get affected with any data discrepancies. Also the main aim of this study was to develop a generic system which can be easily used in the cost estimation of composite part, hence, the overall trend is sufficient to summarize the results.

4.2 Mathematical Set Theory for Logical Knowledge Management

4.2.1 Scope of Knowledge Acquisition

This is a very important aspect of the whole research. It has been seen by understanding and analysing current knowledge databases for cost estimation both for conventional as well as composite technologies, that, knowledge acquisition scope has to be widened. This is because of the fact that knowledge can come from various phases in the life-cycle of a product and by considering only a few of the processes and coupling most others as overheads or extras does not make up a good estimate. It has now been established that cost drivers that come from phases such as inspection, disposal, decision making and maintenance have a considerable impact on the overall price of a part which cannot be ignored. Another important aspect in the scoping is to include a very important need that will become a necessity in the near future. Hence, understanding of carbon signatures of different phases in a life-cycle is important for precise evaluation. To carry out the study and development of a mathematical set-based Knowledge Management (KM) system, it is important to scope the entire knowledge base that has to be created. This scoping for knowledge acquisition for the development of a set-based

KM system is done by taking the combined life-cycle as the basis of the design of this system. The combined life-cycle thus itself becomes the acquisition parameter. This can be visualized from Figure 23.

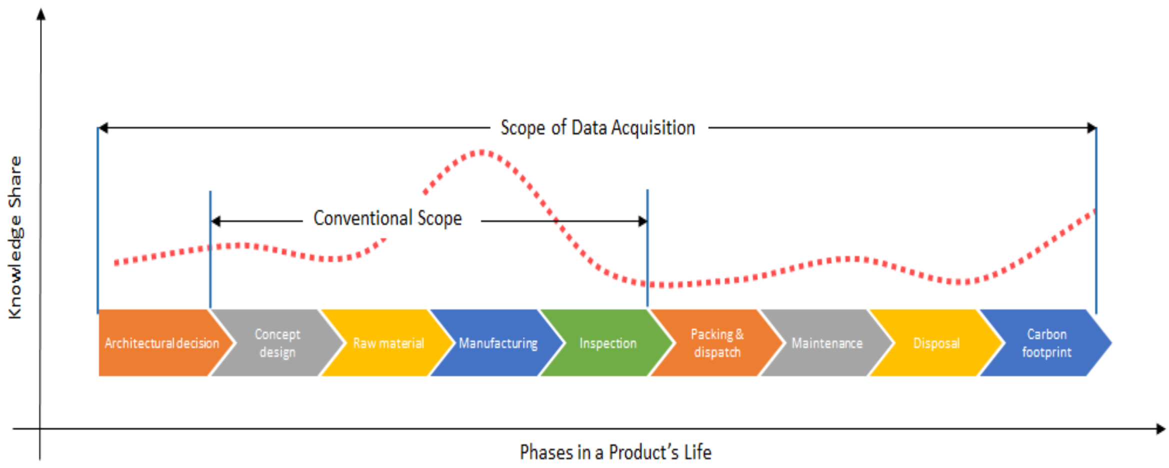


Figure 23: Scope of Knowledge Acquisition

From Figure 23, it is clearly seen that the conventional system of scoping utilizes phases starting from design till the quality inspection. This is usually taken to be a part of the manufacturing phase and the design phase is kept independent. Maintenance is taken to be a part of service and after sales activity and sometimes taken separately. This conventional system of scoping is not good as from the knowledge share distribution shown as a red curve in Figure 23, it is clear that other phases though not considered important have a share in the overall cost and can reduce or increase the likelihood of a project being approved or rejected. Hence, for this study the scope has been taken from the decision making phase up to the disposal phase. Carbon footprint is a phase which runs parallel to the entire life-cycle and thus is also included as a separate element. It can be seen that the knowledge share of carbon footprint is almost similar to that of the manufacturing phase. One of the reasons for such a behaviour is because even though the cost drivers are not much for carbon footprint phase, still the overall share is high due to all other phases contributing to carbon footprint. Another part of the scoping is to keep each and every phase independent in knowledge representation so as to make the interactions logical and manageable. Knowledge is therefore, taken in terms of cost drivers very early in the knowledge capturing phase itself and sorted in a systematic order. This is commensurate to the product's life-cycle phases and thus represents the entire life-cycle. Another most important aspect of this study is the scoping of the materials and the manufacturing phase. As this study concentrates on the use of composite materials and that too in the aero-engine realm, the materials and the manufacturing processes are all kept in the same field. This has been represented in Figure 24 in more details.

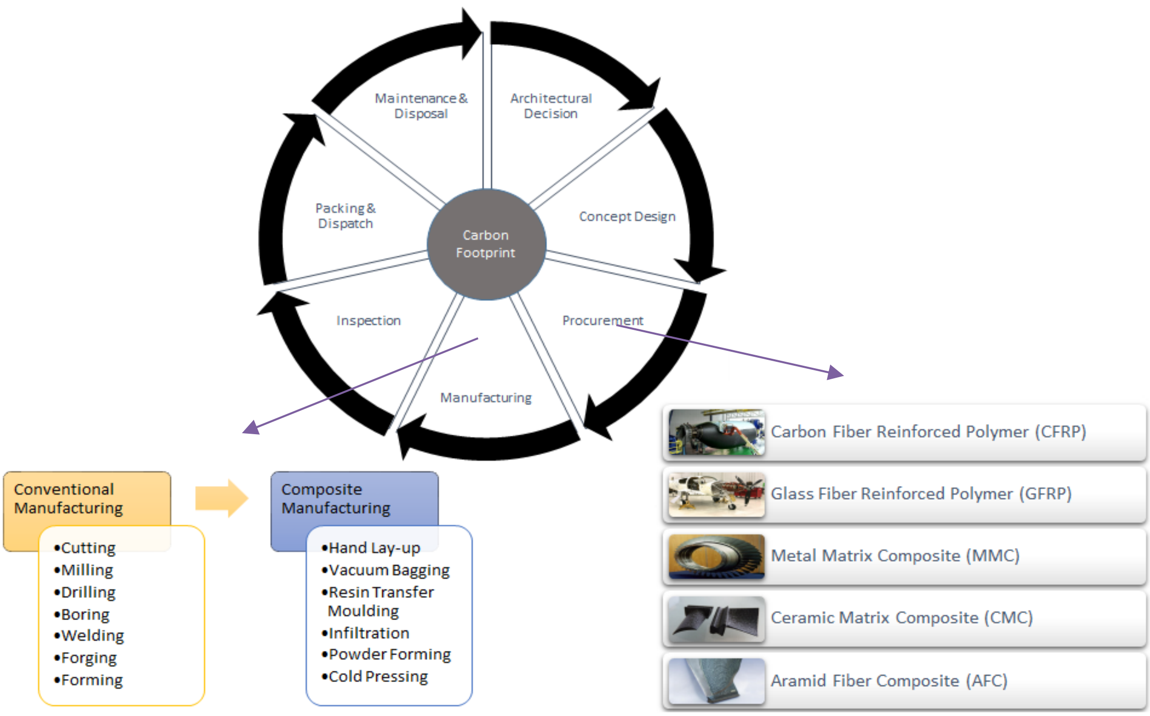


Figure 24: Materials & Manufacturing Scope

The scoping of the materials can be said to lie in aerospace composites such as, Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), Aramid Fiber

Composite (AFC), Metal Matrix Composite (MMC) and Ceramic Matrix Composite (CMC). The choice of the design is scoped down to components under aero-engine category which are being manufactured using composite materials such as, (i) turbine blade, (ii) fan blade, (iii) casing, (iv) combustion linings and (v) auxiliary parts. This way a more concentrated study can be made and an advanced costing system can be easily represented and validated using data from previous studies in these components. Manufacturing techniques, however, are scoped down to a combination of both conventional methods and specific composite methods. This scoping has been made taking into consideration the specific composite material based manufacturing techniques that are coupled to a generic conventional method for achieving a particular design. This scoping is dependent upon both design features and the material choices, hence, is interdependent upon the set of previous choices. The scoping of these phases form the primary knowledge sets and are thus kept independent in mathematical set formulation. The scoping of materials and manufacturing techniques along with the choices in design features are kept as a part of the logical set. This way, a more systematic formulation of knowledge is obtained that can be easily represented in a logical form. Thus, this scope becomes the basis of the proposed mathematical set-based Knowledge based Engineering (KBE) costing system.

4.2.2 Basics of Mathematical Set Theory

Set theory is one of the fields of mathematics that has been used for grouping and solving problems by developing logical relationships with the sets. A set is defined as a collection of objects also known as elements of that set (Munich Centre for Mathematical Philosophy, 2012). This collection of elements in one set and another can be mathematically defined in a logical manner which in turn allows a logical relationship between the sets itself. If x and y are two independent sets and they share some of the elements, such situation can be easily coded in a logical manner using set principles and theorems (Munich Centre for Mathematical Philosophy, 2012). A property of the set is that it can be composed of elements belonging to different natures namely, (i) living beings, (ii) objects, (iii) numerical entities, (iv) signs, (v) functions and (vi) other sub-sets. Another property of the set is that it can be empty/null, finite or infinite valued. These properties of the sets make them highly useful in knowledge management situations. Description of a set follows general rules and some basic notations define those systematically. These rules and notations are described in Table 12 and have been utilized to develop composite knowledge sets for this research work (UMassAmherst, 2006).

Table 12: Basic Rules & Notations in Set Theory

Sr. No.	Notation	Description	Example
1.	Set Representation	Capital Alphabets	A,B,C,D……….
2.	Elements Representation	Name, number, place, small alphabets etc.	a,b,c,d………..
3.	Belongs To	If the elements are contained in a particular set	c ∈ A B ∈ C
4.	Does Not Belong TO	Not contained in a set	d ∉ A
5.	Empty set	When there are no elements in a set	∅ = {}
6.	List Notation	Used for finite sets of elements	A= {1,2,3,4}
7.	Predective Notation	Represents the property of the element	A = {x|x is a positive number <8} Means a set of all positive numbers less than 8.
8.	Recursive Rules	Rules used to generate element of a set	A = {Set of numbers greater than 5} If y ∈ A, y+2 ∈ A
9.	Identical Sets	If elements of two sets are same	Y ∈ A and y ∈ B A=B
10.	Proper Subset	When the elements of one set is contained in another but not equal	A ⊂ B A = {1,2,3} B = {1,2,3,4,5,6}
11.	Subset	When the elements of one set are contained in another	A ⊆ B A = {1,2,3} B = {1,2,3} or B = {1,2,3,4,5,6}
12.	Power Set	Set containing all subsets of a set	*P*(A) If A = {1,2} Then *P*(A) = {∅, {1}, {2}, {1,2}}

13.	Union Operation	Elements of two or more sets combined together in one set	A ∪ B If A= {1,2} and B = {2,3} Then A ∪ B = {1,2,3}
14.	Intersection Operation	Set of common elements of all other sets	A ∩ B If A= {1,2} and B = {2,3} Then A ∩ B = {2}
15.	Difference Operation	Set of elements left in a set after subtracting the elements of another set	A – B If A = {1,2,3,4,5,6} and B = {2,4} Then A – B = {1,3,5,6}
16.	Universal Set	Set of all elements from all the sets and outside of the sets	U U = {-infinity,………,+infinity}
17.	Complement Operation	Set of all elements except the set in question	A' Where A' = {x|x ∉ A} Or A' = U – A
18.	Multiplication Operation	Set of multiplication of every element of set 2 with set 1 in question	A x B If A = {1,2} and B = {3,4} Then A x B = {3,6,4,8}

For solving linear problems or the problems involving linear relationships as is the case with cost estimation, set-theory is a viable alternative. As the categorization in a set form is more appropriate which can define difference in relationships and elements, the complexity in a problem can be simplified. Another advantage of set-theory is that a knowledge can be represented in a generic and independent set form and the elements from a particular set can be connected to the elements of another by a logical connection, making the set application even wider (Dogan, 2011). Sets containing fuzzy information or information with uncertain parameters can also be used to represent knowledge. These representations, when coupled with maxima and minima relationships, are capable of solving complex problems for decision making. This type of capability is very useful in big industrial problems involving multiple pay-offs that control the final decision making. Sets can combine similar decisions in a set and dissimilar in another set, thereby creating a separate entity for every problem. Thus, problems can have multiple solutions with a degree of accuracy that can be predicted (Khedekar et al., 2017). Even in data mining and data clustering, rough set theory is applied. This is then handled with a Min-Mean-Mean-Roughness (MMeMeR) algorithm that makes data clustering even more efficient. Set theory-based data handling reduces the uncertainty in the data to a much lower level which is required for effective use of the algorithm. This method of set formation helps in a step-by-step approach, thereby increasing the accuracy of the knowledge created (Tripathy et al., 2017). A Γ - soft set has been developed that can be used to perform binary operations on big data and complex structures (Rao et al., 2017). The system works by defining sets and subsets of big data and then defining the basic features of these sets. These basic features are called the null sets or the absolute sets. As the sets are defined in a strand of information which runs a series of information of the relationships of these codes, binary operations such as AND, OR and NOT can be easily applied to this structuring (Rao et al., 2017). From this study it is clear that set theory can be utilized to capture, represent, keep and code knowledge in a much more logical manner.

For this research set theory has been selected for representation of knowledge and its utilization. Knowledge Based Engineering (KBE) techniques have been identified with some benefits and drawbacks. The major drawbacks being less logical and less manageable under complex and big data structures. For the purpose of cost estimation in composites, knowledge is unpredictable and contains higher amount of uncertainty. Moreover, the knowledge is in different forms which cannot be directly categorized. To solve this problem set theory seems to be a viable solution. Also, as the knowledge structured in a mathematical set form is more generic, it becomes platform independent. This makes coding of knowledge even more flexible. Another important feature is that coding of knowledge is not necessary to solve problems, manual methods can be easily utilized with the same system to predict outcomes and still maintain knowledge in its logical form. Also, the sets are easy to maintain and understand. This makes any engineer with a basic knowledge of set-theory to maintain and code the knowledge structure as per requirements. For the purpose of knowledge categorization, knowledge keeping and knowledge reuse, set theory is used in this present study. This type of a generic set based representation in addition to the generic life-cycle based knowledge structuring makes the whole system independent in application and coding.

4.2.3 Knowledge Sets for Composite Cost Estimation

Composite material knowledge for costing is dependent upon varying parameters. As the composite material knowledge itself is quite complex, conventional cost estimation methods, when directly applied to composites, make estimation work difficult. A more logical format for knowledge capture and management is required, which can be utilized to generate cost models later in the process. Set theory can be used as a method of keeping knowledge in a systematic and understandable format. Here, the knowledge elements for a particular category are put inside a set as elements of that set. Each set has its own knowledge elements that are necessary for cost estimation. The relationship between the elements of a set or that with elements of another set can be coded using set theory. Thus, a more logical management of knowledge is achieved in the database stage itself, which can be further used for cost estimation. The knowledge sets defined for the present study are derived from literature review analysis conducted in this research, previous thesis in cost estimation (Wong, 2012; Thokala, 2009; Eaglesham, 1998) own experience of various techniques in production and industry experts knowledge. The main cost drivers that are very important from each and every phase of the product life-cycle form a part of the knowledge sets. These cost drivers are derived from each phase in a manner in which they affect the cost. From the literature review done so far, there are various knowledge elements that have showcased that cost drivers exist as part of the activity, resource or an impact in every phase and any change in these has an effect on the overall cost. For this research the cost drivers are captured from each phase of the proposed combined life-cycle and is derived utilizing the mixed cost estimation method. This method converts all the knowledge elements from explicit, implicit or tacit sources into a functional cost knowledge. This cost driver derivation from various phases is shown in Figure 25.

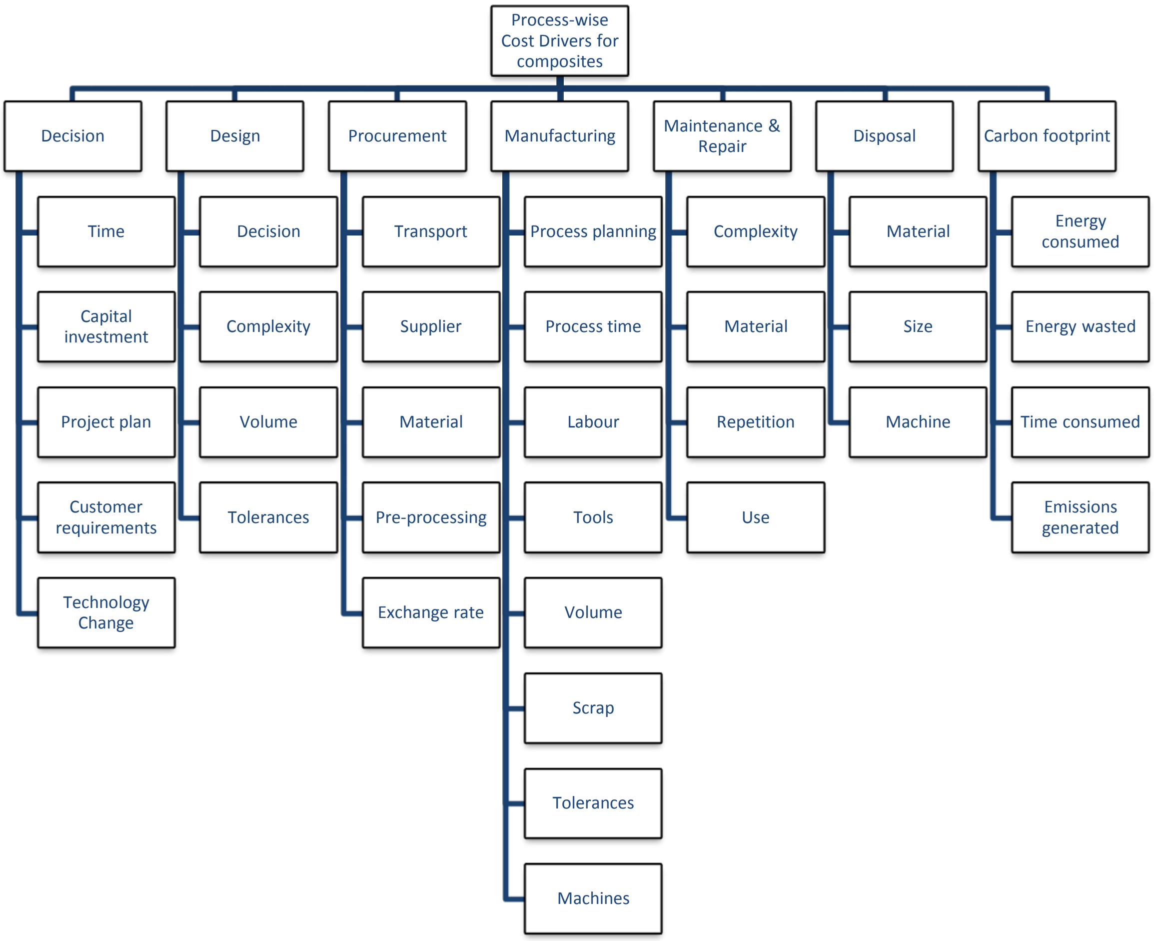


Figure 25: Process-wise Cost Drivers in Composite Life-cycle

There are many activities that are carried out multiple times in a life-cycle and due to this behaviour, the knowledge co-exists in many places. In the old technique, the process parameters were only taken from identified sources leaving out some processes making the overall knowledge uncertain and less precise. This has also been understood and categorization in this method is carried out from identified co-existence once in the life-cycle reducing duplication of knowledge and also making it traceable for proper knowledge set creation further in the study. The activities that co-exist are, (i) condition of supply, (ii) quality assurance and (iii) material handling. Condition of supply is an activity that can be done in three ways depending upon the requirement of a particular project. The condition of supply knowledge that has been extracted for use in this study is shown in Figure 26.

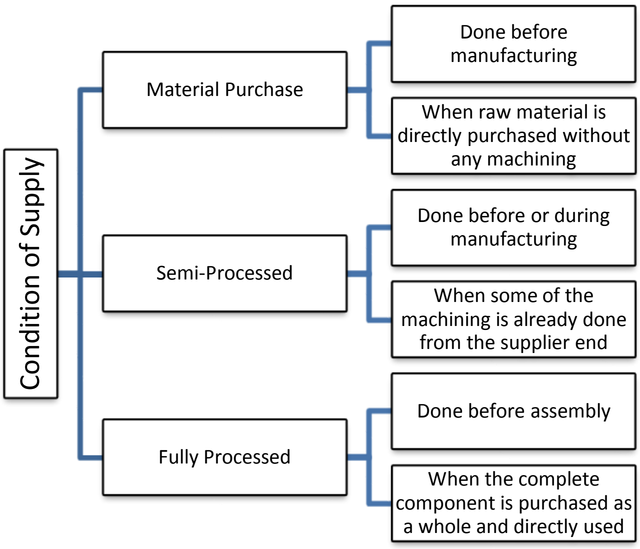


Figure 26: Condition of Supply Knowledge

Quality assurance is an activity that is considered to be ongoing in the entire life-cycle and extremely important in order to assure that the standards and the expected outcomes are maintained. This activity exists in many areas starting from analysing the raw material till signing off the final product. Due to this nature of the quality knowledge, a separate set exists for the same in this method. Certification is also a part of quality assurance.

This knowledge that has been extracted for use in this advanced method is represented in Figure 27.

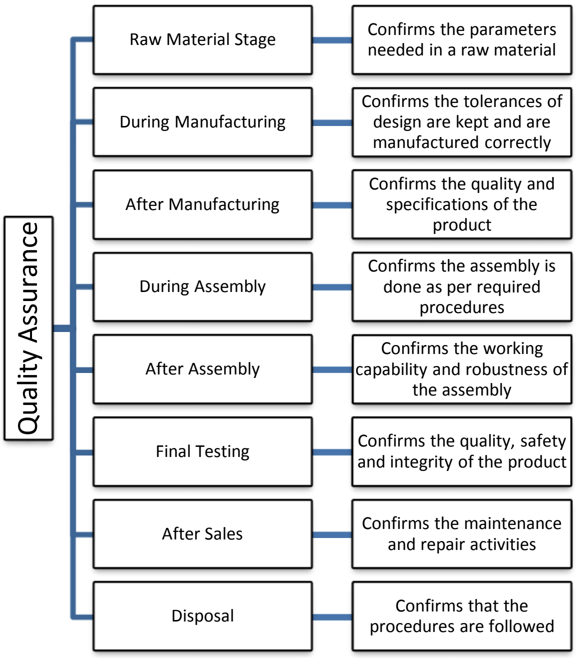


Figure 27: Quality Assurance Knowledge

Material handling is an activity that is requisite for proper flow of the materials and the finished products inside and outside of the factory. This starts from the transport of raw materials and goes until the delivery of the final product. From the knowledge point of view, material handling can be visualized as shown in Figure 28.

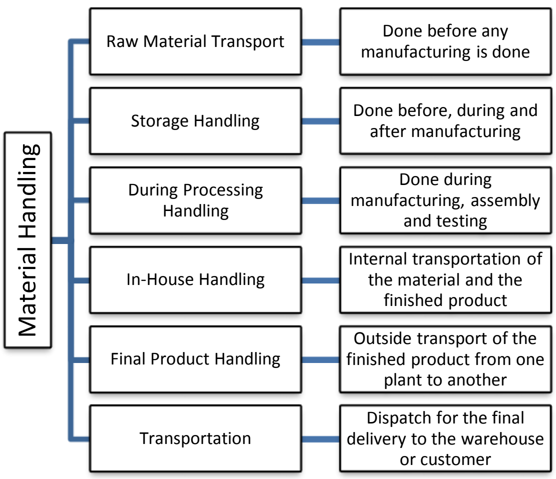


Figure 28: Material Handling Knowledge

All this knowledge is coded into the mathematical format by utilizing only the cost drivers relevant for study from all these sources. The sets that have been derived from the acquired knowledge are converted into useful knowledge for use in this study and are defined as follows:-

(i) Universal Set: represented by **Us**, is the set containing all the knowledge sets, customer specifications, engineering standards and rules.

Us = {all sets, design features, design rules, customer specifications, technical documents, manufacturing rules, machine types, tooling information, material information, carbon information, market information}

(ii) Architectural Decision Set: represented by **A**, is the set of knowledge elements which define the design and the material requirements.

A = {customer requirements/information, material type, design type}

(iii) Research & Development Set: represented by **R**, is the set containing knowledge related to research conducted for finalization of the technical details.

R = {material type, design complexity, prototype time, prototype resource}

(iv) Condition of Supply Set: represented by **CoS**, is the set of knowledge from supply chain that defines the material procurement strategies.

CoS = {raw material type, raw material cost rate, part finished, part finished cost rate, full finished, full finished cost rate, tool, tool cost rate, packing material, packing material cost rate}

(v) Method of Manufacturing Set: represented by **MoM**, is the set of knowledge from a selection of manufacturing styles that can be used for manufacturing.

MoM = {machine type, manufacturing rules, design complexity, machine parameters, machine time, machine cost rate, power consumed, resource consumed}

(vi) Design Set: represented by **D**, is the set of knowledge from a particular product's design parameters and material types.

D = {design features, design complexity, tolerance, volume, weight}

(vii) Raw Material Set: represented by **Ra**, is the set of knowledge describing material styles and specifications.

Ra = {material type, weight, density, material cost rate}

(viii) Manufacturing Set: represented by **M**, is the set of knowledge containing manufacturing related knowledge from composite and conventional material part.

M = {machine type, machine time, machine cost rate, power consumed, power cost rate, resource consumed, resource cost rate, labour requirement, labour cost rate}

(viii) Assembly Set: represented by **As**, is the set containing all the information which defines assembly rules necessary for a smooth assembly of a product. This also includes the design parameters necessary and the functional abilities as desired from the product.

As = {assembly design, tooling information, part information, assembly resources, assembly time, assembly cost rate}

(ix) Quality Assurance Set: represented by **Q**, is the set containing knowledge which defines quality procedures in different phases in the product life-cycle.

Q = {raw material quality types, raw material quality time, raw material quality cost rate, manufacturing inspection types, manufacturing inspection time, manufacturing inspection cost rate, finished part quality types, finished part quality time, finished part quality cost rate, assembly inspection type, assembly inspection time, assembly inspection cost rate, final testing type, final testing time, final testing cost rate}

(x) Material Handling Set: represented by **Mh**, is a set containing knowledge of material flow during and after the product is manufactured in a facility.

Mh = {storage requirement, storage cost rate, raw material handling, raw material handling cost rate, in-house handling, in-house handling cost rate, finished product transport, finished product transport cost rate, raw material shipment cost rate}

(xi) Packing & Dispatch Set: represented by **P**, is the set containing all the information which defines how a product is packed and delivered.

P = {packing material type, packing material requirement, packing material size, packing material cost rate}

(xii) Service & Maintenance Set: represented by **S**, is the set containing information on after sales procedures of a product.

S = {part type, part complexity, part size, service type, service complexity, service time, service cost rate, maintenance type, maintenance complexity, maintenance time, maintenance cost rate}

(xiii) Disposal Set: represented by **Di**, is the set containing information on the end of life of a product.

Di = {part type, part complexity, part size, part material, place of installation, disposal machinery, disposal time, disposal cost rate}

(xiv) Carbon Footprint Set: represented by **Ca**, is the set containing information on emissions and energy usage from all the phases in a product's life-cycle.

Ca = {phase wise energy consumption, electricity cost rate, energy cost rate, fuel cost rate, natural resource cost rate}

(xv) Logical Set: represented by **Lo**, is the set containing logical information which controls the flow of knowledge and the relationships necessary for composite knowledge management.

Lo = {design logics, MoM logics, manufacturing logics, procurement logics, mathematical logics, conditional logics, process logics, graphical logics, carbon logics}

Besides these functional sets, there are certain knowledge sets which are further categorized for keeping the relevant cost information. These sets are the derived sets which contain the transformed knowledge that has been converted from raw form to the functional form for final conversion to output cost sets. These are represented below:-

(i) R&D Cost Set: represented by **RC**, is the set containing cost information necessary for calculating research & development cost.

RC = {r&d time, r&d cost rate, r&d overall cost}

(ii) Design Cost Set: represented by **DC**, is a set containing cost information for calculating design cost for a particular design type.

DC = {design time, design cost rate, design overall cost}

(iii) Raw Material Cost Set: represented by **RmC**, is a set containing cost information used to calculate the raw procurement cost in a project.

RmC = {raw material type, raw material cost rate, raw material overall cost}

(iv) Manufacturing Cost Set: represented by **MC**, is a set containing cost information necessary to calculate the production costs in a project.

MC = {manufacturing time, manufacturing cost rate, manufacturing overall cost}

(v) Quality Cost Set: represented by **QC**, is a set of cost information used to calculate the inspection and testing costs during and after the product's life-cycle.

QC = {quality time, quality cost rate, quality overall cost}

(vi) Assembly Cost Set: represented by **AC**, is the set of cost information necessary to calculate the assembly cost of a product, this may include installation cost information, if the product's actual price is affected by the installation process.

AC = {assembly time, assembly cost rate, assembly overall cost}

(vii) Labour Cost Set: represented by **LC**, is the set of cost information which is necessary to calculate the labour cost in a project.

LC = {labour requirement, labour cost rate, labour overall cost}

(viii) Carbon Cost Set: represented by **CC**, is the set of cost information used to calculate the carbon cost in all the phases of a product's life-cycle and is the converted form of carbon footprint knowledge as cost knowledge.

CC = {r&d carbon, design carbon, raw material carbon, manufacturing carbon, quality carbon, assembly carbon, maintenance & service carbon, disposal carbon, overall carbon, carbon cost rate, overall carbon cost}

Each set contains a set of sub-sets and/or elements. Some of the elements may be common to some of the sets and can also have relationships with other elements following a logical rule. This way a more logical knowledge representation is carried out. The knowledge sets so created are utilized for cost estimation making it faster and manageable. For this, four types of cost estimations are chosen, namely (i) life-cycle cost, (ii) factory cost, (iii) unit cost and (iv) carbon footprint cost. Life-cycle cost is defined as the cost of an asset or a part throughout its life starting from the introduction to its disposal while fulfilling its designated performance. It consists of both recurring and non-recurring costs (Dixon, 2008). Factory cost is the cost incurred in total for manufacturing goods. It consists of direct costs including the overhead costs of a factory. It can be said that the factory cost is the overall cost which is required to be spent to actually perform the production operations inside a factory or in other words cost utilized to run a factory for a particular product (Accounting Tools, 2013). The unit cost is the total cost spent by a company on manufacturing, storing and selling of single unit of a particular product. It is the summation of all the fixed, variable and overhead costs involved in producing that single unit. Mathematically, it is the summation of, variable, fixed and overhead cost divided by the total number of units produced (Investopedia Llc, 2017). The carbon footprint has been a new inclusion in this present research and no work has been carried out to relate the same to cost. In this research it is defined as the summation of all the direct and indirect energy resources consumed by a process or an activity for manufacturing of a product.

The definitions and the knowledge that has been extracted from the previous literature and experience is used to generate a more precise form of information base for the output costs. These bases are again kept in a logical set form and contain relevant elements that contribute to the type of output required. These sets are the final output sets that are used for the calculation, storage and representation of the output cost estimates required by a user forming third level of knowledge flow in this system.

From the definition, the first three costs can be broken down as shown in Figure 29, Figure 30 and Figure 31 respectively (Dixon, 2008; Accounting Tools, 2013; Investopedia Llc, 2017).

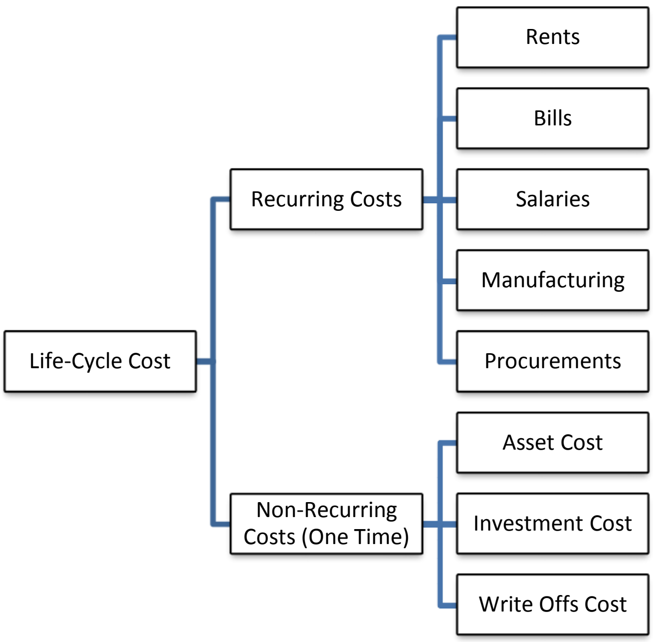


Figure 29: Life-cycle Cost Structure

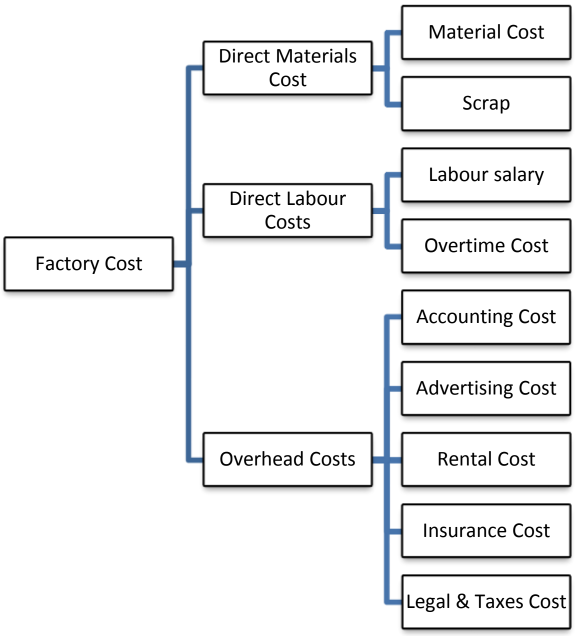


Figure 30: Factory Cost Structure

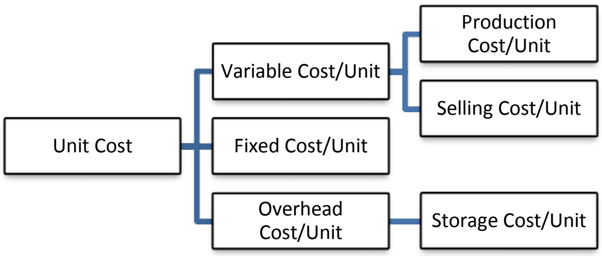


Figure 31: Unit Cost Structure

Based upon the definition of the three basic cost requirements, their breakdown and the knowledge set created, cost sets can be prepared having the information necessary for doing cost estimate of the related requirement. These cost sets contain necessary information about which knowledge sets would interact when a particular cost output is chosen. This way when a user chooses for a particular cost output, only the related knowledge is utilized keeping the other knowledge sets unused and hence improve upon efficiency. As the cost knowledge sets have a systematic grouping of the related knowledge, any modifications needed can be localized and carried out with ease just by targeting requisite knowledge sets and the elements therein. The knowledge sets that are engaged with related cost outputs are represented in the cost sets as discussed below:-

(i) Life-Cycle Cost Set: represented by **LCC**, is the set of cost information which is used to generate life-cycle cost as an output for a particular product/project.

LCC = {overall r&d cost, overall design cost, overall raw material cost, overall manufacturing cost, overall quality cost, overall assembly cost, overall labour cost, overall transport cost, overall maintenance cost, overall scrap cost, overall overhead cost, total life-cycle cost}

(ii) Factory Cost Set: represented by **FC**, is the set of cost information which is used to generate gives overall factory cost as an output for a particular product, design or a project.

FC = {overall direct costs, overall indirect costs, overall overhead costs}

(iii) Unit Cost Set: represented by **UC**, is the set of cost information which is used to generate unit cost of a product as an output.

UC = {variable cost/unit, fixed cost/unit, overhead cost/unit}

(iv) Carbon Footprint Cost Set: represented by **CFC**, is the set of cost information which is used to generate carbon footprint cost of a product as an output.

CFC = {process wise carbon cost, overall carbon cost}

As these cost sets contain most of the elements from the second level knowledge flow, these use the knowledge from the cost sets discussed above. These sets interact with those sets based upon a predefined structure of information that the logical set imposes on these sets. These cost sets are represented in a mathematical form as shown in Table 13.

Table 13: Mathematical Representation of Cost Knowledge Sets

Sr. No.	Set Description	Mathematical Representation
1	Life-Cycle Cost Set	**LCC** = {{**RC** ∪ **DC** ∪ **RmC** ∪ **MC** ∪ **QC** ∪ **AC** ∪ **LC** ∪ **CC**} + {P(**Un**) **-** {**LCC** ∩ P(**Un**)}}
2	Factory Cost Knowledge Set	**FC** = P({**RmC** ∪ **MC** ∪ **MoM** ∪ **QC** ∪ **AC** ∪ **LC** ∪ **CC** ∪ **S**} **-** { **RmC** ∩ **MC** ∩ **MoM** ∩ **QC** ∩ **AC** ∩ **LC** ∩ **CC** ∩ **S**})
3	Unit Cost Knowledge Set	**UC** = {**LCC**/Total Units Produced} Or **UC** = {(*P*(U)}/Total Units Produced)}
4	Carbon Footprint Cost Set	**CFC** = P(**CC**)

From table 13 it can be seen that, life-cycle cost set is the biggest set which is the summation of union of all the knowledge sets and the power set of the elements that are uncommon to the other sets. This means that a life-cycle set will call for all the elements individually from the knowledge blocks and couple them together in a logical sense to come up with an estimate. Factory cost knowledge set is composed of the elements that come from manufacturing, labour, quality, scrap, material and carbon footprint knowledge sets. The elements in this set are a union of all the uncommon elements from the derived sets and hence are independent values in terms of cost. Unit cost knowledge set is sharing its elements from both life-cycle cost set and factory cost set, thus, can be considered to be a dynamic set that can contain elements based upon user choices. Carbon footprint cost set is the individual collection of elements of carbon share from life-cycle knowledge sets that are coupled together in a systematic order. Thus, mathematically it is a power set to itself. Different costs require different knowledge sets and hence, in this way when a particular cost needs to be calculated only the related knowledge sets get involved making the analysis more and more reliable and manageable. Utilizing the knowledge sets in such a manner develops an advanced cost management where the knowledge base becomes dynamic and can be improved from time to time just by adding related information in a particular set. This way the maintainability of the system increases. Also, because the structuring is simplistic and more mathematical and logical, anyone with a basic knowledge can develop and maintain the system. The linkage of these cost sets can be visualized in a graphical manner as shown in Figure 32.

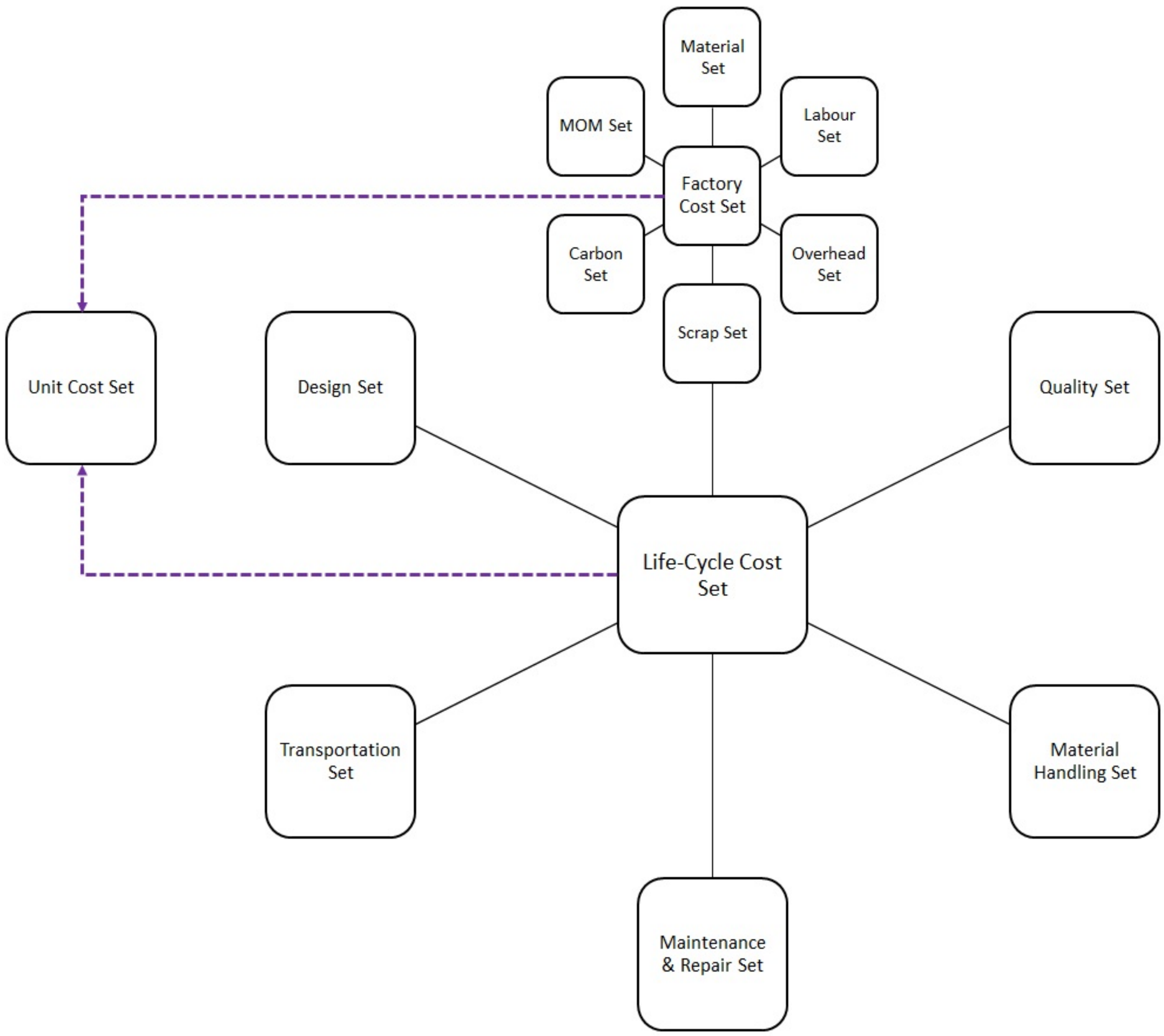


Figure 32: Cost & Knowledge Sets Interaction

From the figure 32 it can be clearly seen that when life-cycle cost is required as an output, whole knowledge base is engaged calling for all the elements contained in those sets. When factory cost is required six primary knowledge blocks out of eleven are engaged. Hence, the knowledge related to only these sets contribute for the factory cost evaluation. However, the unit cost requirement is based upon the user selection and thus can share knowledge from both life-cycle cost knowledge set as well as factory cost knowledge set. This logical knowledge structuring forms the basis of the methodology development and thus, is the basis for the advanced composite cost estimation system developed as an outcome of this research.

4.2.4 Discussion

Set theory has been identified as one of the easiest methods to categorize, capture and code knowledge. It has been utilized in many studies from knowledge acquisition to knowledge structuring and from knowledge coding to knowledge utilization. The uncertainty in Knowledge Information and Data (KID) can be easily handled by logical layout of knowledge which can be achieved by utilizing set theory. As the structuring of knowledge is done in an object oriented fashion that is inherent in the mathematical set method, knowledge becomes easily codable. In this research mathematical set theory is applied to the generic process life-cycle representing them in a parent set form. These parent sets contain, (i) elements, (ii) cost drivers and (iii) child sets. Another set created is the child set which, based on the problem in question can contain, (i) elements, (ii) cost drivers and (iii) sub-sets. Logical sets, however, contain logics that control the flow of knowledge in and around the sets. Output sets also known as the cost sets are the set of parameters in the form of elements that when combined together give the desired output. It has been seen that in terms of KID, the biggest set of all the outputs is the life-cycle cost set which contains entire knowledge from all the phases of the product's life-cycle. Factory cost set is a child set to the life-cycle set and hence can be included or kept inside life-cycle set. The unit cost set on the other hand is a set of logical selections that the user can make so as to draw knowledge either from life-cycle set excluding factory cost set or directly from factory cost set. This is due to the fact that unit cost set does not have the knowledge of its own but shares knowledge from both the cost sets. This way a much logical representation of a child to parent, child to subset, element to set and then element to element or cost driver can be made and vice-versa, making knowledge logical and manageable.

4.3 Logical Knowledge-based Advanced Cost Estimation Methodology (LKACEM)

4.3.1 Introduction to LKACEM

This methodology utilizes the knowledge structuring as discussed in Figure 16 of chapter 3.2 above. It is designed by incorporating three key features, namely, (i) mathematical set-theory for knowledge management for composites, (ii) combined product life-cycle and (iii) carbon footprint knowledge. These three features are the basis of this methodology and these features are inter-related to each other to form an advanced system. To understand this further the overall structure starts with utilization of the combined product life-cycle which becomes the scope and source of Knowledge Information and Data (KID) extraction. KID is extracted in all the identified forms available and is kept in a central system where it is paired and coupled together based upon the category the KID falls into. After this categorization has been completed, the entire knowledge is represented in a mathematical set-based form. The part which does not need coupling is kept directly under a master set also known as the parent set. The other part which is further coupled is kept as element in a child set. This child set, based upon the category it falls into, is kept in the main or the parent set. This way a hierarchy is obtained wherein KID is kept in a systematic fashion. Parallel to these knowledge sets is a separate set that is the carbon footprint set containing all necessary elements as cost drivers for direct utilization. A set of logics control the flow of KID in and out from these sets. These logical sets have three basic stages of operation. The first stage of operation allows the conversion of the master/parent and child sets into functional sets. The second stage allows the conversion of functional sets into primary and derived sets. Primary sets contain relevant process knowledge and the derived sets contain the cost knowledge. The third stage allows an overall relationship that converts the relevant KID into Cost Estimation Relationship (CER) and then based upon the user selection transfers the final outcome to the user for final calculations and estimation. This final logical step can be coupled to the user friendly interface for an interactive representation. This way the entire KID follows a systematic and logical pattern throughout its journey from KID to CER. This framework is represented in Figure 33.

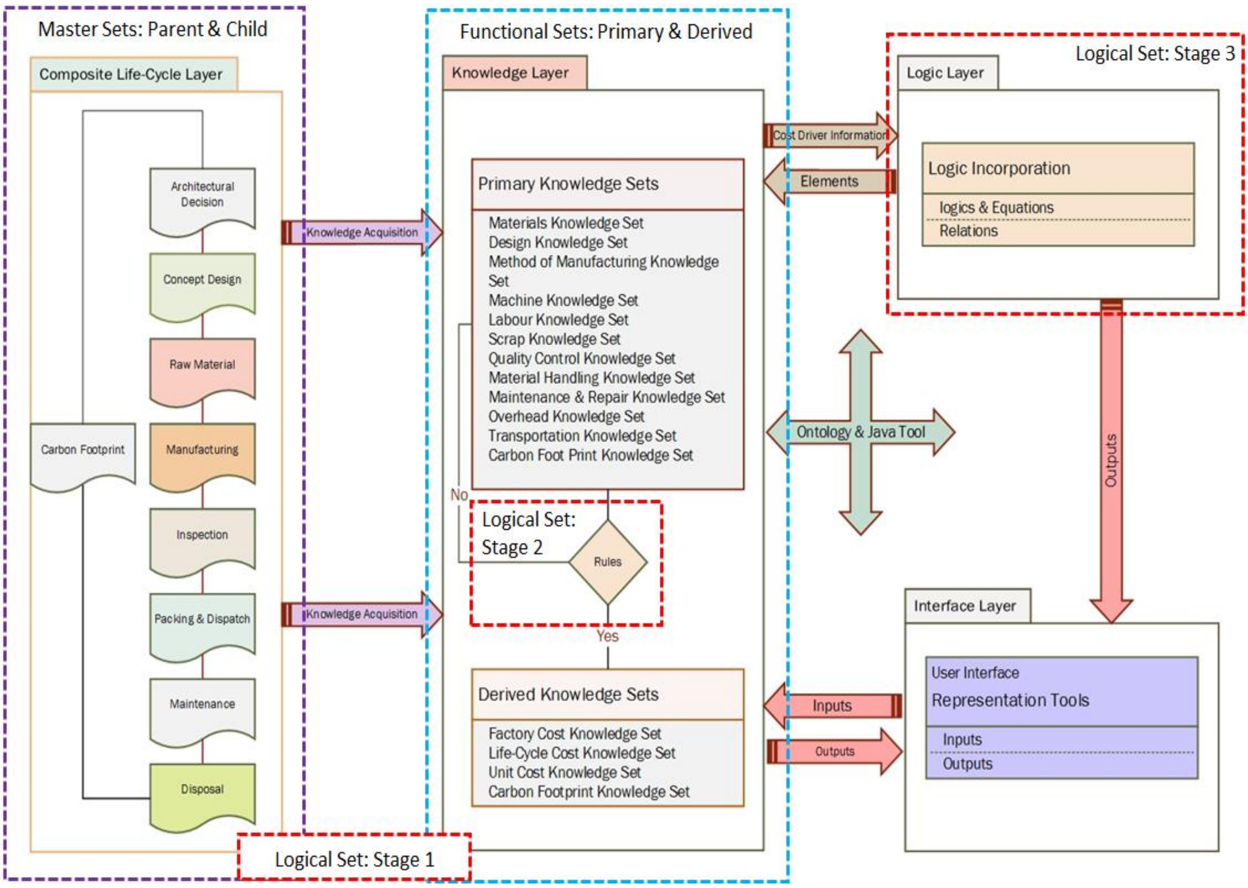


Figure 33: LKACEM Framework

KID starts its journey in the raw form which contains relevant and irrelevant information. This is refined and then passed on to the next levels for further categorization and conversion to useful form. From Figure 33, it can be clearly understood that the master set has been structured taking combined product life-cycle for composite as the basis of its design. As the master set is converted into functional set, a more process specific KID is observed to be included. This can be said to have specific knowledge from different parts of the process, namely, (i) materials, (ii) design, (iii) manufacturing, (iv) testing, (v) labour, (vi) after sales and (vii) equipment. As the KID is further refined and coupled to the cost knowledge, different types of estimates can be observed. For this research four basic types of cost estimates have been included, namely, (i) factory, (ii) life-cycle, (iii) unit and (iv) carbon footprint. The inclusion of carbon footprint as a cost in the existing knowledge is not kept as a separate entity, however, in this research it is taken from the entire life-cycle. It has been clearly shown how the three-stage logical set is incorporated in the different parts of the methodology functioning. This logical set is not a separate set, but contains child sets with different logical elements that are executed depending upon the user selection. This way keeping the set-based knowledge design constant, multiple choices can be executed without the need for separate data base. As this design does not involve complex structures, neither does it require separate designing for different outcomes, the maintainability of the whole system becomes easier.

It has been shown in the framework design that the user based interface design could be done in many forms. Even the representation of the whole system could be achieved in many forms. One of the forms could be an ontology based approach, where the sets can be directly represented in a logical form and then connected using a logical layer on top of it. Another way of representation could be an object oriented programming-based platform which can convert the sets into objects or classes and then can utilize the logics as functional elements to control the flow of KID. This way a separate software package can be designed on top of it. An Industry standard method of representation, "Vanguard Studio" can also be used to represent this methodology and then utilize it in a much user friendly way. For the ease of understanding and ease of application for this research, the methodology is structured in a layered architecture and represented in a simple worksheet-based, "Microsoft (MS) Excel" application. Here the sets can be easily represented as a worksheet and then logical layer can run as a separate sheet coupled to object oriented Excel Macros. These macros convert the logical layer into a user friendly interface and the representation becomes more interactive and easy to use.

For the next part of this study, the method is represented in a layered form and the architectural design of the whole system is done based upon the same. This way an advanced system is created which converts the composite Knowledge Management (KM) into an advanced cost modelling tool. The developed methodology is divided into three layers. These layers are joined by linkages which control the flow of KID. The basic layers of this methodology include: (i) combined life-cycle based data & information layer, (ii) knowledge layer and (iii) logical & interface layer. The linkages that join these layers include, (i) knowledge acquisition, (ii) cost driver information, (iii) user inputs and (iv) interface tools. To understand the methodology in detail it is important to understand the individual roles of these layers.

4.3.2 Layer 1: Data & Information Layer

This layer uses the generic life-cycle proposed for the composite material part. Here, the entire process of a product's journey from a raw material to the final state is defined in a cyclic manner. The carbon footprint is taken parallel to the entire process cycle. The concept here is very simple that every product has to undergo these cyclic phases so as to convert itself from rough idea into a final product and back to rebirth. Layer 1 is very important layer in the methodology as the knowledge related to different cost aspects are acquired from these processes to form the master knowledge sets. All the knowledge sets derive their knowledge from this layer. Another benefit of this layer is that it is detailed in providing all the process parameters and hence the completeness of knowledge is increased. It has been seen that cost drivers are scattered in the entire life-cycle, thus, even the processes which seem to be unimportant in one design aspect may suddenly become more evident in another design aspect. This cost driver distribution has not been precisely understood and most of the studies are concentrated on the manufacturing phase. Whereas cost drivers can come from processes like packing & dispatch, which have been considered as just an overhead in some studies. The carbon footprint has also been found to be very important in cost contribution, not only because green technology will become very important in the near future, but, also because of the fact that energy prices are increasing. All the energy utilized in a particular process contributes to carbon cost. This study becomes important in both process/project analysis and device management techniques in order to achieve better efficiency. The purpose of this layer is to provide all the detailed knowledge from the entire life-cycle including carbon footprint to the next layer in such a way that no knowledge gap remains. The knowledge acquisition is done by utilizing Cost Breakdown Structure (CBS) in various phases of the life-cycle and keeping them as elements of knowledge sets in the next layer. The knowledge relevant to cost becomes necessary information and is the only one allowed to pass to the next layer.

4.3.3 Layer 2: Knowledge Layer

This layer is composed of three elements, namely (i) primary knowledge sets, (ii) rules and (iii) derived knowledge sets. For prediction of cost for any type of material or any kind of design requirement, basic knowledge blocks are required. These knowledge blocks are divided further into knowledge sets so that the required information becomes manageable. Currently, Microsoft (MS) Excel Software is used for ease of understanding and fast reference of the knowledge representation and management, but, this can also be done by using any other software or programming language and can also be done by utilizing any other knowledge representation method like ontology approach. As the first part of the complete cost estimation methodology is generic, therefore, it can be represented in any platform, independent from dependency on any software or programming language or a tool.

The primary knowledge sets is in other words the universal set 'Us', which is composed of all other sets containing information related to cost from all the aspects of actual production of a part. Rules, the second element of the knowledge layer utilizes basic definitions and general requirements necessary for generating the four basic types of cost, namely (i) Life-cycle, (ii) Factory, (iii) Unit cost and (iv) carbon footprint respectively. The rules may be graphical, mathematical or simply observational. These are then used to convert the primary knowledge sets into derived knowledge sets for cost. This process is repeated till complete information is derived. This element, therefore, is the logical element and can also be termed as the brain of this system which can be updated from time to time. Derived knowledge sets, being the third element of the knowledge layer, is simply information packed in a set form for three different basic costs. This layer forms the first pillar in actual cost estimation. Instead of keeping cost information as a value and storing knowledge in a physical static form, the elements (cost driver information) are stored in the knowledge sets. This way knowledge itself becomes dynamic and uses less effort to manage. The related data/value can be fed during next stages and thus the data/value uses a cache memory making it flexible. This way the most important problem of conventional costing, being, not capable of handling scaling in a design, is also eliminated. The dependency of the cost estimation process on a particular manufacturing process or a design is also eliminated by this technique. Although the actual one time making of this layer is time consuming, but once made, different cost estimation for different designs, processes and material combinations can be modelled using this method. As carbon footprint knowledge is a new inclusion, there has been use of information from available literature (Pandey et al., 2011; Institute of Environment and Sustainablility, 2011; US Department of Energy, 2014) which is coupled to process knowledge, own experience and expert information to formulate a carbon footprint knowledge block. Logics related to carbon footprint are also developed in the same manner. This knowledge block as created for this research is a novel work and hence, has a level of uncertainty which can be improved with addition of knowledge elements outside of the present scope. For improving the cost driver knowledge block for carbon footprint, more precise research is needed which is not presently available. The representation of the cost driver knowledge block for carbon footprint for composite cost estimation is shown in Figure 34.

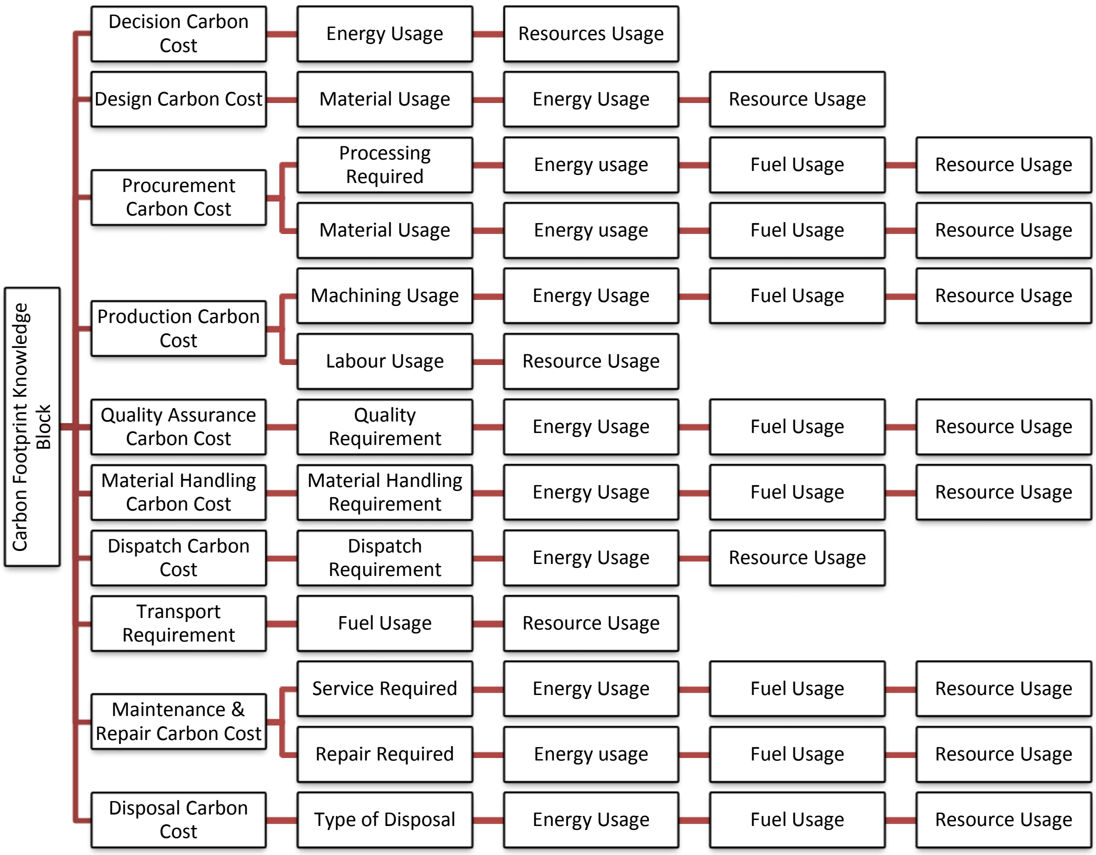


Figure 34: Cost Driver Knowledge Block for Carbon Footprint

This knowledge set is also used for the development of the logics for converting the raw knowledge into cost. This conversion is stored as part of the logical block and is described later in the discussions to follow. Masked data has been used for illustration and proof of concept.

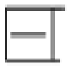
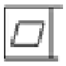
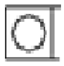
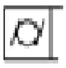
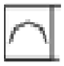
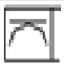
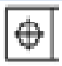
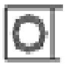
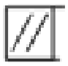
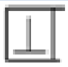
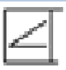
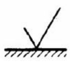
4.3.4 Layer 3: Logical & Interface Layer

It is the physical world of the methodology where information from different sets are actually coded. Here, the elements of different sets and the parent sets are physically related to form a meaningful value. Thus in this layer, equations governing cost driver information are generated with the help of logics and relations. The equations can be mathematical, elemental or logical, where cost drivers are related to the output. This layer also feeds back information into the previous layer to repeat the process until every element is related to the output in a logical format. This is necessary for making the information understandable for the next layer and codifying it for computational and automation purposes. This layer is the final layer where actual data is fed in a physical form to various variables. Here, data is entered in a desired format as input variables and is then evaluated based upon the earlier mentioned layers. Output values are also displayed in this layer and can be further utilized for complete report generation. As the system is platform independent, it does not require any particular interface and can be custom programmed for any platform in place.

The logics that are included in this layer are divided into five basic types, namely, (i) graphical logic, (ii) mathematical logic, (iii) conditional logic, (iv) carbon logic and (v) functional logic. All these logics have their own working and application in the developed system and are discussed below:-

(i) Graphical Logic: is a subset of logics which define the design features that relate a particular design symbol or drawing information to a parametric attribute which can be used to understand a design. These logics are required to understand the fundamental designs and machining requirements that drive knowledge into other sets. An example of this logical sub-set is shown in Table 14 (Bureau of Indian Standards, 1998).

Table 14: Graphical Logic Subset Representation

Sr. No.	Symbol	Meaning
1		Straightness of the surface
2		Flatness of the surface
3		Circularity along the line
4		Cylendricity along the line
5		Profile of Plane to be maintained
6		Orientation of Profile to be maintained
7		Position to be maintained
8		Co-axility to be maintained
9		Parallelism to be maintained
10		Perpendicularity to be maintained
11		Angularity to be checked and maintained
12	 9.6 9.4 $\pm$ 10	Tolerance on the dimensions to be maintained
13		Optional Machining Process

14		High Finish is required in a machining process
15		Material removal is prohibited

(ii) Mathematical Logic: This logical sub-set contains elements of knowledge that define the machining parameters and the statistical relationships of the elements which form the Cost Estimation Relationship (CER). There are many types of the logics in use for this research. Most of the logics are taken from Rolls-Royce internal processes and hence cannot be shown, however an example of some of the logics that have been used from previous literature or open source material and is a part of this research are shown in **Appendix-A** (Paragon Machine Technology, 2014; Sandvik Coromant, 2016).

(iii) Conditional Logics: This is a sub-set containing conditional commands that are responsible for the proper flow and interpretation of Knowledge Information and Data (KID) in the system. The set of commands are “if-else”, “and or”, “index” and “selections”. All these logics are used to pass the KID in a selected manner when a previous condition is fulfilled. This type of logics control the reduction process of knowledge from raw information and set based form to functional forms which are then evaluated using mathematical logics.

(iv) Carbon Logic: This is a subset of elements that are responsible for capturing, keeping and relating the carbon knowledge to the output costs. These logics are included as part of the cost for the first time in this research and hence there are some assumptions made in the cost rates that are chosen to be within the variance limits of 10-20% which is an acceptable value in industries. The representation of the carbon logics can be visualized as shown in Table 15.

Table 15: Carbon Logic Subset

Sr. No.	**Type of Carbon Footprint**	**Logic**
1	Decision Carbon	DCS = {C*complexity*CF} + {(energy*EF)+(resource*RF)} C = 0.1 CF = 0.10 $
2	Design Carbon	DC = {C*material complexity*CF} + {(energy*EF)+(resource*RF)} C = 0.1 CF = 0.15 $
3	Procurement Carbon	PC = {C*procurement complexity*material weight*design complexity*CF} + {(energy*EF)+(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.16 $
4	Production Carbon	PrC = {C*material complexity*design complexity*machining complexity*labour requirement*CF} + {(energy*EF)+(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.20 $
5	Quality Assurance Carbon	QAC = {C*design complexity*QC method*CF} + {(energy*EF)+(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.15 $
6	Material Handling Carbon	MHC = {C*design complexity*size*storage requirement*type of handling*CF} + {(energy*EF)+(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.05 $
7	Dispatch Carbon	DIC = {C*design complexity*size*CF} + {(energy*EF)+(resource*RF)} C = 0.1 CF = 0.10 $
8	Transport Carbon	TC = {C*design complexity*size*type of transport*CF} + {(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.05 $
9	Maintenance & Repair Carbon	MRC = {C*design complexity*part size*type of repair*CF} + {(energy*EF)+(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.20 $
10	Disposal Carbon	DC = {C*design complexity*part size*machine required*CF} + {(energy*EF)+(fuel*FF)+(resource*RF)} C = 0.1 CF = 0.10 $

*Note: Abbreviations used in this figure mean: C=Carbon Rate, CF=Cost Factor, EF=Energy Factor, RF=Resource Factor and FF=Fuel factor.

Here, the complexity is derived from the design features, the greater the features the higher the number. These numbers are defined by the industry for predicting manufacturing costs and are standardised for each design. Carbon Rate is a number which has been derived after discussions with the stakeholders to be 0.1. This number is indicative of the amount of carbon generated for a unit activity. Cost Factor is different for different processes and has a value which has been derived from overhead cost rates for the related process. The Energy Factor, Resource Factor and Fuel Factor are the direct purchase cost rates of the unit quantity of each activity and are indicative of the actual prices of the same during the time of purchase. From this carbon logic sub-set, relevant linkages to the main knowledge set is made and the carbon cost set is generated which in turn is used to generate output cost.

(v) Functional logics: this sub-set of information and knowledge contains all the relevant cost functions that are generated with the help of ABC, parametric costing and expert judgement approaches. The bottom-up approach is used to break the problem into steps starting from first till the last. These functions have been already defined as the cost definitions. Another inclusion in this is the functional logics which controls the output costs and the outputs. All this has been already defined in the discussions above. The details of some of the sub level functions cannot be shared due to IP control. The logical interaction with the user also falls under this category.

Besides this, the interface is applied as a layer on top of these knowledge layers. The interface can be as simple as using MS Excel and as complex as software tool in itself. Ontology-based software tools can also be used to represent this layer, which is not the scope of this research work, however, this can be a future work.

Thus, an ontology-based program can fit into any java or C++ or Python or any other language based platforms. As the structure of the knowledge is logical set-based, even if the representation is made in a particular software tool, still the knowledge remains platform independent.

4.3.5 Methodology Architecture

The methodology framework and the design give a basis for the development of the architecture which governs the 'what and how' of the whole system. This describes different knowledge sets and the relationships of these sets with each other followed by the elements that are present in the sets. The elements are in all the available forms and also in the relevant forms that are needed for a cost estimate. The commodities that will be or can be studied using this methodology can vary from simple to complex and hence, the entire life-cycle has been taken into consideration while designing a future proof architecture. The developed architecture has all the relevant knowledge blocks described as the knowledge sets that have all the relevant set of information which can be represented in any manner so as to come up with different outputs of cost. This way when the user demand changes so does the interactions and finally the output is estimated.

There are multiple ways that have been used to link the information in a generic format. These include process knowledge, design knowledge, rules and standards. This way even though the method is derived using mathematical set, all the relevant knowledge is still with the system and will react to the changes in the parameters or the outputs. This developed architecture for composite material cost estimation has been represented in Figure 35.

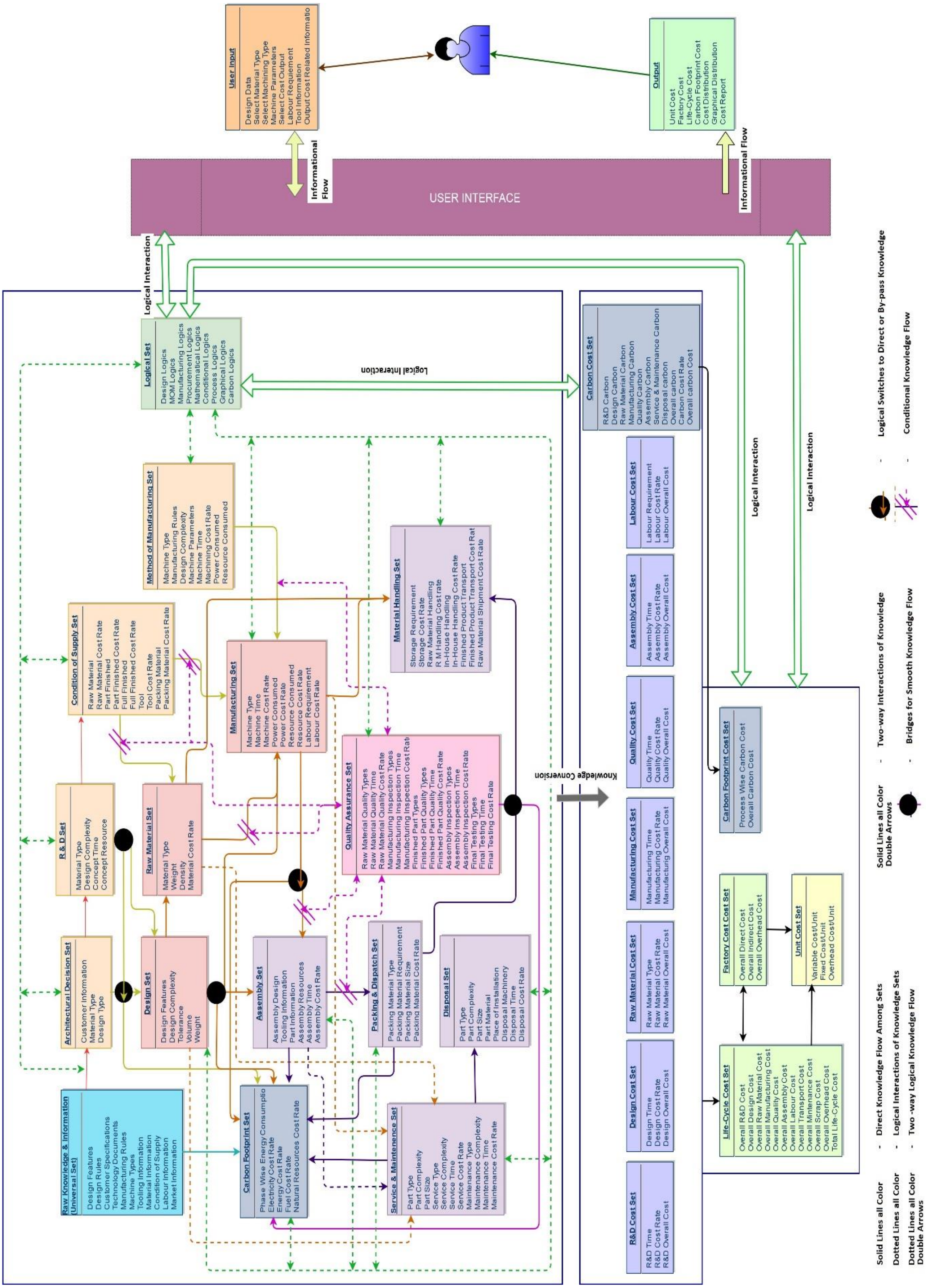


Figure 35: Methodology Architecture

From the figure 35 it can be seen that the universal set which is the raw information and data set is where the architecture design starts. This set contains all the information related to people, process and tools that is necessary to carry out a desired cost estimate. This is then controlled by logics which separate the information into a useful and more understandable form. These are shown by a pale yellow colour. These becomes the parent sets and then these parent sets pass on information to the child sets based upon a logical separation. This allows the knowledge to be more concentrated and specific to that set in a much refined manner. This knowledge which has now become a collection of cost driver elements, is controlled in a set form to keep knowledge separated and much easy to work with. These child sets are represented in orange colour to separate them out with the parent sets. Another set of knowledge which is part of the main sets are the subsets. These sets have cost driver information and knowledge that has interlinkage with other sets. These sets share complete or part of their elements with the child sets. These sets are represented in purple colour. The flow of knowledge, elements sharing and knowledge distribution is controlled by a set of elements from the logic sets. The logical set contains all the different forms of logics necessary for cost knowledge management. These sets are represented in green colour. Logical sets are involved in the entire structure as the nervous system in a human body. These supply relevant areas with logical information to carry out smooth transfer and linkage of the elements stored therein. The logical sets also contain conditional and mathematical logics which contain cost related equations and formulas that relate all the elements to the next set of knowledge and the output cost. The knowledge is then passed on to the next set of elements. These sets now have all the cost driver information that is necessary for a cost estimate.

The knowledge is then transferred to a set of cost elements which form the basis for estimation. This is done by passing the knowledge through cost estimation logics stored in the logical set.

The complexity of any problem is already broken down to a simplistic and much easier time-cost system. This way the only drivers left are stored as elements in the derived sets. These derived sets are the ones which are used to estimate costs for a particular product or process. As the knowledge is managed in a mathematical set based format, it remains platform independent and flexible. The final sets are the output sets which are defined by the logical set and use previous knowledge and elements that are linked to them by the logics so as to store the final output information, which is nothing but different cost estimates in a cost-based format. This part of the sets are physical elements with values that have been calculated using the logical definitions. Hence, this way the complete system interacts to perform a cost estimate and in the same time manage knowledge that is created in a logical fashion.

On top of this system sits a user interface which represents the knowledge and its flow in a user friendly manner and makes the whole system work as an advanced tool for cost estimation. A user passes desired input information to the interface which is directly connected to the logical set and the output cost sets. This information is first refined and then passed on to various sets in some of its elements. Also this input information makes certain selections which guide the logical set to choose information from universal set to relate all the main and derived set elements. Once this information passes into the main sets it follows the architecture that has been created and finally returns a physical output into the cost sets. This information is then again passed to the user interface which converts the information into output results, charts, graphs and reports respectively that can be understood by the user. Design of the user interface can be done in any language or in any particular platform available, hence, it is not required by the methodology to follow a defined design for user interface. This flexibility of choices for representation and knowledge modelling makes this methodology unique and widely applicable.

4.3.6 Discussion

The advanced cost estimation system created utilizes the generic life-cycle as the knowledge and information layer and integrates mathematical set-based knowledge management to create knowledge blocks. This has been done to categorize and keep the knowledge in a proper and well defined fashion which makes it more and more easy to use and model. Knowledge is kept in a mathematical set form which is categorized into parent, child, primary and derived sets. Parent sets, have raw knowledge and child sets as their main elements. Child sets have raw knowledge and subsets as their elements. Primary sets have main process knowledge elements along with subsets as the constituting elements. Derived sets on the other hand are controlled by a set of logics which derive elements from primary sets and create a derived set of elements that are either directly shared or utilized from primary or are calculated from a set of relationships. The derived sets are floating sets as they contain knowledge which is dependent upon user selection of the design, process and the output needed. These sets therefore do not contain a physical form of knowledge, but a cached form of knowledge which can be changed as per the user selection depending upon problem to problem.

This way a knowledge management system is obtained which is a logical Knowledge Based Engineering (KBE) system. This logical KBE is then coupled to a logical layer which has a set of functions, Cost Estimation Relationship (CER)'s and physical logics. This coupling of the logical layer converts the elements into meaningful relations between the elements of the sets that can be utilized for calculations of cost. An interface is made to represent the whole functioning in an easy to use form. This enables the user to control and input, required data into the elemental relationships and find out the required cost estimate. The methodology is therefore highly applicable to a wide variety of applications and can also be used to model projects, processes, manufacturing, knowledge and cost.

4.4 Advanced Logical Knowledge-based Cost Estimation Tool (LKC-Tool)

4.4.1 Overview of Advanced LKC-Tool

This tool has been created utilizing LKACEM and applying it into the advanced version of Microsoft (MS) Excel® application, which is macros enabled with visual basic as the programming language. The platform selected here is a MS enabled operating system having MS Office installed with latest version having macro functions. The advanced method that has been developed is mathematical set-based and is generic in its representation, hence it does not require a special platform or a special programming language as such. Different platforms can have different approaches to represent this advanced system but the knowledge structuring and utilization remains the same. MS Excel® application is a spreadsheet enabled workbook, which can handle data in a structured format with important features like mathematical calculations, advanced functions, graphical tooling and macro functions. This application is very easy to use and the knowledge can be very easily represented in this format. Each cell in the sheet behaves as one node and this node can be easily filled with physical data, a function, a logic, a string or any other format of knowledge (Microsoft, 2016). As most of the businesses utilize MS products and use windows as the operating system, the applicability of this tool becomes easy. Also, no special license needs to be purchased to use all the functionality in this application. Visual Basic for Applications in the form of macro functions manipulates complex knowledge in a simpler manner utilizing standard spreadsheet techniques. Direct codes can be written into the application making the knowledge in it more interactive and automatic. This way a standard spreadsheet can be utilized as a tool for doing certain defined tasks (Microsoft, 2016).

There have been benefits of this application found in industries related to improved productivity. This helps in the businesses to fully utilize their data and knowledge in an efficient and easy manner. The benefits that have been seen include, (i) a structured format for raw knowledge: the knowledge can be represented in a wide variety of forms like grids, cells, charts, tables etc. The major benefit is that whatever the form of knowledge is there, knowledge will be in a systematic pattern, (ii) a logical inclusions in knowledge: different types of logics like graphical, mathematical or conditional etc. can be easily applied on the raw data or data elements, (iii) a categorization of knowledge: the knowledge can very easily be grouped together utilizing different criterion and analysed accordingly, thereby making data utilization easy and effective, (iv) a centralization of knowledge: this application has the ability to pull information from different documents in one unified location including texts and pictorial representations, and (v) a web portability: the application can be used from any location on a web-enabled device so as to allow remote knowledge management and utilization (Microsoft, 2015).

Besides these benefits excel has also been used in many complex situations where highly critical knowledge needs to be represented and made reusable (Stephenson et al., 2010). Production budget estimation or production budgeting is one such problem where excel has been successfully utilized and found to be better than the conventional paper-based methods. Here, the knowledge from different phases is represented as spreadsheets and then linked to each other using rules. This way knowledge from direct materials, direct labour and machining can be utilized to calculate the budget of materials and production. All the knowledge is represented in a spreadsheet form and hence pulling of data from this becomes easy and fast (Stephenson et al., 2010). It has been observed that creating of knowledge base in excel is tedious at the first step, but once created, the database can be utilized again and again without any change to the structuring or understanding of the knowledge represented. Multiple calculations can be easily performed with the cells of this spreadsheet and hence the data suddenly becomes more logical and understandable which is then utilized to calculate cost and budgets (Stephenson et al., 2010).

As there are many benefits of Excel tool, it can be utilized to represent any type of complex knowledge for cost estimation. Thus, due to these benefits as mentioned above, MS Excel has been chosen to represent, structure, model and automate knowledge for cost estimation in this present research. This way knowledge is kept separate from logics and interface is designed separate of the logics. The interface is designed using MS Excel based macro function which is an advanced feature that allows a sheet to work in a user defined and user designed fashion allowing reusability of the created knowledge.

4.4.2 LKC-Tool Design Schema

This research includes various complex parameters related to composite technology, hence, composite technology selection plays a very important role in this research. As such, composite materials of interest specifically to the aerospace sector are selected. This is followed by mapping of the generic product life-cycle including carbon footprint and acquiring and utilizing Knowledge Information and Data (KID) based upon this combined life-cycle breakdown. This breakdown is also known as process breakdown. Now using set-based theory, next step is to identify the key cost drivers for which refinement of information is done by using Knowledge Based Engineering (KBE) techniques. This is then followed by developing a cost modelling technique which is a mixture of basic cost estimation methods that are coupled together for complete analysis. Case studies are identified and utilised for the next analysis from the aero-engine realm. The case studies are taken from composite based products finding use in the aero-engines. After using case studies for validation and simulation, outputs are displayed in a user friendly manner. The tool design schema for the development of advanced costing tool is schematically presented in Figure 36.

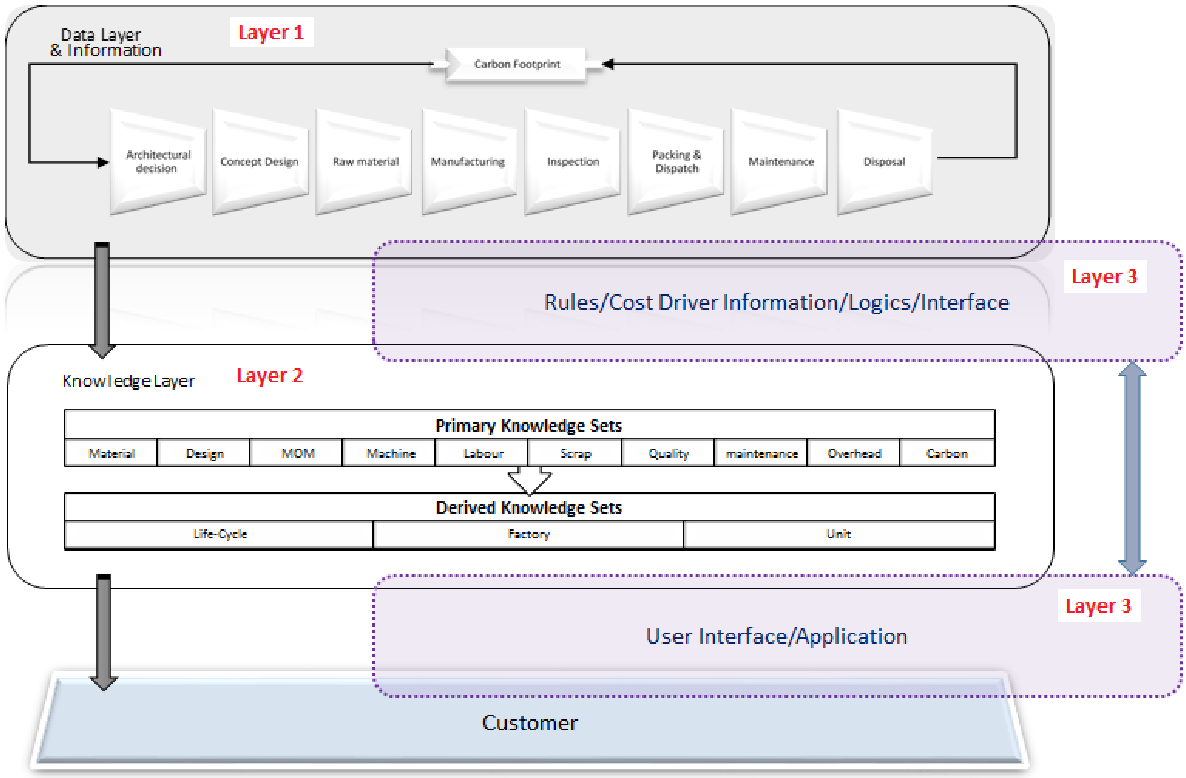
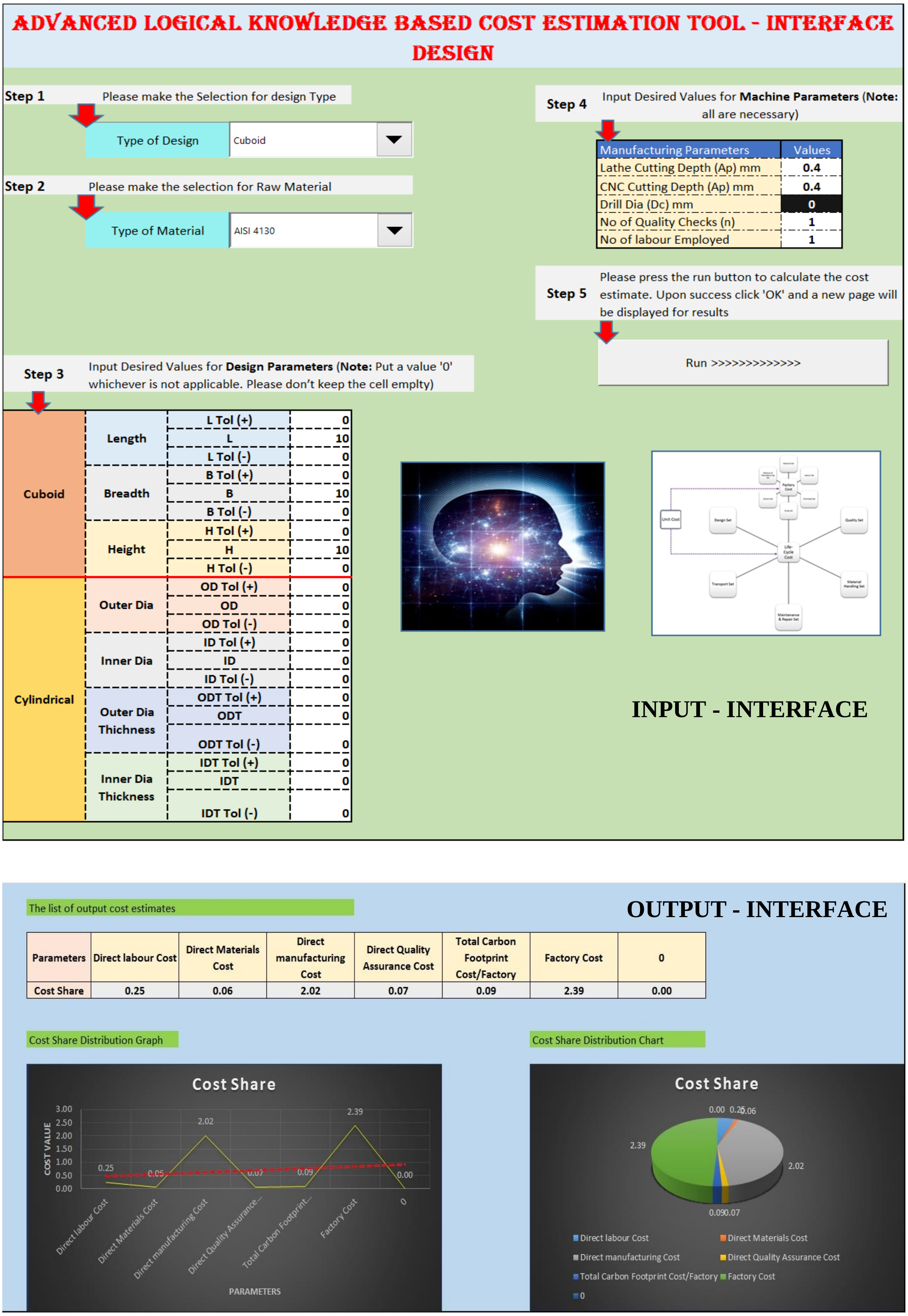


Figure 36: Tool Design Schema Visualization

The schema shown here is showcasing the way this knowledge is represented in Microsoft (MS) Excel. Each sheet in MS Excel is representing a separate knowledge set. Both the main and the derived sets are represented in this sheet format and hence are in the same way related to the main sets as required by Logical Knowledge Based Advanced Cost Estimation Methodology (LKACEM) architecture. Layer 1 for this tool is the main knowledge layer where the knowledge is stored as physical entity and then utilized for further use by linking it to layer 2 with the help of logical interchange. This logical interchange is a set of equations, functions, conditions and information that control how a particular element relates to the other. Layer 2 is a physical entry of derived elements that have been represented in a tabular form to be easily utilized in final cost estimation. The layer 3 or the logical layer has been represented in individual sets directly. As the MS Excel has a feature of including logical information directly to its knowledge elements, the same has been utilized for representation and utilization of the logical information in this tool. User interface has been created using MS Excel macro function and a design for easy usage of the tool has been created. This design can show both input features and output results in a user friendly and interactive manner. The tool so created has been discussed further in the study. The details shown here have been used to represent the way this tool has been created.

The tool interface, which is the screen available to see by the user consists of both the input window and the output window. The input window is the one visible during the start of the tool. This screen allows the user to make selections, input values and parameters with ability to input certain rules. This window is the linkage between the user and the tools internal logic which helps the information from the user to pass to the set of elements that have been kept as sheets in this tool structure. Output screen is visible once the cost estimation calculations have been made by the tool. This remains hidden to the user and only visible once the user has fed all the relevant information from the main window and has clicked the Run button. Clicking of the Run button executes the logical program that controls the flow of knowledge and finally returns the relevant values of physical cost estimates.

The results are then finally represented in a tabular form along with a more interactive graphical form which makes the whole representation and reporting of the outputs interactive to the user. The tools ability to show all the relevant results in one window makes it very usable when it comes to analytical study of the results. This interface is represented in Figure 37.



*Note: Benchmarking has been done using case studies and costs are compared with the outputs from conventional systems.

Figure 37: LKC-Tool Interface Design

`

This tool has the knowledge represented in various worksheets in Excel so as to represent the different knowledge sets. These sheets allow the knowledge to be both represented and coded in the same place. This way the maintenance of knowledge base is much easier and cost effective. The representation of knowledge is shown in Table 16, Table 17, Table 18, Table 19, Table 20, Table 21 respectively.

This shows the worksheet form of knowledge sets that are used in the tool, some of the values have been changed and two major knowledge sets have been omitted for Intellectual Property (IP) protection issues. Here both the primary and secondary sets along with the main sets have been shown. As this is for representation purposes, hence all the details are not shown. This is where the entire knowledge is stored and coded. This can also be understood as heart of the whole tool.

Table 16: Design Knowledge Set for LKC-Tool

Design Type	Length (L)	L Tolerance (+)	L Tolerance (-)	Breadth (B)	B Tolerance (+)	B Tolerance (-)	Height (H)	H Tolerance (+)	H Tolerance (-)
Cuboid	0	0	0	0	0	0	0	0	0
Design Type	Outer Dia (OD)	OD Tolerance (+)	OD Tolerance (-)	Inner Dia (ID)	ID Tolerance (+)	ID Tolerance (-)	OD Thickness (ODT)	ODT Tolerance (+)	ODT Tolerance (-)
Cylindrical	254	0	0	100	0	0	104	0	0
Design Type	Length (L)	Bredth (B)	Height (H)	Hole Dia	Hole Thickness				
Cuboid	0	0	0	0	0				
Design Type	Outer Dia (OD)	Inner Dia (ID)	OD Thickness (ODT)	ID Thickness (IDT)					
Cylindrical	279.4	90	114.4	114.4					
Design Type	Length (L)	L Tolerance (+)	L Tolerance (-)	Bredth (B)	B Tolerance (+)	B Tolerance (-)	Height (H)	H Tolerance (+)	H Tolerance (-)
User Defined	0	0	0	0	0	0	0	0	0
	Surface Area	Machine Length	Drill Length		Length Mod	Bredth Mod	Height Mod		OD Mod
	286782.48	104	0		0	0	0		254
Design Type	Volume	Machine Length	Drill Length						
Cuboid	0	0	0						
Cylindrical	6965838.972	114.4	114.4						
User Defined	286782.48	104	0						
	Machined Length (lm)	Drill Length (lm)	Volume (v)						
Selection	114.4	114.4	6965838.972						
2									
	Design Cost	Design Carbon Cost							
	1393167.794	104487.5846							

*Note: The data contained in the table is a masked data used for representation and proof of concept.

Table 17: Material Knowledge Set for LKC-Tool

Material Type	Material Density	Material Weight Cuboid (kg)	Material Weight Cylinder (kg)	Material Price/kg	Direct material cost Cylinder	Direct material cost Cuboid
AISI 4130	0.00785	0	54.68183593	0.9	49.21365233	0
AISI 4140	0.00786	0	54.75149432	1.5	82.12724147	0
SS 304	0.00803	0	55.93568694	3	167.8070608	0
Monel 400	0.0088	0	61.29938295	0.55	33.71466062	0
Inconel 625	0.00844	0	58.79168092	18	1058.250257	0
Glass Fiber	0.28678248	0.28678248	0.28678248	1.85	0.530547588	0.530547588
Carbon Fiber	0.28678248	0.28678248	0.28678248	10.5	3.01121604	3.01121604
Al-MMC	0.00296	20.61888336	20.61888336	22	453.6154338	453.6154338
Aramid Fiber	0.00164	11.42397591	11.42397591	26	297.0233737	297.0233737
CMC	0.0021	14.62826184	14.62826184	13.6	198.944361	198.944361
Selection	Material Density	Material Weight Cuboid (kg)	Material Weight Cylinder (kg)	Material Price/kg	Direct material cost Cylinder	Direct material cost Cuboid
9	0.00164	11.42397591	11.42397591	26	297.0233737	297.0233737
	Direct Materials Cost	Scrap Cost	Total Materials Cost	Material Weight	Carbon Rate	Carbon Cost
Cuboid	297.0233737	74.25584344	371.2792172	11.42397591	0.16	1.827836146
Cylinder	297.0233737	74.25584344	371.2792172	11.42397591	0.16	1.827836146
User Defined	297.0233737	74.25584344	371.2792172	11.42397591	0.21	62.37490849
	Direct Materials Cost	Scrap Cost	Total Materials Cost	Material Weight	Carbon Rate	Carbon Cost
Selection	297.0233737	74.25584344	371.2792172	11.42397591	0.16	1.827836146

*Note: The data contained in the table is a masked data used for representation and proof of concept.

Table 18: Manufacturing Knowledge Set for LKC-Tool

Machining	Cutting Speed (Vc) mm/min	Metal Removal rate (Q) mm3/min	Machining Time (Tc) min	Net Power (Pc) KW	Carbon Footprint Emmission Co2	Carbon Footprint Cost cent	Machining Price $
Lathe Machining	749518	119922880	0.184516129	4796.9152	1199.2288	651.4210842	14.94580645
CNC machining	1595748	127659840	0.173333333	6170.2256	1542.5564	837.9166365	16.46666667
	Machined Dia (Dm) mm	Feed/Rev (fn) mm/r	Cutting Depth (Ap) mm	Machined Length (lm) mm	Specific Cutting Force (Kc) N/mm2	Spindle Speed (n) rpm	Machining Cost Rate
Lathe Machining	154	0.4	0.4	114.4	2400	1550	0.81
CNC machining	154	0.2	0.4	114.4	2900	3300	0.95
	Cutting Speed (Vc) mm/min	Penetration Rate (Vf) mm/min	Metal Removal rate (Q) mm3/min	Machining Time (Tc) min	Net Power (Pc) KW	Carcon Footprint Emmission Co2	Carbon Footprint Cost cent
Drilling	113040	120	763020000	0.953333333	29884.95	7471.2375	4058.37621
	Spindle Speed (n) rpm	Feed/Rev (fn) mm/r	Drill Dia (Dc) mm	Drill Length (lm) mm	Specific Cutting Force (Kc) N/mm2	Drilling Cost Rate	Carbon Footprint Rate
Drilling	400	0.3	90	114.4	2350	20	0.25
Lathe Machine Cost	CNC Machining Cost	Drilling Cost	Lathe Carbon Cost	CNC Carbon Cost	Drilling Carbon Cost	Total Machining Cost	Total Machining Carbon Cost
14.94580645	16.46666667	1906.666667	651.4210842	837.9166365	4058.37621	1938.07914	5.547713931

*Note: The data contained in the table is a masked data used for representation and proof of concept.

Table 19: MOM Knowledge Set for LKC-Tool

Type	Machine Code	Complexity
MOM 1 for Carbon Fiber manufacturing	1	50
MOM 2 for Glass Fiber Manufacturing	0.2	60
MOM 3 for Conventional Manufacturing	0.4	40
MOM 4 for Mixed Manufacturing	0.6	60
MOM 5 for Generic Composites	0.8	70
MOM 6 for Multi-Machine Use	0.9	90
Selection	Machine Code	Complexity

*Note: The data contained in the table is a masked data used for representation and proof of concept.

Table 20: Quality Assurance Knowledge Set for LKC-Tool

Quality Procedure	Volume	Glass Fiber	Carbon Fiber	Aramid Fiber	CMC	MMC		
Cuboid Inspection Time (min)	0	0	0	0	0	0		
Cylindrical Inspection Time (min)	69.65838972	1044.875846	1044.875846	1044.87585	1741.45974	1393.16779		
Selection	AISI 4130	AISI 4140	SS 304	Monel 400	Inconel 625			
2	1044.875846	1044.875846	1044.875846	1741.45974	1393.16779			
	Time						Material	Time
Selection	4800						AISI 4130	1044.875846
9							AISI 4140	1044.875846
							SS 304	1044.875846
							Monel 400	1741.459743
							Inconel 625	1393.167794
							Glass Fiber	4800
Quality Assurance Cost/unit	QA Cost Rate	No of Quality Checks	Total Quality Cost	Carbon Cost			Carbon Fiber	4800
24000	5	2	48000	720			MMC	4800
							Aramid Fiber	4800
							CMC	4800

*Note: The data contained in the table is a masked data used for representation and proof of concept.

Table 21: Labour Knowledge Set for LKC-Tool

Labour Time	Volume	AISI 4130	AISI 4140	SS 304	Monel 400	Inconel 625
Lathe	6965838.972	2089751.691	2089751.691	2089751.691	2089751.69	2786335.59
CNC	6965838.972	1393167.794	1393167.794	1741459.743	2438043.64	2438043.64
Drilling	6965838.972	696583.8972	696583.8972	1044875.846	1741459.74	1741459.74
	Lathe Time	CNC Time	Drilling Time			
AISI 4130	2089751.691	1393167.794	696583.8972			
AISI 4140	2089751.691	1393167.794	696583.8972			
SS 304	2089751.691	1741459.743	1044875.846			
Monel 400	2089751.691	2438043.64	1741459.743			
Inconel 625	2786335.589	2438043.64	1741459.743			
Glass Fiber	2089751.691	1741459.743	1044875.846			
Carbon Fiber	2089751.691	1741459.743	1044875.846			
Al-MMC	2089751.691	2438043.64	1741459.743			
Aramid Fiber	2786335.589	2438043.64	1741459.743			
CMC	2786335.589	2438043.64	1741459.743			
Selection	Lathe Time	CNC Time	Drilling Time	Total Time		
9	2786335.589	2438043.64	1741459.743	6965838.972		
Total Labour Cost	Labour Cost Rate	Direct Labour Cost Rate	No of Labour Employed	Direct Labour Cost	Carbon Cost	
1393167.794	0.2	87.75	1	1393255.544	1044875.85	

*Note: The data contained in the table is a masked data used for representation and proof of concept.

The logical part of the tool is divided into three sections. The first section of the logics are directly applied on to the different cells of the excel sheets. This part is mostly the mathematical equations and the Cost Estimation Relationship (CER)'s which can be directly applied on to the knowledge sets. These logics are stored in the same excel worksheet format as a separate table with elements. The second section of the logics are conditional logics which are also applied directly on to the cells and sheets that require a conditional logic. These logics are not stored in a sheet but applied directly to the concerned knowledge element. The third section of the logic is the graphical and functional logics, which are applied directly to the interface. These logics are used for interaction between the knowledge sets and the user input information. These are represented in Table 22. Some of the logics that are taken from the industry manuals have not been included to be displayed as these are covered under IP protection laws and hence cannot be shared.

Table 22: Logical Knowledge Set for LKC-Tool

Costing	Labour Cost/Unit	Quality Cost/Unit	Manufacturing Cost/Unit	Material Cost/unit	Design Cost/Unit	Carbon Footprint Cost/Unit	Total Unit Cost
Unit Cost	1393.167794	0.024	1938.07914	1485.116869	1393.167794	19.97177015	6209.555597
Costing	Direct labour Cost	Direct Materials Cost	Direct manufacturing Cost	Direct Quality Assurance Cost	Total Carbon Footprint Cost/Factory	Factory Cost	
Factory	1393.255544	1856.396086	2422.598925	0.048	180.8624022	5672.298555	
Costing	Design Carbon	Material Carbon	Manufacturing Carbon	Quality Carbon	Labour Carbon	Total Carbon Cost	
Carbon Footprint	104.4875846	9.139180731	5.547713931	0.0072	1.393255544	120.5749348	
	A	B	C	D	E	F	G
Unit Cost	Labour Cost/Unit	Quality Cost/Unit	Manufacturing Cost/Unit	Material Cost/unit	Design Cost/Unit	Carbon Footprint Cost/Unit	Total Unit Cost
Factory Cost	Direct labour Cost	Direct Materials Cost	Direct manufacturing Cost	Direct Quality Assurance Cost	Total Carbon Footprint Cost/Factory	Factory Cost	
Carbon Footprint	Design Carbon	Material Carbon	Manufacturing Carbon	Quality Carbon	Labour Carbon	Total Carbon Cost	
	A	B	C	D	E	F	G
Selection	Labour Cost/Unit	Quality Cost/Unit	Manufacturing Cost/Unit	Material Cost/unit	Design Cost/Unit	Carbon Footprint Cost/Unit	Total Unit Cost
1							
	A	B	C	D	E	F	G
Unit Cost	1393.167794	0.024	1938.07914	1485.116869	1393.167794	19.97177015	6209.555597
Factory Cost	1393.255544	1856.396086	2422.598925	0.048	180.8624022	5672.298555	
Carbon Footprint	104.4875846	9.139180731	5.547713931	0.0072	1.393255544	120.5749348	
Selection	A	B	C	D	E	F	G
1	1393.167794	0.024	1938.07914	1485.116869	1393.167794	19.97177015	6209.555597

*Note: The data contained in the table is a masked data used for representation and proof of concept.

These logics are responsible for the smooth functioning of the tool. It can be said that the logical set behaves as the main controller of the tool telling it how to respond if a change in the input or knowledge takes place. This also allows scaling to be carried out without disturbing the knowledge sets created or the logical inferences developed, providing additional advantage. The tool and its versions are discussed in next sections. For the proper understanding of the next sections an example of a simple geometry with conventional material has been chosen. This geometry has been shown in **Appendix-B** with design details. The materials chosen for this example are conventional steel alloys, nickel based alloys and composite materials which form part of the version 1 of the tool. Some more composite materials are added in the version 2 of the tool along with some advanced features. This example is used to illustrate the usage and functioning of the tool and is not a part of tool validation.

4.4.3 Advanced LKC-Tool Version 1.0

During this research a tool has been developed in Microsoft (MS) Excel to make the knowledge reusable and automate some of the processes. This tool keeps knowledge in the defined worksheet format and links the knowledge together using macro functions which are already built-in to the Excel program. For better understanding and the working of the tool, representation of the same is made using a design custom made for representation and proof of concept.

The representation of the first version of this tool uses an example from **Appendix-B**. The tool that has been created is represented in step wise format so as to showcase the entire function and usage of the tool. Figure 38 shows the interface that the user sees. This interface has been created in parts which have been clearly marked as step numbers for better understanding.

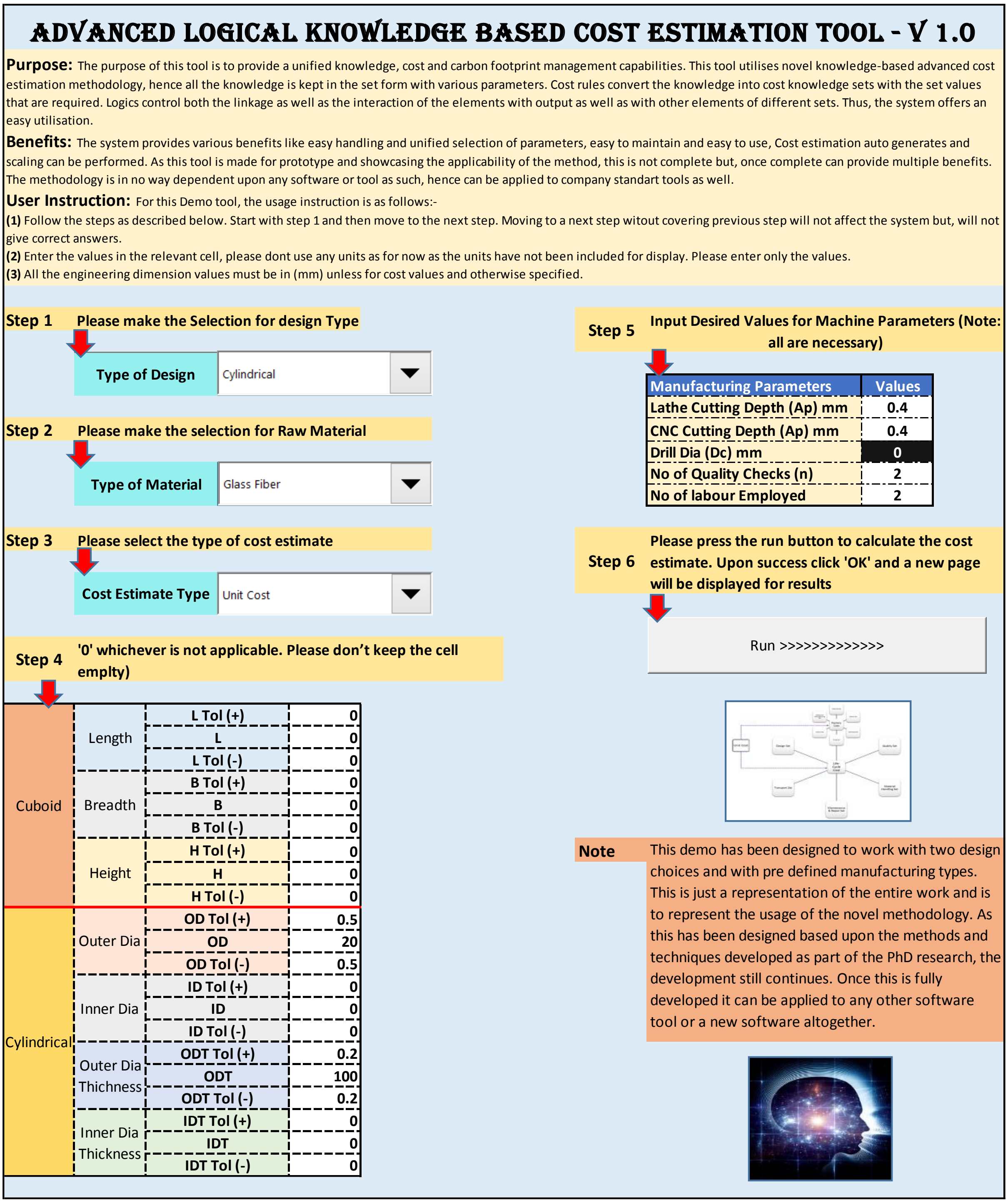


Figure 38: LKC-Tool Ver-1.0 Interface Design

The steps that a user has to follow have been clearly highlighted in this tool interface. From here the next steps will be represented using the example design that has been chosen to be a very simple cylinder and a cuboid. These designs are represented in **Appendix-B** with their design features having tolerance values to make it a bit more complex. Let us see the working of the tool. Here the user has to input certain parameters which are represented in Table 23.

Table 23: Component Parameters

Sr. No.	Component Type	Design Parameters	Tolerances	Material Type	Cost Output Required
1	Cylindrical Rod Case 1	Diameter = 20mm Length = 100mm	Diameter = ± 0.5mm Length = ± 0.2mm	AISI 4130	Factory Cost
2	Cylindrical Rod Case 2	Diameter = 20mm Length = 100mm	Diameter = ± 0.5mm Length = ± 0.2mm	Carbon Fiber	Factory Cost
3	Cuboid Block Case 1	Length = 40mm Breadth = 40mm Thickness = 50mm	Length = ± 0.2mm Breadth = ± 0.2mm Thickness = ± 0.1mm	AISI 4140	Unit Cost
4	Cuboid Block Case 2	Length = 40mm Breadth = 40mm Thickness = 50mm	Length = ± 0.2mm Breadth = ± 0.2mm Thickness = ± 0.1mm	Glass Fiber	Unit Cost

From the table the user can understand that the requirements of the design are different with the material choices and the type of the design along with change of dimensions. There are two cases for each of the design types. The first design type is the cylindrical design which has two cases with change in the material type having factory cost as an output. The design has been kept constant so that it can be shown how material selection can be made keeping all other features same for the component.

For cylindrical design, the user will have to make certain inputs and selections. These are represented in Figure 39, which become the input variables.

Figure 39: Input Parameters for Cylindrical Design in Ver-1.0

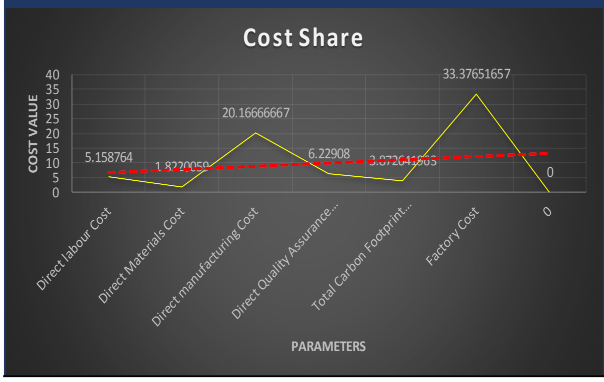
The selections are represented with a red star to make it easily identifiable. In step 1 user has a drop down list of the type of design, this can be replaced by part numbers in industrial applications. In step 2 user has a drop down menu for material choices. These have been pre-loaded in the material knowledge set but a new material can be added based upon specific applications. In step 3 the user has a drop down selection for the type of cost estimate that the user wants to calculate. These cost estimates have been pre-defined and their respective logics built in the tool. Step 4 is the physical inclusion of the design parameters for the related design type. Step 5 is a pre-loaded set of machining values that are standard to the machining types used. Once this has been done, the user checks all the information for any inconsistency in the design and finally clicks the Run button which executes the cost estimation functions to showcase the outputs, this is Step 6. This way an advanced cost modelling is achieved which represents various parameters that contribute to the overall cost. The output is represented in both tabular and graphical manner, as shown in Figure 40.

The list of output cost estimates

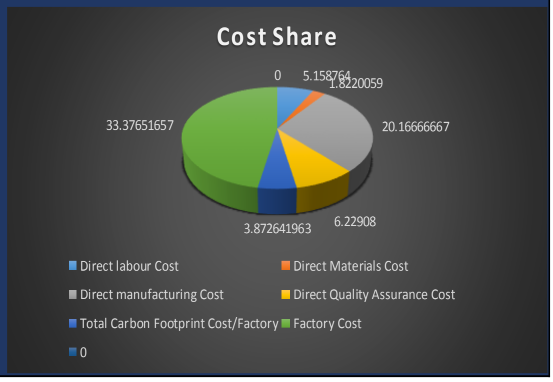
Cylindrical Design: Output for Case 1

Parameters	Direct labour Cost	Direct Materials Cost	Direct manufacturing	Direct Quality Assurance Cost	Total Carbon Footprint	Factory Cost	0
Cost Share	5.158764	1.8220059	20.16666667	6.22908	3.872641963	33.37651657	0

Cost Share Distribution Graph



Cost Share Distribution Chart

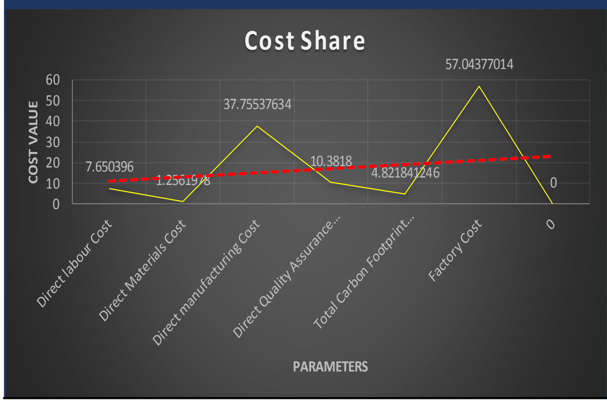


The list of output cost estimates

Cylindrical Design: Output for Case 2

Parameters	Direct labour Cost	Direct Materials Cost	Direct manufacturing	Direct Quality Assurance Cost	Total Carbon Footprint	Factory Cost	0
Cost Share	7.650396	1.2561978	37.75537634	10.3818	4.821841246	57.04377014	0

Cost Share Distribution Graph



Cost Share Distribution Chart

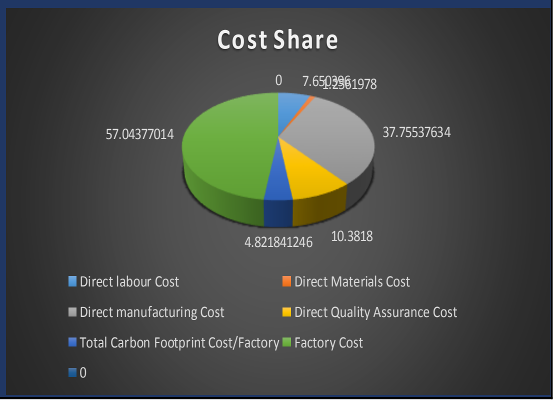


Figure 40: Output Cost Distribution for Cylindrical Design in Ver-1.0

The next part of the representation is a boxy cuboid design. The parameters for the cost estimation lie in the same category. There is a change in the design requirements and output requirements. Material selection also changes for both the cases. In this selection the changes observed in input parameters are represented in Figure 41. Here input parameters for cuboid design are showcased as it is chosen by the user. The selection procedure remains the same but the design parameters for cuboid differ in the amount of complexity. As the dimensions in a cuboid shape have length, breadth and height, there is an extra one parameter that is required to be handled. Moreover as all the three have tolerance values in them, the complexity in the design phase and manufacturing phase increases. For a user the only selection he/she has to make is the step choices as shown in Figure 41.

Figure 41: Input Parameters for Cuboid Design in Ver-1.0

All the input parameters are shown with a red star to make it more visually recognizable. Once these parameters are fed into the system the only next thing a user has to do is to click the Run button to execute the program and get the cost output. For this selection the output is shown in Figure 42.

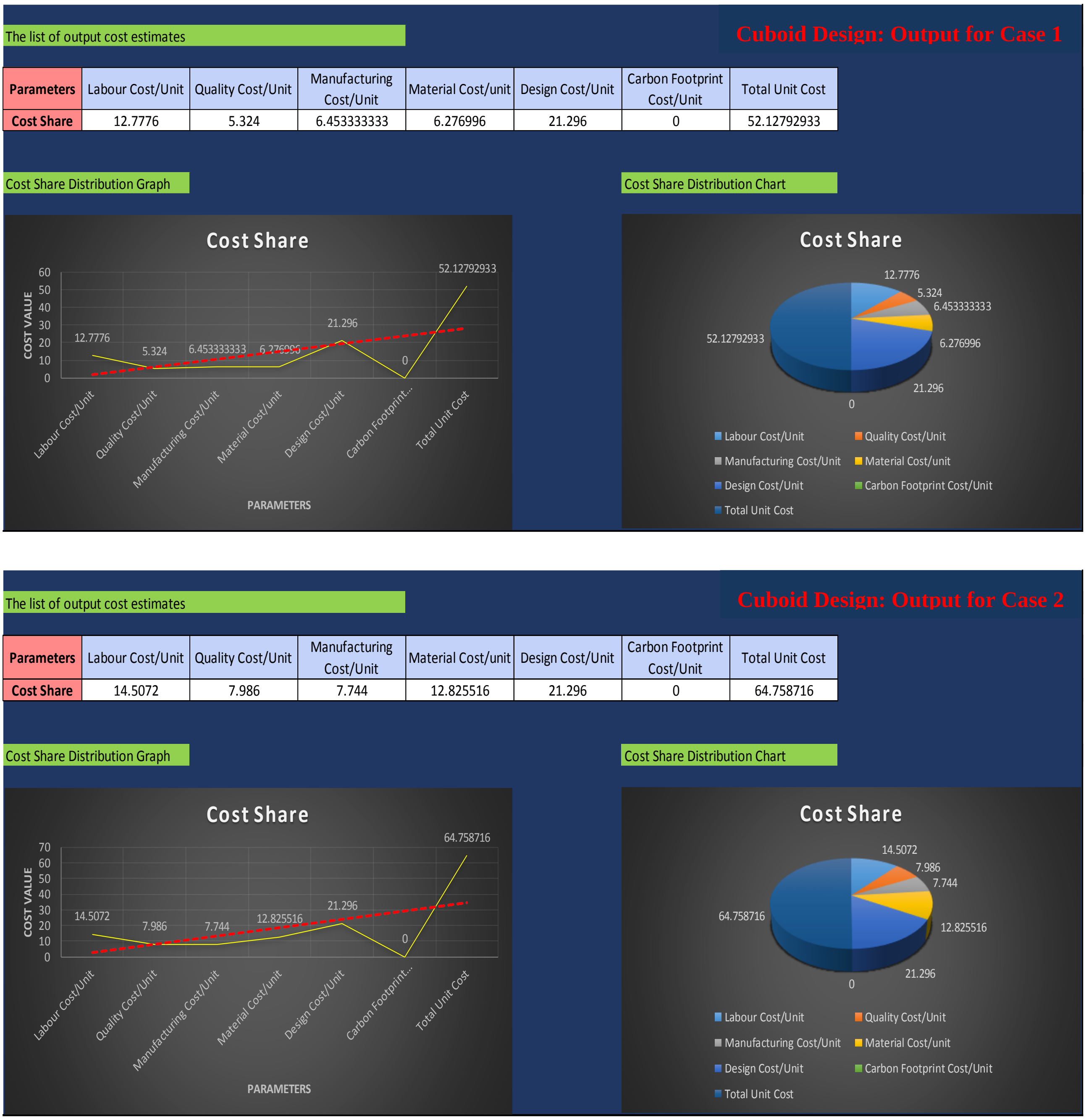


Figure 42: Output Cost Distribution for Cuboid Design in Ver-1.0

This tool is, therefore, ‘intelligent’ enough to understand the difference in design and its complexity, can cope with changes in material, can give different cost outputs for a particular part or design and still be flexible enough for fast and early cost estimation. This tool has been showcased to work both with conventional materials and composite materials and it showed that for a same design, the overall cost of composite material part is higher as compared to conventional material. There are however, certain shortcomings of this version. One of the shortcoming is limited composite knowledge database available for a user to make precise estimates. Another shortcoming is that for this version machining has been pre-defined and remains the same for all the options, also the machining parameters could not be changed or fed into the tool. This does not allow a user to make changes to the machining parameters which are a requirement in real world scenario. These shortcomings are addressed to in the next version of the tool. This next version of the tool is capable of predicting carbon footprint cost along with conventional cost estimation. Also, it has options to input machining parameters and as a result the material choices may be increased.

4.4.4 Advanced LKC-Tool Version 2.0

This version of the tool is the improvement over the first version which has been carried out after consultation with the stakeholders, supervisors and experience. The major shortcomings from the first version were, (i) lack of precise knowledge of composites, (ii) carbon footprint cost is not predictable, (iii) machining parameters could not be changed, (iv) additional advanced features not included and (v) outputs do not have a list of input values used. This version is an update including additions made on the previous version to make it more advanced and user friendly. Also, this version includes extended knowledge which can predict carbon footprint cost as well as incorporate extra machining choices which were limited to a specified method of manufacturing in the previous version. Representation of the tool is still made in the

Microsoft (MS) Excel. All the related knowledge blocks are inbuilt into the structuring of the tool in excel as worksheets and are connected to each other via logical connectors. These logical connectors are mathematical, graphical, functional or logical layers that are embedded into the individual elements of the knowledge sets. This tool is the final version for this research study, but this does not limit its development further as a much advanced and capable system for predicting costs.

For showcasing the functioning of this version, same example from **Appendix-B** has been taken. The parameters for the representation has also been chosen to be the same so as to keep the representation of outputs as close to the previous version as possible and easily compare the differences in the two versions. Here again as in the previous version similar system is required for input of the information. A user has to choose from certain pre-loaded knowledge and add some other parameters which will act as cached knowledge. In the similar fashion, knowledge is fed to the different worksheets by the logical layer and shared among the requisite knowledge sets. This way an advanced costing is obtained.

Similarly, the tool interface design for the previous version this update has the same basic outline of the tool, however, there has been certain additions to the knowledge elements and logical inferences which change the selection parameters and the input parameters. This addition also increases the current capability and makes the estimate even more comprehensive. Besides addition in the material, design and cost output there is an important inclusion in the system which is method of manufacturing. This is important as there are many ways of manufacturing a similar product, but some processes are less costly than others when it comes to the manufacturing cost. Also there may be change in the complexity, which may affect the cost output. It is for this reason this version has that complexity selection. The tool interface for the version 2.0 is similar to the version 1.0 but differs in the features that have been added to it so as to allow extra details to be incorporated as user inputs in the system. The interface that has been designed for this purpose is represented in Figure 43.

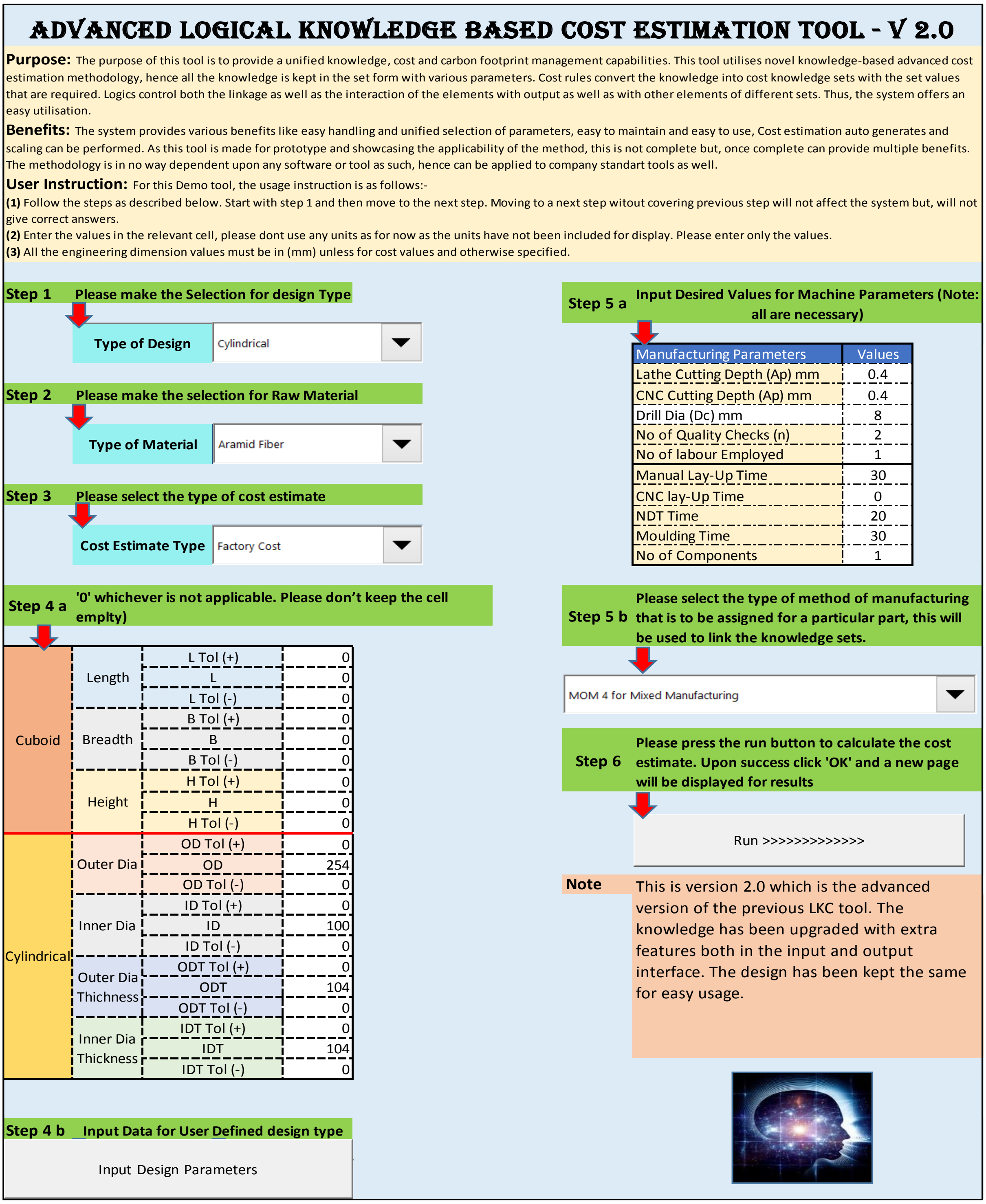


Figure 43: LKC-Tool Ver-2.0 Interface Design

From the figure 43 it can be clearly seen that as an addition to the previous version, some additional capabilities are added which include, additional knowledge elements in the selection parameters and an input button as a function to ensure all features have been added successfully. Machining parameters have also been improved and additional knowledge is included for a much comprehensive cost estimation. There has also been an addition of a selection function for a predefined set of Method of Manufacturing (MOM) techniques. These define the flow of knowledge in different knowledge sets and the functional sets. Logical inference is also taken from this selection which is user defined for better and precise estimation and analysis. It also defines the level of complexity which is used in calculating cost estimates for intricate design components. There has been addition of carbon footprint cost as part of the tool which is calculated based upon the carbon emission logics and some additional assumptions.

The functioning of this tool is also shown using the same example with the same parameters. This is done to showcase the advantage version 2.0 provides and the difference in output cost that this tool estimates. Theoretically as well as practically this version is bound to give different outcomes in cost as there has been extra knowledge elements in the form of composite knowledge sets, machining knowledge sets, MOM sets and carbon footprint sets which also add up to the cost. Also as there has been complexity based selections provided as a functional selection, a logical inference is taken which makes certain assumptions mathematical rather than experience-based, thereby improving upon uncertainty. Also as the complexity differs, there is a difference in assumptive values which are again a percentage of the overall cost and the multiplication factor of the complexity parameter. The complexity parameter defines the amount of cost addition in a set of manufacturing operations. This way when a complexity is chosen elements are derived which affect the values from other sets as well. Overall contribution leads to a cost estimate. The functioning of this version of the tool with both cylindrical and cuboid designs is showcased in two parts. The first part of the representation is a cylindrical design which is shown in Figure 44 for both case 1 and case 2.

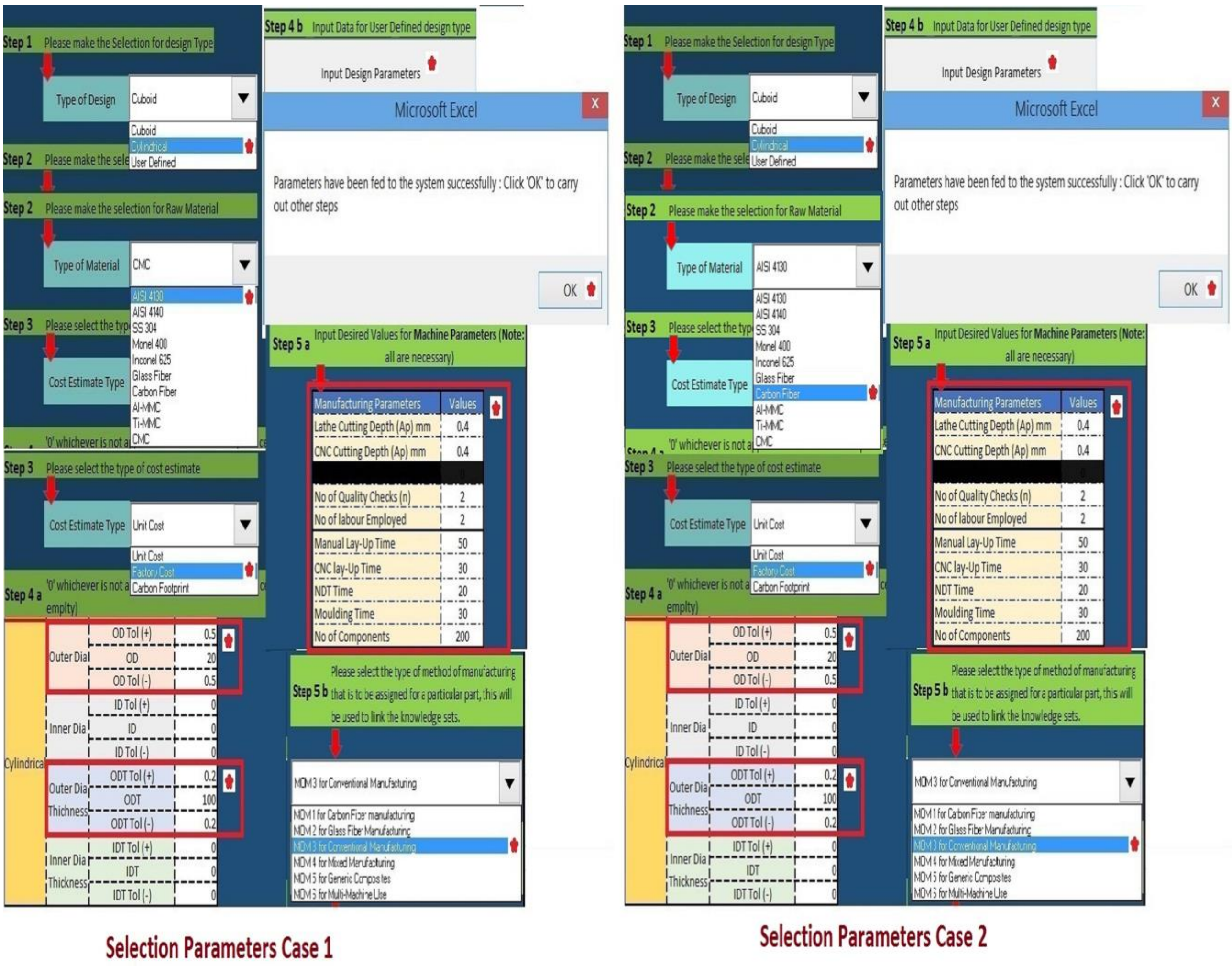


Figure 44: Input Parameters for Cylindrical Design in Ver-2.0

These parameters are fed into the tool using buttons and selectors that are designed by using MS Excel macro functions. From the input interface it is clearly seen that all the logical inference and functional parameters are taken from the user selection. MOM selection triggers the flow of knowledge between the manufacturing, materials, quality and labour sets which are responsible for creating elements and relating elements and subsets to the relational parameters. This creates a flow of knowledge between the sets in a logical manner which is used to solve the cost estimation equations for related cost outputs that are again chosen by user. The output costs so obtained are thus dependent upon the additional features as well and is even more precise than the previous version. As more knowledge is available, more detailed analysis can be obtained. The outputs for the cylindrical design case 1 and 2 are shown in Figure 45.

Figure 45: Output Cost Distribution for Cylindrical Design in Ver-2.0

The next part for this representation is also a boxy cuboid design. The representation is done in the same manner as discussed above, except for the extra knowledge elements that provide a user the capability to choose from different manufacturing techniques. These techniques can affect the cost in many ways, however for this research study this aspect of the representation is not looked into detail. The parameters are taken from Table 23 in the previous section. As the cuboid design is one of the simplest designs that is utilized in many ways in the manufacturing realm, it is considered to have a less complexity impact on the design knowledge transfer. However, with the use of a composite material the complexity level changes in the MOM and the manufacturing knowledge transfer which in turn makes the overall complexity still on the higher side.

For the representation of the version 2.0 with this design, complexity is not an important aspect. In the same way as discussed earlier, parameters are inputted into the tool using the interface as shown in Figure 43. After the selections are made and the parameters inputted, the tool is made to run the logics and functions that are built into it. In the similar manner as discussed earlier, input parameters are the design related parameters which have to be directly fed into the system and the selection based parameters which are inbuilt into the system but needs to be selected for it to get executed. This way the user has to make certain selections depending upon the information in hand and the variables to be used. These parameters define the geometry, material and manufacturing aspects of the product and the cost estimate will be more precise and highly useful in conducting project or process analysis.

The input parameters and the selections made by the user for both the cases of the cuboid design are shown in Figure 46. Here the parameters are directly fed into the tool using the designed interface.

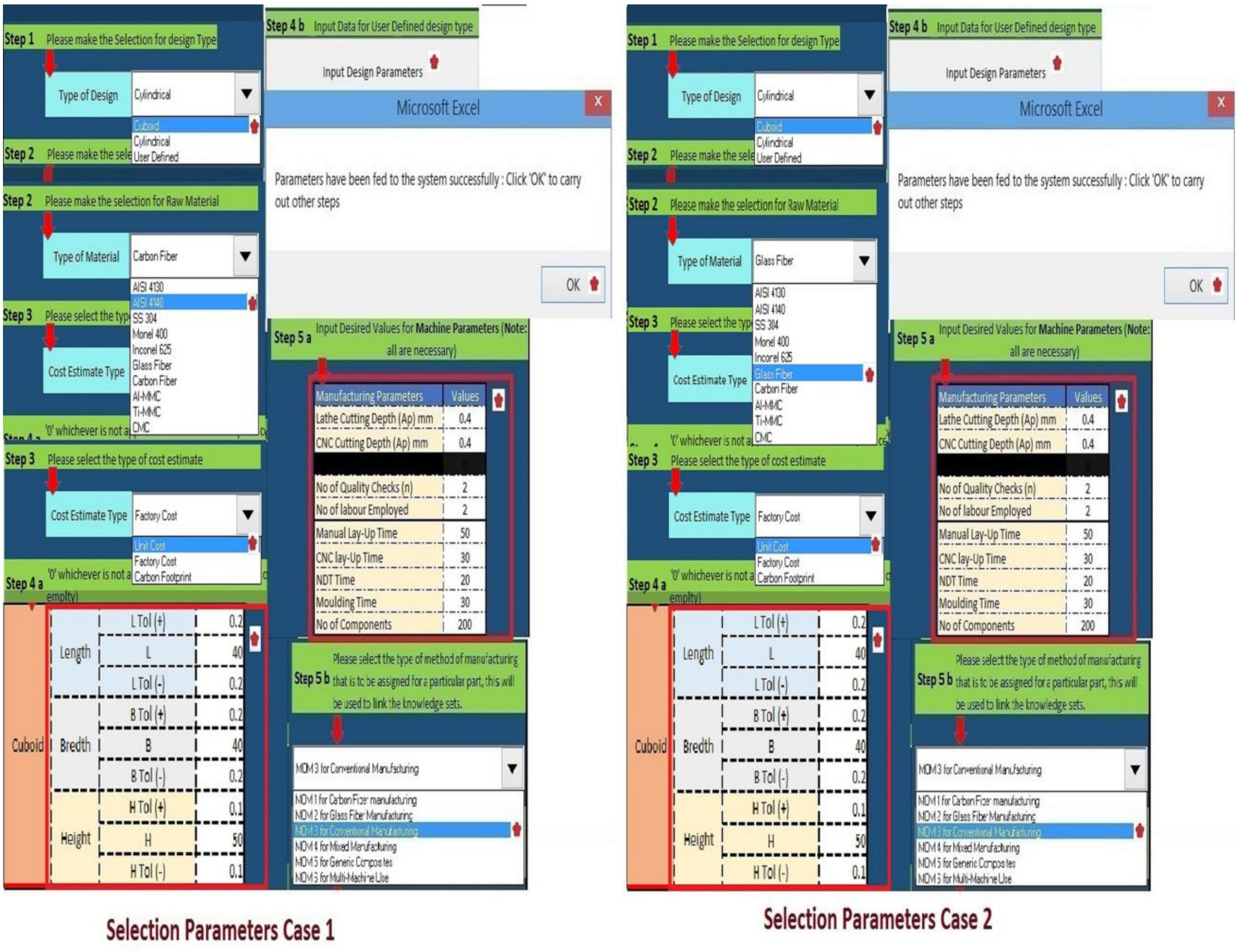
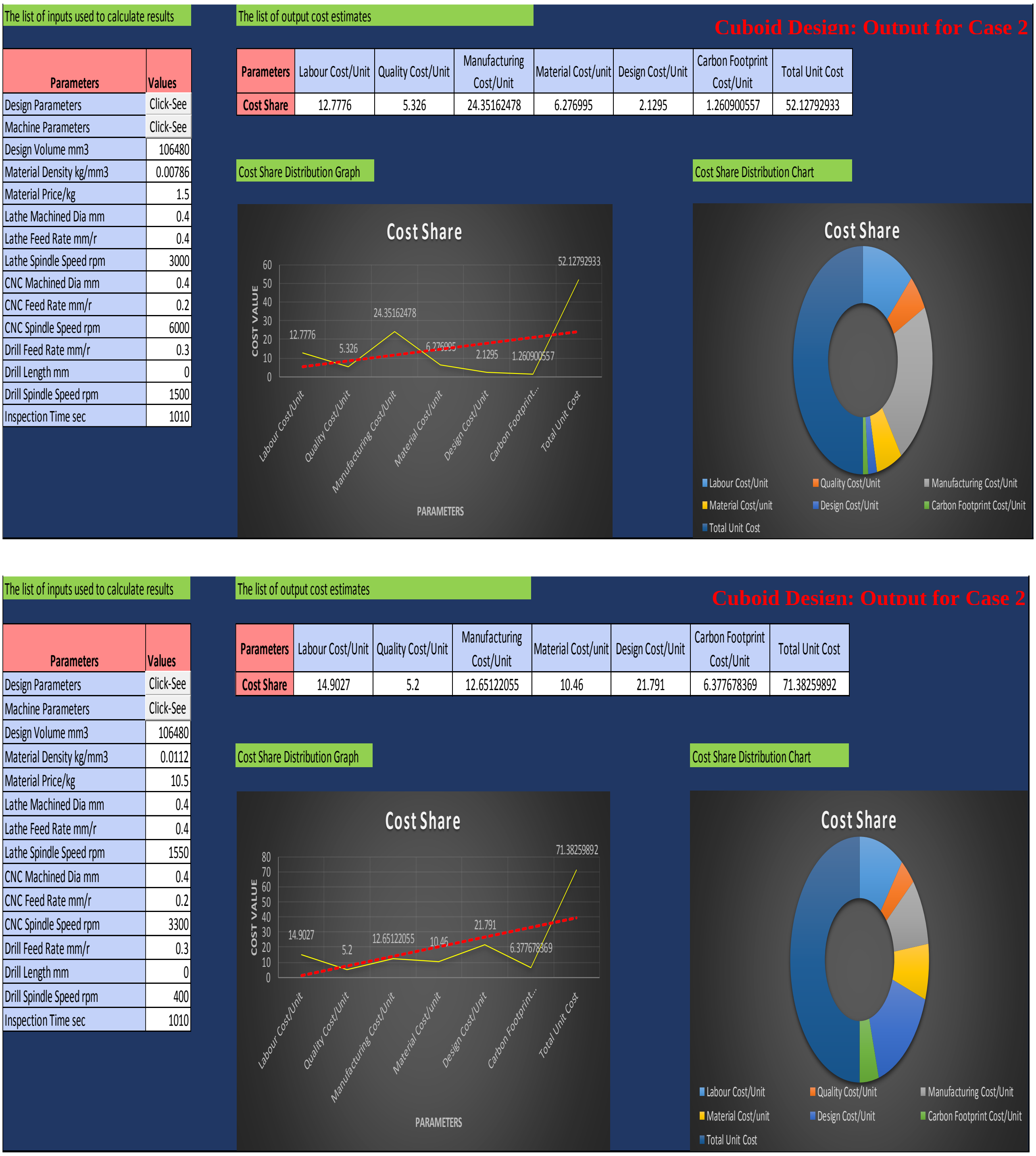


Figure 46: Input Parameters for Cuboid Design in Ver-2.0

As the inputs are fed into the tool through its interface, knowledge is passed on to various knowledge sets with the help of logics that are inbuilt into the tool. The output which is obtained depends upon the selections that have been made and the inputs that have been fed to the system. As the inputs for both the versions are the same, outputs should be the same but there is a slight difference because of extra knowledge and features provided in the version 2.0 which makes it more precise. Even there is a difference in the way the cost is being represented. This is because of the fact that extra knowledge makes the distribution of cost to spread to a broader area and hence cause a scattering of the cost. This scattering of the cost is very important as it makes the outputs more beneficial when it comes to understanding the cost impact and also the overall share of various phases. It helps a user to identify key areas of improvements and calculate the cost benefit of a product or predict its business viability. The outputs as obtained from ver-2.0 are shown in Figure 47.



Parameters	Values
Design Parameters	Click-See
Machine Parameters	Click-See
Design Volume mm3	106480
Material Density kg/mm3	0.00786
Material Price/kg	1.5
Lathe Machined Dia mm	0.4
Lathe Feed Rate mm/r	0.4
Lathe Spindle Speed rpm	3000
CNC Machined Dia mm	0.4
CNC Feed Rate mm/r	0.2
CNC Spindle Speed rpm	6000
Drill Feed Rate mm/r	0.3
Drill Length mm	0
Drill Spindle Speed rpm	1500
Inspection Time sec	1010

Parameters	Labour Cost/Unit	Quality Cost/Unit	Manufacturing Cost/Unit	Material Cost/unit	Design Cost/Unit	Carbon Footprint Cost/Unit	Total Unit Cost
Cost Share	12.7776	5.326	24.35162478	6.276995	2.1295	1.260900557	52.12792933

Parameters	Values
Design Parameters	Click-See
Machine Parameters	Click-See
Design Volume mm3	106480
Material Density kg/mm3	0.0112
Material Price/kg	10.5
Lathe Machined Dia mm	0.4
Lathe Feed Rate mm/r	0.4
Lathe Spindle Speed rpm	1550
CNC Machined Dia mm	0.4
CNC Feed Rate mm/r	0.2
CNC Spindle Speed rpm	3300
Drill Feed Rate mm/r	0.3
Drill Length mm	0
Drill Spindle Speed rpm	400
Inspection Time sec	1010

Parameters	Labour Cost/Unit	Quality Cost/Unit	Manufacturing Cost/Unit	Material Cost/unit	Design Cost/Unit	Carbon Footprint Cost/Unit	Total Unit Cost
Cost Share	14.9027	5.2	12.65122055	10.46	21.791	6.377678369	71.38259892

Figure 47: Output Cost Distribution for Cuboid Design in Ver-2.0

From the representation it is clear that the LKC tool is capable of estimating the cost for a product with any combination of design, material, manufacturing or cost output type without needing a separate model for every problem. This tool can work both with conventional and composite material realms and is not limited to use with aerospace sector. This tool can be used for any engineering or manufacturing problem in a generic way. For this study however, the use is limited to aero-engine components and components manufactured from composite materials to keep the entire scope down to the research's aims and objectives.

4.5 Chapter Summary

From the discussions made so far it was seen that carbon footprint if taken as a cost parameter can improve the overall estimate and can increase the current cost capability. It was showcased that carbon footprint share is almost 20% to the overall cost and hence, its inclusion in the life-cycle analysis is required. Also, it was seen that the understanding of the life-cycle was limited to conventional scoping which needed to be expanded as there are processes like service, maintenance, disposal, architectural decision and procurement which consume a lot of cost and are important for a composite component. This study let to the proposal of a more generic life-cycle which included carbon footprint as part of the processes. The generic life-cycle was used as the basis for the scoping and designing of the advanced cost estimation system. Here, the application of mathematical set-based knowledge management technique integrated to mixed cost estimation method was made and knowledge was categorised and stored as physical sets. These sets were divided into Parent & Child, Primary & Derived and Output Cost. Logical set was kept as a separate set and again divided into three phase logical inference. First phase included mathematical logic applied directly to the elements of the related set. Second phase to the interaction between the user and the knowledge sets and the third to the elements of the output cost knowledge set. This way an advanced system was developed which was later presented in the Microsoft (MS) Excel application. Here, the knowledge sets were represented as worksheets and each node of the worksheet as elements. The logics were applied directly to the nodes and the worksheet to convert the raw Knowledge Information and Data (KID) to functional Cost Estimation Relationship (CER). This representation of the methodology and design using excel was done on two custom designed Three Dimension (3D) design models. This was done to represent the design and structuring of the whole system, therefore, for the application masked data was used so that a proof of concept can be made out.

In the next chapter validation of the methodology and tool will be carried out. This will be done by considering case studies from both industry as well as open market products. Another planned validation comes from the industry experts who have working knowledge of the cost estimation system and can judge the design, structuring, application and outcome without any influence. In this next chapter the application will be made on the actual components from aero-engine realm and their outcome would be compared to the conventional methods so as to prove the novelty of the developed methodology. The outcome would be presented both numerically and graphically so that a thorough analysis can be made out.

5 Research Validation

5.1 Validation Structuring

As the research has progressed to a level that a new methodology has been developed and applied for the development of an advanced costing system, the research needs to be validated and checked for errors. This has been done by following a designed technique. This technique utilizes knowledge from 2 previous studies and industrial projects to be used as test cases where the knowledge from these cases are applied as per the designed methodology to test the functioning of the advanced costing system. To validate the tool and its application, 2 case studies taken from the open marketplace products that are of importance to the aero-engine realm manufactured from composite materials are chosen. This way, the entire application of the components is done in the developed tool and the output from the tool is compared to the cost price of the product, thereby, validating the entire methodology structuring and the system development. In addition to the case study validation the design, structure, tool and application are validated by industry experts in the field of cost estimation using a feedback report format. The feedback is taken after the system is applied in the real life scenario and outcomes from the same are showcased as presentation to the experts. The expert validation is taken in different areas of this research which covers the key foundations of the research and hence validate the same, thereby validating the whole research.

The validation process follows a flowchart based technique for conducting these validations as this will ensure that the validation process will work smoothly and the results thus obtained would be recorded systematically. The technique that has been designed for validation can be visualized from Figure 48. This technique provides a baseline structure which needs to be followed for validation.

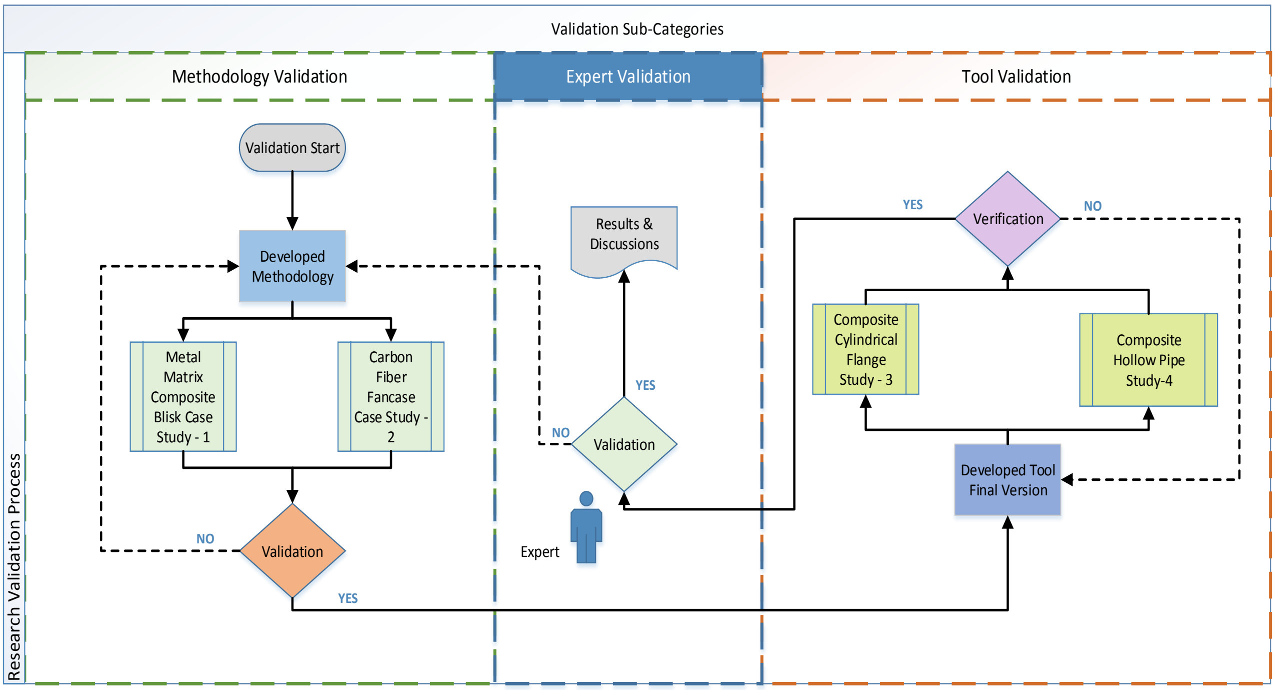


Figure 48: Research Validation Flowchart

From the figure 48 it can be seen that the validation has been divided into three parts. The first part is the validation of the developed methodology for which two case studies from industry available projects are used. These case studies use the real time data from used projects from industries and previous studies with all the design details and machining details intact. These are very high in design complexity and rich in information and hence, very effective in validating the structure, logics, flexibility and robustness of the advanced system created. Also, the first two case studies are directly from aero-engine parts hence they are very relevant to the research in hand. For validating the methodology, a representation is made in two different software tools, one which is readily available and used in any windows based platform and the other one is industry specific Java based tool that has its own software package and can run on multiple platforms. This has been done to showcase the platform independent nature of the methodology design and knowledge structuring. This validation represents the case studies based on LKACEM and keeping the same input parameters, the outputs are obtained and compared. This showcases attributes in LKACEM, namely, (i) robustness and reliability, (ii) flexibility of application, (iii) platform independent design and (iv) logic in knowledge management.

The second part of the validation process is the validation of the developed advanced costing tool. This is an additional validation that is done to verify that, the tool is capable of handling complex design and manufacturing information, able to provide various parametric selections for the user, automatic in calculating cost, intelligent enough to understand a variety of input combinations, able to predict cost and capable of having a flexible and maintainable structure. This is done by using two case studies of commercially available aero-engine components. The component data and design information is taken from an open marketplace which is an online market website 'Alibaba.com'. This information is then used to predict the unit cost of that component. This unit cost is predictive of the selling price of the component which should have a marginal value added to it. This marginal value is the profit which a company usually applies to all its products. Another technique employed is the comparison of the cost outputs of multiple components with their cost price. Once this comparison has yielded a considerable result, the validation is considered to be complete. This validation showcases the attributes namely, (i) easy to handle and maintain, (ii) addition of knowledge to the existing capability, (iii) flexibility of use and application and (iv) platform independent nature of the system.

The third type of validation process is a validation taken from industry experts. This is done by applying the developed methodology and tool into real life scenarios and then presenting the method, tool, their structure and results in a presentation form to experts from industry having more than 10 years of experience in the related field of cost estimation. The experts are then given a feedback form to fill and give their opinion on the work done and validate the whole system based upon their expert knowledge, expertise and practical experiences. The experts chosen are from the same field and working on the same projects that are used for validation of this study. This validation is done to verify that the research conducted is a considerable work and that the application of the developed work is very much relevant to the industrial problems. It also validates the basic structuring and designing of the advanced system and confirms that carbon footprint knowledge is an additional advantage to the current cost capability. The whole validation process is discussed in more detail in the sections to follow.

5.2 Methodology Validation

For the methodology validation two case studies from the aero-engine realm has been chosen. These case studies have been taken from the industrial problems which have relevance in the real world scenarios and are complex in their design and manufacturing attributes. These case studies are the components manufactured from composite materials which are the main area of this research.

The first case study is the aero-engine blisk which is the combination of disc and blades mounted together as one component. The material of choice is from the metal matrix family of composites that have been acknowledged as advanced materials and have already been explained in detail in the previous studies. The second case study is a polymer matrix composite family-based aero-engine fan case. This component is a critical part of the aero-engine and has complexity in manufacturing and inspection. These case studies validates the methodology as such with special consideration given to the logical knowledge base created, application and maintainability, complexity handling capability, robustness and flexibility of operation and platform independent design for achieving advanced cost estimation system.

5.2.1 Metal Matrix Composite Blisk - Case Study 1

Metal Matrix Composite (MMC) is one of the materials used in the component manufacturing for aero-engines. The material is light in weight and has the capability to bear high temperatures and still maintain dimensional stability. The normalization/omissions/changes have been done on initial values of the process data itself following a technique of changing the values to a higher or lower number so that the general rules and the structure is not altered. Units are omitted from the values. For the application of this developed methodology, a MMC Blisk is chosen as the case study and a factory cost model is made. In this case study blisk represents a part with highest level of complexity both in design and manufacturing. This way, the set-based representation of knowledge and its utilization can be verified. By representing the factory cost model in industry standard advanced tool and conventional software tool, the flexibility of this methodology is also verified. MMC is one of the materials used in the component manufacturing for aero-engines. The material is light in weight and has the capability to bear high temperatures and still maintain dimensional stability. The Blisk design is considered for the purpose of this study. Blisk is a term used to describe a blade mounted on the rotor disc. The diagram in Figure 49 represents blisk design (University of Trento, 2003).

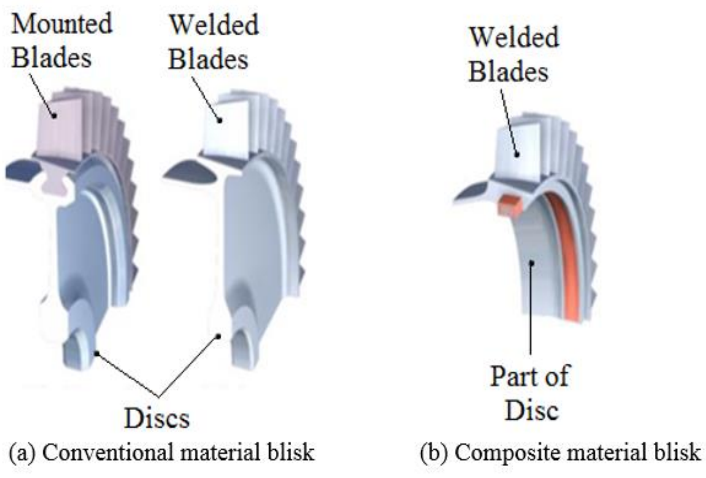


Figure 49: Blisk Design Types (University of Trento, 2003)

The data and process parameters, including the process breakdown, are taken from industry led previous used cases and literatures (Cheung et al., 2009), (NASA, 2004). As the source of data and knowledge is from industry related projects published as open source, the used case is an industry accepted case. The normalization/omissions/changes has been done on initial values of the process data itself following a technique of changing the values to a higher or lower number so that the general rules and the structure is not altered. The units are omitted from the values so that the logic remains undisturbed. Blisk design is chosen for the study because of its high level of complexity both in design and manufacturing. Number of features in the design, such as, intricate grooves followed by blade mounted on the periphery makes it a highly complex design situation and similar complexity is reflected in the costing environment. The MMC Class of composite material is considered for the blisk as the base material. Factory Cost Model is chosen to be prepared for the purpose of this analysis. For the development of the cost model Microsoft (MS) Excel and Vanguard System^{TM} Cost Modeling are used independently. MS Excel being the simplest and easiest way to represent data is used to keep data in a statistical format using a worksheet format (Sets), also it is used to capture general rules relating to the cost parameters and then apply LKACEM for cost estimation. Vanguard System^{TM} Cost Modeling being a cost modelling tool used in most of the industries and also being one of the best softwares relating to interactive representation of parameters and outcomes, is used for developing and representing the cost model in a conventional manner using LKACEM (Vanguard Software Corporation, 2016). This way, it is shown how the developed methodology handles complexity in design and is flexible for use with different software tools.

To begin the analysis, it is important to understand the process map which controls the flow of manufacturing. This process map is a generalized form of the actual process for a MMC blisk manufacturing. The data is in a tabular form and is therefore put into Microsoft Excel for easy inclusion later in the method. The process map for use in the cost estimation is represented in **Appendix-C** which will form the layer 1 of the methodology in both cases. From **Appendix-C** (layer 1) the process chart is broken down as per the generic life-cycle and knowledge sets are created based on the breakdown. These knowledge sets contain the cost related information in a tabular manner which is utilized by applying LKACEM. The process chart is first broken down into activities and then each activity is modelled individually using the generic rules. The parametric relation between the activity and the outcome is achieved and modelled in the activity model. This way, using the proposed method, the entire process of manufacturing of MMC part is mapped in an easy to understand and logical manner, forming layer 2 of the methodology. The layer 2 so generated is represented in Figure 50.

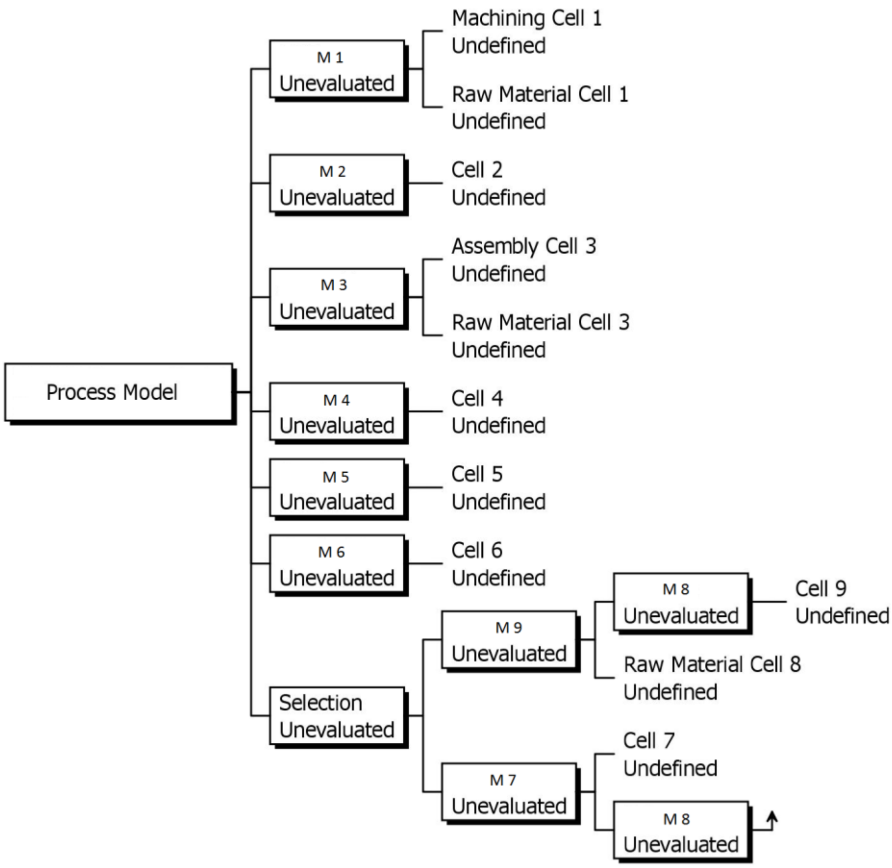


Figure 50: MMC - Blisk Process Model

From the figure 50 it can be seen that the life-cycle process of the MMC Blisk has been broken down into subsets starting from M1 till M9. These subsets contain manufacturing knowledge of the set they represent. M1 represents the first manufacturing process in the life-cycle chain for the MMC blisk. Here, raw material starts getting converted into processed part. Processes M2 till M6 are the next machining steps which involve the making and the baking of the final product. The node selection represents the quality inspection phase where after verifying the products dimensions and mechanical parameters, it is sent for either M7 or M9, which is the welding and joining process respectively. M8 is the final balancing stage where dynamic and static balancing of the part takes place.

This way, the process model is derived from set theory-based knowledge system and thus represents the knowledge sets necessary for inclusion in the factory cost. The cost driver information related to each and every set is defined in their corresponding cells or nodes. After this has been made, generic rules governing the process parameters and the cost drivers are applied to the nodes by physically including all the parametric, mathematical and relational rules/equations in the nodes. The whole system generates a cost model having all the cost drivers represented in the node format, which forms layer 3. After completing the representation and application of layer 3, the input and output parameters are defined, modified and fed into the nodes. The data or information that is fed into the model so created is carried out to the node by first defining the related nodes as the input nodes.

Once the nodes are selected as input nodes, as soon as the data or information is fed to the system, value gets reflected in the selected node. The data sheet that has been used for the creation of this model and input values that is fed into the model is represented in **Appendix - D**. Now the entire model is given input values from the data sheet, which when run generates output cost estimations that are represented as part of the layer 3. This part of the layer 3 is the user interface. In the vanguard-based software tool, there is no separate interface and the only representation is the tabular input and output parameters along with a tree structure representing the model itself. The representation of the entire model, is hence in a single place which is a bit complex when a lot of knowledge or information needs to be modelled.

This way, the entire complexity related to the blisk design problem is broken down into simple steps and the knowledge is categorised based upon the machining steps which gets addressed by this system of cost estimation. Thus, the development of the cost model becomes systematic, fast and easy. Also the complexity is reduced dramatically including ease of handling and scaling of design. Each and every process model's sub-divisions are the knowledge sets and hence contain further sub-sets and also elements. These elements are now introduced in the knowledge sets in the nodal points in Vanguard generated tree structure. As the details are added to the nodes directly, detailed information related to cost drivers in all the process model's sub-divisions are easily added and handled. Node-by-node a factory cost model is generated. Some logics are also added to the nodes to make them a bit intelligent in handling knowledge across the model.

This way, a complete factory cost model is prepared. The factory cost model then has all the relevant nodes needed to convert the input information to the output cost estimate. This output cost estimate can then be compared to the outputs from other methods or for process/project analysis. The developed factory cost model as discussed above is shown in more detail with all the nodes and their related elements in Figure 51.

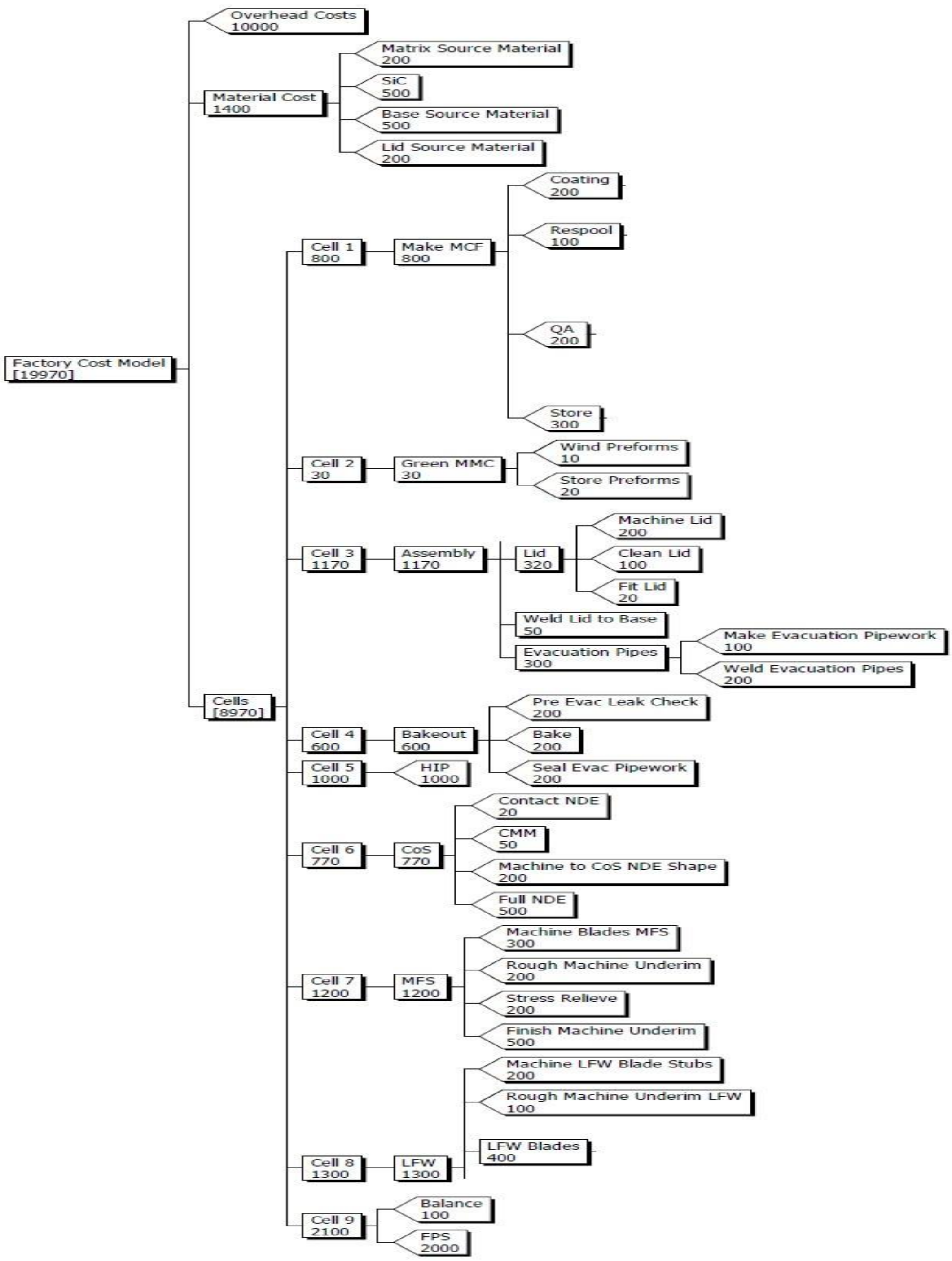


Figure 51: MMC - Blisk Factory Cost Model

For the ease of understanding and systematic representation for next stages of analysis, the input and output parameters from layer 4 and their corresponding values are represented in a tabular form. This way the outputs from advanced cost model can be compared to the outputs

`

generated by a different software tool. The tabular representation is shown in Table 24 and Table 25. The input table being same will be used in the same form for the next study.

Table 24: Input Parameters for MMC - Blisk Factory Cost Model

Sr. No.	Input Parameters	Input Values (Units vary)
1	Coating	200
2	Quality Assurance	210
3	Respool	100
4	Store	320
5	Store Preforms	20
6	Wind Preforms	10
7	Machine Base	200
8	Machine Lid	200
9	Bake	310
10	Hot Isostatic Pressing	1000
11	Machine Blade	350
12	LFW Blades to Disc	180
13	LFW Blade Stubs	180
14	Balance	120
15	Base Source Material	500

Table 25: Output Cost Estimates for MMC - Blisk from Vanguard

Sr. No.	Output Parameters	Output Values (Units of Cost)
1	Machining Cell 1	800
2	Machining Cell 2	30
3	Machining Cell 3	1170
4	Machining Cell 4	600
5	Machining Cell 5	1000
6	Machining Cell 6	770
7	Machining Cell 7	1200
8	Machining Cell 8	1300
9	Total Material Cost	1600
10	Factory Cost	19970

The outputs achieved by this method shows that machining cell 3 which is the machining operation phase in the process chart contributes the highest to the overall factory cost. This is followed by material cost and then the joining operation of blades on the disc. Overall, the output has showcased a positive result without any errors in the logic meaning thereby a successful use of the methodology in cost estimation for composite blisk.

The same method of cost estimation is now applied using MS Excel software. Here, the procedure remains the same but is more evident and precise as some of the attributes which could not be applied in the previous method because of an academic license used for vanguard software, can be easily applied and shown in the Excel format. LKACEM is applied here by following different stages namely, (i) Development of Process Activity Sheet (layer 1), (ii) Development of Knowledge Sets (layer 2), (iii) Development of Cost Set (layer 2), (iv) Applying Logics (layer 3) and (v) Feeding input values (layer 3). The data being very large cannot be shown in the entirety but for proper understanding some parts of it would be shown. As the knowledge itself is kept in the Excel format refining knowledge to get proper information becomes easy. The universal knowledge set that is being used for preparing the cost set is shown in Table 26 which becomes Layer 1 and is the same taken from **Appendix-C**. The data set that has been used to develop and model the factory cost in MS Excel is also the same as that of the vanguard system and is taken from **Appendix-D**.

This data sheet is utilised to convert the raw knowledge into a universal knowledge set which is represented in excel as a worksheet. This worksheet contains both the process and material knowledge which is necessary to calculate cost. Modelling of factory cost is achieved by converting this knowledge indo different sets as required by blisk Method of Manufacturing (MOM). The process distribution and the machining sequences can be utilized to design the knowledge sets and the same can then be put as a separate worksheet so that a linkage can be made between the worksheets and an output evaluated. The universal set is shown in Table 26.

Table 26: Universal Knowledge Set for MMC - Blisk

Universal Cost set			
Parameter	**Method of Cost Evaluation**	**Parameter**	**Method of Cost Evaluation**
Cost of Facility per Year	Cost Units/Year	**Cost of HIP**	Cost Unit/Year
Cost of QA Performed	Cost Units/Year	Cost of Contact NDE	Cost Unit/Year
Cost of Respooling	Cost Units/Year	Cost of CMM	Cost Unit/Year
Cost of Spool Storage	Cost Units/Year	Cost of Machining to CoS	Cost Unit/Year
Cost of MCF Produced	Cost Units/Year	Cost of Full NDE	Cost Unit/Year
Total Cost of Manufacturing	Cost Units/Year	**Total Cost of QA**	Cost Unit/Year
Cost of Winding Preform	Cost Unit/Year	**Number of Required Machines**	No.
Cost of Preform Storage	Cost Unit/Year		
Number of Preforms	No./Year	Mass of MCF Produced	Weight/Year
Total Cost of Preforms	Cost Unit/Year	Length of MCF Produced	Length/Year
Cost of Machining Base	Cost Unit/Year	Cost per Pound of MCF	Cost Unit/Weight
Cost of Cleaning Base	Cost Unit/Year	Cost per Metre of MCF	Cost Unit/Length
Cost of Machining Lid	Cost Unit/Year	Cost of Desired MCF (m)	Cost Unit
Cost of Cleaning Lid	Cost Unit/Year	Cost of Desired MCF (lb)	Cost Unit
Total Cost of Machining	Cost Unit/Year		
		Number of Forgings per Year	No./Year
Cost of Preforms and Forging	Cost Unit/Year		
Cost of Lid Fitting	Cost Unit/Year	Cost of Pre-evac & Leak Check	Cost Unit/Year
Cost of Welding Lid	Cost Unit/Year	Cost of Bake	Cost Unit/Year
Cost of Welding Evacuation Pip	Cost Unit/Year	Cost of Sealing of Evac Pipe	Cost Unit/Year
Total Cost of Welding	Cost Unit/Year	**Total Cost of Bakeout**	Cost Unit/Year

This universal knowledge set is used to make factory cost knowledge set as per LKACEM. The conversion of the universal set into the cost set is based upon the principle that factory cost is the summation of material costs, labour costs, manufacturing costs, overhead costs and scrap costs. Hence, the cost sets, which are only important for factory cost are taken for study by using the set formula from Table 13 above, which says that Factory Cost **(FC)** = P({**RmC** ∪ **MC** ∪ **MoM** ∪ **QC** ∪ **AC** ∪ **LC** ∪ **CC** ∪ **S**} **-** { **RmC** ∩ **MC** ∩ **MoM** ∩ **QC** ∩ **AC** ∩ **LC** ∩ **CC** ∩ **S**}). This then forms the Layer 2. The Carbon Footprint (CC) is not taken into consideration for this study but will be included in the next sections of this work. Next upgradation would be inclusion of a carbon footprint set and will contain process wise carbon footprint price, forming a part of cost estimation. The factory cost set is achieved by refining the Knowledge Information and Data (KID) from the parent knowledge set and converting it into process wise knowledge sets. The knowledge sets contain both the cost driver information as well as subsets that contain another set of cost driver elements. The factory cost knowledge set, which is derived from the universal knowledge set, is shown in Table 27. From here all the related cost drivers are linked so as to function as a Cost Estimation Relationship (CER) and become usable for predicting cost.

Table 27: Factory Cost Knowledge Set for MMC - Blisk

Factory Cost Set					
Overhead Set		**Assembly Set**		**Machining Set**	
Parameters	**Units**	**Parameters**	**Units**	**Parameters**	**Units**
Building Rent	Cost Units/year	Respooling Required?	Boolean Selection	Mass of MMC Lid Forging	Weight
Service Charge	Cost Units/year	Cost per Respooling Machine	Cost Units	Mass of Machined Lid	Weight
Gas Cost	Cost Units/year	Depreciation Years for Respool	Time	Inspection Cost per Lid	Cost Units
Water Cost	Cost Units/year	Cost per Empty Spool	Cost Units/spool	Other Costs per Lid	Cost Units
Electricity Cost	Cost Units/year	Length of MCF per Spool	Length	Number of Lids per Part	No.
Cost of Radio License	Cost Units/year	Power required per Respool Machine	Power		
Cost of Key Holding	Cost Units/year	Respooling Rate	Length/Time	**Material Set**	
Cost of Clean Room	Cost Units	Service Cost of Respool machine	Cost Units/year	**Parameters**	**Units**
Clean Room Depreciation Years	Years	Service Time of Respool machine	Time/year	Number of NPI this Year	No.
Clean Room Servicing Cost	Cost Units/year	Respooling Machine Turnaround Time	Time	Desired Amount of MCF	Length
Cost Rate of Power	Cost Units/kW	Rate of use of paper	Weight/Length	Desired Amount of MCF	Weight
Hourly Rate of Bought in Services	Cost Units/hr	Cost per Pound of Paper	Cost Units/Weight	Length of MCF per Pound	Length/Weight
Nominal Length of Working Day	Time			Cost of MMC forging per lb	Cost Units/Weight
Estimated Proportion of Time Worked	Percent	**Machining Set**		Cost Rate for MMC Machining	Cost Units/Volume
Length of Working Day	Time	**Parameters**	**Units**		
		Mass of MMC Base Forging	Weight	**Quality Assurance Set**	
Welding Set		Mass of Machined Base	Weight	**Parameters**	**Units**
Parameters	**Units**	Inspection Cost per Base	Cost Units	QA Cost per Run	Cost Units
Cost of Welding per Container	Cost Units	Other Costs per Base	Cost Units	QA Performed?	Boolean Selection
		Density of MMC	Weight/Volume		

After forming the factory cost set next layer which is the logic layer is applied on to the knowledge layer. Here, the cost driver information is applied to the existing information to generate meaningful relations. Based upon these relations, input and output is produced in the interface layer. Both the layers are carried out in the Excel itself. Some of the logics used for cost estimation are represented in Table 28. This is a part of layer 3. The complete set of logics is quite large and are covered under Intellectual Property (IP), so a representation of some important ones is made in this table. Other set of logics are pre-defined into LKACEM and is shown in **Appendix-A**.

Table 28: Logics for MMC - Blisk Factory Cost Model

Logic Description	Mathematical Relation for the Logic
QA Cost	QAC = (QA Cost per run*No. of Runs)
Cost of Machining Lid	MLC = (Total cost of lid*No. of bases)
Total Cost per Lid	TCL = (Cost of lid material+Cost of lid machining+other)
Cost of Respool	CR = (Respool req+((Cost per pound*rate per pound*length per pound)+power required))
Total Cost for Base	TCB = (Cost of base material+Cost of base machining+other)
Total Cost for Composite	TCC = (Cost of QA+Cost of respooling+Cost of production+Cost of storage)
Cost of Bake	CB = (Cost of pre-machine+Cost of bake+Cost of sealing)
Welding Cost	WC = (No. of containers*Welding cost per weld)

Once this is achieved, the second part of layer 3 is compiled using mathematical operations inside Excel. These are the mathematical functions governing the flow of knowledge and information inside the system and also in the interface representation. Logics are applied in the related cells of the table to calculate the output cost. These logics are also mathematical functions and/or operations to link one cell with another and one worksheet with another. The input parameters being same as in Table 24, is not represented again and is directly fed to the developed system for achieving a cost estimate. This is also done in the cells and the worksheet directly as MS Excel does not require a special interface. MS Excel has the ability to show the results in a tabular as well as graphical manner which is very interactive, hence it does not require any special interface to input data, execute functions and represent the outcome. The outputs so obtained are represented in a tabular form as shown in Table 29.

Table 29: Output Cost Estimates for MMC - Blisk from MS Excel

Output Parameters for MMC Blisk Factory Cost		
Sr. No.	Output Parameters	Output Values (Units of Cost)
1	Machining Cell 1	810
2	Machining Cell 2	32
3	Machining Cell 3	1170
4	Machining Cell 4	600
5	Machining Cell 5	1000
6	Machining Cell 6	772
7	Machining Cell 7	1203
8	Machining Cell 8	1320
9	Total Material Cost	1600
10	Factory Cost	19986

This way it has been shown that LKACEM can be applied to complex problems in cost estimation where it breaks down the complex problem into steps, manages knowledge related to composites and then calculates cost. Here it can be seen once again that machining cell 3 is the major contributor to the overall factory cost. This is followed by material cost and then joining phases. Hence, it is concluded that the methodology is both consistent and reliable in cost estimation. The results from this study can be summarized by comparing the outcomes from both the software tools. The application of this method in two different software tools and using a complex geometry part (blisk) was done to test five important parameters, namely, (i) flexibility and robustness of application with different tools, (ii) ease of handling complex problems, (iii) creating single unified system for composite knowledge management and costing (iv) consistency in cost estimation and (v) ease in cost modeling and maintaining. Theoretically as the methodology, design problem and data used are same in both the cases, therefore, the outcomes should be the same. However, it is seen that there is a difference in values in some outcome parameters as well as the overall factory cost. This is evident from the graphical representation of the outcomes from Case 1: LKACEM in Vanguard and Case 2: LKACEM in Excel. This is because of the fact that vanguard software tool has an academic license and most of the advanced features in it could not be used, hence some assumptions were made in the model representation which were later quantified in Excel based representation. This representation and combined comparison is shown in Figures 52, 53 and 54 respectively.

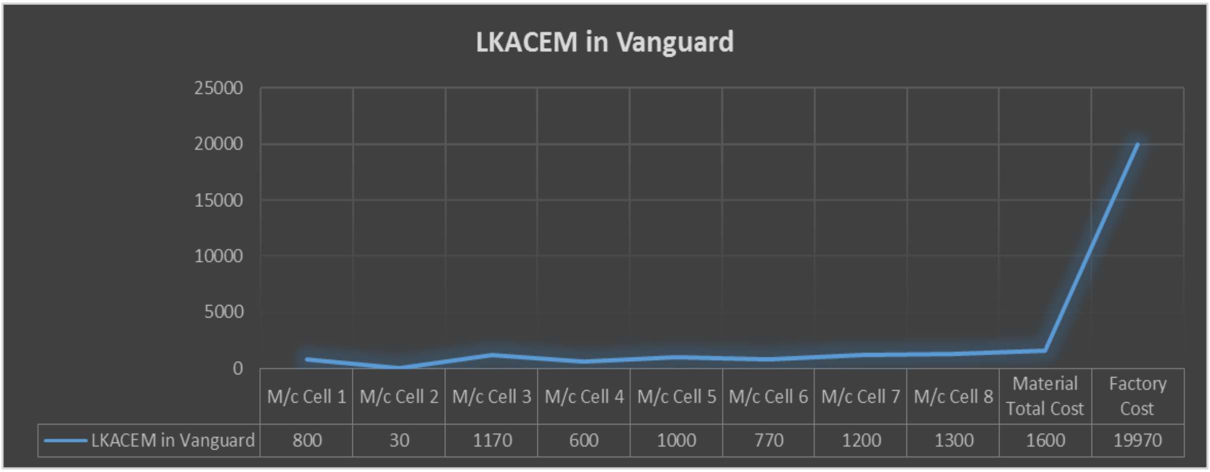


Figure 52: Cost Distribution Case 1 of MMC - Blisk

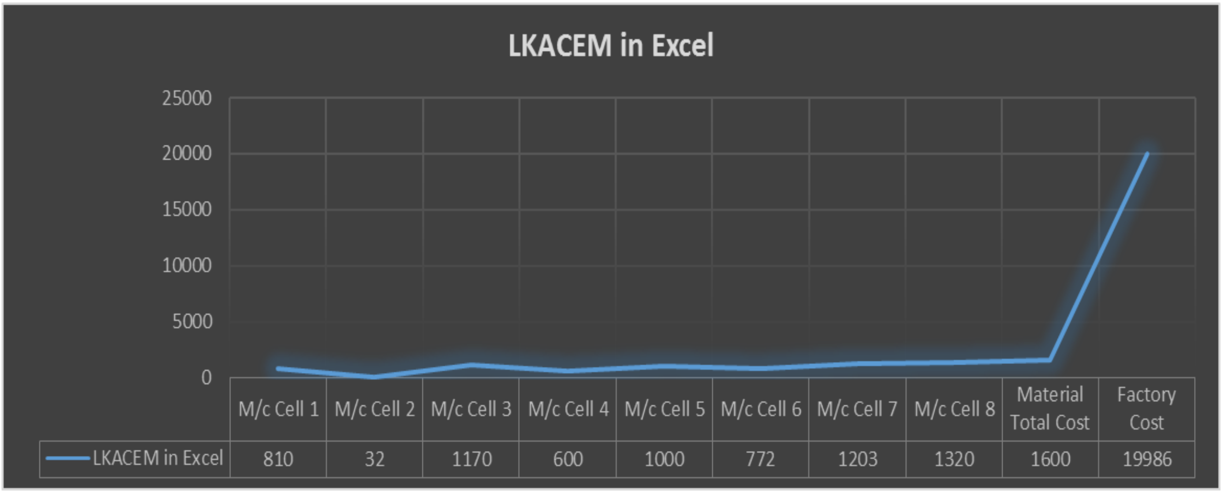


Figure 53: Cost Distribution Case 2 of MMC - Blisk

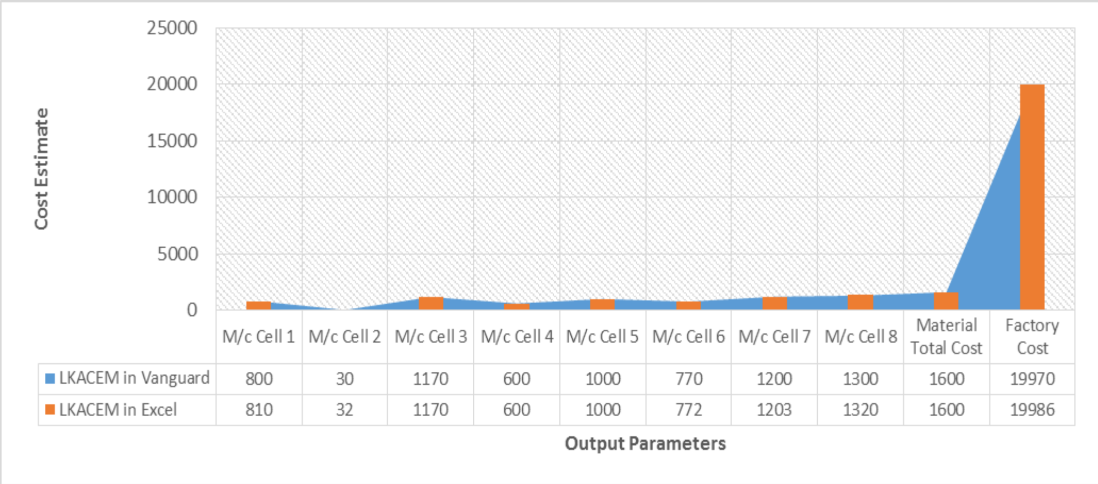


Figure 54: Combined Factory Cost Distribution of MMC - Blisk

The difference in cost estimates is in the order of 0% - 6.67% in machining cells combined, and, 0.08% in the overall factory cost. This is represented in graphical form in Figure 55. It can be seen by analysing all the graphs that the difference in output cost is found to be very small and is only due to the extra assumptions that have to be made in vanguard software. Still, the difference is small and hence, can be neglected. Also the processes which show maximum difference indicate the amount of assumptions made and hence show need for more study for precise quantification of the same.

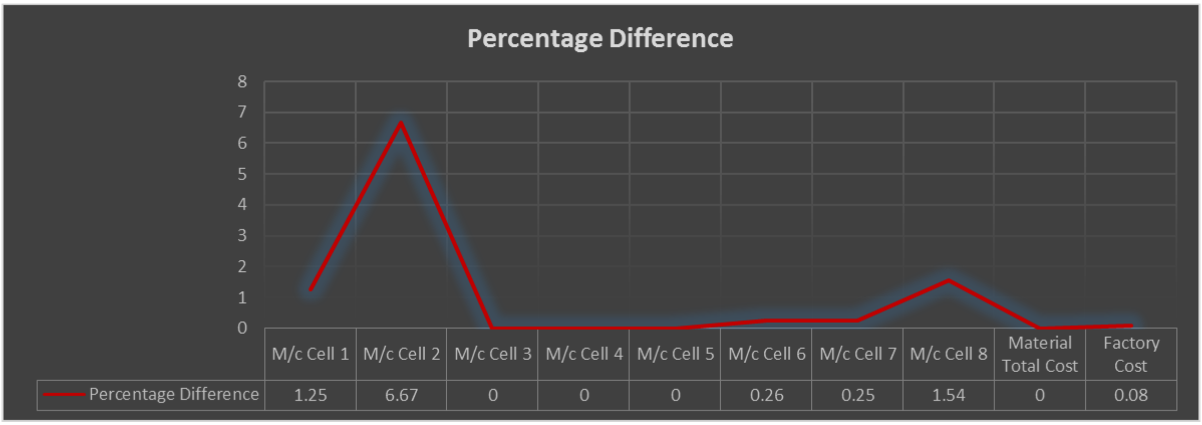


Figure 55: Percentage Difference in Cost Outputs for MMC - Blisk

The variation in cost from two software tools is due to extra assumptions made in the variable values from the first software tool (Case 1), whereas, part quantification of the same was done in the other tool (Case 2). The variation observed is only due to some extra assumptions, also as the variation is minimal, difference in cost estimates can be neglected. Hence, it can be concluded that this method of Cost Estimation can make reliable cost estimates, can handle complexity, is flexible for use with different software tools, can be used for composite cost knowledge management & costing and is an easy step-by-step logical approach in modeling cost. It has been highlighted in many studies that cost estimation for composite material parts is difficult because of less knowledge, lack of unification, highly complex nature and lack of dedicated cost estimation techniques for composites. There have been other advanced cost estimation techniques using simple systems to complex artificial learning techniques, but, still problems highlighted above could not be solved. Also, one of the problems with the conventional system of costing was being process or product dependent. This way the cost model would work only for a particular manufacturing process and a particular design, but the same tedious task needed to be performed for a new design or a part. The presented case study has showcased that by using LKACEM coupled to advanced representation of the same composite cost estimation could be achieved. This technique is neither design dependent nor process dependent and can work for any design combination or any manufacturing process chosen for a particular design. This is further showcased in the next case study.

5.2.2 Carbon Fiber Composite Fan Case - Case Study 2

This case study is taken from one of the most important and critical part of aero-engine technology, the fan case. This critical component of the aero-engine forms the outer shell of compressor stage 1 to stage 3. Stage 1 compressor is the fan that is the only visible component when seen from outside as fitted in an airplane. This casing covers the entire fan and provides a very small clearance between itself and the fan allowing it to rotate freely inside. This makes the casing prone to heavy forces generated during the running of the engine. Also, this part is considered to be a safety feature that holds fast moving debris from leaving the engine in the event of an engine failure. Not only this during bird strikes, engine is encountered with tons of forces that rip apart the fan and its pieces which are leaving the engine at lightning speeds capable of tearing an aircraft's shell. This type of an event is a catastrophic event which poses serious threat to the safety of the passengers and proper functioning of the airplane. This component is the only available safety feature that keeps the debris intact and does not let them to cause damage. Another most important feature of this part is to provide structural stability to some of the inherent components of the engine.

The design of the fan case, though simple has critical functions to perform and thus has high complexity involved in manufacturing and inspection. A representation of the fan case is shown in Figure 56 (NASA, 2006; Composites World, 2017).

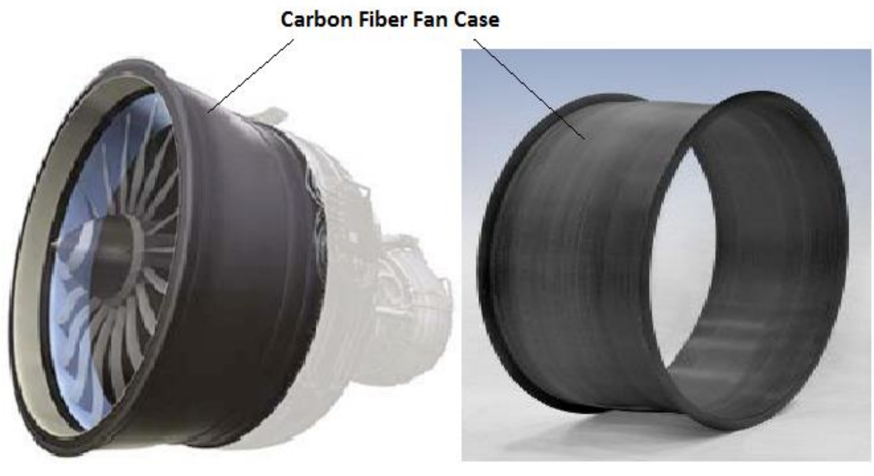


Figure 56: Carbon Fiber Fan Case Design (NASA, 2006; Composites World, 2017)

The design complexity of this part is considered to be on the lower side as compared to other parts of the engine, however, the manufacturing complexity is higher. This is due to the material, which is carbon fiber composite and the tight tolerances involved in its manufacturing. This material has a property of providing high strength to weight ratio and is resilient to impact forces. This material is also quite stable in extreme weather conditions and temperature differences, keeping the tolerances of the design under acceptable limits even in very high temperature differences. The coefficient of thermal expansion is low, which keeps the clearance under tolerance norms, keeping the efficiency of the engine intact. The case study is divided into two parts. The first part is the representation of the process as a chart. This is where the entire manufacturing process is divided into steps and is systematically represented. This representation allows the knowledge to be represented in the set based form using LKACEM. This way structuring of knowledge gets represented in the set form and the flow of knowledge is controlled by the logics stored in the logical set. The process chart for fan case is represented as **Appendix-E**, from where the knowledge sets are created and Method of Manufacturing (MOM) is defined. The data sheet for the same is taken from the previous used industrial cases and is consolidated in a simplistic form. The data is again represented as in Case 1 by rounding off to the nearest possible upper value or lower value and units have been omitted. Omission of the units does not mean that the logics do not have these units incorporated in them, but just to make the data represented in a form that does not hinder the IP of the company, the omission has been made. Also, representing the units is not important as the relationship between the elements in the set are of more importance and govern the flow of knowledge not the units. After the data and the process chart are analysed, a generic process breakdown is created. This breakdown allows the knowledge to be structured in a set based format as per LKACEM. This will then form the layer 1 of the whole system. This case study is also represented in both Microsoft (MS) excel and the company standard Vanguard System™ Cost Modelling software. Both these representations is done to show that the logics that have been designed and the knowledge base that has been designed using LKACEM are correct and there is no error in those representations. Another reason is to show the platform independence capability that this methodology and the system offers. As for the first part of the study the representation is made in Vanguard System^{TM} Cost Modelling Software. Here the layer 1 is represented in a form of a process model. This model is the general representation of the MOM for fan case and can be utilized to model any fan case design with any composite material. For this study the general representation of the fan case process model is made using MOM for carbon fiber composite material. The model so generated is shown in Figure 57.

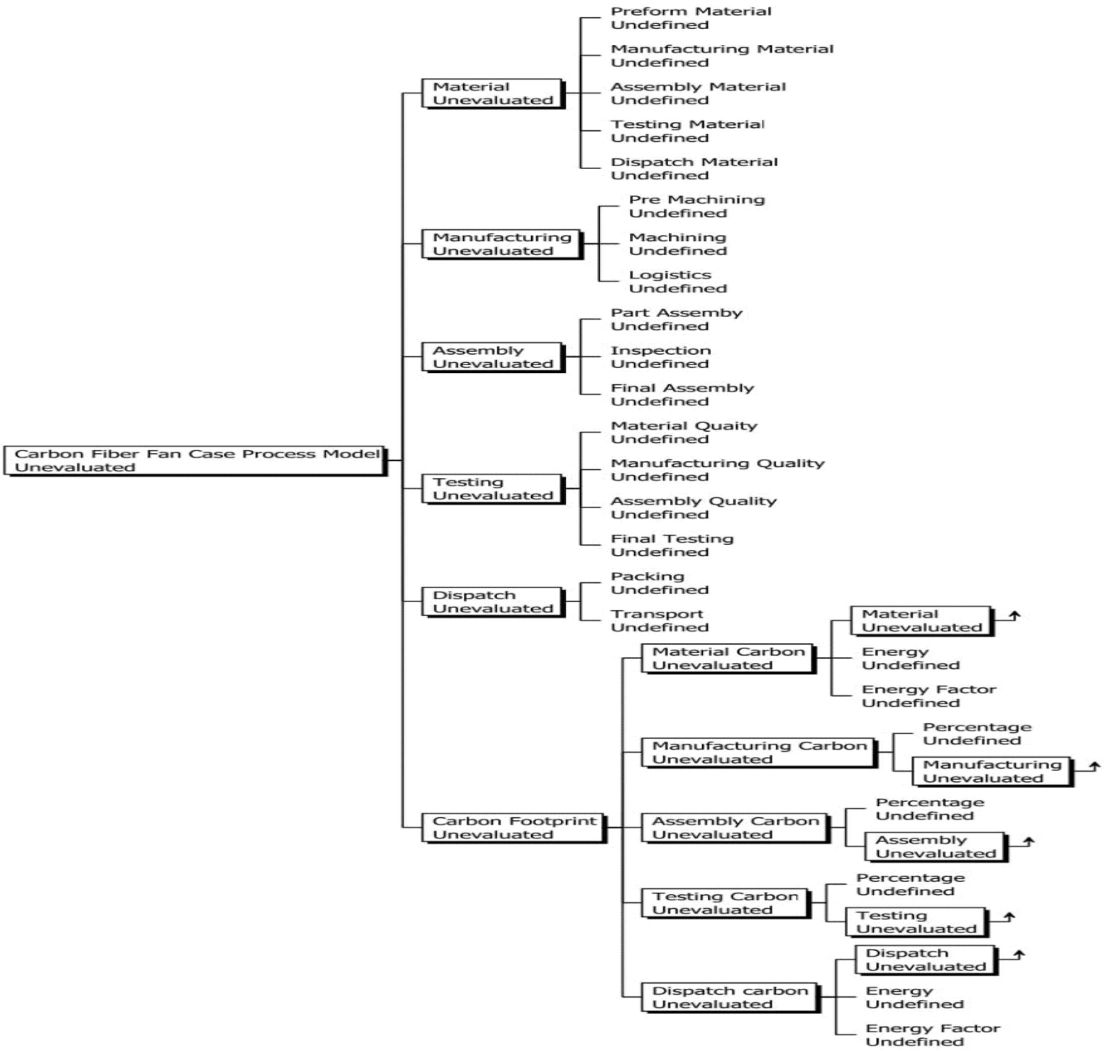


Figure 57: Carbon Fiber Fan Case Process Model

The process model, as shown in figure 57, is used to generate unit cost model. The process model is the set-based representation of the whole complex process. The complex process for manufacturing is shown in **Appendix - E**. The complex process is broken down into simple and much easy to maintain sets. The first line of sets are the main knowledge sets.

The second layer of sets are the secondary knowledge sets and the third layer of sets are the derived sets. Finally the overall knowledge is then refined to the final output set which is the cost set. This way entire knowledge flows through the system and becomes dynamic knowledge. This way raw knowledge is converted into functional knowledge which becomes the layer 2 of the system. Now, layer 2 needs logical and mathematical information to relate the knowledge elements with each other, define cost drivers and define relationships that govern the entire costing system. This logical layer becomes layer 3. This layer 3 is very important in the present system as it defines the flow of knowledge in all the system with start to end and define relationships to elements in these knowledge blocks. User interface is the last layer which is relevant to the data and information exchange and knowledge representation. The interface can be designed as per user requirements in any of the languages because the basic structure involves the use of mathematical set-based theory.

In vanguard the user interface is in the same window where the modelling is done. It also uses the same window and the tree structure to input the data and represent the data, hence the unit model is represented in the same window. The first layer of knowledge is expanded utilizing the manufacturing process for the fan case. The elements of the fan case manufacturing process come from all the activities from the manufacturing process. These activities form the first part of the knowledge block and become the sets in layer 2. Each main activity has the elements in them which come from sub-activity of the main activities and coupled together based upon contribution to the overall cost. These elements are the cost driver information that are used in mathematical logics to calculate output cost estimate. In vanguard, all this is represented in a cell form also known as the node form and the information, knowledge and physical value is directly applied to this node. The logics and mathematical and parametric equations are directly applied to these nodes. In this case study the information from the manufacturing process detail is converted to the set-based generic process model.

After this has been done, elements are defined for each particular node, which is the set representation to include the necessary detail in the structure. In the next level of detailing elements in the form of input values and derived values are directly utilized and related to each other in a logical manner. The logics come under a variety of forms viz. graphical logics, mathematical logics, conditional logics and carbon logics. These logics are responsible for the proper flow of the knowledge in the model and also the actual physical evaluation of the cost estimate. The input from the user is first fed to the input nodes which are then evaluated and sent to the relevant nodes in the model. These nodes take up the physical values and the user selections and convert the knowledge element into the next level knowledge element. This way from one node to another knowledge passes and as each node has a set of mathematical logics and conditional logics the elements gets converted to functional variables. Finally, these variables relate the cost drivers to each other forming the cost estimate.

The input values of the case study are applied to the input nodes, which have been defined in the structuring of the representation. The vanguard cost model so generated with unit cost estimate as an outcome for fan case is represented in Figure 58 for a more elaborate understanding.

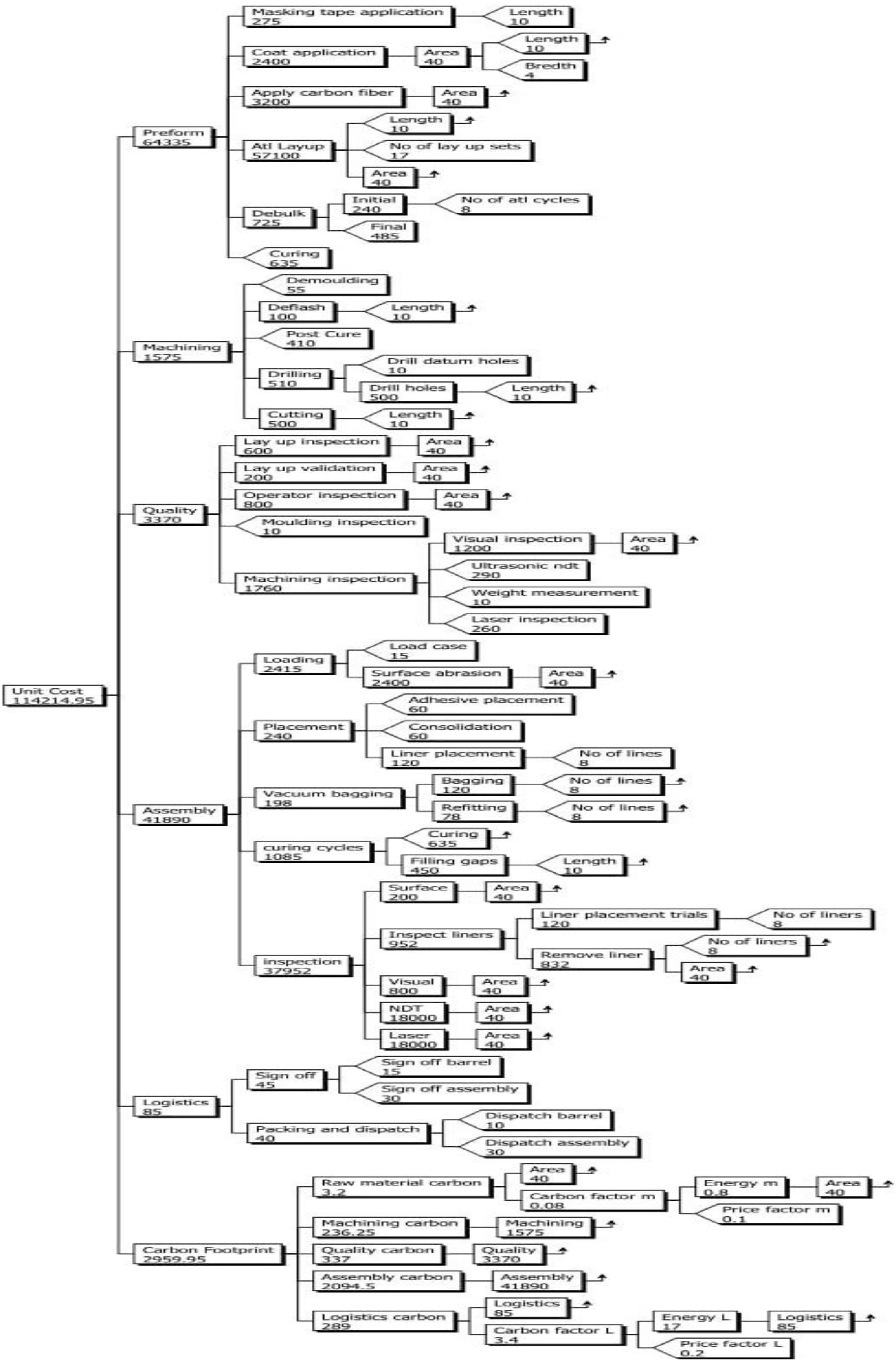


Figure 58: Unit Cost Model for Fan Case in Vanguard

`

The input values have been taken from the process parameters which are represented in **Appendix-F**. The process parameters include all the related Knowledge Information and Data (KID) for designing and manufacturing a fan case using carbon fiber as the material choice. The parameters also include labour requirement along with the logistics involved in this process. These parameters are then refined for a set of input variables that have been chosen as per the industrial case. The parameters have been normalized and the data has been modified to suit the Intellectual Property (IP) requirements of the company. The principle of modification has been chosen to omit any units used in the data and rounding off the data to a nearest upper or lower value. The logics and the relationships have not been changed or modified and hence the generated case study becomes a true representation. The set of inputs and the related outputs for this fan case unit cost model are shown in the Table 30 and Table 31 respectively

Table 30: Input parameters for Fan Case Model

Sr. No.	Operation Sequence	Parameter Description	Value
1	1	Length	4
2	1	Diameter	10
3	1	Post Curing	410
4	1	Initial Curing	635
5	2	Final Curing	485
6	2	Number of Alternate Cycles	8
7	2	Number of Lay-up Cycles	17
8	3	Moulding Inspection	10
9	3	Demoulding	55
10	3	Adhesive Placement	60
11	4	Joining	60
12	5	Load Case	15
13	6	Drilling	10
14	7	Laser Inspection	260
15	7	Ultrasonic NDT	290
16	7	Weight Measurement	10

17	8	Number of Operations	8
18	9	Number of Machining Lines	8
19	10	Validation of Barrel	15
20	10	Dispatch of Barrel	10
21	10	Assembly & Validation	30
22	10	Dispatch Assembly	30
23	11	Price Factor for Logistics	0.2
24	12	Price Factor for Machining	0.1

The input values are fed into the model directly to the input nodes and the rest of the nodes infer the values based on the logics controlling the flow of knowledge in the model. The output parameters are represented in Table 31.

Table 31: Output Cost Estimate for Fan Case Model from Vanguard

Sr. No.	Parameter Description	Value
1	Preform Cost	64335
2	Machining Cost	1575
3	Assembly Cost	41890
4	Quality Assurance Cost	3370
5	Logistics Cost	85
6	Carbon Footprint Cost	2959.95
7	Unit Cost	114214.95

The same is applied to the Microsoft Excel by creating knowledge blocks as the individual excel worksheets. These worksheets keep KID in a logical format which can be easily related to other elements of a different set or of the same set by using Excel in-built functions. These functions have the capability of doing physical calculations along with logical relationships. The knowledge blocks so created in excel are represented in Table 32.

Table 32: Knowledge Sets for Fan Case Model

Design Set			
Type	**Description**	**Attribute**	**Value**
cylinder	carbon fiber cylinerical casing	Diameter	10
Holes	Flange Holes	Diameter	2
Casing	Size of Casing	Length	4
Surface Area			Logic Based
Weight			Logic Based

Manufacturing Set			
Type	**Manufacturing**	**Machine**	**Time**
Manual	Masking	Mould	92
Manual	Lay-up	Mould	30
Auto	CNC lay-up	CNC	850
Manual	Debulking	Clamps	290
Auto	Curing	Auto Clave	640
Manual	Demaoulding	Clamps	60
Auto	Post Curing	Furnace	415
Semi-Auto	Drilling	Drill Machine	15
Manual	Loading	Cranes	20
Manual	Abrasion	Abraser	65
Manual	Adhesion	Mould	65
Semi-Auto	Vacuum Bagging	Mould and Pump	130
Auto	Curing	Auto Clave	282
Semi-Auto	Installation	Tools	65

Method of Manufacturing Set			
Type	**Method**	**Machine**	**Job**
Manual	application of masking tape followed by carbon fabric	Mould	lay-up
Manual	Visual inspection of the lay-up	Mould	lay-up
Automatic	Automated lay-up of the fibre with resin application	CNC	lay-up
Automatic	Curing and flange forming	Auto Clave	Hardnening
Manual	Removing of the formed cylinder from the mould	Clamps	Demoulding
Semi Auto	Inspection followed by quality assurance	NDT	Inspection and Testing
Semi Auto	Loading into another mould	Cranes	Handling
Manual	Abrasing of the formed cylinder	Abraser	Refining rough surface
Semi Auto	Vacuum infusion method for further addition	Pump	Infusion
Automatic	Curing of the newly formed complete assembly	Auto Clave	Hardnening and bonding
Manual	Installation of the assembly in the engine cavity	Tools	Joining
Semi Auto	Inspection followed by quality assurance	NDT	Inspection and Testing

Quality Set			
Type	**Method**	**Machine**	**Time**
Manual	Visual Inspection	NA	25 - 30
	Manual Inspection	NA	15 - 20
	Weighing	Force Meter	20
NDT	Ultrasonic Testing	Ultrasonic M/c	300 - 325
	Laser Testing	Laser M/c	265 - 330
	X-Ray Testing	X-Ray M/c	30 - 65

This becomes layer 2 of the system and all the knowledge elements are taken from this universal set. This set contains all the relevant knowledge elements that are necessary to categorize and utilize material, design, manufacturing, process and product knowledge. Quality inspection is also included in the knowledge sets and it contains the advanced methods used for quality inspection purposes. These methods are very specific to composites and are costly in operation.

After this knowledge is captured and categorised into set form a refining of knowledge is done into functional sets. Once the knowledge is refined and related to each other a set of logical sets i.e. layer 3 is applied on top of the knowledge sets. These sets of logics are represented in Table 33.

Table 33: Logical Set for Fan Case Model

Logical Set		
Sr. No.	**Operation Sequence**	**Logical Information**
1	1	25*length+1
2	1	80*area+1
3	1	15*area
4	2	30*length+(no of lay up-1)*50*area+31
5	2	35*no of debulking cycles
6	3	20*area
7	3	10*length
8	3	25*length+10
9	3	60*area
10	4	5*area
11	4	15*no of liners
12	5	15*no of liners
13	5	6*no of liners+5
14	5	20*area
15	5	300*area+20
16	6	300*area+20
17	6	20*area

These logics are directly applied in Excel as it has a feature of having an interface built-in in the sheets itself. Each and every logic or formula or relationship can be directly applied on to a particular cell in an excel worksheet and that cell becomes a functional node for the rest of the KID. In this problem every cell has its own set of logical information which allows it to be dynamic in nature and intelligent in application. This way the entire system works as a unified structure generating cost estimates that can be utilized for further analysis. The physical input values in directly inputted in the input cell defined in the system and the output cost is generated. This output cost estimate is also stored as a worksheet and is represented in a tabular form. Theoretically, as the input values and logics are same in both the cases, the output values should be the same without any variation. However, as there are certain extra assumptions which have been made to simplify a complex logic into a normal 2 degree logic, this variation is observed. This is because of the license issue and IP issue discussed in previous studies. The input parameters being the same and already represented in Table 30, have not been represented again. The output parameters derived from the cost estimate is represented in Table 34.

Table 34: Output Cost Estimates for Fan Case Model from MS Excel

Output Parameters		
Sr. No.	**Output Parameter**	**Value**
1	Preform Cost	64320
2	Machining Cost	1680
3	Assembly Cost	41890
4	Quality Assurance Cost	3275.5
5	Logistics Cost	85
6	Carbon Footprint Cost	3100.5
7	Unit Cost	114351

A comparison between the output values of the representation in Excel and that in Vanguard is made utilizing graphical method. Here, the output values are plotted against the parameters for both the cases in a combined form and percentage difference in estimates is calculated. By doing this it can be observed that the logical information and the knowledge structure works well even with in both the cases. It can also be observed that complex problems, like the fan case cost estimation has been very easily represented and the problem broken down into manageable steps for proper cost estimation. The output shows that even if some of the complex logics are broken down into simple form, still the variation observed in is not too big to be invalid. The representations made are shown in Figure 59, Figure 60 and Figure 61 respectively.

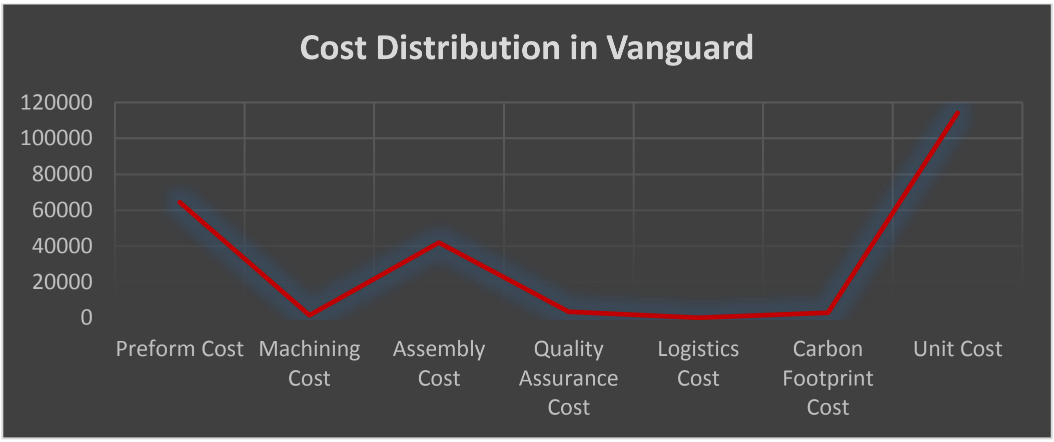


Figure 59: Cost Distribution in Fan Case Model from Vanguard

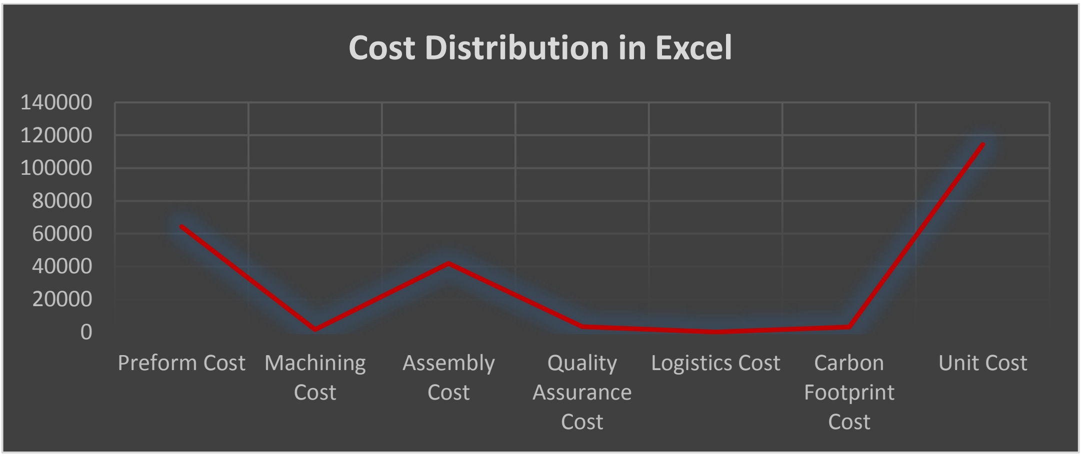
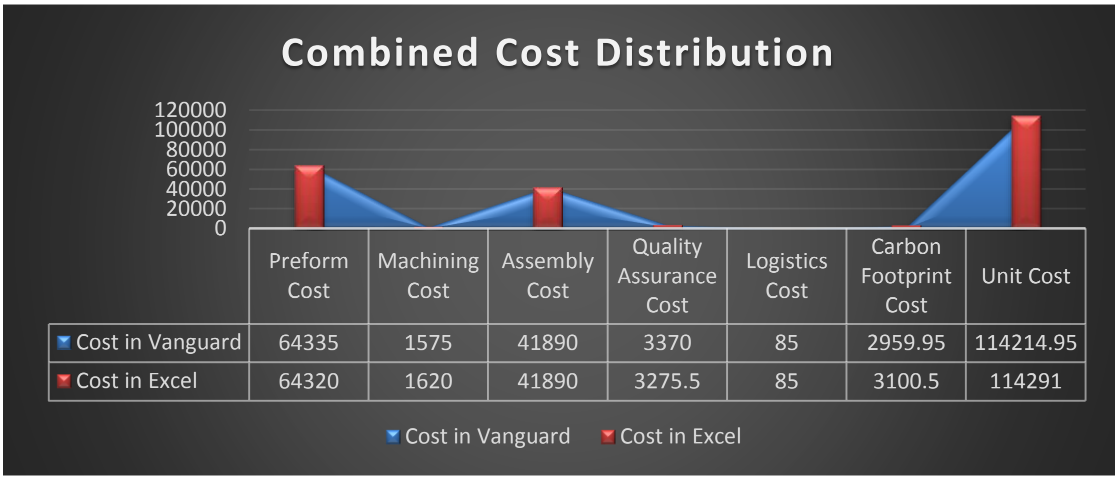


Figure 60: Cost Distribution in Fan Case Model from MS Excel



	Preform Cost	Machining Cost	Assembly Cost	Quality Assurance Cost	Logistics Cost	Carbon Footprint Cost	Unit Cost
Cost in Vanguard	64335	1575	41890	3370	85	2959.95	114214.95
Cost in Excel	64320	1620	41890	3275.5	85	3100.5	114291

Figure 61: Combined Cost Distribution for Fan Case Model

From the comparison charts it can be seen that the percentage difference is not too high and ranges from 4.7% in carbon footprint cost output parameter to 0.02% in preform cost output parameter respectively. The case study has revealed that the system is an easy representation of a complex problem and because it is mathematical in design, it is more manageable. Another observation is that as the maximum difference in the overall unit cost is within the acceptable range of 0 - 5%, which is in this case 0.067%, the logical information as well as the KID representation made using LKACEM is correct and has high accuracy. This percentage difference is plotted in a graphical form so as to have a proper understanding of the outputs in two different representations.

From this representation it can be seen that there is less quantification of the logical information in vanguard which has to be assumed as some of the linkages could not be made. These were mostly done in manufacturing set and carbon footprint set. This in turn had some impact on the quality set. However, the impact was very less hence the overall difference is so small that it is not noticeable and can be neglected. The graphical representation of the percentage difference made is shown in Figure 62.

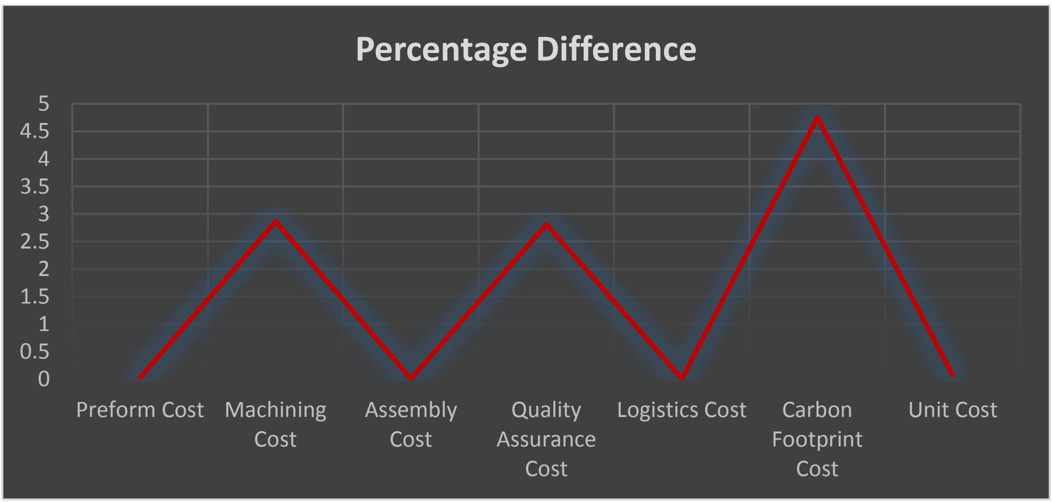


Figure 62: Percentage Difference in Cost Outputs for Fan Case Model

The representation made in two different software applications utilizing two different forms of design and structuring, shows that the methodology utilized is platform independent in its architecture and is generic in application around all composite applications. The reliability and the efficiency both depends upon the logical information which depends upon the information collected from the source. As for this research it is considered that whatever information is captured is closest to reality, the outputs are considered to be possessing higher accuracy. However, if the logical information has flaws, so does the outputs and the estimates. This, in no way mean that the methodology developed is non-functional or is not accurate. The methodology developed can be applied to any problem regardless of the accuracy in the KID. If the KID is having higher accuracy so will the output estimates and vice-versa but the methodology will still function well.

From the case studies done, it can be concluded that the methodology developed is validated to work for composite problems both simple and complex without any error. It has also been validated that the methodology is generic in structure that can be applied to a number of problems ranging in materials, design, application and manufacturing techniques. Another point has been validated that the methodology design is platform independent, which allows it to be applicable in different software applications or different language platforms without conversion. This way, it is validated that the methodology is viable to be utilized for cost estimation problems and hence, can be utilized in creating an advanced costing tool. This tool has been represented in MS Excel for this research and its validation is discussed in next section.

5.3 Tool Validation

For the validation of the tool two case studies are used. These case studies are the actual products that are available in the real market and have their own selling prices. These selling prices include the unit cost of the product plus the profit margins. As it is difficult to measure the profit margins these case studies are taken as the final prices and a percentage range is defined to be acceptable as profit margin. If the estimate generated by the tool lies in the acceptable range the tool is considered to be providing with good results. To test the robustness of the tool, the same component with different design is estimated. If the range of the estimate again falls in the acceptable range the tool is considered to be validated. This part of the validation can be considered to be having a part of the methodology validation hence, whenever the tool passes the estimate test, it is considered to validate the logics, structure and applicability of the methodology design as well and the advanced costing system so created.

As the case studies are from the aero-engine realm, the components are of application to the aero-engine. The validation is a two part validation which is done by using two case studies utilizing the same principle. The first case study is the composite flange which uses a complex design with complexity in the manufacturing as well. The second part of the validation is a composite tube which looks to be a simple in design and manufacturing, but involves a high level of complexity overall as it needs a higher level of complex MOM which is chosen specifically for this case studies. Each case study has two parts which are specifically chosen to increase the complexity in the selection of materials and check for any errors that might arise out of it. If the tool does not break down with these selections, it is said to pass the validation process and is considered to be estimating costs with a high degree of acceptability. The design details of the parts are shown in **Appendix-G**. The data sheet utilized for the estimate is shown in Table 35. From this data table a size based selling price is utilized as the input parameter along with the number of holes and other selection parameters.

Table 35: Composite Case Study 3 & 4 Data Sheet

Case Study No.	Component Detail	Supplier Name	Selling Price US $	Design Details	Material Type	Pressure Rating
Case Study 3: Part a	High Pressure Composite Flange	GRE Fittings, China	150	OD=156 Holes=4 Thickness=74.5 ID=70	Aramid Fiber	1400 PSI
Case Study 3: Part b	High pressure Composite Flange	GRE Fittings, China	550	OD =254 Holes = 8 Thickness = 104 ID=100	Aramid Fiber	600 PSI
Case Study 4: Part a	Carbon Fiber Tube	HUAHAOFRP, Jiangsu, China	110	Dia = 50 Thickness = 5 Length = 100	Carbon Fiber	NA
Case Study 4: Part b	Carbon Fiber Tube	HUAHAOFRP, Jiangsu, China	180	Dia = 40 Thickness = 5 Length = 200	Carbon Fiber	NA

The case studies for the tool validation have been divided into two parts, part-a and part-b for both case study 3 and 4. Both part-a and part-b have same basic design and same material but differ in design parameters. In other words, it can be said, that keeping the structural design and material same, design parameters are varied or scaled up. These are then directly applied to the LKC-Tool and an output Unit Cost is obtained. The unit cost is then compared with the cost price, which is a mathematically calculated utilizing the formula for selling price as shown below:-

Selling Price (SP) = Cost Price (CP) + Profit (P)

CP = SP - P

It is assumed that, P = 15/100 * SP (15% of the selling price)

Therefore, CP = SP - {15/100*SP}

Or

CP = 85/100*SP

For the sake of simplicity it has been assumed that the profit margin for both the cases ranges from 10-15% of the selling price and for this particular validation it has been taken to be the maximum value that is 15%. The design details for both the cases including part-a and part-b are shown in **Appendix - G**. The case study is represented in detail in the sections to follow.

5.3.1 High Pressure Composite Flange - Case Study 3

High pressure composite flange is the part used in pipe fittings of the aero-engine as well as in other pipe fittings. This part is not a specific part to the aero-engine but is a generic part which finds applications in many areas including aero-engine. Part-a of the design is used in aero-engine pipe fittings and part-b is used both in aero-engine design and other pipe fittings. The main purpose of the flange is to provide connection between two pipes and bear the pressure in the joint. It provides a sturdy and air tight connection between the two pipes. In aero-engine, there are several pipes running around the engine, which provides fuel supply and necessary lubrication along with hydraulic fluid supply for proper functioning of the engine. The pressure and temperature in the pipe fittings are immense and can subject any fitting to extreme loading and stress.

This design detail is taken from **Appendix - G** and are directly inputted into the cost estimation tool version 2.0. Unit cost is calculated and compared to the cost price of the product. The inputs and output parameters for part-a of the case study are shown in Figures 63 and 64.

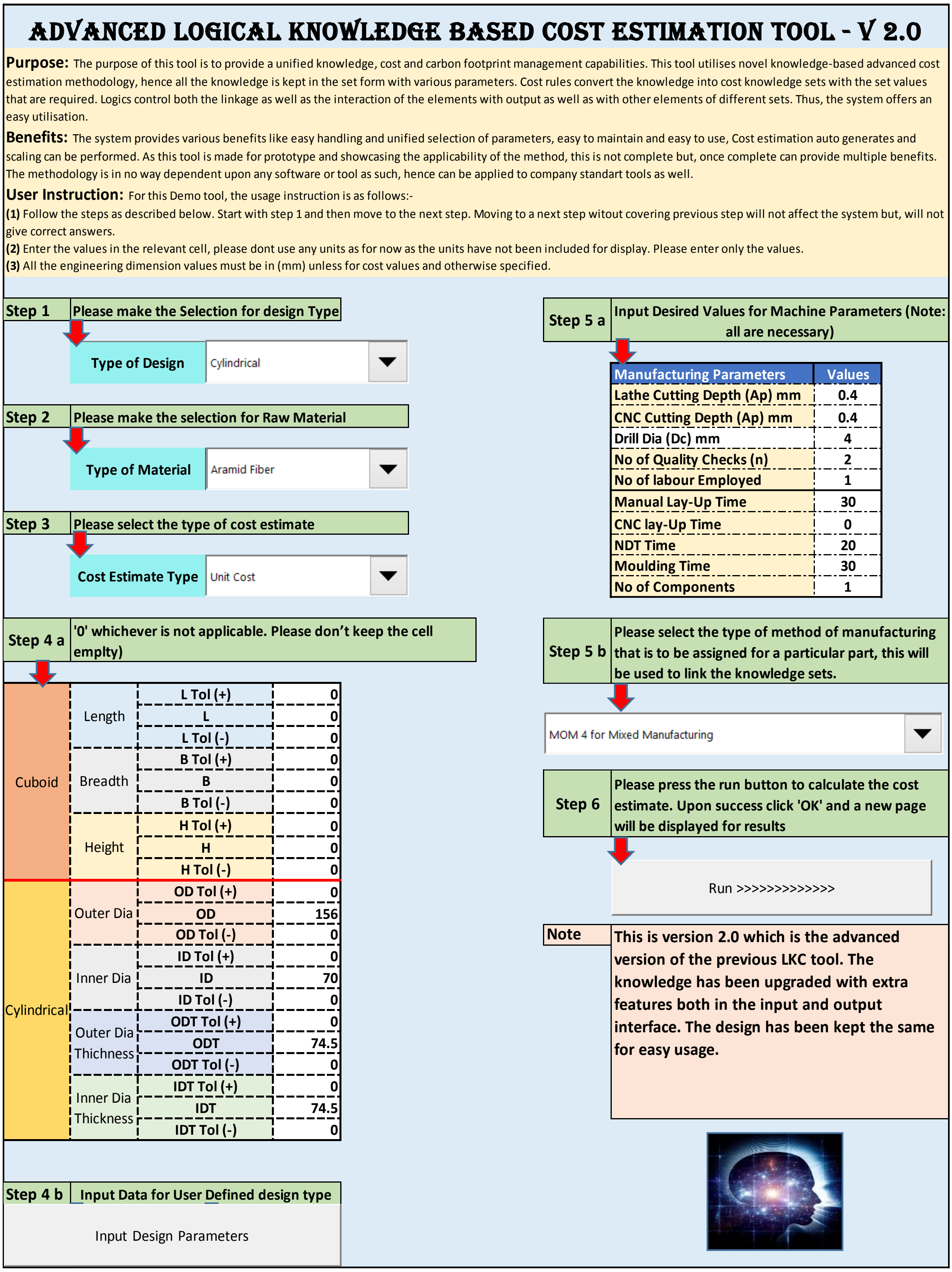


Figure 63: Input Parameters for Case Study 3 Part-a

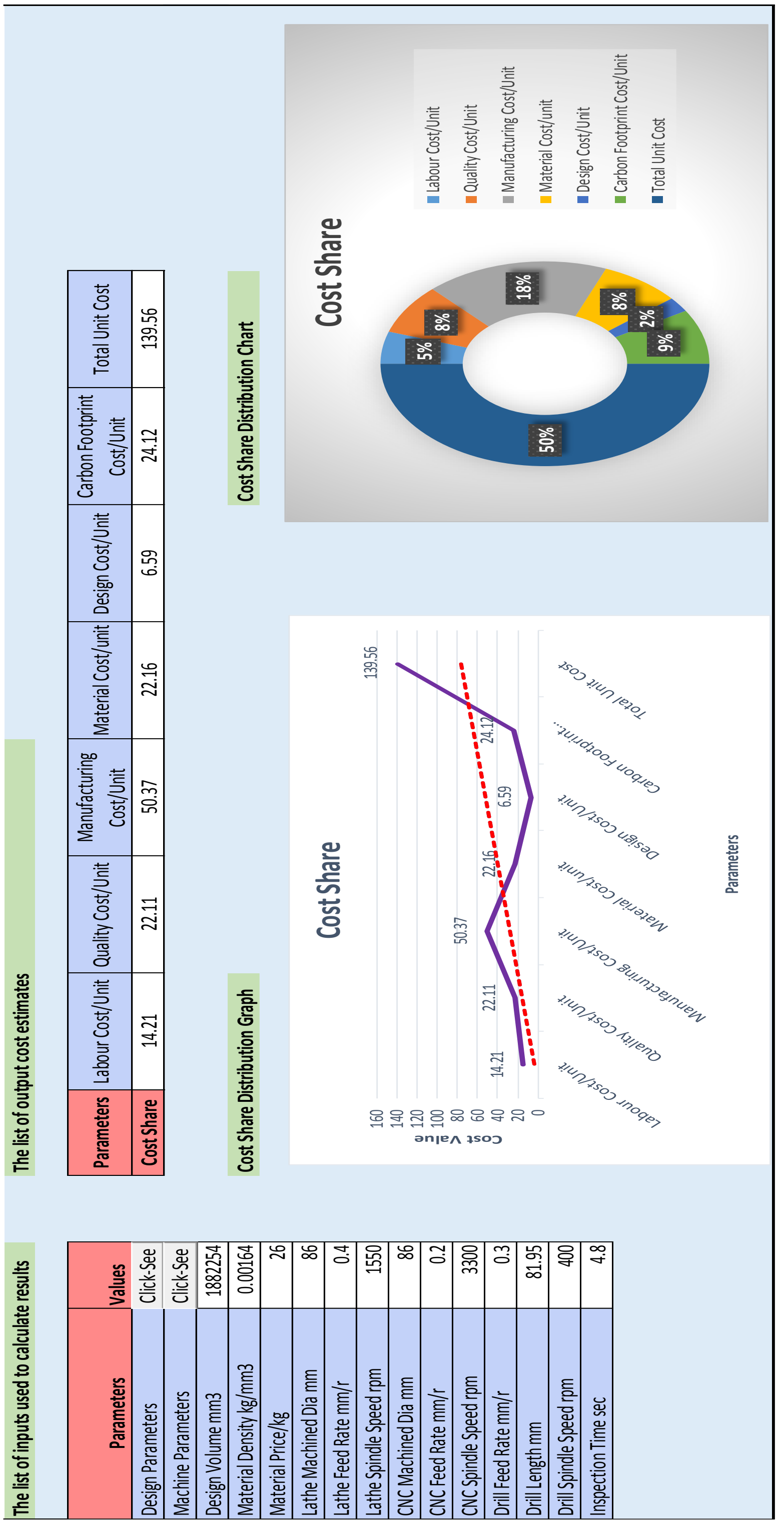


Figure 64: Output Parameters for Case Study 3 Part-a

From figure 64, it can be seen that manufacturing cost has the maximum share in the overall unit cost followed by carbon footprint, material, quality, labour and design processes. This shows that manufacturing of the composite material part is costlier due to extra times involved in the lay-ups and pre-setting of the moulds before actual manufacturing. The same representation has been made for part b of the case study. This representation of the input and output parameters of the part-b of case study 3 is represented in Figures 65 and 66.

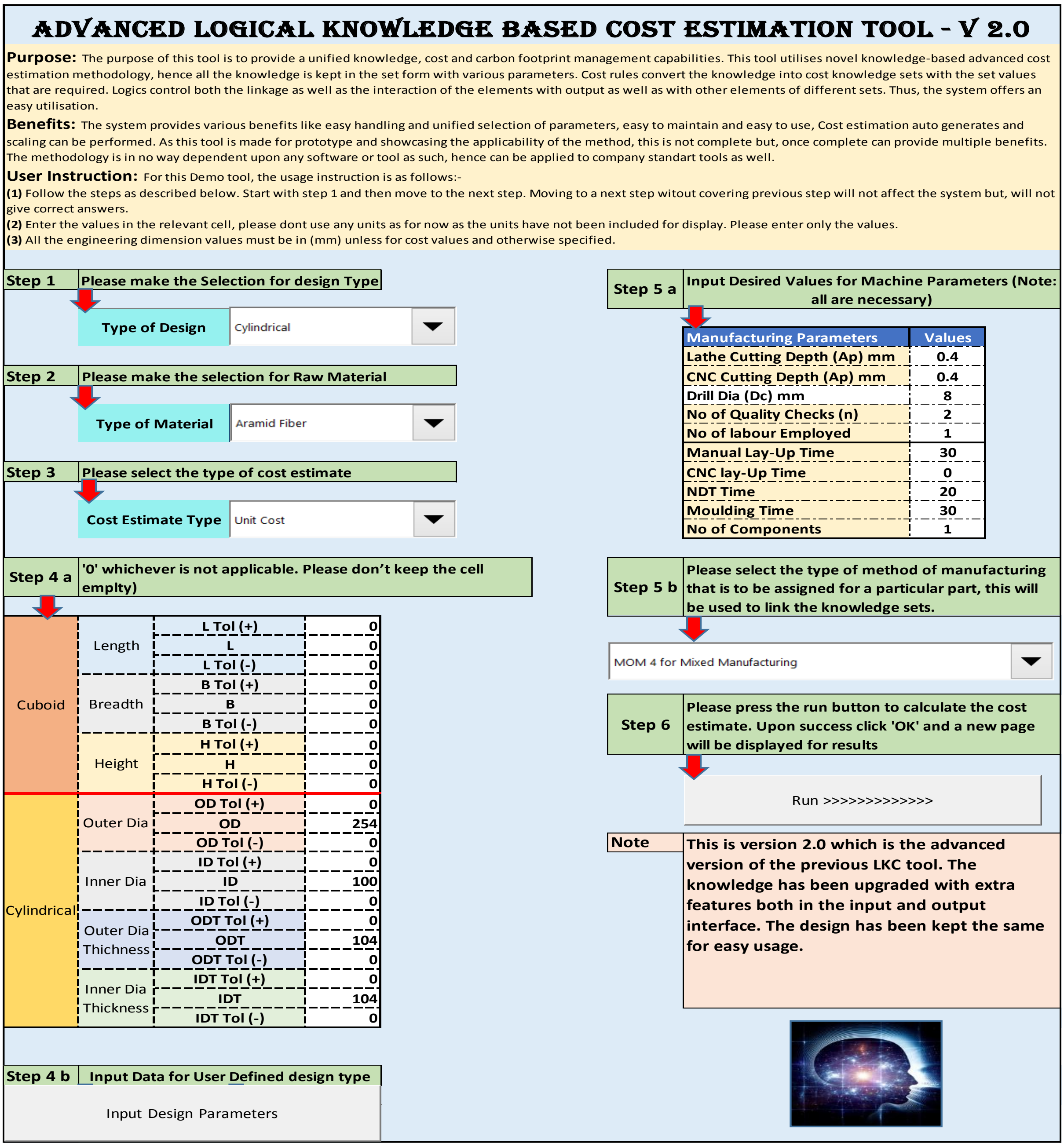


Figure 65: Input Parameters for Case Study 3 Part-b

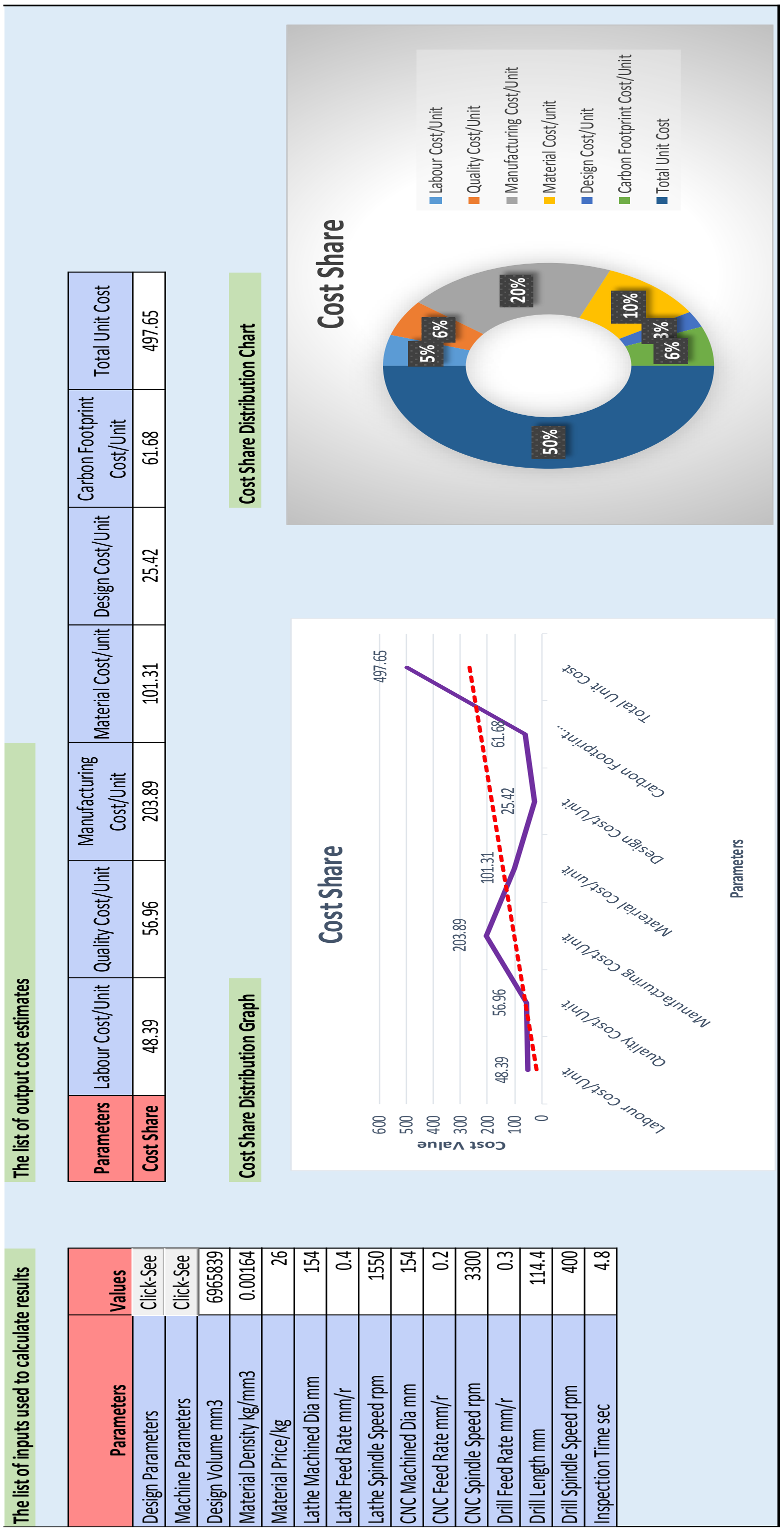


Figure 66: Output Parameters for Case Study 3 Part-b

From this it can be seen that again the major part of the overall cost is the manufacturing cost which is followed by the material cost. The next processes to follow are the carbon footprint, quality, labour and design respectively. As the output cost is the only parameter that will be evaluated against the selling market price of part-a & b of the study, a tabular representation of the difference in cost is made out. This representation is shown in Table 36.

Table 36: Cost Estimates & Market Price for Case Study 3

Case Study No.	Component Detail	Selling Price US $	Profit Margin US $	Cost Price US $	Unit Price Predicted US $
Case Study 3 : Part a	High Pressure Composite Flange	150	22.50	127.50	139.56
Case Study 3: Part b	High pressure Composite Flange	550	82.50	467.50	497.65

The outputs are plotted in combined charts so as to clearly understand the output predicted and the market price based indicated price. The cost price indicates the actual price which has been calculated from the market selling price by reducing the selling price with an assumed profit margin of 15%. The output predicted from the LKC-Tool Version 2.0 is compared against the cost price of the part. By doing this comparison the costs are compared against each other. For the estimates to be correct, the output unit cost should be equal to the overall cost price of the product without any profits whatsoever. However, there is always a difference in the output cost estimate and the cost price due to the fact that some of the activities can never me modelled which is due to discrepancy in the knowledge itself. Another reason is that actual cost price of a product is never known unless the project is provided by a company itself. Therefore, assumptions of the profit margin leaves an area of uncertainty. This is due to this reason cost estimate is always under some range of uncertainty.

The comparisons between the output cost and the cost price are shown in Figure 67.

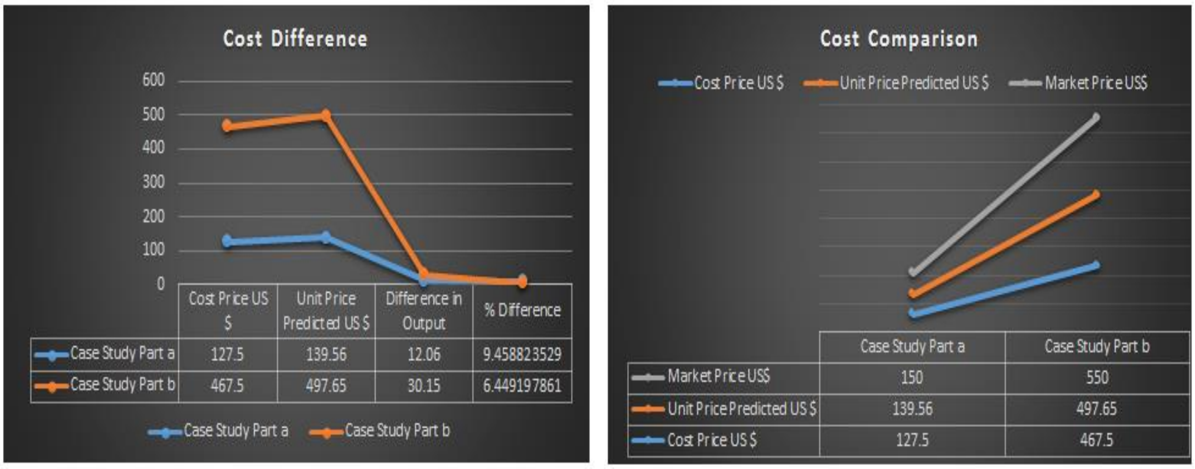


Figure 67: Cost Comparison Analysis for Case Study 3

It can be seen from the comparison that the output cost estimate that has been made using LKC-Tool Version 2.0 is very close to the cost price that has been deduced from the market selling price. It can be argued that the profit margin has been taken to be 15% of the selling price which may differ in real practice, however, the percentage difference in estimate will still not exceed the industry allowable or acceptable limit of less than 15% variance. Hence it can be said that the tool is very much capable of predicting cost with a closeness of less than 15% to the actual cost of the product. It can also be deduced that the closeness can be further reduced by increasing the knowledge in the tool or by adding some additional logics for a particular product or a process. For this research the values observed are accepted to be highly likely estimates and the tool is considered pass in this validation case study.

5.3.2 Carbon Fiber Tube - Case Study 4

High pressure Carbon fiber tube is the composite replacement of conventional tubes that are used to convey fluids from one part to another. These tubes have different uses ranging from extremely high pressure and highly corrosive environments to less reactive and low pressure environments. These pipes have not yet been fully used in the aero-engine design, but are constantly been debated for being better in performance and lower in weight that can replace conventional material tubes in aero-engines. There has, however, use of carbon fiber tubes to convey high pressure hydraulic fluid and fuel in aerospace sector for some of the space applications. These tubes have the ability to perform intended task with an additional advantage of being low weight. Low weight is a very important factor in aero-engine's overall performance and its efficiency as it decides the range, cost and weight carrying capacity of the aircraft using that engine. Pipes in aero-engines are extremely important as there are a number of functions to be controlled in an aero-engine. Fuel supply, hydraulic circuits and pneumatic supply lines are certain important functions that need tubes as an integral component. Usually these tubes are also made of the same material as the rest of the engine like, aluminium, for low to medium temperature applications and titanium alloy, for high temperature applications. These pipes run like a network of nerves in a human body and supply vital fluids to an engine to keep it functioning at optimal levels at all times. These should be capable of withstanding extreme environments and still maintain stability and remain lighter in weight.

For the next part of the tool validation, carbon fiber tubes with two different designs and applications have been chosen. The input parameters are taken from Table 35 above. From here these input parameters are fed to the LKC-Tool interface along with additional selections that have been made using experience and expert judgement technique. Once the selection is made the design parameters are inputted into the cost estimation tool and features are defined. As this tube can be considered to be a hollow cylinder, cylindrical design is chosen to be the basis of the model. This way a cost prediction is made using cylindrical logics that have been already pre-modelled into the tool. The selections made and the input parameters are fed through the interface of the tool. The selections made and the input and output parameters for part-a of the case study 4 are shown in Figures 68 and 69.

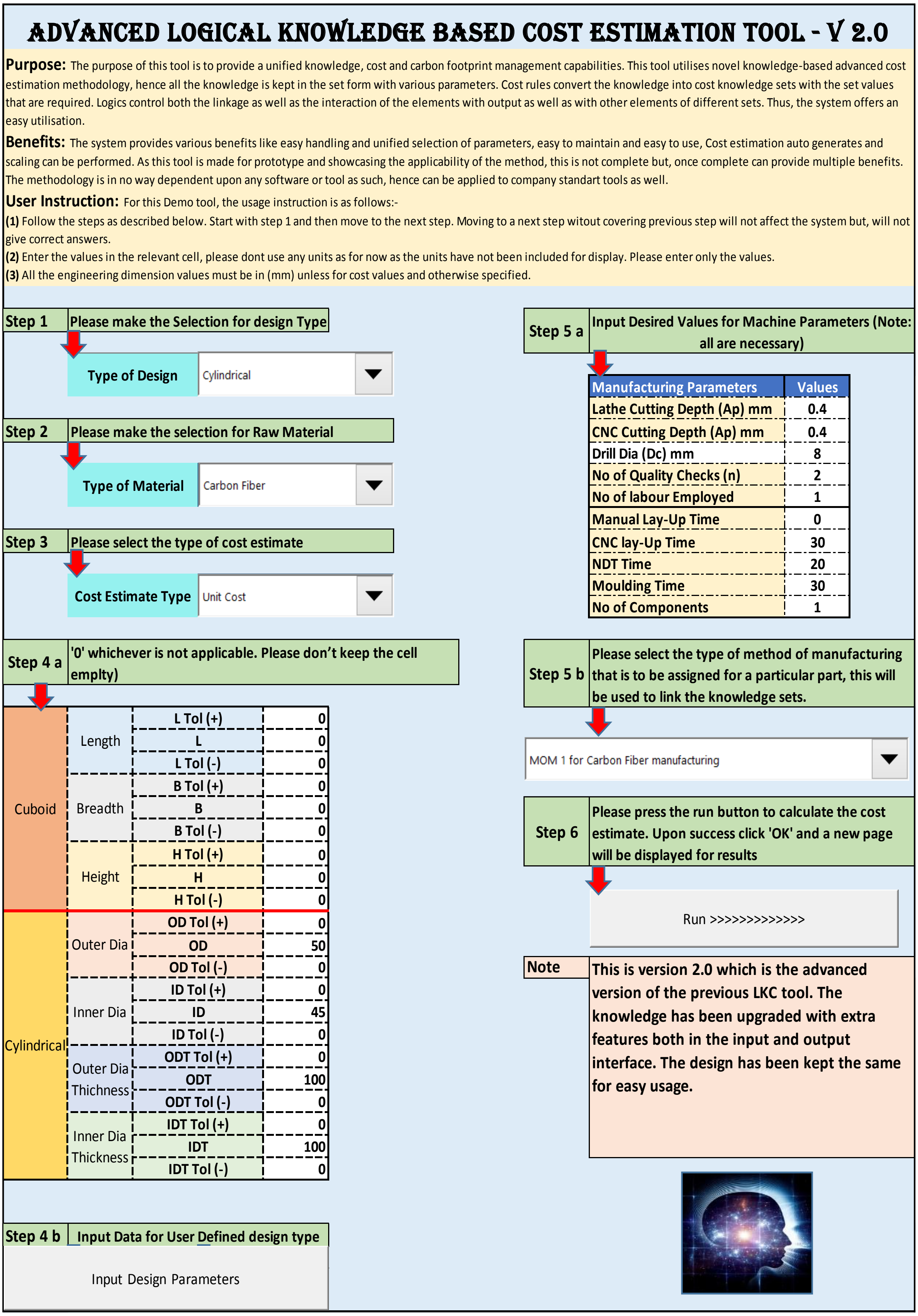


Figure 68: Input Parameters for Case Study 4 Part-a

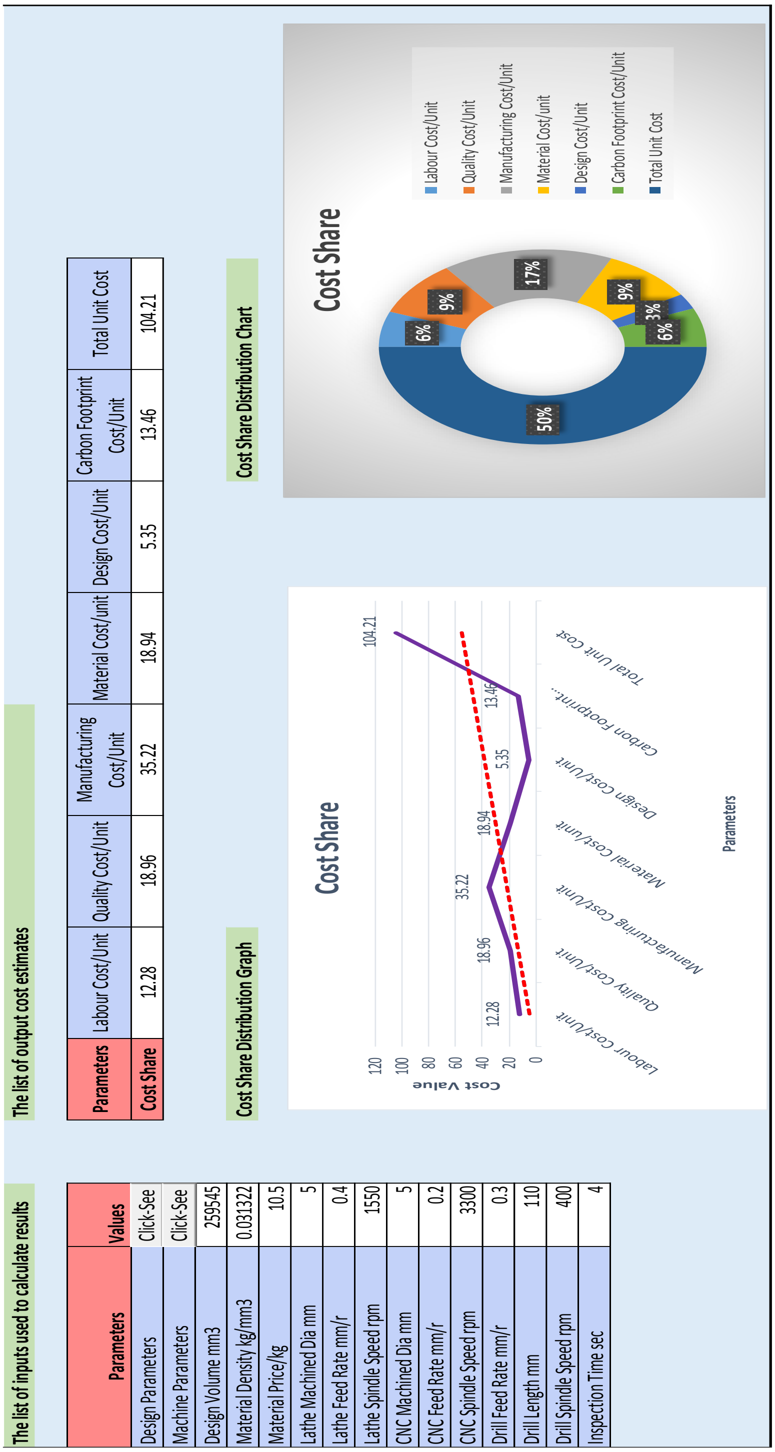


Figure 69: Output Parameters for Case Study 4 Part-a

From here it can be seen that the maximum share of the cost is from manufacturing process which is followed by quality, material, carbon footprint, labour and design. Labour cost is found to be greater than design, this is because for manufacturing of carbon fiber tubes, CNC lay-up is used which requires skilled labour that is costlier than normal machining labour. The same application is now done for the part-b of the case study 4. In the same principle, input parameters are fed to the tool through its interface. The input and output parameters for case study 4 part b is shown in Figures 70 and 71.

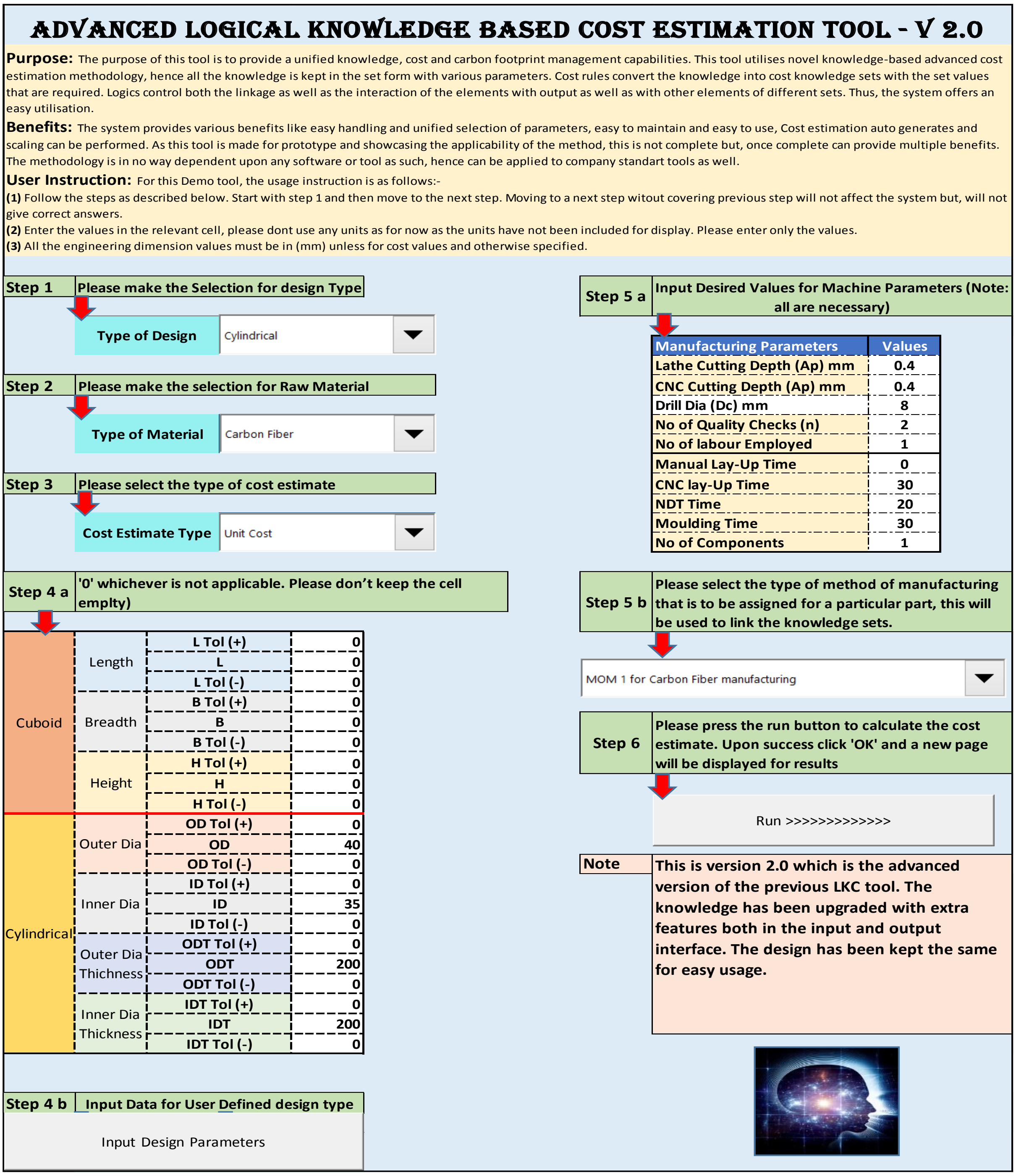
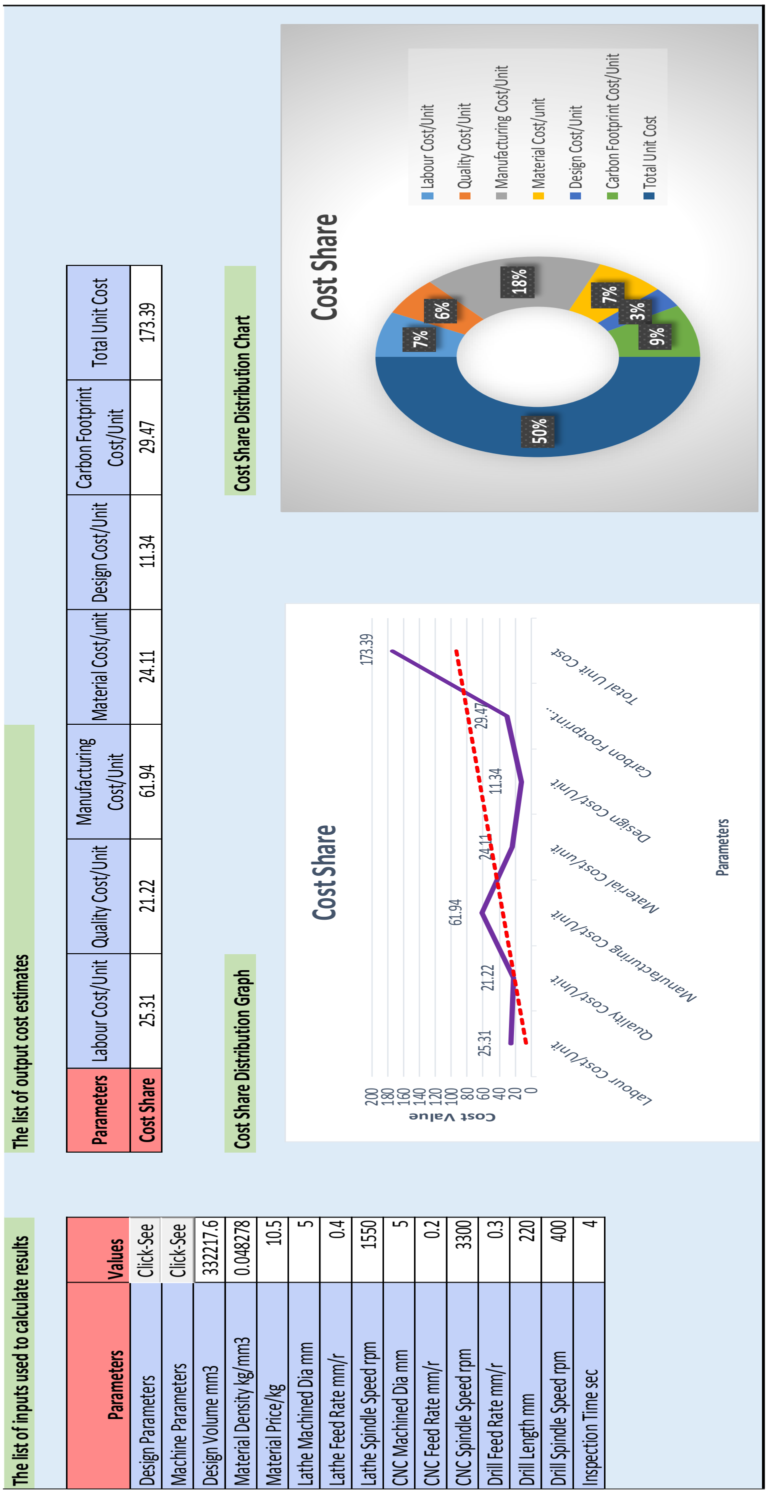


Figure 70: Input Parameters for Case Study 4 - Part b



Parameters	Values
Design Parameters	Click-See
Machine Parameters	Click-See
Design Volume mm3	332217.6
Material Density kg/mm3	0.048278
Material Price/kg	10.5
Lathe Machined Dia mm	5
Lathe Feed Rate mm/r	0.4
Lathe Spindle Speed rpm	1550
CNC Machined Dia mm	5
CNC Feed Rate mm/r	0.2
CNC Spindle Speed rpm	3300
Drill Feed Rate mm/r	0.3
Drill Length mm	220
Drill Spindle Speed rpm	400
Inspection Time sec	4

Parameters	Labour Cost/Unit	Quality Cost/Unit	Manufacturing Cost/Unit	Material Cost/unit	Design Cost/Unit	Carbon Footprint Cost/Unit	Total Unit Cost
Cost Share	25.31	21.22	61.94	24.11	11.34	29.47	173.39

Figure 71: Output Parameters for Case Study 4 - Part b

From here it can be seen that the major contributor to the cost is again manufacturing process. The next ones to follow are carbon footprint, labour, material, quality and design respectively.

`

It can be observed here that carbon footprint cost in this case is more than previous cases, this is because of the reason that as the size increases the machine has to work more which increases the amount of energy consumed and hence the carbon footprint. Also there is more requirement of material which generates more carbon signature of the component and thus increases its costs. As the output cost is the only parameter that will be evaluated against the selling market price of the part-b, tabular representation is made along with the difference in the cost. This representation is shown in Table 37.

Table 37: Cost Estimates & Market Price for Case Study 4

Case Study No.	Component Detail	Selling Price US $	Profit Margin US $	Cost Price US $	Unit Price Predicted US $
Case Study 4 : Part a	Carbon Fiber Tube	110	16.50	93.50	104.21
Case Study 4: Part b	Carbon Fiber Tube	180	27.00	153.00	173.39

The outputs are plotted in combination charts as done for previous case, so as to fully understand the output predicted and the market-based indicated price. The cost price indicates the actual price which has been calculated from the market selling price by reducing the selling price with an assumed profit margin of 15%. The outputs predicted from the LKC-Tool Version 2.0 is compared against the cost price of the part.

Again the comparison is done against the cost price as it is considered to be a function of the product's unit cost. Thus, to validate the output estimate this is the best possible method. The comparison is shown in Figure 72.

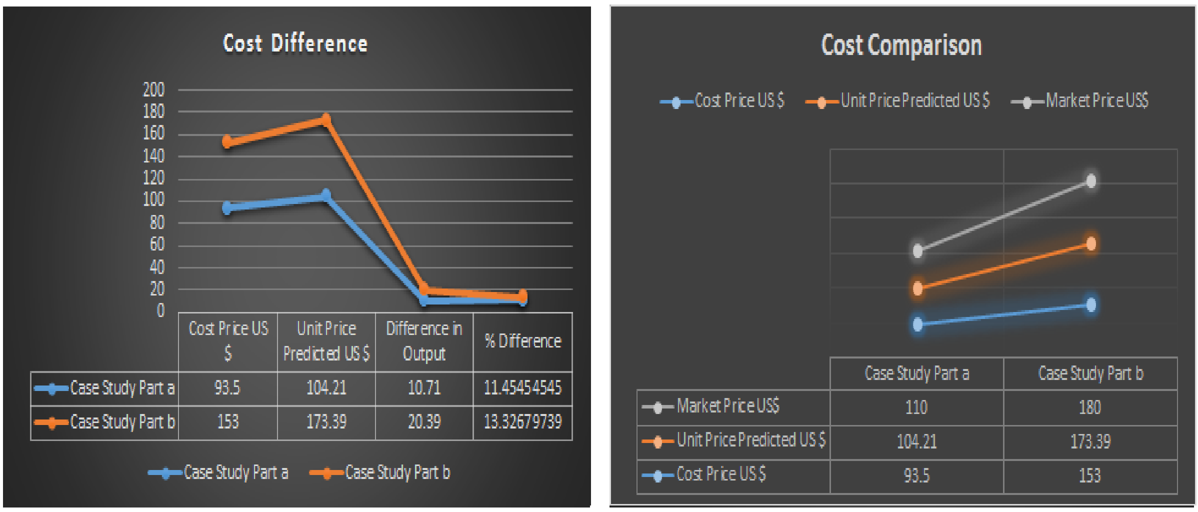


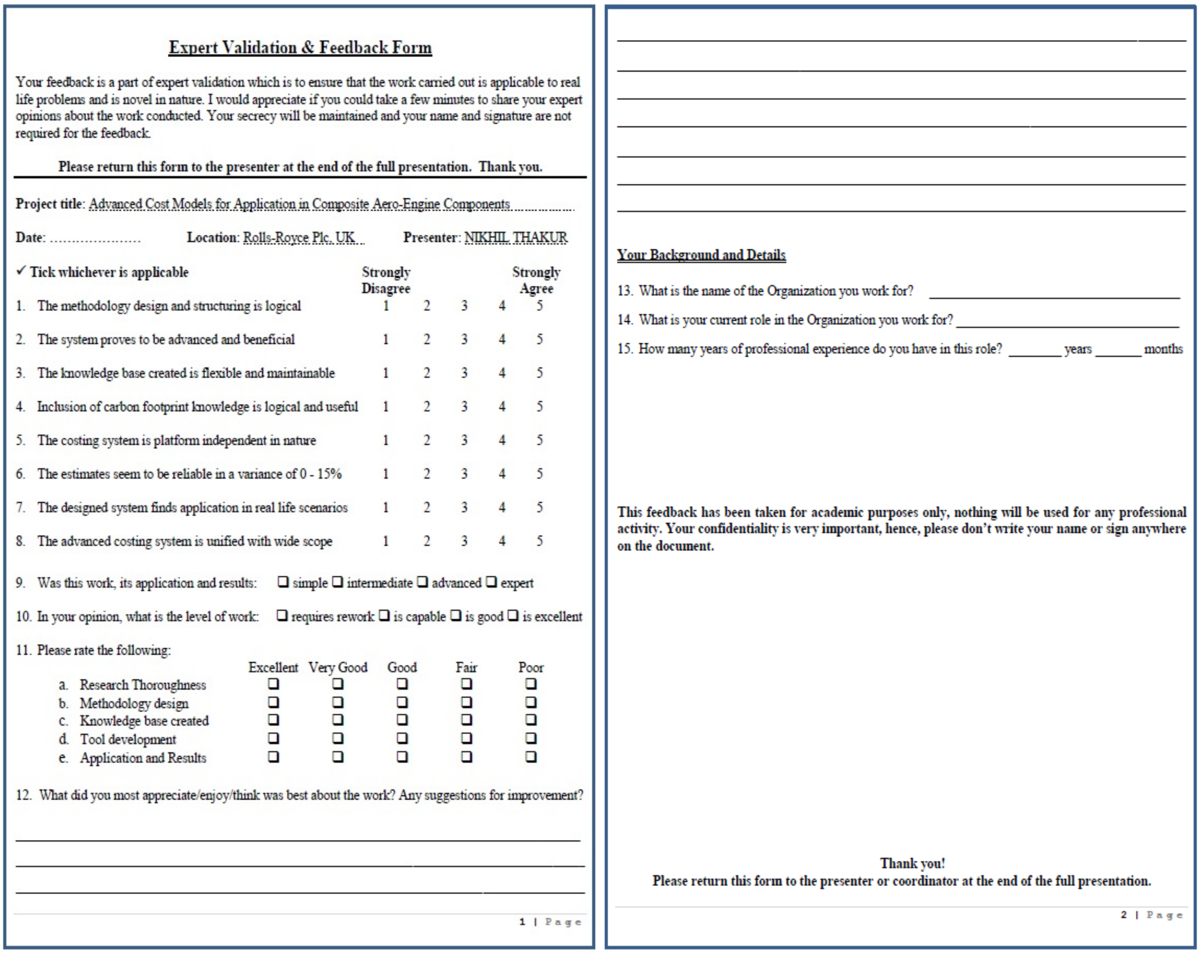
Figure 72: Cost Comparison Analysis for Case Study 4

It can be seen from the comparison that the output cost estimate that has been made using LKC-Tool Version 2.0 is having a greater difference from the cost price that has been deduced from the market selling price as compared to the previous case study. However, if analysed closely the estimate made here is still under the industry allowable or acceptable limit of less than 15%. Hence, it has been verified again that the closeness with which the tool can predict cost is somewhere in the region of 0-15% which makes it reliable in making early predictions. It has previously been discussed that the closeness of the estimate to the actual value can be further reduced by increasing the knowledge base in the tool itself or by adding some additional logics which come from the process itself. For this research purpose the values observed are accepted to be highly likely estimates and the tool is passed in this validation case study.

5.4 Expert Validation

To finally validate the whole research work and the developed method and tool, expert validation is conducted. This validation process follows major steps namely, (i) choosing a method of validation, (ii) selection of the experts, (iii) representation of the research work and results, (iv) recording of expert opinions and (v) representation of the results. For conducting this validation process, the developed system was tested under some real life scenarios, for which the whole research and its developed system was put into use. As this usage was carried out inside of the industry, the actual data could not be shared due to company's intellectual property control. The method chosen was a feedback system which could capture all the major attributes of the research and validate the research as a whole. As a second step selection of experts was made by fulfilment of three basic criterion, namely, (i) expert should be a part of the projects under consideration or application of the research, (ii) expert should have more than 10 years of experience and (iii) expert should have experience of the cost estimation field. These criteria were taken into consideration so as to make the validation as precise as possible and also make the whole process fair. In the third step, as the research needed to be represented to the experts, a presentation method was adopted. This method contained a detailed representation the whole research work along with its application in real life scenarios and the results therefrom.

As the experts had been chosen from the same projects and had more than 10 years of experience on which the research was applied into the industry, they had complete knowledge of the work conducted and hence presentation method was sufficient to summarize the entire work and its results. The fourth step was the recording of the expert feedback and validation opinions. To do this, a feedback form was designed and distributed among the experts. This feedback form contained all the relevant aspects of the research work from different categories and presented a questionnaire for easy recording and understanding. The aspects covered design, development, application and validation pillars of this research and hence presented a consolidated validation of the whole research. Moreover, it was on outcome of the application of this advanced system in real life industrial problems, the feedback meant that the research is complete in all forms. The feedback form so developed has been represented in Figure 73.



Expert Validation & Feedback Form

Your feedback is a part of expert validation which is to ensure that the work carried out is applicable to real life problems and is novel in nature. I would appreciate if you could take a few minutes to share your expert opinions about the work conducted. Your secrecy will be maintained and your name and signature are not required for the feedback.

Please return this form to the presenter at the end of the full presentation. Thank you.

Project title: Advanced Cost Models for Application in Composite Aero-Engine Components ....

Date: .... **Location:** Rolls-Royce Plc, UK **Presenter:** NIKHIL THAKUR

✓ Tick whichever is applicable	Strongly Disagree				Strongly Agree
1. The methodology design and structuring is logical	1	2	3	4	5
2. The system proves to be advanced and beneficial	1	2	3	4	5
3. The knowledge base created is flexible and maintainable	1	2	3	4	5
4. Inclusion of carbon footprint knowledge is logical and useful	1	2	3	4	5
5. The costing system is platform independent in nature	1	2	3	4	5
6. The estimates seem to be reliable in a variance of 0 - 15%	1	2	3	4	5
7. The designed system finds application in real life scenarios	1	2	3	4	5
8. The advanced costing system is unified with wide scope	1	2	3	4	5

9. Was this work, its application and results: ❑ simple ❑ intermediate ❑ advanced ❑ expert

10. In your opinion, what is the level of work: ❑ requires rework ❑ is capable ❑ is good ❑ is excellent

11. Please rate the following:

	Excellent	Very Good	Good	Fair	Poor
a. Research Thoroughness	❑	❑	❑	❑	❑
b. Methodology design	❑	❑	❑	❑	❑
c. Knowledge base created	❑	❑	❑	❑	❑
d. Tool development	❑	❑	❑	❑	❑
e. Application and Results	❑	❑	❑	❑	❑

12. What did you most appreciate/enjoy/think was best about the work? Any suggestions for improvement?

1 | Page

Your Background and Details

13. What is the name of the Organization you work for? ____________________

14. What is your current role in the Organization you work for? ____________________

15. How many years of professional experience do you have in this role? _______ years ______ months

This feedback has been taken for academic purposes only, nothing will be used for any professional activity. Your confidentiality is very important, hence, please don't write your name or sign anywhere on the document.

Thank you!
Please return this form to the presenter or coordinator at the end of the full presentation.

2 | Page

Figure 73: Feedback Form for Expert Validation

From Figure 73 it can be seen that the feedback is divided into three sections. The first section contains questions from 1-8 which are recorded as points, the second section contains questions from 9-11 which are recorded as selectors and the third section is a suggestion box which contains space for recording suggestions or improvements in the research. For the representation of the research, which is the fifth step, the feedback is converted into mathematical numbers. These numbers are then recorded against all the questions and the corresponding experts, thereby generating a consolidated result. As the questions 1-8 were already recorded in numbers there conversion was not required. The method used to convert feedback of questions 9-11 into numerical value has been defined in Table 38.

Table 38: Conversion of Feedback into Mathematical Rank

Question Number	Question	Feedback Style	Corresponding Mathematical Value
9	Was this work, its applications and results	❑ simple ❑ intermediate ❑ advanced ❑ expert	Simple = 1 Intermediate = 2 Advanced = 3 Expert = 4
10	In your opinion what is the level of work	❑ requires rework ❑ is capable ❑ is good ❑ is excellent	Requires rework = 1 Is capable = 2 Is good = 3 Is excellent = 4
11	Please rate the following: a. Research Thoroughness b. Methodology Design c. Knowledge Base Created d. Tool Development e. Application and results	❑ Excellent ❑ Very Good ❑ Good ❑ Fair ❑ Poor	Excellent = 5 Very Good = 4 Good = 3 Fair = 2 Poor = 1

This way the complete feedback report except for question number 12 which is suggestions and improvement is converted into a numerical value. For continuing with this part of the validation two experts having more than 10 years of experience working in the cost and value engineering department of Rolls-Royce Plc have been chosen who were part of the projects under study. The feedback taken from them is represented in **Appendix - H** at the last section of this thesis. The complete feedback report converted into the mathematical ranking system is shown in Table 39.

Table 39: Expert Validation Report

Expert Feedback Report Converted to Mathematical Rank															
Question Numbers	Q 1	Q 2	Q 3	Q 4	Q 5	Q 6	Q 7	Q 8	Q 9	Q 10	Q 11 a	Q 11 b	Q 11 c	Q 11 d	Q 11 e
Expert 1 Feedback Mathematical Rank	5	4	4	5	5	4	5	4	4	4	5	4	4	3	4
Expert 2 Feedback Mathematical Rank	5	4	5	4	5	4	5	5	3	4	4	5	4	4	5

The validation report, as shown in Table 39, is represented in a graphical format to analyse the combined feedback of the two experts. This graphical representation shows a maximum ranking value and the average rank value which evaluates and validates the research wholeness. The representation made is shown in Figure 74.

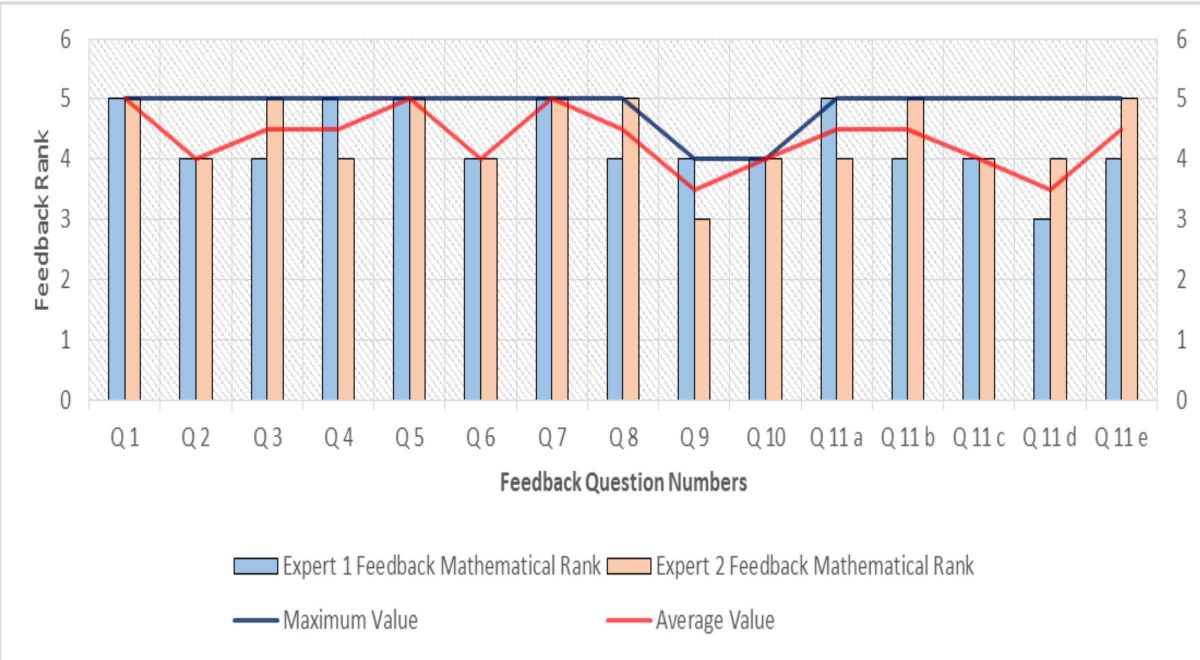


Figure 74: Graphical Representation of Expert Validation

From the representation it can be seen that the feedback of both the experts lie in the region of 4-5 which is the region considered to be advanced. The overall average of the ranks as given by the two experts is 4.33 which is again in the region of advanced to expert. Hence, it can be concluded that the research work conducted, methodology developed, validation and its subsequent results all lie under an advanced ranking. This validates the overall research and proves the advanced costing system to be working well with a variance in results from 0-15%, well under industry acceptable limits.

Some points of suggestion related to the inclusion of the coolant and lubricating oils in carbon footprint have been made. Another suggestion is to include Three Dimension (3D) printing technology in manufacturing. All these suggestions have been considered, however, as 3D printing is still under research, it cannot be included in this work. This inclusion can be considered in the future work for researchers to work upon in the coming times.

5.5 Chapter Summary

The validation of the research is a very important activity which confirms the design, structure, application and the findings from a research. For this research a three step validation was carried out which started by validating the developed methodology by utilising two case studies from previous literature and open source literature. The case studies were chosen from aero-engine realm manufactured by using composite materials. The materials for these case studies lied in different families, one from Metal Matrix and the other one from Polymer Matrix. This way the methodology was tested under different design and material parameters. A factory cost model and a unit cost model were made and the representation was done in two different softwares. One which is the industry standard Vanguard based tool and the other one which is a much simpler Microsoft (MS) Excel tool. The results from both the softwares were compared and it was found that the variation in results were in an order of a maximum of 6.67%. The next step of validation was the validation of the advanced cost estimation tool which has been designed in MS Excel. Here, two case studies were used from the open market products manufactured by using composites and having a selling price associated with them. The components used for the validation were from piping field which have use in the aero-engine. In this method cost price was deduced from the selling price of the components by assuming a profit margin of 15% on the selling price. A unit cost estimate was made using the advanced cost estimation tool and the output was compared against the product's selling and cost price. It was observed that the output estimate was in between 0-15% variance which is an acceptable limit and hence, the tool was considered verified. The last step of validation was the expert validation where the research and its outcomes were showcased to industrial experts having more than 10 years of work experience in the field of cost estimation to rank the overall research. The ranking was recorded using a feedback approach. The results from this validation revealed that the research conducted and the results therefrom are true and the ranking average was 4.33 out of 5. From the validation conducted so far it has been proved that the method is robust, maintainable, platform independent, handles complex information, can estimate composite cost and can predict carbon footprint as a cost value which adds up to the current cost capability.

In the next chapter the results from the research are presented in a systematic fashion, duly recorded and discussed in more detail. Here, the contribution to knowledge has been highlighted and the shortcomings and/or any future areas of research are showcased. The novelty in the research is also discussed in this chapter and the final conclusion of the entire research forms the part of this chapter.

6 Research Outcomes

6.1 Results & Discussions

This research has been conducted aimed at developing an advanced cost estimation system in the field of composite technology in aero-engine components. With the advancement in this research, a novel methodology of cost estimation has been developed which utilizes the Knowledge Based Engineering (KBE) elements and mathematical set theory so as to achieve a higher level of logical Knowledge Management (KM). Later, this KM is coupled to cost estimation techniques so as to achieve an advanced cost estimation system. In this research carbon footprint has been studied and included in cost estimation which is a new addition to cost capabilities. The scoping of knowledge was also kept as wide as possible and included all the processes from a product's life-cycle, thereby adding knowledge blocks to the existing structure and increasing its capabilities. The main knowledge elements come from composite aero-engine equipment design and manufacturing, hence, it contains parameters and logics from these areas.

The validation process was divided into three major parts namely, (i) methodology validation: this utilized two industry based used cases as the case study from complex composite components; (ii) tool validation: this utilized two case studies, from an open market, of components that have a more generic usage in aerospace and non-aerospace applications made up of composite materials and (iii) expert validation: this utilized industry experts from cost realm to validate the application, design, structure and results from an industry led scenario. In methodology validation, the used cases were utilized and revised into a generic process chart which was then used as the basis of the knowledge database development. This was then developed as per different sets that are modelled in two different software applications. The output from the two software applications were compared against each other to find out the difference in cost outputs. This way knowledge representation, modelling and reuse was validated. Tool validation was done by using components from the open market with selling prices that was reduced to a cost price. This cost price was compared to the unit cost outputs estimated by the tool. The output’s percentage difference was also plotted for understanding the variance of the estimate which should lie between 0-15%. If the value predicted lied within selling and cost prices, the estimate was considered to be an acceptable result. As the research has been conducted in steps from the literature review till the final validation, observations and results have been found in the entire journey. These results with the journey milestone have been shown in Figure 75.

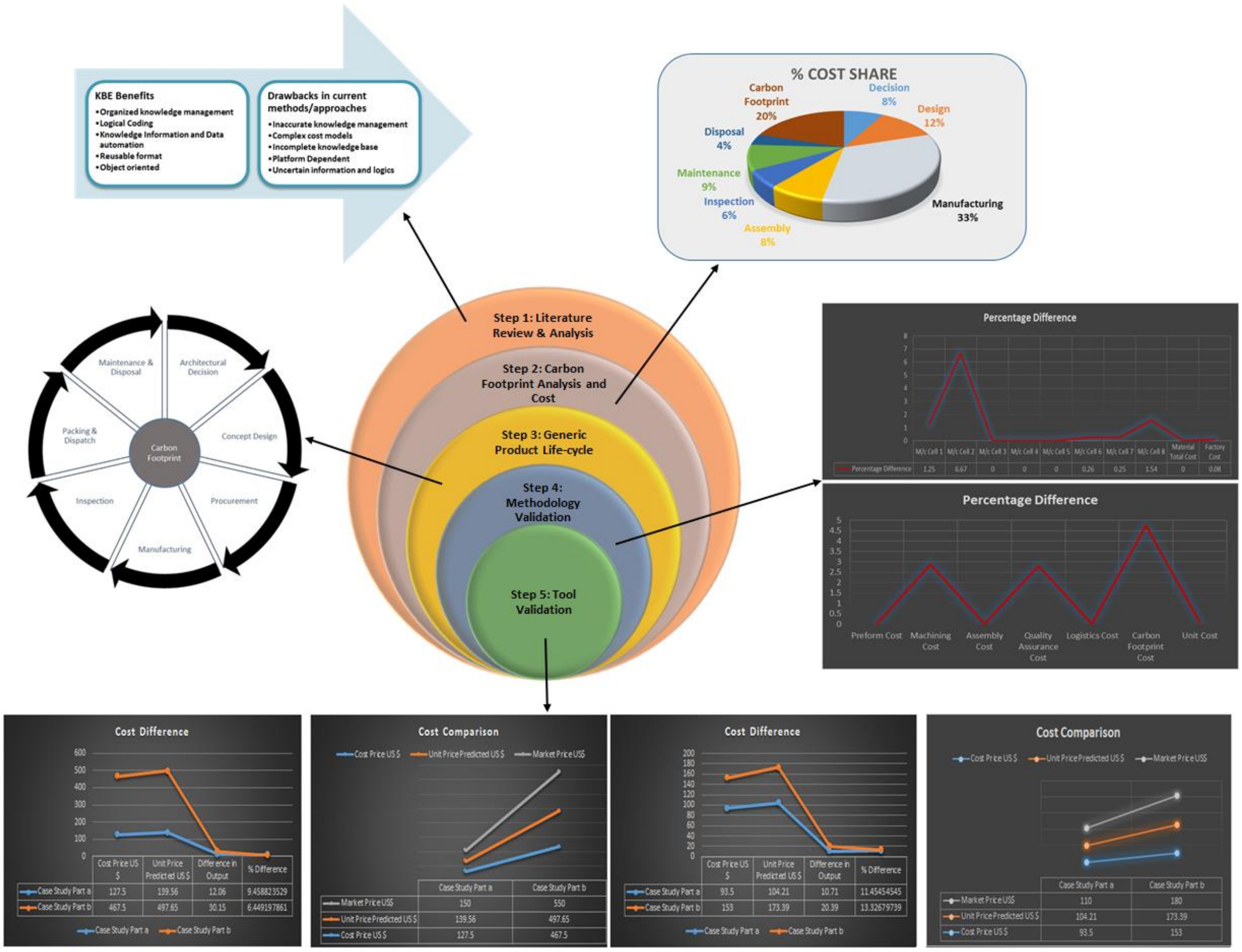


Figure 75: Milestones & Results

In the journey of this research the milestones are represented by different steps. The first step is the milestone achieved in the initial phase of the research, which is the literature review and analysis. In this, from the comprehensive study carried out and the comparison analysis done it has been observed that the current system has drawbacks namely, (i) lack of complete composite knowledge, (ii) complex cost models, (iii) improper knowledge management, (iv) difficult to develop and maintain, (v) platform dependent structure, (vi) information on composite manufacturing not mature, (vii) carbon footprint not part of cost estimation, (viii) either process based or product based design and (ix) lack of proper scoping for knowledge extraction for cost driver information. These drawbacks have been found to be complemented by the benefits that KBE has. This has shown that benefits of KBE can be directly applied to overcome the drawbacks in the current costing system. Another observation is that the benefits of KBE may be coupled to an advanced logical KM system to develop an advanced costing system which is platform independent in its structuring and can be used in any application available.

The second milestone in this research is the analysis that has been carried out by analysing the Cost Breakdown Structure (CBS) and the process breakdown. The combination of the two have been analysed in this research for composite material technology and the results have shown that there are many processes which should be included in the cost analysis that were otherwise thought to be not important. It has also been shown that carbon footprint accounts for almost 20% in the overall cost of a product, if taken as a cost value. It has been seen that as carbon footprint has a big share in the overall cost it should be a part of the life-cycle of the product and hence should be analysed separately in cost.

In the third milestone, processes such as disposal, architectural decision, assembly and inspection have been analysed and it has been found that these processes though having a small part in the overall cost from 4-9% should also be included in the life-cycle so as to have a proper understanding of the distribution of cost and achieve complete knowledge capture. As part of this outcome a combined life-cycle including carbon footprint has been proposed and used as the basis for the methodology design. This combined life-cycle includes all the main processes and secondary processes as part of the main process. The carbon footprint is at the center of the life-cycle as it shares knowledge from all the processes and is present in each process.

In the fourth milestone, knowledge that has been captured is completely utilized to develop a methodology. The development of this methodology and its validation has revealed certain interesting results. It has been seen that the methodology design is generic in structure and is logical, hence, it is capable of being developed in any software application making it platform independent in nature. Another interesting fact is that as the structuring of knowledge utilizes set based theory which is a logical mathematical way of relating complex Knowledge Information and Data (KID) together, methodology becomes logical and knowledge based. As the logical set is kept separate from the cost knowledge data sets, the system becomes dynamic in nature and any change/modification/inclusion in the logical set can manipulate the data sets without the need to remodel them. This increases the maintainability of the whole system. For validation of the methodology two case studies from aero-engine component design having high level of complexity were chosen and applied to both vanguard based and excel based application. The results show that the overall cost difference is very small and hence can be neglected. It was also shown that the complex KID was very comfortably handled by the entire system without any errors in calculation and the KID was smoothly transferred between different nodes that act as a separate set. It was also found that the methodology developed is, (i) very good in handling complex information, (ii) reliable in estimating cost, (iii) platform independent, (iv) logical in knowledge management for composites and (v) easy to maintain and model.

The fifth milestone is the tool validation that has been carried out by modelling the cost for the open market available components that have a selling price in US$ applicable in both aerospace as well as conventional applications. Here the case studies utilize a more complex flange design and a less complex tube design made up of Polymer Matrix Composite (PMC) material. The estimates that the LKC-Tool has generated have been compared to the market price, which is the selling price and cost price of that component. It has been assumed that the profit margin of these components is a maximum of 15% of the selling price. The results from these analysis show that the cost output lies in between the selling price and the cost price and more towards the selling price. It has also been seen that the cost outputs are under a variance of less than 15%, which is the industry allowed limit. The uncertainty in the output is because of the uncertainty in understanding the cost price and profit margin. Another reason of the variance is the inclusion of carbon footprint cost, which is a new inclusion and is almost 0-20% of the overall cost. This further verifies the observation made earlier regarding carbon footprint. It has been shown that the LKC-tool is generating costs that are very good for early estimations and can be further improved to give close estimates for use in a highly prediction sensitive application. The tool design is simple and easy to maintain, and, as the basic structuring is mathematical set based, could be developed in any software based application. This has further validated the methodology which is the basis for this tool design. To further validate the entire methodology and the tool development, expert validation has been carried out as an addition to the main validations. This is done by applying the developed system to a real life scenario and later present the results along with the methodology utilised and the system developed as a presentation to industry experts who have more than 10 years of experience in the related field. A ranking is obtained by the experts using a feedback form system. An overall average of the ranks as given by the two experts is 4.33 out of 5 which confirms the applicability of this research in industry led problems and validates the use of carbon footprint knowledge as an additional advantage in the current cost capability.

6.2 Novelty & Contribution to Knowledge

This research has started work on the gap areas identified from the literature analysis and understanding of the current system. Later as the research progressed a new field of study, carbon footprint was also included into the research. The novelty and contribution to knowledge of this research lies in the following main areas as discussed below:-

(A) Novelty in composite technology cost estimation: Most of the research done till date have concentrated their expertise in developing cost models for conventional material based component design, applications and their manufacturing processes. The research that has been done so far is concentrated towards the composite materials being used in automotive sector and that too has not been fully developed for understanding cost. This research has applied the composite knowledge from aero-engines to the cost realm and has related design, material, manufacturing and after life of a composite product to cost estimation.

(B) Novelty in knowledge structuring: The knowledge structuring in this research has been carried out utilizing Knowledge Based Engineering (KBE) elements and coupling them to mathematical set theory for logical structuring. This is different from conventional methods where KBE methods/approaches are directly modified or used as independent entity or a hybrid version. A drawback with this is that KBE system itself becomes bulky and complex for an application and a user to understand and maintain. This makes the usage limited and restricts its use to complexity in cost estimation. The proposed design of the knowledge base is not only logical but easy to maintain and less complex. The logical sets and knowledge sets are kept separate so that no interference between the two can take place. This type of mathematical structuring makes the knowledge dynamic and platform independent which is easy to code, reuse and maintain.

(C) Novelty in scoping of knowledge: The knowledge in this research has a very wide scope which utilizes a combined life-cycle. The scoping takes into account all the processes that any product is deemed to undergo in its complete period of service till its end of life. The current methods/techniques are either process dependent or product dependent or design dependent which makes the cost models applicable to a particular process or a particular product and any change in the design needs a separate cost model. The method proposed here is capable of predicting different costs with different designs using different materials working under different methods of manufacturing under one roof. This makes the applicability and usage of this method even wider and easier.

(D) Novelty in Cost Capability: The present methods of cost are more concentrated towards design, unit, service and disposal phases of the product life-cycle and concentrate on the main three i.e. design, unit and service to predict most of the costs. This makes the estimates uncertain and outputs less informative and less mature. The cost capability that has been added into the present cost structure includes some of the key processes like architectural decision making, procurement, inspection, packing and dispatch. Another most important inclusion is the carbon footprint knowledge and costing. This provides new cost capability to the existing system making it future proof. The carbon footprint knowledge is an additional most important inclusion that has been made in the cost. It has been found to come from all the processes and hence runs parallel to the life-cycle.

Besides being novel the research has added to the existing knowledge in all these areas. Composite technology knowledge containing knowledge from materials to design and from manufacturing to applications has been added. Cost driver information and composite techniques that are very useful in aerospace has also been added. There has also been addition to the understanding of cost drivers which includes the way cost is classified and predicted. The cost elements that are very important from all the phases have also been analysed and knowledge improved. Addition of knowledge from new areas like carbon footprint is a contribution to existing knowledge that has not been done till now.

Most of the work in carbon footprint was concentrated towards knowing a particular manufacturing technique and that too from conventional materials and not advanced materials like composites. Bringing carbon footprint knowledge to composites and then to the cost estimation of the same in composite technology realm is a new addition to the existing knowledge. Finally the generic structuring and then its application to develop an advanced cost estimation tool for application into aero-engine composite component, is an important addition to the knowledge available till now.

6.3 Limitations & Future Work

This research has been conducted taking the composite technology as the basis and the application field as aero-engine realm. The methodology and the structuring was kept as generic as possible but still there are certain limitations of this research. The limitations are observed in some main areas of this research, namely (i) knowledge capture, (ii) data collection, (iii) data representation, (iv) validation and (v) tool development. From the knowledge capture area the limitation was the maturity level of the knowledge itself which was not at a higher level due to the limited application of composites in aero-engine technology. Most of the knowledge sets and the information had to be derived from other areas where composites were used. Although, care was taken to utilize the maximum possible knowledge, more information would have meant better results under a variance of < 10%. From data collection the main limitation was the Intellectual Property (IP) protection in Rolls-Royce, which made most of the knowledge non-usable and non-presentable. This required use of knowledge from literature or coding expert knowledge which was difficult and time consuming. Another problem with the IP protection was the representation of the knowledge, which could only be done with modifications to the actual names and real data of the processes and products. This led to making assumptions in some machining parameters, although the essence of the research or the methodology itself was not affected, but assumptions led to a higher level of uncertainty in some parts of the research outputs.

For validation purposes two case studies from industry and two from open market were taken. As there was no other available case studies, finding others from literature which very closely matched with the research in hand was difficult. For second part of validation open market component was chosen whose selling price had to be converted to cost price by taking a 15% profit margin. This margin was an assumed number, however, this assumption did not affect the functioning or prediction capabilities of the advance cost estimation system that has been created. To overcome the limitation in the field of validation an expert validation was added at the end of the whole process to validate and confirm the major building blocks of this research. Hence, the limitation on validation did not have a considerable effect in the benchmarking of the advanced cost modelling system.

This research has showcased many aspects in a composite part cost estimation and has showcased method of predicting cost in a logical and generic way. As this research is concentrated on the composite materials in aero-engine realm and unlike any other research time constraint forces the research to focus on some key areas, there are certain gap areas that have not been touched in this research but are existing as future areas of study. These areas of study have been discussed in brief as under:-

(A) The first area is the understanding of composite materials in other realms other than aero-engine components and find out new manufacturing techniques that have been developed or under development to make the manufacturing of these components highly productive.

(B) The second area is an autonomous method or technique of knowledge capture that can be utilized in a manner that the knowledge does not require refining or restructuring and is readily available whenever it is sought for. Cross applicability of materials, design and systems need to be completely defined and understood in the Knowledge Management (KM) which is very important in its overall performance.

(C) This research has been represented in a very simple excel application which utilizes the knowledge blocks as separate worksheets and interface has been designed utilizing excel based macro functions. The application of this method in different platforms can be analysed and a new interface or a software application can be developed that used LKACEM principles.

At the end it can be said that knowledge can never be static or limited to a finding that has been made. There is always scope of doing things differently or thinking out of the box. This possibility is no exception to this research and hence the research is open for anyone to carry forward, analyse and improve upon the developed system or the cost modelling tool.

7 Conclusion

The research has been conducted on four main areas of engineering namely, (i) Composite Material Technology, (ii) Cost Estimation, (iii) Knowledge Based Engineering (KBE) and (iv) carbon footprint. The aim of this research lied in the intersection of these fields. The research work started by doing an extensive literature review which included latest and previous works published both as online webpage discussions, articles and blogs and paper based research works like academic peer reviewed journals, thesis, conference proceedings and archive reports. Cost estimation has been found to be a very important factor when it comes to a product's overall success. In this research many different techniques of cost estimation were discussed and understood. These techniques use various methods in manufacturing and design as the basis and derive cost contributing factors, termed as cost drivers which are used to develop a Cost Estimation Relationship (CER). The CER is then mathematically or graphically modelled so as to make the cost more representative and automated. It has been observed in this research that the use of cost estimation techniques for cost estimation of a project/process/part cost depends upon the problem in hand and the knowledge available to model the cost parameters. For some problems, detailed parametric and Activity Based Costing (ABC) method is good and for others, a very simple and crude expert judgement is beneficial. No method can, therefore, can be termed as the best overall method.

The other part of the review was composite technology knowledge for which knowledge from all the realms of composite technology was important. From the review it has been clearly identified that composite materials can be broadly classified as (i) Polymer Matrix Composite (PMC), (ii) Metal Matrix Composite (MMC) and (iii) Ceramic Matrix Composite (CMC). These classifications have further combination of materials available depending upon the type of fiber reinforcement and/or the matrix material used. The research also concentrated upon the different types of manufacturing techniques. For a more comprehensive analysis all the manual, semi-automatic, automatic processes were studied. The processes still under development were also analysed for the review. As this research concentrated on aero-engine component design as the basis, composite technology useful to aerospace was of much more importance and hence, was finally brought to this realm.

The third major part of the review was to understand the ways and methods of Knowledge Management (KM). For this, a promising engineering method called KBE was studied. This field of engineering gives methods and techniques to capture and reuse Knowledge Information and Data (KID) so as to make the processes automated and reduce the cycle times for better efficiency. The analysis revealed that for the cost estimation problem in composite technology and the complexity that is in hand, KBE seems to be a viable alternative as the benefits KBE has can be directly applied to overcome the drawbacks in the current methods and techniques of cost estimation.

In the next section of the research a methodology was proposed which, instead of utilizing a previously developed methods, used the basic principles of KBE. These elements being knowledge capture, knowledge keeping, knowledge modelling and knowledge reuse. These were later applied in combination with a logical study in mathematics called set theory to come up with advanced logical KM system for composites. The methodology used set-based mathematical techniques to capture, refine, categorize and model KID. The scope of KID was kept wide which used a generic product life-cycle which was proposed as part of a study made to understand the cost distribution of different processes in the overall product's cost. Here a study of the carbon footprint was also conducted and its inclusion in the overall life-cycle was made and a more generic combined life-cycle was proposed for use with composite aero-engine cost estimation. LKACEM had all the benefits from logical knowledge modelling and advanced cost estimation which were later applied to develop an advanced cost estimation and modelling tool. Two versions of the tool were developed for use with composite material and conventional material based products. As this research concentrated on aero-engine components from composite material realm the overall designing of the tool as well as the methodology concentrated on this area.

In the last section of the research, validation was carried out which was done for both methodology and tool. The validation was made by modelling KID and logics and then applying them to different application platforms. Complex information was passed to see difference in results and the final output of cost. These were then compared and found to be in a very small range of variance with each other. This proved that the methodology developed is platform independent, can handle complexity, has additional knowledge elements and can predict carbon footprint. The results of validation revealed that this research has proven to be an added advantage in the current cost capability and has a very wide application. Even the inclusion of carbon footprint as a cost burden is innovative and would be helpful in advanced analysis. This research has, therefore, shown that KBE techniques can be effectively utilized to overcome the drawbacks of the current systems and methods of cost estimation. Another important proof has been made about the use of mathematical techniques in knowledge modelling that can be coupled to KBE to develop an advanced logical KM system for composites which can be used for complex problems. The advanced cost estimation tool and the cost estimation done in this research shows that a generic tool can be made using the simplest of applications to model and estimate composite components. These components can range from any composite material and can have any design feature with any application. This research has certain gaps which comes from the fact that this research is concentrated more on composite technology and aero-engine components. As the application and material knowledge has not been wide in this research, there is scope of making the tool more and more advanced with extra features. Another gap is the selection of the application for the tool development itself. This can be done in a much advanced Java based application or a platform independent ontology based application which has not been utilized for this research. Carbon footprint cost is a new inclusion that has been done to cost in this research, because it's a new inclusion and no work has been carried out in this regard so far, the knowledge elements are more assumptive. This can be improved by further understanding of this subject and the factors that contribute to the same. It can therefore be finally said that LKACEM is found to be successful in advanced cost estimation for composite aero-engine component design, but the scope of improvement is still there.

References

Abumeri, G. H., Kuguoglu, L. H. and Chamis, C. C., NASA (2004) *Composite Fan Blade Design for Advanced Engine Concepts, February 2004*. [pdf] Ohio: NASA. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040040080.pdf [Accessed 10 January 2017].

Abu-Rumman, A. K., Muslih, I. and Barghash, M. A. (2017) Life Cycle Costing of PV Generation System. *Journal of Applied Research on Industrial Engineering*, 4(4), pp. 252-258.

Accounting Tools, (2013) *Factory Cost*. Available at: https://www.accountingtools.com/articles/what-is-factory-cost.html [Accessed 10 August 2017].

Accudyne Systems Inc (2015) *Applying Automation to the Fabrication of Composite Based Aerospace Parts and Developing a Machine Specification*. Available at: http://www.aerospacemanufacturinganddesign.com/FileUploads/file/AMD-TMDTES/Applying%20Automation%20to%20the%20Fabrication%20of%20CFRP%20for%20Aerospace%20applications [Accessed 11 August 2016].

Adolphy, S., Gericke, K., and Blessing, L. (2009) Estimation and its Role in Engineering Design - An Introduction. In: *International Conference on Engineering Design, ICED 09*, Stanford, CA, USA, 24-27 August 2009, Stanford University, pp. 255-265.

Ahn, T. (1998) Cost Drivers of Manufacturing Overhead: A Cross-Sectional Analysis of Automobile Component Manufacturing Plants. *Seoul Journal of Business*, 4(2), pp. 71-96.

Airlines UK, UK (2017) *Responding to the Carbon Challenge*, *January 2017*. [pdf] London: The Association of UK Airlines. Available at: http://airlinesuk.org/wp-content/uploads/

2017/01/Airlines-UK-Responding-to-the-Carbon-Challenge.pdf [Accessed 11 March 2017].

Alexander, C. (2017) Parametric Cost and Schedule Modeling for Early Technology Development. In: *ICEAA Professional Training and Development Workshop*. Portland, Oregon, 06-09 June 2017. USA: ICEAA, pp. 1-53.

Al-Mukhtar, A. M. (2012) The Effected parameters for Designing the Single Layer Composite Materials. *International Journal of Mechanical Engineering and Robotics Research,* 1(3), pp. 358-370.

Al-Qudah, L. A. M. and Al-Hroot, Y. A. K. (2017) The Implementing Activity-based Costing Technique and its Impact on Profitability: A Study of Listed Manufacturing Companies in Jordan. *International Journal of Economics and Financial Issues*, 7(2), pp. 271-276.

American Chemistry Council. (2015) *Technical Report on Plastics and Polymer Composites in Light Vehicles*. Available at: https://plasticscar.com/lightvehiclereport [Accessed: 12 April 2016].

Anno, G. D., Partridge, I. K., Cartie, D. D. R., Hamlyn, A., Chehura, E., James, S. W. and Tatam, R. P. (2012) Automated Manufacture of 3D Reinforced Aerospace Composite Structures. *International Journal of Structural Integrity*, 3(1), pp. 22-40.

Aurora, B. C. (2013) The Cost of Production Under Direct Costing and Absorption Costing - A Comparative Approach. *Annuls of the Constantin Brancusi: University of Targu Jiu: Economy Series*, 2013(2), pp. 123-129.

Backman, Daniel, G. and Williams, J. C. (1992) Advanced materials for aircraft engine applications. *Journal of Science: New Series*, 255(5048), pp. 1082-1087.

Bakis, C. E., Bank L. C., Brown, V. L., Cosenza, E., Davalos, J. F., Lesko, J. J., Machida, A., Rizkalla, S.H. and Traintafillou, T. C. (2002) Fiber-Reinforced Polymer Composites for Construction-State-of-the-art Review. *Journal of Composites for Construction*, 6(2), pp. 73-87.

Barlow, D. A., Scott, M. L. and Clayton, G. (2002) *Calculating The Cost of a Carbon Fibre Composite Structure from within a Finite Element Model: 23rd International Congress of Aeronautical Sciences*. Toronto, Canada, 8-13 September 2002. Optimage Ltd: UK, pp. 1-10.

Barton, J., Niemczyk, A., Czaja, K., Kosach, L. and Majewska, B. S. (2014) Polymer Composites, Biocomposites and Nanocomposites. Production, composition, properties and application fields. *CHEMIK*, 68(4), pp. 280-287.

Bhojaraju, G. (2005) Knowledge Management: Why do we Need it for Corporates. *Malaysian Journal of Library & Information Science*, 10(2), pp. 37-50.

Biahmou, A., Stjepandic, J. and Liese, H., Prostep, AG (2007) *Closing the Gap Between Design and Simulation by KBE Technology Approaches to Increase Engineering Productivity*. Available at: https://web.mscsoftware.com/events/vpd2007/emea/presentations/Interactive-PROSTEP-Biahmou [Accessed 12 January 2017].

Birmingham City University, Knowledge Based Engineering Lab, United Kingdom (2011) *Knowledge Based Engineering*. Available at: http://www.bcu.ac.uk/engineering/research/the-kbe-lab [Accessed 20 March 2016].

Bohar, F., Lammer, L. and Laarman, B. (2016) *Composites in Commercial Aircraft Engines*. Available at: http://aviationfacts.eu/uploads/thema/file_en/585919d470726f2696000000/Composites_in_Commercial_Aircraft_Engine_Fact_sheet [Accessed 22 February 2017].

Bureau of Indian Standards (1998) *Engineering Drawing Practice for Schools & Colleges*. New Delhi: Bureau of Indian Standards.

Cao, Y. H., You, J. X. and Liu, H.C. (2017) Optimal Environmental Regulation Intensity of Manufacturing Technology Innovation in View of Pollution Heterogeneity. *Journal of Sustainability*, 9(1240), pp. 1-14.

Carbon Footprint Ltd, UK (2017) *Carbon Footprint Standard Qualification Requirements*. Available at: https://www.carbonfootprint.com/docs/2017_1_cfs_qualification_requirements_11 [Accessed 02 September 2017].

Carbon Trust (2017) Carbon Footprinting. Available at: https://www.carbontrust.com/media/44869/j7912_ctv043_carbon_footprinting_aw_interactive. [Accessed 10 March 2017].

Cardinaels, E. and Labro, E. (2008) On the Determinants of Measurement Error in Time-Driven Costing. *The Accounting Review*, 83(3), pp. 735-756.

CEDIA, Indiana (2015) *Cost Estimating Bottoms-Up vs Top Down*. Available at: http://www.cedia.net/insights/cedia-blog-detail/blog/2015/03/23/cost-estimating-bottom-up-vs.-top-down [Accessed 22 February 2017].

Chaple, A. R., Khedakar, S. S., Dharmadhikari, S. R. and Chaple, N. R. (2013) Newly Developed Automatic Lay-Up Process for Manufacturing of FRP Sheets. *International Journal of Computational Engineering Research*, 3(3), pp. 92-97.

Chapman, C. B. and Pinfold, M. (2001) The Application of a Knowledge Based Engineering Approach to the Rapid Design and Analysis of an Automotive Structure. *Journal of Advances in Engineering Software,* 32(12), pp. 903-912.

Chawla, K. K. (2012) Composite Materials: Science and Engineering. New York: Springer Science & Business Media.

Cheong, F. C. and Steve (2012) Cost Drivers and Company Activities. *AAT Journal of Management Accounting*, 3(1), pp. 1-4.

Cheung, J. M. W., Scanlan, J. P. and Wiseall, S. S. (2009) An Aerospace Component Cost Modelling Study for Value Driven Design. In: *CIRP IPS2 Conference 2009: Industrial Product-Service Systems*, UK, Cranfield University, 01-02 April 2009. UK: Cranfield University, pp. 1-5.

Choi and Woo, J. (2009) Architecture of a knowledge based engineering system for weight and cost estimation for a composite airplane structures. *Journal of Expert Systems with Applications*, 36(8), pp. 10828 - 10836.

Chua, M. H., Smyth, B. M., Murphy, A. and Butterfield, J. (2015) Understanding Aerospace Composite Components' Supply Chain Carbon Emissions. In: *Irish Manufacturing Conference, IMC 32*, Belfast, UK, 02-04 September 2015. Northern Ireland: IMC, pp. 3-12.

Civil Aviation Authority, Sussex, UK. (2017) *Information on Aviation's Environmental Impact*. West Sussex: Civil Aviation Authority.

Cokins, G. (2010) Cost Drivers, Evolution and Benefits. *Journal of Theoretical and Applied Economics*, XVII(549), pp. 7-16.

Colson, A. R. and Cooke, R. M. (2017) Cross Validation for the Classical Model of Structured Expert Judgement. *Journal of Reliability Engineering and System Safety*, 163(1), pp. 109-120.

Committee on Climate Change, UK (2017) *Reducing Emissions and Preparing for Climate Changes*. Available at: https://www.theccc.org.uk/publication/reducing-emissions-and-preparing-for-climate-change-2015-progress-report-to-parliament/ [Accessed 15 January 2018].

Composites World, Gardner Business Media Inc., Ginger Gardiner (2017) *Automated Preforming: The Numbers and Landscape*. Available at: https://www.compositesworld .com/blog/post/automated-preforming-the-numbers-and-landscape. [Accessed: 11 December 2017].

Corallo, A., Margherita, A., Pascali, G. and Turrisi, G. (2010) Streamlining New Product Development (NPD) in Aerospace Through Knowledge Based Engineering (KBE). In: *POMS 21st Annual Conference on Operations in Emerging Economics*. Vancouver, Canada, 7-10 May 2010. Canada: POMS, pp. 1-21.

Cordero, P. (2013) Carbon Footprint Estimation for a Sustainable Improvement of Supply Chains: State of the Art. *Journal of Industrial Engineering and Management*, 6(3), pp. 805-813.

CPE Courses (2018) *Factory Cost*. Available at: https://www.accountingtools.com/articles /what-is-factory-cost.html [Accessed 05 February 2018].

Curran, R., Gilmour, M., McAlleenan, C. and Kelly, P. (2009) A KBE Genetic-Casual Cost Modelling Methodology for Manufacturing Cost Contingency Management. In: *9th AIAA Aviation Technology, Integration, and Operations Conference*. Hilton Head, South Carolina, 21-23 September 2009. South Carolina: AIAA, pp. 1-16.

Curran, R., Watson, P. and Cowan, S. (2011) An Agile Cost Estimation Methodology for Aerospace Procurement Operations: Genetic Casual Cost CENTRE-ing. *Journal of Aeronautics and Astronautics*, 1(1), pp. 461-486.

Cytec Industries. (2014) *Composite Materials for Automotive Applications*, June 2014. [pdf]. Available at: https://www.cytec.com/sites/default/files/files/IM-3001-EN-Automotive _Aformat_SINGLE.pdf [Accessed: 14 May 2016].

Darla, S. P. (2017) Product Life Cycle Cost Estimation at Early Design: A Review on Techniques and Applications. *International Journal of Engineering Development and Research*, 5(4), pp. 1558-1561.

Deng, J., Lee, M. M. K., Wan, B. and Amato, G. (2017) Fibre Reinforced Polymer Composites for Structural Applications in Construction. *International Journal of Polymer Science*, 2017(1), pp. 1-8.

Department of Army (1997) *Technical letter on Engineering and Design Composite Materials for Civil Engineering Structures*, March 1997. [pdf] USA: Department of Army. Available at: http://www.dtic.mil/dtic/tr/fulltext/u2/a403282.pdf [Accessed 15 May 2016].

Department of Energy, The National labs, United States of America (2015) *Energy Efficient Thermoplastic Composite Manufacturing*. Available at: https://energy.gov/sites/prod/files/2016/07/f33/R25%20-%20Energy%20Efficient%20Thermoplastic%20Composite%20Man%202016_Compliant [Accessed 21 December 2016].

Dijk, R. V., Zhao, X., Wang, H. and Dalen, F. V. (2012) Multidisciplinary Design and Optimization Framework for Aircraft Box Structures. In: *3rd Aircraft Structural Design Conference*, Delft University, The Netherlands, 09-11 October 2012. UK: Royal Aeronautical Society, pp. 1-25.

Dixon, W. (2008) *What is Whole Life Costing, Life Cycle Analysis and Life Cycle Costing*. Available at: https://www.willmottdixon.co.uk/asset/9449/download?1424952248 [Accessed 03 July 2016].

Dobbins, T. (2015) Composites Manufacturing. *Official Magazine of the American Composites Manufacturers Association*, 31(1), pp. 1-36.

Dogan, H. (2011) Set Theory in Linear Algebra. *The Journal of Mathematica Aetema*, 1(5), pp. 317-327.

Doloi, H. K. (2011) Understanding Stakeholders’ Perspective of Cost Estimation in Project Management. *International Journal of Project Management*, 29(1), pp. 622-636.

Dragos, S., Tomita, V. and Cora-Ionela, D. (2009) Acceptance Criteria for a Cost Estimating Relationship. *Journal of Economy and Business Administration*, 2(1), pp. 693-696.

Dysert, L. R. (2008) An Introduction to Parametric Estimating. *AACE International Transactions*, 3(1), pp. 1-7.

Eaglesham, M. A. (1998) *A Decision Support System for Advanced Composites Manufacturing Cost Estimation*. PhD. Thesis. Virginia Polytechnic Institute and State University, USA.

Elzey, D. M. and Wadley, H. N. G. (1995) Assessing the Affordability of High Performance Composites. In: *Proceedings of the 8th Annual HITEMP Review*. Ohio, USA, 24-25 October 1995. NASA: USA, pp. 1-18.

European Composites Industry Association (2017) *Composites Recycling Made Easy*. Available at: http://www.avk-tv.de/files/20130212_recycling_made_easy [Accessed 21 January 2017].

Evans, D. K., Lanham, J. D. and Marsh, R. (2006) *Cost Estimation Method Selection: Matching User Requirements and Knowledge Availability to Methods*. Report. University of the West of England, Bristol.

Fairuz, A. M., Sapuan, S. M., Zainudin, E. S. and Jaafar, C. N. A. (2014) Polymer composite manufacturing using a pultrusion process: a review. *American Journal of Applied Sciences*, 11(10), pp. 1798-1810.

Feng, S. C. and Song, Y. (2005) Preliminary Design and Manufacturing Planning Integration Using Web-Based Intelligent Agents. *Journal of Intelligent Manufacturing*, 16(4), pp. 1-18.

Ferraz, S. B., Buhamra, C., Laroche, M. and Veloso, A. R. (2017) Green Products: A Cross Cultural Study of Attitude, Intention and Purchase Behavior. *Revista de Administração Mackenzie - RAM: Mackenzie Management Review*, 18(5), pp.12-38.

Florin, B. (2011) Bottom-up/Top-down Budgeting. In: *The 6th International Scientific Conference on Defense Resources Management in the 21st Century*, Brasov, Bucharest, Romania, 2-3 December 2011, Joint Logistics Command, pp. 160-164.

Freeman, W. T., Louis, F. V. and Siddiqi, S. (1990) A Unified Approach for Composite Cost Reporting and Prediction in the ACT Program. In: *First NASA Advanced Composites Technology Conference*. Washington, USA, 29 October - 01 November 1990. NASA: USA, pp. 357-369.

French, S. S., Fischer, M., Kunz, J. and Paulson, B. (2003) A Generic Feature-driven Activity-based Cost Estimation Process. *Advanced Engineering Informatics*, 17(1), pp. 23-39.

Fuchs, E. R. H. (2003) *The Significance of Production Cost Inputs in Regional Technology Choice: Composite Automotive Body-In-Whites in the US versus China, April 2003*. [pdf] USA: Massachusetts Institute of Technology. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.453.2422&rep=rep1&type=pdf [Accessed 12 May 2016].

Garcia, D. B., University of Bristol, UK (2017) *Ceramic Matrix Composites-Manufacturing and Applications in the Automotive Industry*, January 2017. [pdf] Bristol: University of Bristol. Available at: https://www.bristol.ac.uk/engineering/media/accis/cdt/news/bracho-garcia.pdf [Accessed 17 January 2018].

García, P. B. and Fan, I. S. (2002) A KBE System for the design of wind tunnel models using reusable knowledge components. In: *Proceedings of the VIth Congreso Internacional de Ingeniería de Proyectos*. Barcelona, Spain, 23-25 October 2002. Spain: UPC, pp. 594-604.

Gardner Business Media Inc. (2014) *Composites World, Fabrication Methods.* Available at: http://www.compositesworld.com/blog/post/fabricationmethods [Accessed 07 May 2016].

Georgia Institute of Technology (2011) *Composites Processing: Version 1*. Available at: http://atc.fragnel.edu.in/materials/composites1 [Accessed 16 May 2016].

Gerami, M. (2010) Knowledge Management. *International Journal of Computer Science and Information Security*, 7(2), pp. 234-238.

Gill, A. (2017) Activity Based Job Order Costing in Product Storage. *International Journal of Management and Applied Science*, 3(2), pp. 46-49.

Gonzalez, R. V. D. and Martins, M. F. (2017) Knowledge Management Process: a Theoretical-Conceptual Research. *Journal Gest. Prod.: Sao Carlos*, 24(2), pp. 248-265.

Goodwinds Composites. (2011) *Carbon Vs Fiberglass*. Available at: http://gwcomposites.com/carbon-vs-fiberglass [Accessed 10 April 2016].

Goren, A. and Atas, C. (2008) Manufacturing of polymer matrix composites using vacuum assisted resin infusion moulding. *Journal of materials Science and Engineering*, 34(2), pp. 117-120.

Gorski, F. (2017) Building Virtual Reality Applications for Engineering with Knowledge-Based Approach. *Management and Production Engineering Review Journal*, 8(4), pp. 64-73.

Griffin, P. W., Hammond, G. P. and Norman, J. B. (2016). Industrial Energy Use and Carbon Emissions Reduction: A UK Perspective. *Journal of WIREs Energy and Environment*, pp. 1-31.

Grimshaw, M. N., Grant, C. G. and Diaz, J. M. L. (2001) Advanced Technology Tape Laying for Affordable Manufacturing of Large Composite Structures. In: *International SAMPE Symposium and Exhibition, 46th, Society for the Advancement of Material and Process Engineering*, Long Beach, California, 6-10 May 2001. Covina: SAMPE, pp. 2484-2494.

Guo, W., Wen, J., Shao, H. and Wang, L. (2015) Implementation of Knowledge-Based Engineering Methodology in Hydraulic Generator Design. *Journal of Advances in Mechanical Engineering*, 7(5), pp. 1-13.

Hale, R. D. and Schueler, K. (2002) Knowledge-Based Software Systems for Composite Design, Analysis and Manufacturing. *Journal No. 2002-01-1536. SAE Technical Paper*, 1(1), pp. 1-13.

Hale, R. D. and Vasey-Glandon, V. M. (2001) PACKS: An affordable knowledge driven composite design for manufacturing process. *Journal of Materials and Processes Odyssey*, 46(1), pp. 1 - 14.

Halliwell, S. M. (2000) Polymer Composites in Construction. London: BRE Publications.

Harris, B. (1999) Engineering Composite Materials. Volume 673. Institute of Materials London: IOM Press

Herbell, T. P. and Eckel, A. J. (1992) Ceramic Matrix Composites for Rocket Engine Turbine Applications. In: *International Gas Turbine and Aeroengine Congress and Exposition*. Cologne, Germany, 1-4 June 1992. ASME, pp. 1-7.

Hueber, C., Horejsi, K. and Schledjewski, R. (2016) Review of Cost Estimation: Methods and Models for Aerospace Composite Manufacturing. *Journal of Advanced Manufacturing: Polymer & Composite Science*, 2(1), pp. 1-13.

Hussain, F., Hojjati, M., Okamoto, M. and Gorga, R.E. (2006) Review Article: Polymer-matrix Nanocomposites, Processing, Manufacturing and Application: an Overview. *Journal of Composite Materials*, 40(17), pp. 1511-1575.

IIT Delhi, India (2006) *Selecting and Planning the Process of Manufacture*. Available at: http://web.iitd.ac.in/~pmpandey/Process_engg_html/Selecting%20and%20Planning%20the%20Process%20of%20Manufacture [Accessed 18 August 2016].

IIT Kharagpur, India, (2009) *Module 11 Software Project Planning, Version 2*. Available at: http://nptel.ac.in/courses/106105087/ pdf/m11L27 [Accessed 22 September 2016].

Inakollu, S., Morin, R. and Keefe, R. (2017) Carbon Footprint Estimation in Fiber Optics Industry: A Case Study of OFS Fitel, LLC. *Journal of Sustainability*, 9(865), pp. 1-16.

Infosys Limited (2017) *Aircraft landing Gear Design and Development-How Advanced Technologies are Helping to Meet Challenges?*. Available at: https:// www.infosys.com /engineering-services/white-papers/Documents/landing-gear-design-and development [Accessed: 10-Mar-2018].

Infosys Limited (2017) *Knowledge Based Engineering (KBE) Applications in Aircraft Structural Repair*. Available at: https://www.infosys.com/engineering-services/white-papers/Documents/KBE-applications-structural [Accessed 24 February 2018].

Institute of Environment and Sustainablility, Italy (2011) *Analysis of Existing Environmental Footprint Methodologies for Products and Organizations: Recommendations, Rationale and Alignment*. Available at: https://ec.europa.eu/environment/eussd/pdf/Deliverable [Accessed 21 September 2016].

Investopedia Llc, (2017) *Unit Cost*. Available at: http://www.investopedia.com/terms/u/unitcost.asp [Accessed 24 August 2017].

Iowa State University (2007) *Product Life Cycle*. Available at: https://www.extension.iastate.edu/AGDM/wholefarm/pdf/c5-211 [Accessed 30 May 2016].

John, F. V. (2012) Life Cycle Cost Considerations for Complex Systems, Systems Engineering - Practice and Theory. *InTech Journal of Systems Engineering*, pp. 127-146.

Jokhio, M. H., Panhwar, M. I. and Unar, M. Ali. (2011) Manufacturing of Aluminium Composite Material Using Stir Casting Process. *Mehran University Research Journal of Engineering & Technology*, 30(1), pp. 53-64.

Jolliet, Olivier, Blanc, I., Schwab-Castella, P., Gomez-Ferrer, M., Ecabert, B., Manson, J., Wakeman, M. and Emery, D. (2007) Coupled Cost and Environmental Life Cycle Modelling of Composite Car-Bodies for a Korean Tilting Train. In: *International Life Cycle Assessment and Management Conference*. Potland, Oregon, 2-4 October 2007. Institute for Environmental Research and Education, pp. 113-114.

Joshi, R., Raina, A. A. and Pant, R. S. (2009) Conceptual Design of an Airship Using Knowledge Based Engineering. In: *18th AIAA Lighter-Than-Air Systems Technology Conference*. Seattle, Washington, 04-07 May 2009. USA: AIAA, pp. 1 - 9.

Juszczyk, M., lesniak, A. and Zima, K. (2018) ANN Based Approach for Estimation of Construction Costs of Sports Fields. *Journal of Complexity*, 2018(1), pp. 1-12.

Kabinlapat, P. and Sutthachai, S. (2017) An Application of Activity-Based Costing in the Chicken Processing Industry: A Case of Joint Products. *International Food and Agribusiness Management Review*, 20 (1), pp. 85-97.

Kals, H., Brinke, E., Lutters, E. and Streppel, T. (1999) *Integrated Cost Estimation Based on Information Management*. Available at: http://citeseerx.ist.psu.edu/viewdoc/download ?doi=10.1.1.200.3229&rep=rep1&type= [Accessed 18 August 2016].

Karlsson, M., KTH Engineering Sciences (2013) *The development of a technical cost model for composites, June 2013*. [pdf] Sweden: KTH Engineering Sciences. Available at: htt ps://www.diva-portal.org/smash/get/diva2:676718/FULLTEXT01.pdf [Accessed 18 August 2016].

Khedekar, M. D., Bapat, M. S., Yadav, S. N. and Aher, S. J. (2017) An Application of Fuzzy Game Theory to Industrial Decision Making. *Research Journal of Mathematical and Statistical Sciences*, 5(3), pp. 9-12.

Khoonsari, S. H. M. (2009) Life Cycle Cost Analysis for Passenger Cars: Steel versus Composites. In: *9th Automotive Composites Conference & Exhibition*. Lake Road, Troy, 15-16 September 2009. Troy: MSU, pp. 1-29.

King, W. R. (2009) *Knowledge Management and Organizational Learning: Annals of Information Systems*. Vol. 4, New York: Springer.

Komornicki, J., Bax, L., Vasiliadis, H., Magallon, I. and Ong, K. (2017) *Polymer Composites for Automotive Sustainability*, 2017. [pdf]. Available at: www.suschem.org/files/library /Publications/POLYMERS_Brochure_Web.pdf [Accessed 07 January 2018].

Kortbeek, P., Beers, C. and Weenink, X., Neetherlands Aerospace Centre (2018) *Roadmap Aeronautics 2018-2025*. Available at: http://www.nlr.nl/wp-content/uploads/2018/03/ Roadmap-Aeronautics-2018-2025.pdf [Accessed: 09-Mar-2018].

Kumar, A., Kumar, S. and Kapil (2014) Knowledge Based Engineering in Integration with Computer Aided Designing. *International Journal of Research in Mechanical Engineering & Technology*, 5(1), pp. 80 - 85.

Kumar, J. and Kendall, E. (1999) Complexity Based Cost Estimation Model for Composite Aerospace Structures. In: *International Conference on Composite Materials, ICCM - 12, Volume 2.0*. Paris, France, 5-9 July 1999. Woodhead Publishing, pp. 1-10.

Lacombe, A., Spriet, P., Habarou, G., Bouillon, E. and Allaria, A. (2009) Ceramic Matrix Composites to make breakthroughs in aircraft engine performance. In: *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Spring, California, 4-7 May 2009, Aerospace Research Central, pp. 2675-2686.

Lambert, D. B. (2011) *Composite Aircraft Life Cycle Cost Estimating Model, March 2011*. [pdf]. Ohio: Department of The Air Force Air University. Available at: http://www.dtic .mil/dtic/tr /fulltext/u2/a538329 .pdf. [Accessed 03 May 2016].

landschuetzer, C., Jodin, D. and Wolfschluckner, A. (2011) Knowledge Based Engineering-an Approach via Automated Design of Storage/Retrieval Systems. *Journal on Proceedings in Manufacturing Systems*, 6(1), pp. 3-10.

Langmaaka, S., Wiseallb, S., Brub, C., Adkinsc, R., Scanlana, J. and Sóbestera, A. (2013) An activity-based-parametric hybrid cost model to estimate the unit cost of a novel gas turbine component. *International Journal of Production Economics*, 142(1), pp. 74-88.

Lee, Y. C. and Lee, S. K. (2007) Capabilities, Processes and Performance of Knowledge Management: A Structural Approach. *Journal of Human Factors and Ergonomics in Manufacturing*, 17(1), pp. 21-41.

Leterrier, Y. (2000) Life Cycle Engineering of Composites. *Journal of Comprehensive Composite Materials*, 2(1), pp. 1073-1102.

Lindemann, C., Jahnke, U., Moi, M. and Koch, R. (2012) Analysing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing. In: *Procedure* *of the Solid Freeform Fabrication Symposium*. Austin, Texas, 6-8 August 2012. USA: TCT, pp. 177–188.

Lopata, A., Ambraziunas, M., Gudas, S. and Butleris, R. (2012) The Main Principles of Knowledge-Based Information Systems Engineering. *Journal of Electronics and Electrical Engineering*, 120(4), pp. 99-102.

Malhotra, Y. (2002) Why Knowledge Management Systems Fail? Enablers and Constraints of Knowledge Management in Human Enterprises. *International Journal Handbook on Information Systems: Handbook on Knowledge Management*. 1(1), pp. 1-21.

Mann, T., Smeltzer, S., Grenoble, R., Mason, B., Rosario, S. and Fairbairn, B. (2012) Sizing and Lifecycle Cost Analysis of an Ares V Composite Interstage. In: *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. Honolulu, Hawaii, 23-26 April 2012. American Institute of Aeronautics and Astronautics, pp. 1770-1781.

Mar-Bal Inc. (2016) *History of Composites.* Available at: http://www.marbal.com/language/en/applications/history-of-composites [Accessed 24 March 2016].

Marino, J. and Chemaly, A. (2002) Structural Design, Analysis, Optimization, and Cost Modeling Using the Adaptive Modeling Language. *Journal of AIAA Paper 1296*, 1(1), pp.1-8.

Marsden, W. and Warde, S. (2010) Data Management for Composite Materials. *Journal of Granta Technical Paper: Granta Designs Limited*, 2(1), pp. 1 - 17.

Massachusetts Institute of Technology, USA (2002) *A Knowledge Based Approach to Facilitate Engineering Design*. Available at: http://web.mit.edu/adamross/www/SESHASAI_MENG [Accessed 21 June 2016].

Massachusetts Institute of Technology, USA (2011) *Introduction to Knowledge Management*. Available at: https://mitpress.mit.edu/sites/default/files/titles/content/9780262015080_sch_0001 [Accessed 15 June 2016].

Matsuzaki Laboratory, Tokyo University of Science, Japan (2011) *3D Printing of Continuous Fiber Reinforced Plastic*. Available at: http://www.rs.tus.ac.jp/rmatsuza/files/3D%20printing%20of%20continous%20CFRP [Accessed 05 June 2016].

Mendez, G. G., Hinrichs, U. and Nacenta, M. A. (2017) Bottom-up vs Top-down: Trade-offs in Efficiency, Understanding, Freedom and Creativity with InfoVis Tools. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. Denver, USA, 06-11 May 2017. New York: ACM, pp. 841-852.

Meng, F., University of Nottingham (2017) *Environmental and cost analysis of carbon fibre composites recycling, July 2017*. [pdf] Nottingham: University of Nottingham. Available at: http://eprints.nottingham.ac.uk/46518/1/PhD%20thesis_Fanran%20Meng_4201331_after%20correction_final.pdf [Accessed 15 January 2018].

Microsoft, USA (2015) *5 Benefits of Microsoft Excel*. Available at: https://blogs.business.microsoft.com/en-gb/2016/07/08/top-5-benefits-microsoft-excel/ [Accessed 02 September 2016].

Microsoft, USA (2016) *Microsoft Excel*. Available at: https://products.office.com/en-us/excel [Accessed 11 February 2016].

Min, J. B., Harris, D. L. and Ting, J. M. (2011) Advances in Ceramic Matrix Composite Blade Damping Characteristics for Aerospace Turbomachinery Applications. In: *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. Delver, Colorado, 4-7 April 2011. Colorado: USA, AME, pp. 1-11.

Mohammed, J., May, J. and Alavi, A. (2008) Application of Computer Aided Design (CAD) in Knowledge Based Engineering. In: *IAJC-IJME International Conference on*

Engineering & Technology: Globalization of Technology - Imagine the Possibilities!. Sheraton, USA, 17-19 November 2008. USA: California State University, pp. 83-112.

Montali, J., Overend, M., Pelken, P. M. and Sauchelli, M. (2017) Towards Facades as Make-to-order Products: The Role of Knowledge Based Engineering to Support Design. In: *ICBEST Istanbul International Conference*. Istanbul, Turkey, 15-18 May 2017. Istanbul: ITU, pp. 1-10.

Mrazova, M. (2013) Advanced Composite Materials of the Future in Aerospace Industry. *INCAS BULLETIN*, 5(3), pp. 139 - 150.

Muktinutalapati and Rao, N. (2011) Materials for Gas Turbines-An Overview. *Journal of INTECH*, 2011 (1), pp. 293-314.

Munich Centre for Mathematical Philosophy (2012) *Basic Set Theory*. Available at: http://www.mcmp.philosophie.uni-muenchen.de/students/math/basic-set-theory [Accessed 10 Aug 2016].

Nagavally, R. R. (2017) Composite Materials-History, Types, Fabrication, Techniques, Advantages and Applications. *International Journal of Mechanical and Production Engineering*, 5(9), pp. 82-87.

Naimoli, S., Kodjak, D., German J. and Schultz, J. (2017) International Competitiveness and the Auto Industry: What's the Role of Motor Vehicle's Emission Standards?. *The International Council of Clean Transportation*, 2017(1), pp. 1-13.

Narayan, P. and Pandey, D. (2014) Knowledge-Based Software System for Space Exploration. *International Journal of Computer Sciences*, 11(2), pp. 181-185.

NASA, USA (2006) *Damage-Tolerant Fan Casings for Jet Engines*. Available at: https://spinoff.nasa.gov/Spinoff2006/T_1.html [Accessed 22 July 2017].

NASA, USA (2015) *NASA Cost Estimating Handbook: Version 4.0*, *February* 2015. [pdf] USA: NASA. Available at: https://www.nasa.gov/pdf/263676main_2008-NASA-Cost-Handbook-FINAL_v6.pdf [Accessed 19 June 2017].

Naslain, R. R. and Zamawiany, A. (2005) Fiber-Reinforced Ceramic Matrix Composites: State of the art, Challenge and Perspective. *Journal of Kompozyty (Composites)*, 5(1), pp. 3-19.

Nayak, N. V. (2014) Composite Materials in Aerospace Applications. *International Journal of Scientific and Research Publications*, 4(9), pp. 1-10.

Nishi and Malik, V. (2018) A Review Paper on Software Cost estimation Using Fuzzy Logic. *International Journal of Advance Research, Ideas and Innovation in Technology*, 4(2), pp. 406-409.

Novak, P. and Popesko, B. (2014) Cost Variability and Cost Behaviour in Manufacturing Enterprises. *Journal of Economics and Sociology*, 7(4), pp. 89-103.

Oak Ridge National Laboratory. (2001) *The Cost of Automotive Polymer Composites: A Review and Assessment of DOE'S Lightweight Materials Composites Research*, January 2001. [pdf]. Available at: http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2000_283.pdf [Accessed: 21 April 2016].

Oluwagbemiga, O. E., Olugbenga, O. M. and Zaccheaus, S. A. (2014) Cost Management Practices and Firm's Performance of Manufacturing Organizations. *International Journal of Economics and Finance*, 6(6), pp. 234-239.

Owens, J. (2007) *Project Cost Control Tools & Techniques*. Available at: http://www.jasonowens.com/wp-content/uploads/2009/12/ProjectCostControlTools_and_Techniques [Accessed 30 July 2016].

Pandey, D., Agrawal, M. and Pandey, J. S. (2011) Carbon Footprint: Current Methods of Estimation. *Journal of Environmental Monitoring and Assessment*, 178(4), pp. 135-160.

Paragon Machine Technology, Texas, USA (2014) *Technical Guide-Machining Formulas*. Available at: https://pmttx.com/v/vspfiles/forms/MACHINING%20FORMULAS [Accessed 10 June 2017].

Paul, D., Collopy and David, J. H. E. (2001) Aerospace Manufacturing Cost Prediction from a Measure of Part Definition Information. *Technical Paper of Society of Automotive Engineers*, 1(1), pp. 1-17.

Pervaiz, M., Panthapulakkal, S., Sain, M. and Tjong, J. (2016) Emerging trends in Automotive Lightweighting Through Novel Composite Materials. *Journal of Materials Sciences and Applications*, 7(1), pp. 26-38.

Petter, A., Ola, I. and Tobias, L. (2011) A Case Study of how Knowledge Based Engineering Tools support Experience re-use. In: *ICoRD 11th International Conference on Research into Design*. Bangalore, India, 10-12 January 2011. Bangalore: ICoRD, pp. 66-73.

Pora, J. (2001) Composite Materials in the Airbus A380 - From History to Future-. In: *Thirteenth International Conference on Composite Materials (ICCM-13)*, Beijing, China, 25-29 June 2001, China, pp. 1-10.

Pritzkow, W., Nöth, A. and Rüdinger, A. (2015) Oxide Ceramic Matrix Composites - Manufacturing, Machining, Properties and Industrial Applications. *Journal of Ceramic Applications*, 3(2), pp. 48-54.

Quinn, M., Elafi, O. and Mulgrew, M. (2017) Reasons for not Changing to Activity-Based Costing: A Survey of Irish Firms. *Journal of PSU Research Review*, 1(1), pp. 63-70.

Radu, A. L., Scrieciu, M. A. and Caracota, D. M. (2013) Carbon Footprint Analysis: Towards a Projects Evaluation Model for Promoting Sustainable Development. *The Procedia of Economics and Finance*, 6(1), pp. 353-363.

Rajkumar, G. and Alagarsamy, K. (2013) A Systematic Review of Cost Estimation Models. *Journal of Global Research in Computer Science*, 4(5), pp. 33-36.

Raluca, V. (2012) Development of composite aircraft components in INCDT COMOTI, Bucharest. *Journal of INCAS Bulletin*, 4(4), pp. 189-192.

Rao, S. T., Kumar, S. B. and Rao, H. S. (2017) A Study on Fundamentals of Γ- Soft Set Theory. *International Journal of Chemical Sciences*, 15(2), pp. 136-145.

Rasula, J., Bosiljvuksic, V. and Stemberger, M. I. (2012) The Impact of Knowledge Management on Organizational Performance. *Economic and Business Review Journal*, 14(2), pp. 147-168.

Reinforced Plastics (2010) *Building on the Advantages of Composites in Construction*, October 2010. [pdf] Elsevier Limited. Available at: https:\\www.csmres.co.uk/cs.public.upd/article-downloads/construction-final.pdf [Accessed 11 January 2017].

Resatsch, F. and Faisst, U. (2004) Measuring the Performance of Knowledge Management Initiatives. In: *The Fifth European Conference on Organizational Knowledge, Learning and Capabilities*. Augsburg, Germany, 2-3 April 2004. Austria: University of Innsbruck, pp. 1 - 27.

Rocca, G. H. La and Tooren, M. J. L. van. (2015) A KBE-enabled Design Framework for Cost/Weight Optimization Study of Aircraft Composite Structures. In: *AIP Conference Proceedings*, 1618(1), pp. 394-403.

Rolls-Royce Plc. (2016) *UltraFan*. Available at: http://www.rollsroyce.com/products-and-services/civil-aerospace/products/future-products/ultrafan.aspx [Accessed: 15 January 2017].

Rush, C., Falque, J. and McRitchie, K. (2003) Real Time Cost Impact Assessment of Composite and Metallic Design Alternatives. *Journal of Galorath Incorporated*, 1(1), pp. 1 - 11.

Saidani, M., Yannou, B., Leroy, Y. and Cluzel, F. (2017) Hybrid Top-down and Bottom-up Framework to Measure Products' Circularity Performance. In: *Proceedings of the 21st International Conference on Engineering Design*. Vancouver, Canada, 21-25 August 2017. Canada: ICED, pp. 1-12.

Sainter, P., Oldham, K., Larkin, A. and Murton, A. (2000) Product knowledge management within knowledge-based engineering systems. In: *Design Engineering Technical Conference*. Baltimore, Maryland, 10-13 September 2000. New York: ASME, pp. 1-8.

Salam, A., Bhuiyan, N. and Gouw, G. J. (2013) Parametric Cost Estimating Relationships for Design Effort Estimation. *International Journal of Industrial and Manufacturing Engineering*, 7(7), pp. 1359-1364.

Sandvik Coromant (2016) *Machining Formulas and Definitions*. Available at: https://www.sandvik.coromant.com/en-gb/knowledge/machining-formulas-definitions /pages/default.aspx [Accessed 07 October 2017].

SAS Institute Inc. (2012) *How can we understand our true costs and cost drivers to maximize financial outcomes*. Available at: https://www.sas.com/content/dam/SAS/en_us/doc/so lutionbrief/healthcare-true-costs-and-cost-drivers-106105 [Accessed 13 March 2017].

Scacchi, W. and Mi, P. (1997) Process Life Cycle Engineering: A Knowledge-Based Approach and Environment. *Journal of Intelligent Systems in Accounting, Finance and Management*, 6(1), pp. 83-107.

Schmid, T. E., Pratt & Whitney (1992) *Ceramic Composites for Advanced Gas Turbine Engines, July 1992*. [pdf] Florida: Pratt & Whitney. Available at: http://www.tms.org/ Superalloys/10.7449/1992/ Superalloys_1992_401_408.pdf [Accessed 28 January 2017].

Schreve, K. and Basson, A. H. (2004) Small Volume Fabrication Cost Estimation Models for Embodiment Design. *R&D Journal incorporated into S A Mechanical Engineers*, 20(1), pp. 9-15.

Shehab, E., Essam, M. and Abdalla, H. (2002) A design to cost system for innovative product development. *Journal of Engineering Manufacture*, 216(7), pp. 999 - 1019.

Shehab, E., Essam, M. and Abdalla, H. (2002) An intelligent knowledge-based system for product cost modelling. *The International Journal of Advanced Manufacturing Technology*, 19(1), pp. 49-65.

Shekhar, S. and Kumar, U. (2016) Review of Various Software Cost Estimation Techniques. *International Journal of Computer Applications*, 141(11), pp. 31-34.

Shermon, D. and Gilmour, M. (2013) Cost Estimating Health Check - How Good are your Numbers?. In: *ICEAA Professional Development and Training Workshop*. New Orleans, Los Angles, 18-21 June 2013. Annandale: ICEAA, pp. 1-12.

Simion-Melinte, C. (2016) Factors Influencing the Choice of Cost Estimates Types and the Accuracy of Estimates for Construction Projects. In: *The proceedings of the 10th International Management Conference*: *Challenges of Modern Management*, Bucharest, Romania, 3-4 November 2016, Bucharest University of Economic Studies, pp. 50-56.

Singer, D. and Borrmann, A. (2015) A Novel Knowledge-Based Engineering Approach for Infrastructure Design. In: *The Fourth International Conference on Soft Computing*

Technology in Civil, Structural and Environmental Engineering. Prague, Czech Republic, 1-4 September 2015. Prague: Czech Technical University, pp. 1-16.

Singerman, S., Jackson, J. and Lynn, M. (1996) Titanium Metal Matrix Composites for Aerospace Applications. In: *Superalloys 1996, proceedings of eighth international symposium on superalloys*, Champion: Pennsylvania, 22-26 September 1996, Pennsylvania, pp. 579-586.

Smith, P. A. and Yeomans, J. A. (2011) Benefits of Fiber and Particulate Reinforcement. *Journal of Materials Science & Engineering*, II, pp. 1-22.

Song, Y. S., Youn, J. R. and Gutowski, T. G. (2009) Life Cycle Energy Analysis of Fiber-reinforced Composites. *Composites, Part A: Applied Science and Manufacturing*, 40A(8), pp. 1257-1265.

Sreekanth, D. N. and Lokesh, P. (2014) *Unit Cost Model for Product Cost Management, June 2014*. [pdf] Bangalore: QuEST Global Services. Available at: https://www.quest-global.com/.../Unit-Cost-Model-for-Product-Cost-Management.pdf [Accessed 03 May 2017].

Stanford University (2006) *Cost Estimating Procedure, March 2006*. [pdf] UK: Stanford University. Available at: http://www.ssrl.slac.stanford.edu/lcls/reviews/2007_oct9-12_eir/eir_docs/cam_cost_est_1.1-021 -r0.pdf [Accessed 11 August 2017].

Stephenson, T., CMA and Porter, J. (2010) Excel-Based Budgeting for Production. *Journal of Strategic Finance*, 1(1), pp. 33-41.

Takeshi, N., Takashi, O., Kuniyuki, I., Ken-ichi, S. and Masato, I. (2014) Development of CMC Turbine Parts for Aero Engines. *Journal of IHI Engineering Review*, 47(1), pp. 29-32.

Tenney, D. R., Davis, J. G., Pipes, R. B. and Johnston, N. (2009) *NASA Composite Materials Development: Lessons Learned and Future Challenges*. Available at: *https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090037429 [Accessed 11 May 2016]*.

The Edinburgh Centre for Carbon Management (2008) *What is Carbon Footprint?*. Available at: http://www.palletcarboncalculator.org/CarbonFootprintReport10_logo [Accessed 05 February 2017].

The Institute of Cost Accountants of India (2014) *Preface to Cost Accounting Standard Board*. Available at: http://icmai.in/upload/CASB/icwaicas1 [Accessed 14 January 2017].

The Pennsylvania State University, USA (2000) *Achieving Benefits from Knowledge-Based Engineering Systems in the Longer Term as well as in the Short Term*. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.105.8471&rep=rep1&type [Accessed 02 October 2016].

The World Bank Group (2011) *Overview of Cost Definitions and Cost Methods by James Ruth*. Available at: http://siteresources.worldbank.org/INTPRS1/Resources/3836061201883571938/Cost_Definitions_and_Methods [Accessed 05 July 2016].

Thokala, P. (2009) *Life Cycle Cost Modelling as an Aircraft Design Decision Support Tool*. PhD. Thesis. University of Southampton, UK.

Thompson, P. (2012) The Relationship between Unit Cost and Cumulative Quantity and the Evidence for Organizational Learning-by-Doing. *Journal of Economic Perspectives*, 26(3), pp. 203-224.

Thori, P., Sharma, P. and Bhargava, M. (2013) An Approach of Composite Materials in Industrial Machinery: Advantages, Disadvantages and Applications. *International Journal of Research in Engineering and Technology*, 2(12), pp. 350-355.

Toozandehjani, M., Kamarudin, N., Dashtizadeh, Z., Lim, E. Y., Gomes, A. and Gomes, C. (2018) Conventional and Advanced Composites in Aerospace Industry: Technologies Revisited. *American Journal of Aerospace Engineering*, 5(1), pp. 9-15.

Torp, O. and Klakegg, O. J. (2016) Challenges in Cost Estimation under Uncertainty-A Case Study of the Decommissioning of Barseback Nuclear Power Plant. *Journal of Administrative Sciences*, 6(14), pp. 1-21.

Tripathy, B. K., Goyal, A., Chaudhary, R. and Sourav, P. A. (2017) MMeMeR: An Algorith for Clustering Heterogeneous Data Using Rough Set Theory. *International Journal of Intelligent Systems and Applications*, 8(1), pp. 25-33.

Tsutomu, M., Hideo, M. and Kuzuki, O. (2014) Development of Composite fan System. *Journal of IHI Engineering Review*, 47(1), pp. 57 - 61.

Tutorials Point Pvt. Ltd. (2015) *Knowledge Management, January 2015*. [pdf] Hyderabad: Tutorials Point. Available at: https://www.tutorialspoint.com/knowledge_management /knowledge_management_tutorial.pdf [Accessed 28 February 2017].

U.S. Department of Energy (2015) *Cost Estimating Guide*. Available at: https://www.directives .doe.gov/directives-documents/400-series/0413.3-EGuide-21-admchg1/@@images/fi le [Accessed 25 June 2017].

U.S. Department of Energy, USA (2018) *Understanding Manufacturing Energy and Carbon Footprints*. Available at: https://www1.eere.energy.gov/manufacturing/pdfs/understa nding_energy_footprints [Accessed 24 April 2018].

UMassAmherst, Information technology, (2006) *Basic Concepts of Set Theory, Functions and Relations*. Available at: http://people.umass.edu/partee/NZ_2006/Set%20Theory%20 Basics [Accessed 05 September 2016].

Unde, M. and Krishna, M. (2016) Optimizing Product Realization Costs Across the Value Chain. *Cognizant 20-20 Insights*, 2016(1), pp. 1-10.

University of Trento (2003) *PROCESSI TECNOLOGICI*. Available at: http://www.ing.unitn.it/~colombo/TURBOFAN/files/tecnologia.htm [Accessed 24 June 2017].

US Department of Energy, USA (2014) *Understanding the 2010 Manufacturing Energy and Carbon Footprints*. Available at: https://www.energy.gov/sites/prod/files/.../understanding_2014_energy_footprints [Accessed 24 March 2017].

Uschold, M., Jasper, R. and Clark, P. (2000) Three Approaches for Knowledge Sharing: A Comparative Analysis. In: *Proceeding of the 12th European Workshop on Knowledge Acquisition, Modeling and Management*. London, UK, 02-06 October 2000. London: Springer, pp. 1-13.

Van Der Laan, A. H. and Van Tooren, M. J. L. (2008) Incorporating cost analysis in a multi-disciplinary design environment for aircraft movables. *Journal of Engineering Design,* 19(2), pp. 131-144.

Van Der Lan, A. H. (2008) *Knowledge Based Engineering Support for Aircraft Component Design*. PhD. Thesis. Delft University of Technology, Faculty of Aerospace Engineering, Netherlands.

Vanguard Software Corporation (2016) *Vanguard System™ Cost Modeling*. Available at: http://www.va nguardsw.com/cost-modeling/ [Accessed 17 December 2016].

Vector Infomatik GmbH (2011) *Estimation Tools and Techniques*. Available at: http://vector.com/portal/medien/vector_consulting/publication/Ebert_Estimation_IEEESoftware_2011V28N3 [Accessed 15 February 2016].

Verhagen and Wim, J. C. (2012) Knowledge-based cost modelling of composite wing structures. *International Journal of Computer Integrated Manufacturing*, 25(4), pp. 368 - 383.

Voss, E. and Overend, M. (2012) A Tool That Combines Building Information Modeling and Knowledge Based Engineering to Assess Façade Manufacturability. *Journal of Advanced Building Skins*, 14(15), pp. 1 - 10.

Waghmode, S. and Kohle, K. (2014) A Novel Way of Cost Estimation in Software Project Development Based on Clustering Techniques. *International Journal of Innovative Research in Computer and Communication Engineering*, 2(4), pp. 3892-3899.

Wang, P., Du, F., Lei, D. and Lin, T. W. (2010) The Choice of Cost Drivers in Activity-Based Costing: Application at a Chinese Oil Well Cementing Company. *International Journal of Management*, 27(2), pp. 367-380.

Washington State Department of Transportation, USA (2015) *Cost Estimating Manual for Projects*. Available at: http://www.wsdot.wa.gov/publications/manuals/fulltext/M3034 /EstimatingGuidelines.pdf [Accessed 08 September 2016].

Wasim, A., Shehab, E., Abdalla, H., Al-Ashaab, A., Sulowski, R. and Alam, R. (2013) An Innovative Cost Modelling System to Support Lean Product and Process Development. *The International Journal of Advanced Manufacturing Technology*, 65(1), pp. 165-181.

Watson, P., Curran, R., Murphy, A. and Cowan, S. (2006) Cost Estimation of Machined Parts within an Aerospace Supply Chain. *Journal of Concurrent Engineering*, 14(1), pp. 17-26.

Watson, R. and Kwak, Y. H. (2004) Parametric Estimating in the Knowledge Age: Capitalizing on Technological Advances. In: *IAMOT-2004 13th International Conference on Management of Technology*, Washington, DC, USA, 3-7 April 2004, The George Washington University, pp. 1-11.

Wiecek, D. (2013) Implementation of Artificial Intelligence in Estimating Prime Costs of Producing Machine Elements. *Journal of Advances in Manufacturing Science and Technology*, 37(1), pp. 43-53.

Wilmers, J. and Lenhof, B. (2014) Comparison of Different FE-Approaches for Modelling of Short Fibre Composites. *Journal of TECHNISCHE MECHANIK*, 34(2), pp. 90-103.

Wim J.C., Verhagen, Garcia, P. B., Mariot, P., Cotton, J. P., Ruiz, D., Redon, R. and Curran, R. (2010) Knowledge Based Cost Modelling of Composite Wing Structures. *International Journal of Computer Integrated Manufacturing*, 25(5), pp. 368-383.

Wong, J. S. (2012) *Whole Life Cost Methods for Aero-Engine Design*. PhD. Thesis. University of Southampton, UK.

Xudong, L. (2009) *Cost Analysis for Manufacturing of Composite Aerospace Products with Uncertainties*. M.A. Sc. Thesis. Concordia University, Canada.

Zhao, Xiaojia, Wim, J. C., Verhagen and Curran, R. (2015) Estimation of aircraft component production cost using knowledge based engineering techniques. *Journal of Advanced Engineering Informatics*, 29(3), pp. 616 - 632.

Zhao, Y., Harrison, A., Roy, R. and Mehnen, J. (2011) Aircraft Engine Component Deterioration and Life Cycle Cost Estimation. In: *18th CIRP International Conference on Life Cycle Engineering.* Braunschweig, Germany, 02-04 May 2011. Germany: Technische Universität Braunschweig, pp. 657-662.

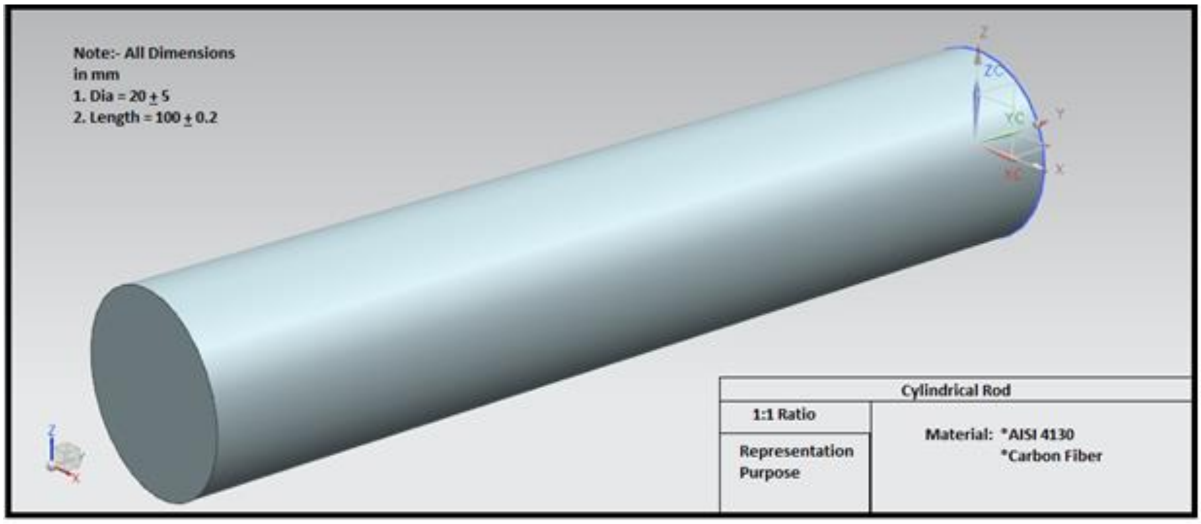
Zok, F. W. (2016) Ceramic-Matrix Composites Enable Revolutionary Gains in Turbine Engine Efficiency. *Journal of American Ceramic Society Bulletin*, 95(5), pp. 22-28.

Appendices

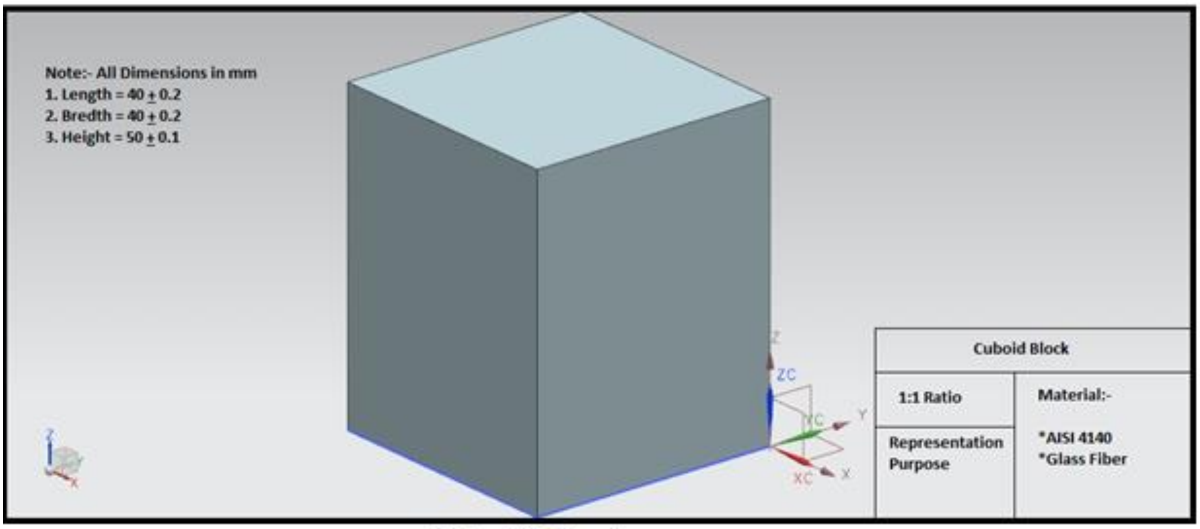
Appendix - A: Machining & Tooling Logics for Cost Estimation

Sr. No.	Parameter	Logic
1	Cutting speed v_c (m/min)	$v_c = \frac{D_m \times \pi \times n}{1000}$
2	Spindle speed n (rpm)	$n = \frac{v_c \times 1000}{\pi \text{ x } D_m}$
3	Metal removal rate Q (cm^3/min)	$Q = v_c \times a_p \times f_n$
4	Net power P_c (kW)	$P_c = \frac{v_c \times a_p \times f_n \times k_c}{60 \times 10^3}$
5	Machining time T_c (min)	$T_c = \frac{l_m}{f_n \times n}$
6	Table feed, v_f (mm/min)	$v_f = f_z \times n \times ZEFF$
7	Feed per tooth, f_z (mm)	$f_z = \frac{v_f}{n \times ZEFF}$
8	Feed per revolution, fn (mm/rev)	$f_n = \frac{v_f}{n}$
9	Torque, M_c (Nm)	$M_c = \frac{P_c \times 30 \times 10^3}{\pi \times n}$
10	Penetration rate, (v_f) m/min	$v_f = f_n \times n$
11	Feed per revolution, (f_n) mm/rev	$f_n = \frac{v_f}{n}$
12	Specific cutting force, (k_c) N/mm²	$k_c = k_{c1} \times (f_z \times \sin \kappa_r)^{-m_c} \times \left(1 - \frac{\gamma_0}{100}\right)$
13	Feed force, (F_f) N	$F_f \approx 0.5 \times k_c \times \frac{D_c}{2} \times f_n \times \sin \kappa_r$
14	Machining time, (T_c) min	$T_c = \frac{l_m}{v_f}$

Appendix - B: LKC-Tool Representation Design Details

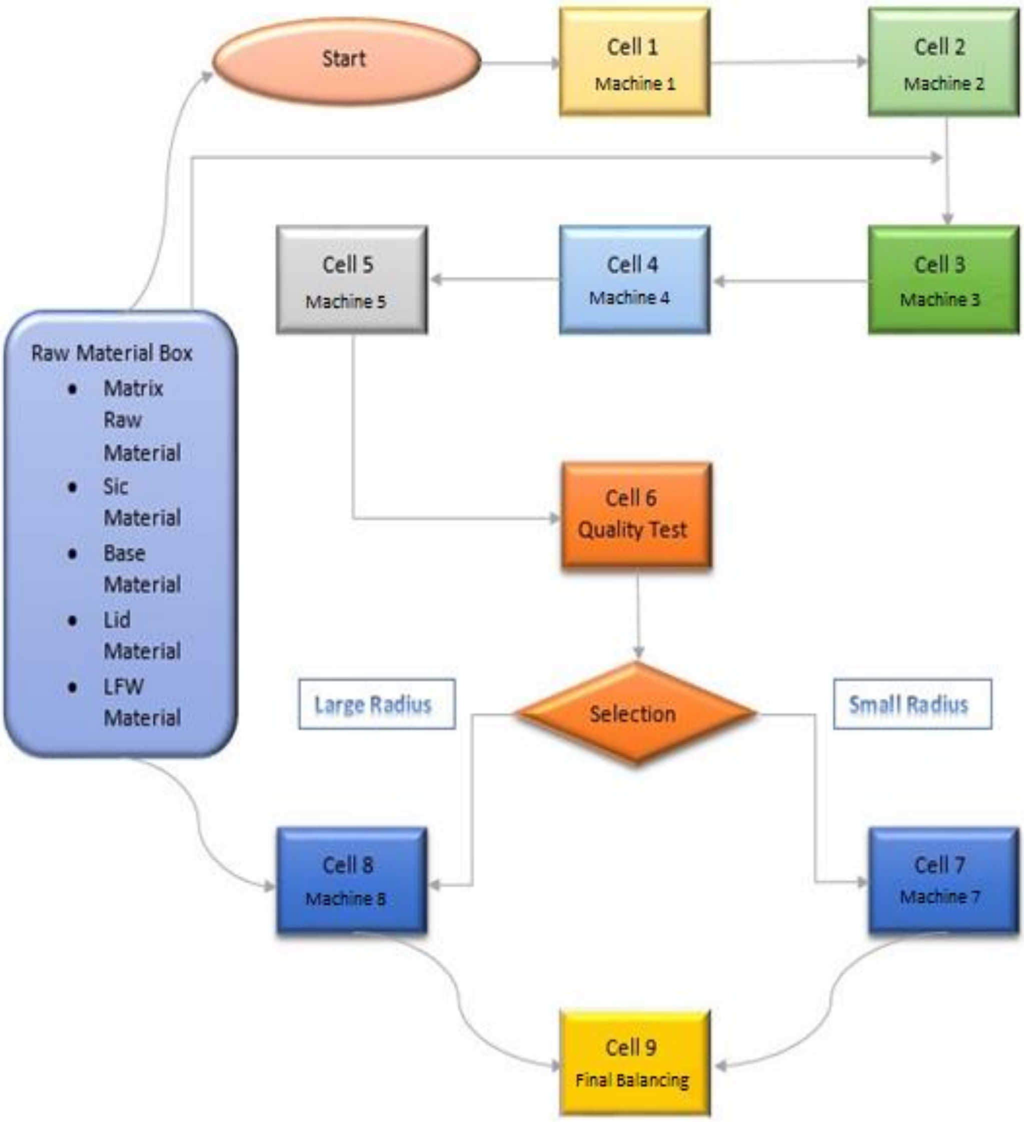


Cylindrical Design



Cuboid Design

Appendix - C: Generic Process Chart for MMC - Case Study 1



Appendix - D: Data Sheet for MMC - Case Study 1

Quality Assurance	
Inputs	**Value**
QA Cost per Run	350
QA Performed?	No

Machining 1	
Inputs	**Value**
Respooling Required?	No
Cost per Respooling Machine	6,000
Depreciation Years for Respool	20
Cost per Empty Spool	3.5
Power required per Respool Machine	0.6
Respooling Rate	400
Service Cost of Respool machine	300
Service Time of Respool machine	20
Respooling Machine Turnaround Time	0.8
Rate of use of paper	0.5
Cost per Pound of Paper	2.5

Machining 3	
Inputs	**Value**
Winding Machine Turnaround Time	0.80
Volume of Adhesive per Preform	0
Cost of Adhesive per Litre	2.00
Cost per Winding Machine	6,000
Depreciation Years for Winding	25
Power Required per Winding Machine	0.8

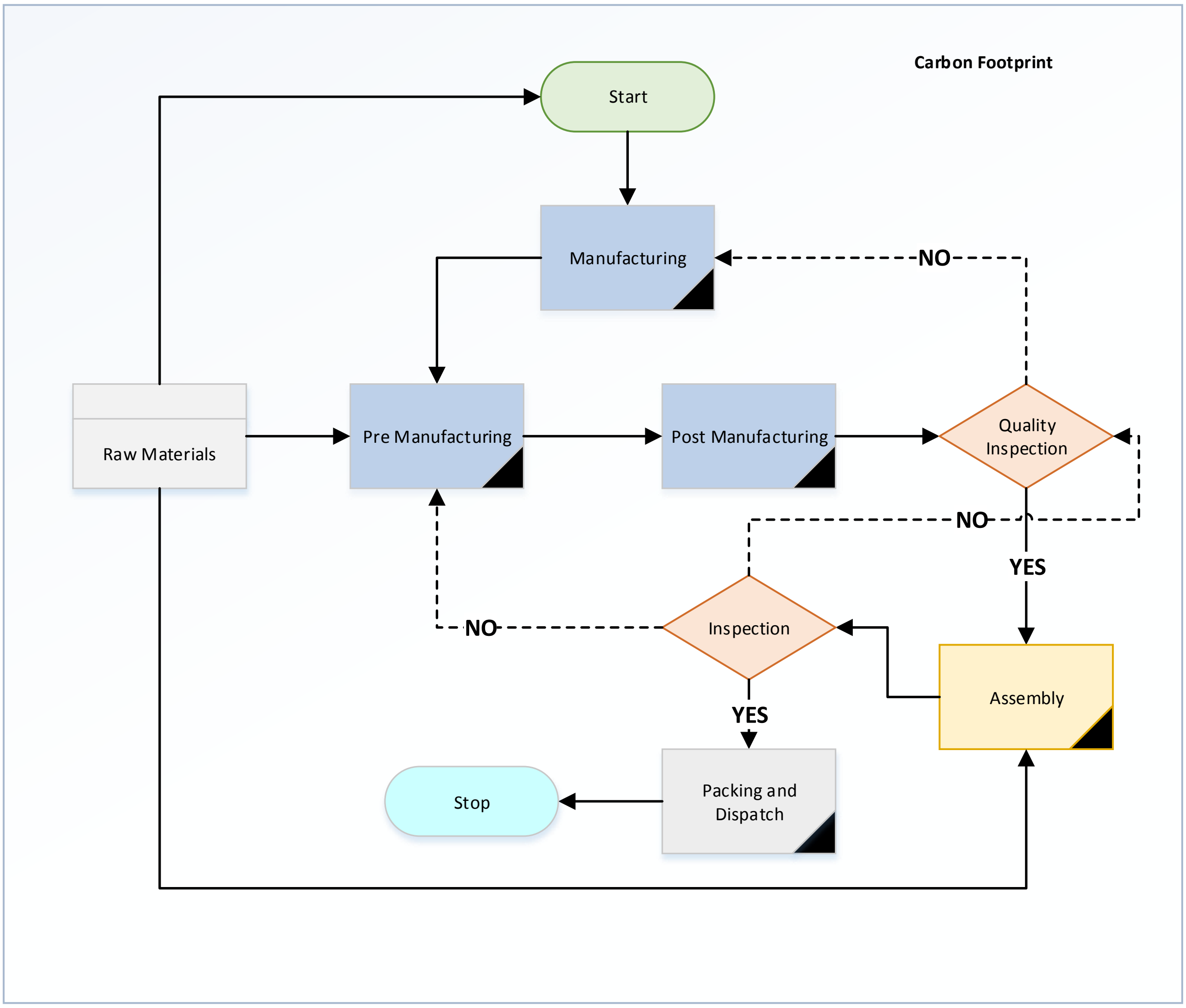
Storage	
Inputs	**Value**
Cost of storage space	-
Storage Required per spool	0.30
Cost of storage per spool	0.40

Machining 2	
Inputs	**Value**
Preform Storage Rate	15
Power Required per Storage Machine	0.15
Cost per Storage Machine	6,000
Depreciation Time per Storage Time	20
Service Cost of Storage machine	300
Service Time of Storage machine	15
Storage turnaround time	0.8

Machining 4	
Inputs	**Value**
Mass of Titanium Lid Forging	15
Mass of Machined Lid	8
Inspection Cost per Lid	48
Other Costs per Lid	22
Number of Lids per Part	1

Machining 5	
Inputs	**Value**
Cost of Cleaning per Lid	30

Appendix - E: Process Chart for Carbon Fiber Fan Case - Case Study 2

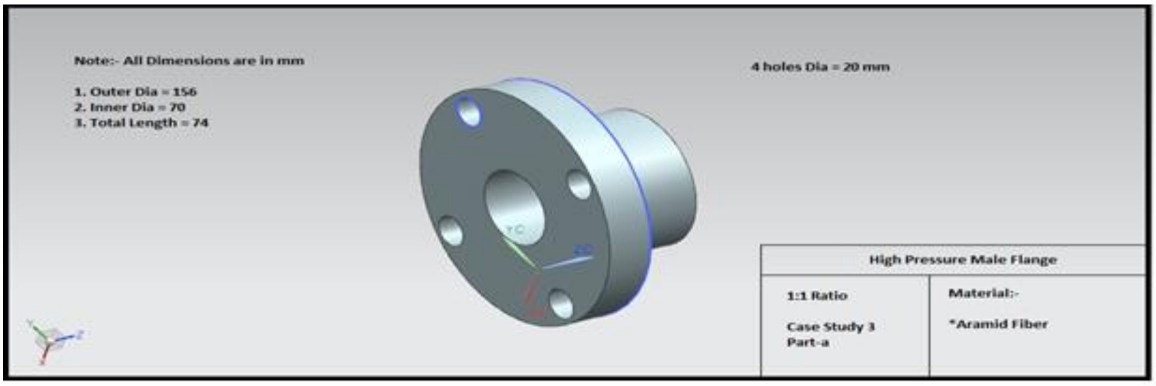


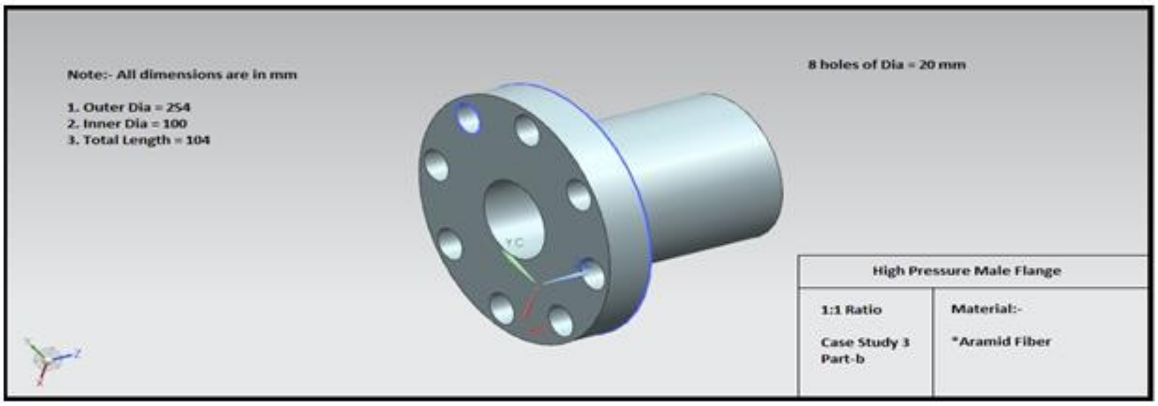
Appendix - F: Data Sheet for Carbon Fiber Fan Case - Case Study 2

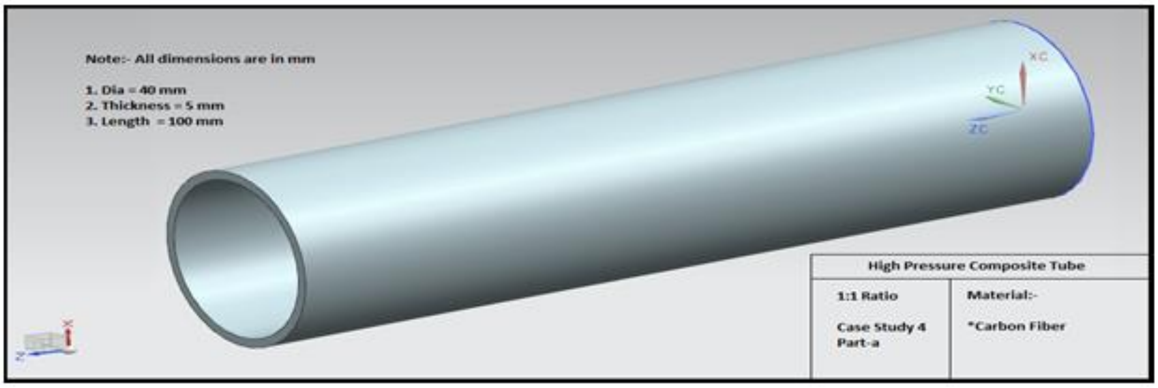
Barrel Data Set				
Operation	Description	Task Detail	Process Time	Logic
1	Apply masking tape	Manual	30	25*length+1
1	Apply Fiber Fabric	Manual	62	80*area+1
2	Visual Inspection	Manual	18	15*area
3	Automatic Lay up	Computerised Machining	850	30*length+(no of lay up-1)*50*area+31
4	Debulking	Manual	290	35*no of debulking cycles
5	Curing and Flange Forming	Automated Heating	640	direct inclusion
6	Demoulding	Manual	60	direct inclusion
7	Visual Inspection	Manual	25	20*area
8	Handling	Manual	15	10*length
9	Post-Curing	Automated Heating	415	direct inclusion
10	Inspection	Manual	15	direct inclusion
11	Drilling	Manual Machining	15	direct inclusion
12	CNC Machining	Computerised Machining	40	25*length+10
13	Ultrasonic Testing	Automated Machining	300	direct inclusion
14	Weighing	Manual	20	direct inclusion
14	Laser Inspection	Automated	265	direct inclusion
15	Quality Assurance	Manual	20	direct inclusion
16	Dispatch	Manual	15	direct inclusion

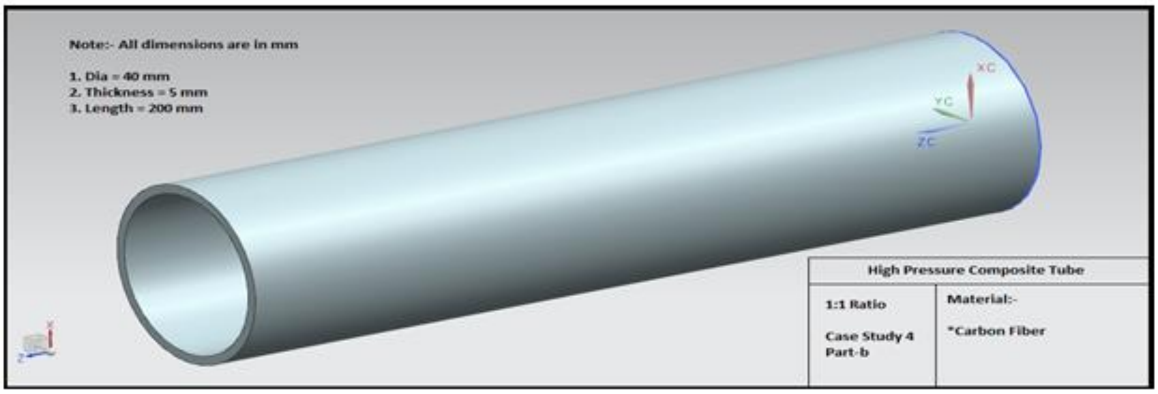
Assembly Data Set				
Operation	Description	Task Detail	Process Time	Logic
1	Loading Case	Automated	20	direct inclusion
2	Barrel Abraising	Manual	65	60*area
3	Surface Inspection	Manual	10	5*area
4	Adhesion	Manual	65	direct inclusion
5	Vacuum Bagging	Manual	65	direct inclusion
5	Liner Placement	Automated	130	15*no of liners
5	Vacuuming	Automated	130	15*no of liners
6	Liner Refitting	Manual	58	6*no of liners+5
7	Curing	Automated Heating	282	direct inclusion
8	Visual Inspection	Manual	25	20*area
8	Ultrasonic Testing	Automated Machining	325	300*area+20
8	Laser Inspection	Automated	330	300*area+20
9	Installation	Manual	65	direct inclusion
10	Quality Assurance	Manual	25	20*area
11	Dispatch	Manual	35	direct inclusion

Appendix - G: Design Details for Case Study 3 & 4









Appendix - H: Expert validation & Feedback Form

H.1 Feedback Form of Expert 1

Expert Validation & Feedback Form

Your feedback is a part of expert validation which is to ensure that the work carried out is applicable to real life problems and is novel in nature. I would appreciate if you could take a few minutes to share your expert opinions about the work conducted. Your secrecy will be maintained and your name and signature are not required for the feedback.

Please return this form to the presenter at the end of the full presentation. Thank you.

Project title: Advanced Cost Models for Application in Composite Aero-Engine Components

Date: 21/09/2018 **Location:** Rolls-Royce Plc. UK **Presenter:** NIKHIL THAKUR

✓ Tick whichever is applicable	Strongly Disagree 1	2	3	4	Strongly Agree 5
1. The methodology design and structuring is logical	1	2	3	4	(5)
2. The system proves to be advanced and beneficial	1	2	3	(4)	5
3. The knowledge base created is flexible and maintainable	1	2	3	(4)	5
4. Inclusion of carbon footprint knowledge is logical and useful	1	2	3	4	(5)
5. The costing system is platform independent in nature	1	2	3	4	(5)
6. The estimates seem to be reliable in a variance of 0 - 15%	1	2	3	(4)	5
7. The designed system finds application in real life scenarios	1	2	3	4	(5)
8. The advanced costing system is unified with wide scope	1	2	3	(4)	5

9. Was this work, its application and results: ❑ simple ❑ intermediate ❑ advanced ☑ expert

10. In your opinion, what is the level of work: ❑ requires rework ❑ is capable ❑ is good ☑ is excellent

11. Please rate the following:

	Excellent	Very Good	Good	Fair	Poor
a. Research Thoroughness	☑	❑	❑	❑	❑
b. Methodology design	❑	☑	❑	❑	❑
c. Knowledge base created	❑	☑	❑	❑	❑
d. Tool development	❑	❑	☑	❑	❑
e. Application and Results	❑	☑	❑	❑	❑

12. What did you most appreciate/enjoy/think was best about the work? Any suggestions for improvement?

INTRODUCING THE CARBON FOOT PRINT CONCEPT INTO THE COST MODEL CONCEPT IS EXCELLENT AS IT BRINGS TO US A DIFFERENT WAY OF

1 | Page

CONSIDERING ENERGY + ENVIRONMENTAL COSTS. IT IS GOOD THAT A LIFE CYCLE APPROACH HAS BEEN TAKEN TO THE COST MODELS.

Your Background and Details

13. What is the name of the Organization you work for? ROLLS - ROYCE PLC
14. What is your current role in the Organization you work for? LEAD COST ENGINEER
15. How many years of professional experience do you have in this role? 15 years _______ months

This feedback has been taken for academic purposes only, nothing will be used for any professional activity. Your confidentiality is very important, hence, please don't write your name or sign anywhere on the document.

Thank you!
Please return this form to the presenter or coordinator at the end of the full presentation.

H.2 Feedback Form of Expert 2

Expert Validation & Feedback Form

Your feedback is a part of expert validation which is to ensure that the work carried out is applicable to real life problems and is novel in nature. I would appreciate if you could take a few minutes to share your expert opinions about the work conducted. Your secrecy will be maintained and your name and signature are not required for the feedback.

Please return this form to the presenter at the end of the full presentation. Thank you.

Project title: Advanced Cost Models for Application in Composite Aero-Engine Components

Date: 21/09/2018 **Location:** Rolls-Royce Plc, UK **Presenter:** NIKHIL THAKUR

✓ **Tick whichever is applicable**	**Strongly Disagree** 1	2	3	4	**Strongly Agree** 5
1. The methodology design and structuring is logical	1	2	3	4	(5)
2. The system proves to be advanced and beneficial	1	2	3	(4)	5
3. The knowledge base created is flexible and maintainable	1	2	3	4	(5)
4. Inclusion of carbon footprint knowledge is logical and useful	1	2	3	(4)	5
5. The costing system is platform independent in nature	1	2	3	4	(5)
6. The estimates seem to be reliable in a variance of 0 - 15%	1	2	3	(4)	5
7. The designed system finds application in real life scenarios	1	2	3	4	(5)
8. The advanced costing system is unified with wide scope	1	2	3	4	(5)

9. Was this work, its application and results: ☐ simple ☐ intermediate ☑ advanced ☐ expert

10. In your opinion, what is the level of work: ☐ requires rework ☐ is capable ☐ is good ☑ is excellent

11. Please rate the following:

	Excellent	Very Good	Good	Fair	Poor
a. Research Thoroughness	☐	☑	☐	☐	☐
b. Methodology design	☑	☐	☐	☐	☐
c. Knowledge base created	☐	☑	☐	☐	☐
d. Tool development	☐	☑	☐	☐	☐
e. Application and Results	☑	☐	☐	☐	☐

12. What did you most appreciate/enjoy/think was best about the work? Any suggestions for improvement?

CUTTING OIL TO BE ACCOUNTED FOR IN CARBON FOOTPRINT
3D PRINTING TECHNOLOGY TO BE INCLUDED.
PIZZA BREAKDOWN DEFINITION EXCELLENT.

1 | Page

Your Background and Details

13. What is the name of the Organization you work for? Rolls Royce Plc.

14. What is your current role in the Organization you work for? Cost & Value Engineer

15. How many years of professional experience do you have in this role? 26 years 0 months

This feedback has been taken for academic purposes only, nothing will be used for any professional activity. Your confidentiality is very important, hence, please don't write your name or sign anywhere on the document.

Thank you!

Please return this form to the presenter or coordinator at the end of the full presentation.

Special Thanks

- Kashmir Singh Thakur
- Vaishali Thakur
- Sahil Thakur
- Dr. Apurva K. Sinha
- Dr. Nikita Thakur Sinha
- Aniket Sinha
- Yogender Singh Dhariwal
- Sheela Dhariwal
- Shilpa Dhariwal
- Sumeet Dhariwal
- Shelly Dhariwal
- Sandhya Bisht
- Prof. Michal Krzyzanowski
- Prof. Ilias Oraifige
- Dr. Pathmeswaran Raju
- Prof. Craig B. Chapman
- Dr. Phani Chinchapatnam
- Dr. Stuart Jinks
- Rolls-Royce Plc.
- Birmingham City University