# Logical Knowledge-based Advanced Cost Estimation Methodology (LKACEM) Applied to Metal Matrix Composite Aero-Engine Blisk

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## 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.

## Keywords
Cost Estimation, Composite Materials, Cost Models, Knowledge Automation and Knowledge Management.

## Nomenclature:
ABC: Activity-Based Costing
LKACEM: Logical Knowledge-Based Advanced Cost Estimation Methodology
CAD: Computer Aided Design
CBS: Cost Breakdown Structure
CER: Cost Estimation Relationship
KBE: Knowledge-Based Engineering
KM: Knowledge Management
MMC: Metal Matrix Composite
MTM: Method Time Measurement
NASA: National Aeronautics and Space Administration
OOA: Out-of-Autoclave
PCAD: Process Cost Analysis Database
SEER-DFM: Software Evaluation and Estimation of Resources - Design For Manufacture
SUV: Sport Utility Vehicle

## I. Introduction
As composites have become a choice for many designers, engineers and project planners for use in structural and non-structural parts, their in-depth study has become important. Detailed analysis of the material properties and material mixtures were carried out for polymer automotive composites, which revealed that for detailed study and analysis of composites, sufficient design data, complete material database, analytical models and cost durability information is very important [1]. Some of the design softwares like ANSYS, have introduced properties of composites in their library of materials. Hence, a considerable amount of work has been done on mechanical properties of composites with certain ongoing improvements/advancements [2]. However, cost related study for composites has not been carried out to that extent. The application of composites in aerospace and that too in aero-engine components has open a new field all together. Cost estimation is a very important tool for process and project management and also used for design and analysis of the product. In case of conventional materials there are vast majority of cost models and tools which still need improvements. For their use in composites, they have not yet been modified. Some work has been done in case of a specific composite material and a specific process but still there is a strong need to develop a cost estimation method for composites as a whole [3]. Single unified system having the capability of handling different composite materials and different processes needs to be developed.

To develop any costing method or any management method as a whole, proper knowledge management is necessary [4]. Vast number of choices in material orientation and selection followed by complex and independent manufacturing methods make capturing and utilising the composite knowledge difficult. There is also lack of logics due improper cost driver information for composites. This paper proposes a mathematical set theory-based advanced costing methodology which uses a logical structure for knowledge management to capture, refine and keep knowledge in a set form. This knowledge structure is coupled to mixed methods of cost estimation chosen to be ABC and Parametric to form an advanced costing system. The scope of knowledge, information and data extraction is kept as wide as possible, hence the methodology utilises the entire product's life-cycle. Another inclusion to the knowledge is the inclusion of carbon footprint knowledge which runs parallel to the entire life-cycle. This way the entire methodology is structured and utilised for cost estimation

 

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that can work for both composite and conventional material parts. In the second phase of this paper, the developed methodology is validated for usage, flexibility and complexity utilising a MMC Blisk which is derived from different sources, such as NASA reports, composite files and other open source thesis/literature. For the validation purposes a factory cost model is prepared in two different softwares namely, Vanguard SystemTM Cost Estimation Software and MS Excel Software. Finally the paper compares factory cost output from the two softwares by analysing the percentage difference in cost predictions which further validates the methodology.

## II. Knowledge Management

KM is very effective in increasing the efficiency of a process or a project. To achieve competitive advantage many companies use KM at an early stage of product/project development. The research was conducted on the effectiveness of KM using various variables, namely (i) Capabilities, (ii) Processes and (iii) Performance. A hypothetical relationship was developed among the variables and then tested in different scenarios. Both questionnaire based study and data collection were adopted from randomly selected 74 companies. The measurement criterion was customer performance and financial performance. It was found that KM plays a very important role in shaping the overall effectiveness of an organisation as a whole and implementing it early in the process could make the processes numerically traceable [5]. The only drawback is that time lag has not been taken into account. Thus, the research is not precise in terms of variable values. Another important use of KM is related to organisational process planning and management. It has been observed that in order to take full advantage of the knowledge value, different phases of KM should be effectively executed. The phases are, (i) Creation of knowledge, (ii) Management of knowledge, (iii) Sharing of knowledge and (iv) Utilisation of knowledge. It has also been observed that, if there is an increase in accuracy of the knowledge that is available with a manager on a particular project or a process, better project management is achieved [6]. KM strategy is used effectively to solve this problem to a great extent but still needs improvement. In a process of product development that requires planning, designing and execution, co-ordination plays a very important role. The research work has been conducted to investigate the interrelationships of various processes in product development, in which principles from a complex system, whose parts behave differently, were used to find out the ability of standardised interfaces in a product development process [7]. Hierarchical co-ordination is created using modular product architecture to achieve modular organisational design. Loosely coupled design decomposition is found to be a good method of breaking the problem into a simplistic form. It has also been found that standardising interfaces achieved from a perfect knowledge management strategy in modular system architectures may provide flexibility and inter-organisational connectivity in a design process [7]. A question based survey conducted in the European manufacturing industries show highlights, that, companies both big and small have knowledge scattered in structured and unstructured form. The ability to design new products and market them depends upon identifying and utilising knowledge in a proper way. The findings from this survey revealed some major problems, namely (i) Difficulty in capturing knowledge (51% share), (ii) Lack of proper communication of knowledge (55% share) and (iii) Ignorance of the extent of knowledge already available (52% share). Thus knowledge management strategies are important for the proper flow of the knowledge. However, there is a drawback associated with openly flowing knowledge. This drawback is loss of intellectual property but, if these strategies are not used effectively a greater risk is there, which less innovation in products and companies is getting out of competition altogether [8]. Considering various issues in effective KM, a study revealed need for development of a Next Generation Knowledge Management system [9]. In this work, a comprehensive study was made on the existing KM processes and more emphasis was given to intellectual property, communication and codification problems. The following aspects, namely (i) knowledge process and (ii) knowledge model, which were considered different, were incorporated as a single entity. A demand-pull management philosophy was utilised in development of this Next Generation Knowledge Management System. This system comprises of the following themes: (i) strategic focus, (ii) use of information technology, (iii) use of knowledge models, (iv) use of historical knowledge to create new, (v) collaborative knowledge flow and (vi) intellectual asset management [9]. Although this study presents a system as theoretically viable, the same has not been properly validated or tested in a realistic problem. In the field of KM in composite materials, GRANTA MI: COMPOSITESTM is one of the best available tools [10]. This has become a standard in many companies for managing complex composite information. It includes a materials' database coupled to an industry database, which work together to solve a particular problem. The system proves to be efficient in data handling and error reduction [10]. A drawback with this tool is that it is concentrated towards the mechanical behaviour of the material and therefore cannot be used for financial product or project planning.

It can be concluded that knowledge management has many benefits when it comes to knowledge keeping and utilisation. It also provides a standardised structure for knowledge keeping that can be coded for reuse in different ways. These benefits when combined with existing KBE techniques, can be utilised for structuring cost knowledge. This way a proper knowledge base is created that can be made logical by utilising cost rules and relationships. Thus knowledge-based engineering & management is chosen for this research.

## III. Cost Estimation in Composites

Composite materials being complex in their structure and design possibilities makes cost estimation a tedious task. Cost estimate is also both difficult and uncertain in many respects. There are a number of techniques used for Cost Modeling in a composite material manufacturing. Process-based manufacturing and assembly cost modelling tool uses a predefined sequence of manufacturing processes and sub-assemblies [11]. Different scenarios in a manufacturing process are mapped in order to estimate the time. It is assumed that time is driven by geometry parameters and hence cost estimate could be carried out. Computer aided process planning automatically or semi-automatically enlists the manufacturing processes, which when coupled to artificial intelligence method estimates costs. Non-Discrete cost estimation method on the other hand works on the principle of assigning simple cost models to existing optimisation problems. In such a way simplistic design problems could be easily associated with cost. Feature-based design methodology uses design features from CAD model and links them with related manufacturing knowledge to predict the manufacturing features and then the related manufacturing cost. Another type of a cost estimation method is The Process Link Program, where PCAD is directly linked to the CAD model. Manufacturing features are defined by user and costing is automated using querying technique from external database to have cost estimates [11]. The major drawback is that the methods are either process specific or design specific making it difficult to generalise for varying scenarios. It has been discussed in one of the research that, manufacturing cost estimates in the case of composites is a blend of science of statistical relationships and the art of precise cost prediction. In the research it has been highlighted that a manufacturing cost estimate should contain six different cost values namely, (i) cost of the matrix and the reinforcement, (ii) supply cost, (iii) cost of labour, (iv) cost of tools, (v) rate at which production takes place and (vi) cost of equipment's/machines [12]. As manufacturing cost is just a part of the overall cost share, other processes needs to be analysed for a perfect estimate of the cost of a product. One of the major cost drivers in case of composite manufacturing is the complexity in the design. This complexity makes it difficult to estimate cost. One of the simplest methods for cost estimation in such a scenario is 'Advanced Composite Cost Estimating Manual Program.' The method being an empirical method, contains variables that lack physical significance to a product or a process and hence is not accurate. The complexity related to layup, bonding or vacuuming involves lot of variables. In order to overcome such problems a MTM approach is used. This technique is used to find the fabrication time and then the cost. The procedure uses the principle of breaking the design into acceleration and deceleration motion patterns which then map the entire design in terms of time required to complete the acceleration and deceleration tasks. Finally the type of motion is converted to time and then to cost [13]. The method is easy to overcome complexity but not so precise. Another method applied to composite materials is SEER-DFM, a process specific cost estimation model [14]. It is a detailed model where the design is not the criteria for cost calculation but the entire process of manufacturing is utilised. Parametric costing method is used to generate the relationships between the cost drivers in that process. This way a considerable amount of detailed analysis could be carried out. This method has been applied to composite servo piston and SUV fender [14]. The manufacturing process chosen for analysis was fabrication and hence most of the variables for parametric relationships were also from the same process. This method showed that cost could be considered as a design variable and applied to the process directly during manufacturing [14]. Being just applied to one manufacturing process, the technique still needs study and improvement.

Cost analysis is important not only for predicting the viability of the product but also to do detailed study for proper planning. A study was conducted on a composite material part made by using a widely used method, 'Autoclave' and then, it was compared to Out-of-Autoclave method. In this study complexity of the part was increased by (i) using an L-shaped design for making design complex and (ii) using convex and concave moulds for increasing the manufacturing complexity. CBS of the detailed process was made and then analysis was done using both microscopic and macroscopic approaches. Total cost was then the summation of a number of independent components namely, (i) cost of material, (ii) cost of cutting and laying up and (iii) equipment cost including cost of electricity used [15]. From this analysis it was made clear that OOA processes are less costly in production but initial material cost is high. Also it was observed that doing processes parallel, will decrease production time and hence cost. Thus cost estimation is a good tool for decision making in product design and manufacturing. Carbon fibre composites are one of the materials widely used for manufacturing of engineering parts. This material has a high demand in fields like automotive, aerospace and sea. With the advancement in automation techniques and their use in manufacturing carbon fibre material parts, the processes are becoming cost effective. New automation techniques developed in processing of raw materials and finished product has made the process cheaper than before. Use of robotic machinery to do tedious and labour intensive jobs followed by non-destructive testing are all contributing to make carbon fibre best for engineering use in terms of advanced composite materials [16]. Though the material has been made cost effective to certain extent but, proper cost estimation is required to have precise analysis so that new inventions could be carried out.

It can be concluded that proper cost estimation is required for analysis and project/process planning. For composites, there are no modifications done in the existing techniques and the one that have been developed are still incomplete. To develop an advanced costing solution, the existing techniques can be modified and coupled to KBE techniques that can utilise the benefits from both the realms and hence increase the current capability of cost estimation.

## IV. Development of a Logical Knowledge Management System

For solving the problem of cost estimation it is important to develop a knowledge-based system for knowledge acquisition and knowledge keeping. For achieving this the development phase is carried out which uses a generalised product's life-cycle for defining the scope of knowledge, information and data extraction. Carbon footprint knowledge is an added scope which runs parallel to the entire life-cycle. This extracted knowledge is kept in a standardised format which is chosen to be mathematical set-based, being one of the best methods to make the knowledge base logical. This type of structuring not only makes the knowledge manageable and logical but also platform independent in nature and hence can be coded using any software or language available today. The development phase is explained in detail.

### A. Introduction to 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 [17]. 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 [17]. 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 and (v) Other sub-sets. Another property of the set is that it can be empty/null, finite and infinite valued [18]. These properties of the sets makes 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 1 and have been utilised to develop cost knowledge sets for this research work [18].

  

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Table 1: Basic Rules and Notations in a 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<br>B ? C |
| 4. | Does Not Belong TO | If the elements are not contained in a set | d ? A |
| 5. | Empty set | When there are no elements in a set | Ø = {} |
| 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}<br>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}<br>If y ? A, y+2 ? A |
| 9. | Identical Sets | If elements of two sets are same | Y ? A and y ? B<br>A=B |
| 10. | Proper Subset | When the elements of one set is contained in another but not equal | A ? B<br>A = {1,2,3}<br>B = {1,2,3,4,5,6} |
| 11. | Subset | When the elements of one set are contained in another | A ? B<br>A = {1,2,3}<br>B = {1,2,3} or B = {1,2,3,4,5,6} |
| 12. | Power Set | Set containing all subsets of a set | *P*(A)<br>If A = {1,2}<br>Then *P*(A) = {Ø, {1}, {2}, {1,2}} |
| 13. | Union Operation | Elements of two or more sets combined together in one set | A ? B<br>If A= {1,2} and B = {2,3}<br>Then A ? B = {1,2,3} |

### B. Composite Knowledge Sets

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, makes estimation work difficult. A more logical format for knowledge capture and management is required, which can be utilised 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 as follows:-

1. **Material Knowledge Set:** Represented by M, is the set containing all the information regarding purchase methods and availability of the composite materials.
2. **Design Knowledge Set:** Represented by D, is the set containing information on design cost, based upon the design attributes for a particular part.
3. **Method of Manufacturing Knowledge Set:** Represented by MOM, is a set containing information regarding material related MOM and the cost related to each MOM.
4. **Machine Knowledge Set:** Represented by Mc, is the set containing all the information regarding machines required for each MOM and the tools required for each MOM followed by their price.
5. **Labour Knowledge Set:** Represented by L, is the set containing information on labour requirement per MOM and the labour price.
6. **Quality Control Knowledge Set:** Represented by Q, is the set containing information on quality assurance required per MOM and the total quality price per MOM.
7. **Scrap Knowledge Set:** Represented by S, is the set containing information on scrap produced per MOM.
8. **Material Handling Knowledge Set:** Represented by Mh, is the set containing information on the price and type of material handling required per MOM.
9. **Maintenance & Repair Knowledge Set:** Represented by Mr, is the set containing information of maintenance and repair prices which are calculated based upon the type of material and the MOM.
10. **Overhead Knowledge Set:** Represented by O, is a set containing information on the cost of overheads.
11. **Transportation Knowledge Set:** Represented by T, is the set containing information on the type of transportation required for each product and the material.
12. **Carbon foot print Knowledge Set:** Represented by C, is the set containing all the information regarding energy consumption and price per MOM and material.

### C. Mathematical Representation of Composite Knowledge Sets

Composite knowledge sets are represented in a mathematical form using general rules as described in Table 1. The representation is described in Table 2.

Table 2: Mathematical Representation of Knowledge Sets

| Sr. No. | Set Description | Mathematical Representation |
|---|---|---|
| 1 | Universal Knowledge Set | U = {M,D,MOM,Mc,L,Q,S,Mh,Mr,O,T,C} |
| 2 | Material Knowledge Set | M = {Material Type, Purchase Method, Purchase Price} |
| 3 | Design Knowledge Set | D = {Material Type, Design Specifications, Volume of Design, Design Price} |
| 4 | Method of Manufacturing Knowledge Set | MOM = {Material Type, Manufacturing Methods, Cycle Time, MOM Price} |
| 5 | Machine Knowledge Set | Mc = {Machines Required, Tools Required, Machine Price, Tools Price, Idle Price} |
| 6 | Labour Knowledge Set | L = {Labour Required, Hours Consumed per MOM, Labour Price} |
| 7 | Scrap Knowledge Set | S = {Manufacturing Scrap, Assembly Scrap, Testing Scrap, Quality Scrap, Dispatch Scrap} |
| 8 | Quality Control Knowledge Set | Q = {Quality Assurance Required, Time consumed per MOM, Quality Price} |
| 9 | Material Handling Knowledge Set | Mh = {Material handling Required, Time Consumed, Handling Price} |
| 10 | Maintenance & Repair Knowledge Set | Mr = {Service Price, Overhaul Price, Repair Price, Disposal Price} |
| 11 | Overhead Knowledge Set | O = {Accounting, Advertising, Insurance, Interest, Legal fees, Rent, Taxes, Travel, Misc} |
| 12 | Transportation Knowledge Set | T = {Material Incoming Price, Product Outgoing Price} |
| 13 | Carbon Foot Print Knowledge Set | C = {Energy Consumed, Energy Wasted, Usage Carbon Price, Disposal Carbon price} |

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 area of research is concentrated to composites and cost estimation techniques, thus the elements of the sets are chosen to accommodate that. This method can be applied to other fields as well by changing the elements.

### D. Application of Knowledge Sets in Cost Estimation

The knowledge sets created can be utilised for cost estimation making it faster and manageable. For this, three basic types of cost estimations are chosen, namely (i) life-cycle cost, (ii) factory cost and (iii) unit 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 performance. It consists of both recurring and non-recurring costs [19]. 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 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 utilised to run a factory for a particular product [20]. 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 of that single unit. Mathematically it is summation of, variable, fixed and overhead cost and dividing it by the total number of units produced [21]. From the definition, the three costs can be broken down as shown in Figure 1, Figure 2 and Figure 3 respectively [19-21].

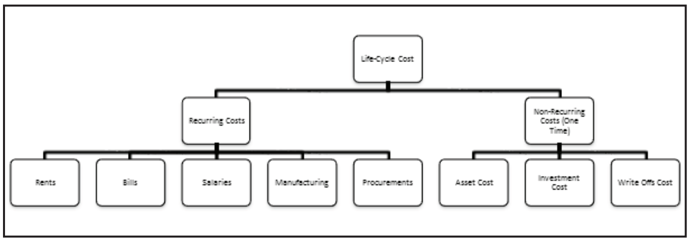


Fig. 1: Life-cycle Cost Structure

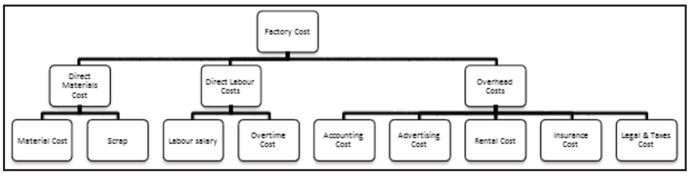


Fig. 2: Factory Cost Structure

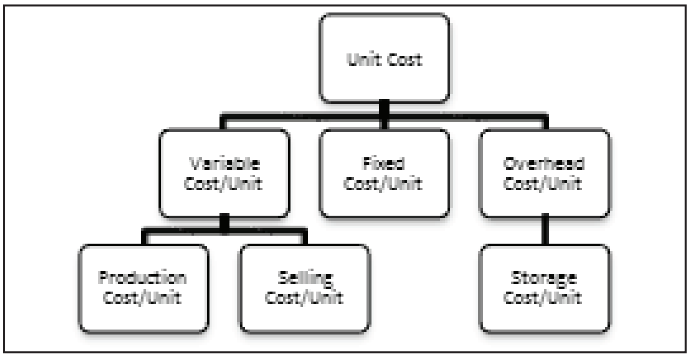


Fig. 3: Unit Cost Structure

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 utilised 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 localised 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. These cost sets are represented in a mathematical form as shown in Table 3

Table 3: Mathematical Representation of Cost Knowledge Sets

| Sr. No. | Set Description | Mathematical Representation |
|---|---|---|
| 1 | Factory Cost Knowledge Set | Fc = {M ? L ? MOM ? O ? S ? C} |
| 2 | Life-Cycle Cost Knowledge Set | Lc = {*P*(U)} |
| 3 | Unit Cost Knowledge Set | Un = {Lc/Total Units Produced}<br>Or Un = {(*P*(U)}/Total Units Produced)} |

The mathematical representation of the cost knowledge sets is used to link the knowledge sets with the type of cost required. Different costs require different knowledge sets and hence 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. The understanding that has been developed makes knowledge management logical and highly usable for cost estimation. Not only this, utilising 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 particular sets. Thus, this system can understand the linkages between knowledge elements and can manage cost driver information as groups. This linking of the sets can be visualised in a graphical manner as shown in Figure 4.

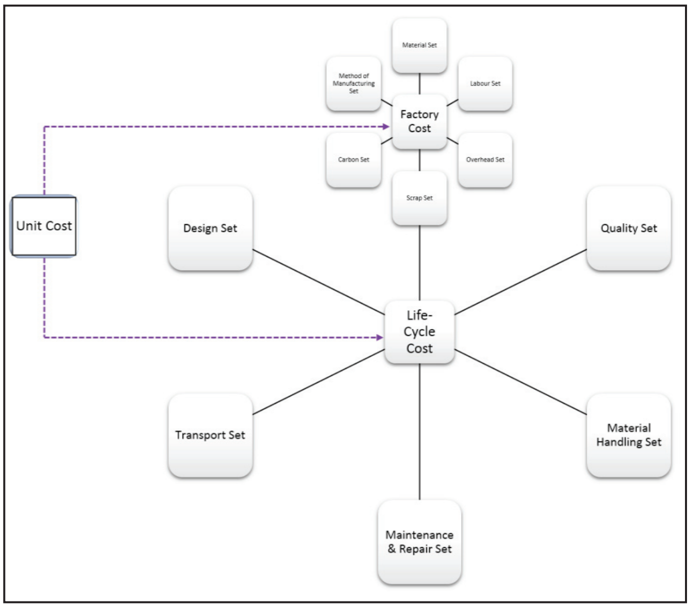


Fig. 4: Cost & Knowledge Set Interaction

From the figure it can be clearly seen that when life-cycle cost is required as an output, whole knowledge base is engaged and

  

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when factory cost is required six knowledge blocks out of eleven are engaged. However, 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 first part of the methodology.

## V. Logical Knowledge-based Advanced Cost Estimation Methodology (LKACEM)

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 utilising KID based upon this generic composite 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 KBE techniques. This is then followed by developing a cost modelling technique which is a mixture of two basic cost estimation methods, namely (i) ABC and (ii) Parametric. After using case studies for validation and simulation, outputs are displayed in a user friendly manner. The methodology is schematically presented in Figure 5.

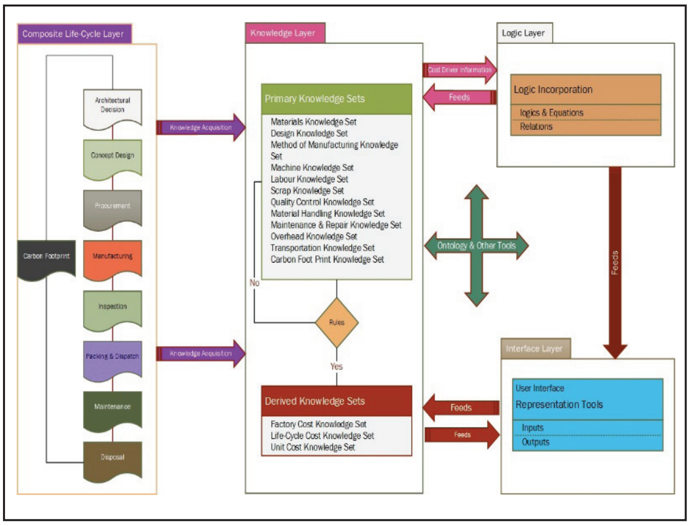

Fig. 5: Schematic Representation of the Methodology

The methodology is divided into four layers. These layers are joined by linkages which control the flow of knowledge/information/data. The four basic layers of this methodology include: (i) composite life-cycle layer, (ii) knowledge layer, (iii) logic layer and (iv) interface layer. The linkages that join these layers include, (i) knowledge acquisition, (ii) cost driver information, (iii) feeds and (iv) tools. To understand the methodology in detail it is important to understand the individual roles of the layers.

### A. Layer 1: Composite Life-Cycle 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. Carbon footprint is taken parallel to the entire process cycle. The concept here is very simple that every product has to undergo from various steps of a cycle. This layer is very important layer in the methodology as the knowledge related to different cost aspects are acquired from these processes to form the base 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 properly 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. Carbon footprint has also been found to be very important in cost contribution. Not only because green technology will become very important in the future, but, also because of the fact are that energy prices increasing. All the energy utilised 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 [22].

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 utilising 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. In the composite material realm as well all the cost related information is picked to be utilised in the next layer.

### B. 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 kind of material or any kind of design requirement, basic knowledge blocks are required. These knowledge blocks are divided into knowledge sets so that the required information becomes manageable. Currently Microsoft Excel Software is used for ease of understanding and fast reference of the knowledge representation and management, but, this can be done by using any other software or programming language and can also be done by utilising 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.

Primary knowledge sets is in other words the universal set 'U', 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 utilises basic definitions and general requirements necessary for generating the three basic types of cost, namely (i) Life-cycle, (ii) Factory and (iii) Unit cost 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 brain of this layer 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 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 modeled using this method in a very efficient manner, thereby reducing time and effort.

### C. Layer 3: Logic Layer

It is the physical world of the methodology where information from different sets are actually coded. Here 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 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.

### D. Layer 4: Interface Layer

This layer is the final layer where actual data is feeded 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 utilised 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 interface can be as simple as using Microsoft 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.

## VI. Metal Matrix Composite (MMC) Case Study

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 set-based representation of knowledge and its utilisation 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. This case study is thus divided in sections which describe the case, implement LKACEM, generate outputs and compare results, as discussed in sections to follow.

### A. Metal Matrix Composite Case Study Description

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. 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 6 (a,b) represents blisk design [23].

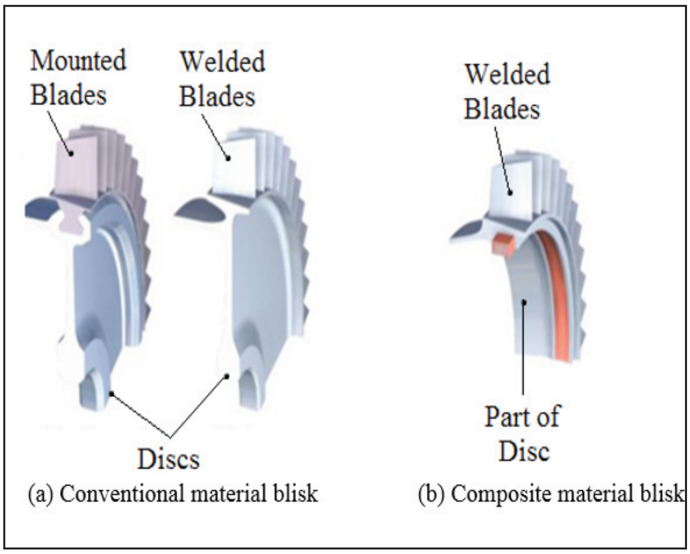


Fig. 6: Blisk Design [23]

The data and process parameters including the process breakdown is taken from previous used cases, NASA files and literatures. 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. Units are omitted from the values so that the logic remains undisturbed. The 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 and 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. Metal Matrix Composite 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 analysis. For the development of the cost model Microsoft Excel and Vanguard SystemTM Cost Modeling are used independently. Microsoft Excel being the simplest and easiest way to represent data is used to keep data in a statistical format (Sets), also it is used to capture general rules relating to the cost parameters and then apply LKACEM for cost estimation. Vanguard SystemTM 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 [24]. 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 generalised form of the actual process for a Metal Matrix Composite 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 Figure 7 which will form the layer 1 of the methodology in both cases.

  

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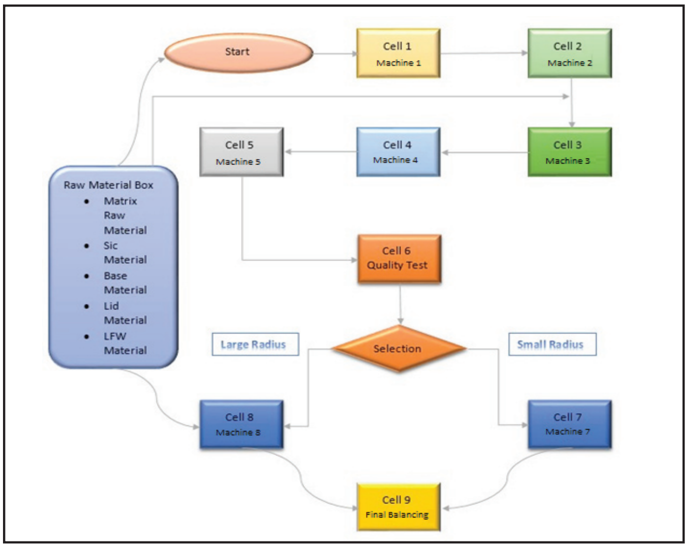


Fig. 7: Generic Process Chart for MMC Blisk Manufacturing

### B. Factory Cost Model for MMC Using LKACEM in Vanguard SystemTM Cost Modeling Software

From Figure 7 (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 cost related information in a tabular manner which is utilised 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. The layer 2 so generated is represented in Figure 8.

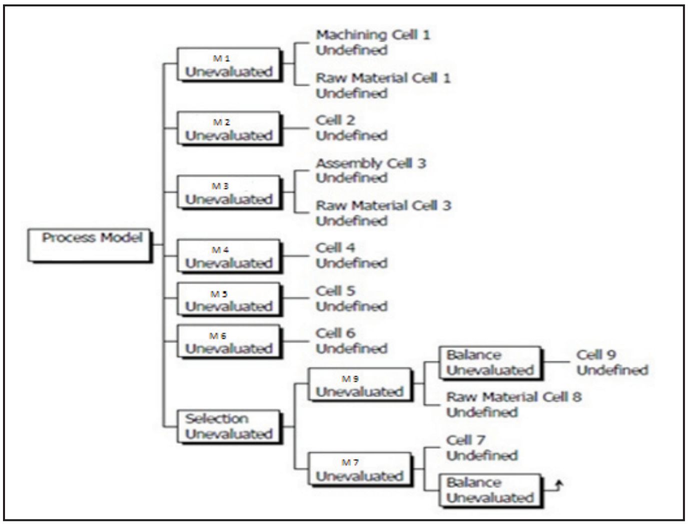


Fig. 8: MMC Blisk Manufacturing Process Model

The process model is derived from set theory based knowledge system and thus represents the knowledge sets necessary for inclusion in the factory cost. 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 decided. Now the entire model is given input values from the data table which when run generates output cost estimations forming layer 4. This way the entire complexity related to the blisk design problem is broken down into simple steps and addressed by this system of cost estimation. Thus the development of 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 the Vanguard generated tree structure. As the details are added to the nodes, detailed information related to cost drivers in all the process model's sub-divisions are added. This way a complete factory cost model is prepared. The developed model is shown in Figure 9.

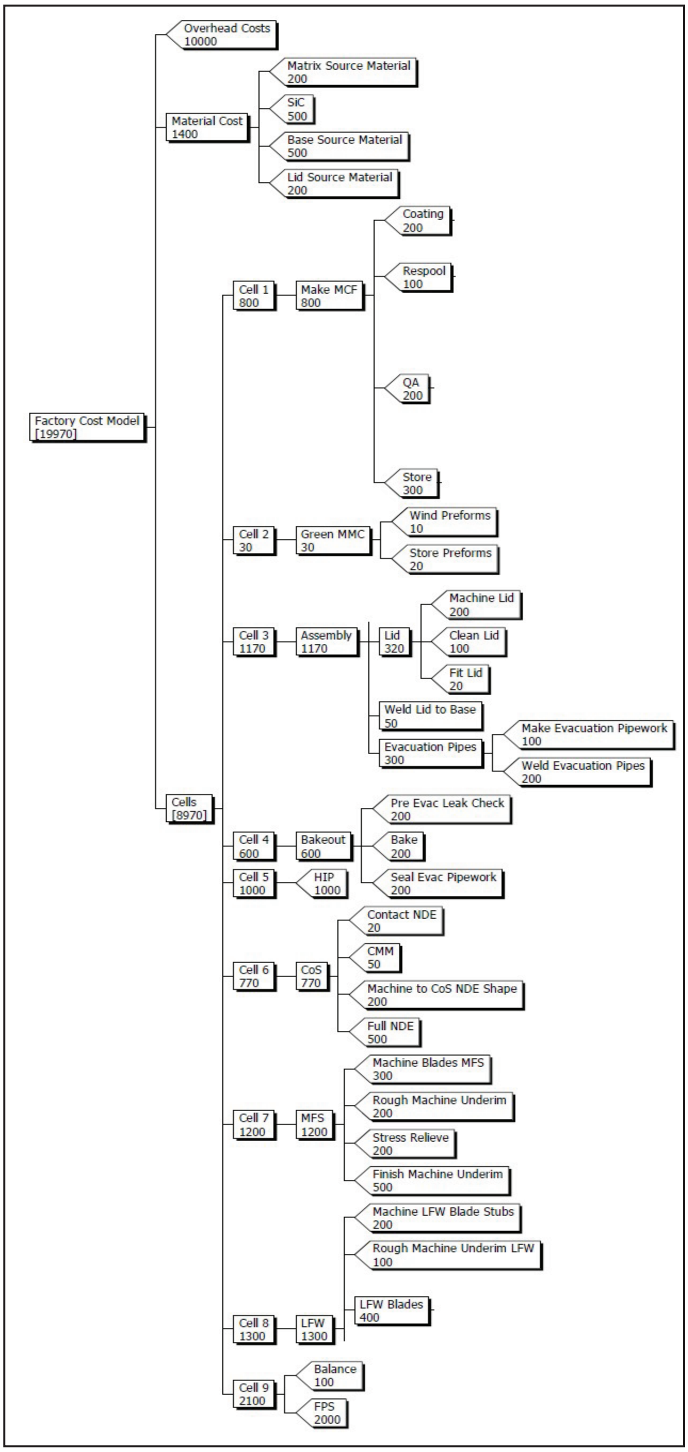


Fig. 9: MMC Blisk Factory Cost Model

For the ease of understanding and proper 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 advanced cost model can be compared to the other generated by a different software tool. The tabular representation is shown in Table 4 and Table 5. The input table being same will be used in the same form for the next study.

Table 4: Input Parameters of 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 5: Output Parameters of MMC Blisk Factory Cost Model

| 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 input and output 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.

### C. Factory Cost Model for MMC Using LKACEM in Microsoft Excel Software

The same method of cost estimation is now applied using Microsoft 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 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 4). 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 6. Layer 1 is same and is already represented in Figure 7.

Table 6: 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 Pipe | 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 cost sets only important for factory cost is taken for study by using the set formula from Table 3, which says that Factory Cost (Fc) = $\{M \cup L \cup MOM \cup O \cup S \cup C\}$. This then forms the Layer 2. Carbon Footprint (C) is not taken into consideration for the current study but will be included in the future work which is still ongoing. Next updation 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 of the KID from the parent knowledge set and converting it into process wise knowledge sets. The knowledge sets contain both cost driver information as well as sub-sets 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 7. From here all the related cost drivers are linked so as to function as a CER and become usable for predicting cost.

  

Table 7: 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 8. This is a part of layer 3. The complete set of logics is quite large so a representation of some important ones is made in the table.

Table 8: 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, layer 4 is completed using mathematical operations inside Excel. The logics are applied in the related cells of the table to calculate the output cost. The input parameters being same as in Table 4, is not represented again, whereas the output is shown in Table 9.

Table 9: Output Parameters from 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.

## VII. Analysis and Benefits of LKACEM

The results from this study can be summarised 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 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. 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 and the combined comparison as shown in Figure 10 (a), 10 (b) and 10 (c) respectively.

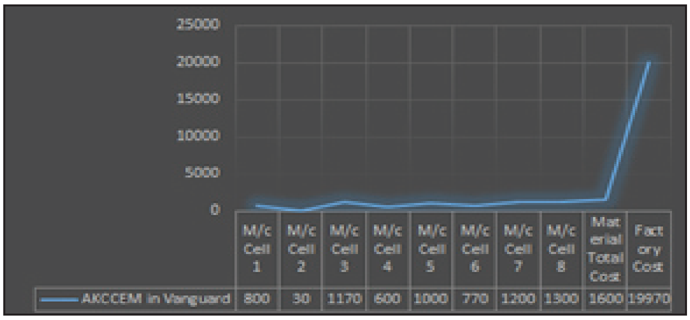


Fig. 10 (a): Cost Distribution Case 1

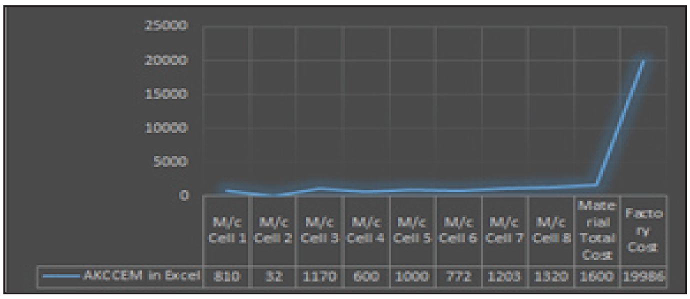


Fig. 10 (b): Cost Distribution Case 2

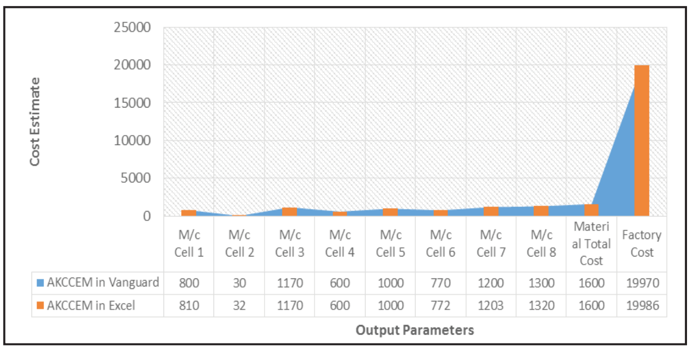


Fig. 10 (b): Combined Cost Comparison

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 11. When all the graphs are analysed the difference is found to be very small. Also the processes which show maximum difference indicate the amount of assumptions made and hence show need for more study for proper quantification of the same.

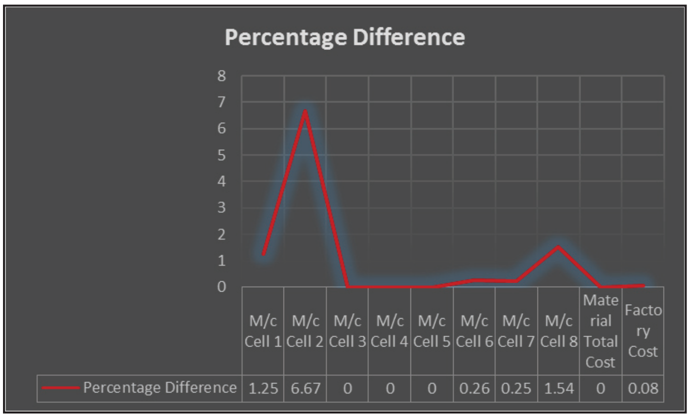


Fig. 11: Percentage Difference in Cost

The variation in the 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 in different software tools, can be used for composite cost knowledge management and is an easy step by step approach in modeling cost. In the future, this method can also be applied using ontology approach, making it applicable in cross platforms and also codable using different programming languages, hence automating the cost estimation process and providing an Advanced Composite Knowledge-Based Cost Estimation Tool.

## VIII. Conclusion

Cost estimation has always been an important part of a company as it is a tool which provides help in both project as well as process planning. It is also very useful in other management activities and for decision making. As such designers, project planners and managers require cost estimation well in advance to perform their function fully and to achieve innovative product design and manufacturing. It has been highlighted many times 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 has been other advanced cost estimation techniques using simple systems to complex artificial learning techniques, but, still problems highlighted above could not be solved. Moreover, in terms of composite material part application, these cost estimation techniques could not achieve good results. 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. Even the same application could not be achieved to this extent for composite material part.

The present study has been conducted concentrating on the area of composite material part cost estimation and develop an advanced cost estimation methodology. This paper highlighted the importance of knowledge management and its use in various processes. Then a need of having a proper knowledge management was also highlighted. Based upon the previous study and the gap areas a new set-based knowledge management applicable for composite material costing was proposed and discussed. This set-based method was utilised for the development of LKACEM. The methodology proposed being knowledge based and using cost logics was found to be more applicable in complex situations like composite material part cost estimation. To prove the working and analyse the methodology in detail a MMC-based blisk design was considered for case study. This case study being derived from industry-based open source data sources, was directly representing a real life scenario. LKACEM was then applied to the case study involving highly complex geometry and complex parameters in two different software tools. One being a simple but time consuming Microsoft Excel and another being complex but faster Vanguard SystemTM Cost Estimation. As the assumptions made in certain values were different for the two softwares there was a slight difference in the output costs, which being very small were neglected. The results have shown that this methodology seems acceptable in application to composite material part cost estimation and meets the above five parameters, which thus become its benefits. Ontology approach can be used for the development of the advanced cost estimation in future studies and thus will make it more flexible and applicable in different programmable language platforms. This will make the entire process more interactive and generic to all processes and product designs. Also by doing this the entire process will be automated, further reducing time and increasing efficiency.

## IX. Acknowledgement

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