A Task based Manufacturing Knowledge Maintenance Method

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A Doctoral Thesis

Submitted in partial fulfilment of the requirements
for the award of

Doctor of Philosophy of Loughborough University

April 2013

Loughborough
University

ABSTRACT

The effective use of computer based tools to support decision making in manufacturing industry is critical to business success. One of the most critical areas is during product design and especially in design for manufacture. This research will help in understanding of how manufacturing knowledge can be effectively maintained for an existing knowledge base. The work will use modern product lifecycle management tools in combination with a knowledge based environment in order to explore the effectiveness of the methods produced.

This work is a part of the SAMULET (Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies) research program and was done in association with an aerospace manufacturing company. The main focus of this research is to define a novel method for maintaining the machining knowledge associated with manufacturing of Xtra Wide Body **(**XWB) High Pressure (HP) turbine blade. The four main elements explained in this thesis are, a) the literature review done on knowledge management and knowledge maintenance, b) industrial investigation done on a manufacturing facility, c) detailed explanation of a novel manufacturing knowledge maintenance method d) four iterative case studies used for the evaluation and iterative improvement of the method.

The research concludes that the aspect of knowledge maintenance is important. It is imperative to set out a formalised and mandated knowledge maintenance process in an organisation to keep the knowledge up-to-date and relevant. It has been shown that a novel task based knowledge maintenance method comprising a Knowledge Maintenance Process (KMP) and a Knowledge Maintenance Template (KMT) provides an effective route to knowledge maintenance. Three maintenance tasks, check relevancy, knowledge filtering, and integrity checking have been considered in detail for successful knowledge maintenance. Four iterative case studies have been conducted for the experimental evaluation of the maintenance method. As the result of these evaluations a novel method for maintaining the machining knowledge of XWB HP turbine blade was defined.

ACKNOWLEDGEMENTS

First of all, I like to thank my supervisor Dr. Bob Young for choosing me as his PhD student and providing this wonderful opportunity. His continuous professional support and guidance are invaluable.

I would like to thank Liam Frazer and Guy Wells for continuously making all the arrangements for the induction, meetings and trainings in Rolls-Royce.

I am also thankful to David Hunt and Collin Taylor and all the associated Rolls-Royce engineers for providing timely support and encouragement for this project

I greatly appreciate the support given by Dr. Esmond Urwin. His professional help and friendship is so significant for my research work.

I thank all my colleagues at my research group Zahid, George, Imran and Tish for their friendly discussions, help and support throughout this research. I also wish to thank Sankar, Jaya, Pradeep, Subash and Ram for their support throughout my study. Friends like you are difficult to find.

Finally, this research work is funded by EPRSC in association with Loughborough University and Rolls-Royce, and is deeply acknowledged.

DEDICATION

This thesis is dedicated to:

My parents Govindan and Rajalakshmi, without them I won't be here in this position. The sacrifices they undergone throughout their life for me are myriad. I am so proud and happy to have them as my parents…I love you.

To my wife Lalitha, who has constantly provided me with her moral support and motivation throughout my research and beyond…MAD, I love you so much.

To my sister Menaka, brother-in-law Veeramani, and lovable nieces Samyu & Kani, who have provided me unconditional love and continuous support throughout my study…I am so glad to have you all with me

To God, thank you for giving me everything at right time…

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ABBREVIATIONS

AHP	-	ANALYTICAL HIERARCHY PROCESS
BPMN	-	BUSINESS PROCESS MODELING NOTATION
CAD	-	COMPUTER AIDED DESIGN
CAM	-	COMPUTER AIDED MANUFACTURING
CMM	-	COORDINATE MEASURING MACHINE
CP	-	PROCESS CAPABILITY
CPK	-	PROCESS CAPABILITY INDEX
EPSRC	-	ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL
FKRS	-	FEATURE KNOWLEDGE RELATIONSHIP STURCTURE
HP	-	HIGH PRESSURE
IC	-	INTELLECTUAL CAPITAL
ICT	-	INFORMATION AND COMMUNICATION TECHNOLOGIES
IT	-	INFORMATION TECHNOLOGY
IDEF	-	INTEGRATION DEFINITION FOR FUNCTION MODELING
IDEF0	-	INTEGARTION DEFINITION FOR FUNCTION MODELING 0 (0 - Part of IDEF family)
KBE	-	KNOWLEDGE BASED ENGINEERING
KBS	-	KNOWLEDGE BASED SYSTEMS
KIF	-	KNOWLEDGE INTERCHANGE FORMAT
KIM	-	KNOWLEDGE AND INFORMATION MANAGEMENT
KM	-	KNOWLEDGE MANAGEMENT
KMP	-	KNOWLEDGE MANITENANCE PROCESS
KMS	-	KNOWLEDGE MANAGEMENT SYSTEMS

KMT	-	KNOWLEDGE MAINTEANCE TEMPLATE
MFIKM	-	MANUFACTURING FACILITY INFORMATION AND KNOWLEDGE MODEL
MOM	-	METHOD OF MANUFACTURE
MRP	-	MATERIALS REQUIREMENTS PLANNING
OEM	-	ORIGINAL EQUIPMENT MANUFACTURER
PDM	-	PRODUCT DATA MANAGEMENT
PFMEA	-	PROCESS FAILURE MODE EFFECT ANALYSIS
PLM	-	PRODUCT LIFECYCLE MANAGEMENT
Pp	-	PROCESS PERFORMANCE
Ppk	-	PROCESS PERFORMANCE INDEX
RLEST	-	ROOT LEADING EDGE SEAL TIP
RTEST	-	ROOT TRAILING EDGE SEAL TIP
SAMULET	-	STRATEGIC AFFORDABLE MANUFACTURING IN THE UK THROUGH LEADING ENVIRONMENTAL TECHNOLOGIES
SCU	-	SUPPLY CHAIN UNIT
TB	-	TURBINE BLADE
TBF	-	TURBINE BLADE FACILITY
UML	-	UNIFIED MODELLING LANGUAGE
XWB	-	X-TRA WIDE BODY

CHAPTER 1 - INTRODUCTION

1.1 CONTEXT

The creation of a new product in manufacturing industry is a complex task, characterized by uncertainty and variability. It requires the cooperation of experts in different fields and the analysis of various aspects involved. Research has shown that up to 70% of a product's manufacturing cost is dictated by decisions made during the product design phase (Parsaei *et al*., 1996). Due to inherent complexity companies cannot achieve significant efficiency gains unless they provide a global workforce with streamlined access to highly technical information. This requires a unified content value chain, where information can be easily shared within and between relevant organisations (Documentum, 2004)

Owing to the growth of information and Internet technologies, knowledge management (KM) has gained more efficiency, accuracy and flexibility. Efficient knowledge construction, extraction and management have drawn attention in the knowledge-oriented business environment. Traditionally, most KM tasks are carried out by knowledge engineers or knowledge providers. As a result, much human effort is required and the management consistency cannot be guaranteed.

In a manufacturing environment with high product and process varieties, knowledge construction and maintenance become complicated. In recent years Knowledge Management Systems (KMS) have been used in the product development process to support manufacturing and design decision (Rezayat, 2000; Liu and Young, 2004). These systems utilise large amount of knowledge related to manufacturing and design activities. To keep a KMS fully functional and active over the period of time is a challenge. This may involve the regular updating of content as content changes. But it may also involve a deeper analysis of the knowledge content. Hence knowledge maintenance is vital and it is necessary for the continuous improvement of KMS. However there is a need to develop a method, which enables the knowledge to be readily maintained, assuring the long-term use of these systems.

Knowledge maintenance is the science of controlling change in a knowledge based system. More precisely, knowledge maintenance is the process of reflecting over some knowledge based system in order to handle a new situation (Menzies and Debenham, 2000). Knowledge maintenance is essential to ensure the continuous usability of knowledge.

This thesis defines a novel method for manufacturing knowledge maintenance, ensuring that knowledge already captured in a knowledge base is kept up-to-date. It details the significant maintenance tasks and its functions that need to be carried out on the knowledge for successful knowledge maintenance.

The knowledge needs to be maintained whether or not it is in a computational form. Due to this a knowledge maintenance template approach has been developed for the representation of information and knowledge. This template approach provides an easy and effective way to keep the knowledge up to date in a paper based knowledge base (KB). This thesis also defines a knowledge maintenance process and the actors involved. The process provides the flexible environment to add new knowledge and to modify existing knowledge in the KB.

This research work was done in association with an aerospace manufacturing company. The main focus is to define a method for maintaining the machining knowledge associated with manufacturing of High Pressure (HP) turbine blades. The initial understanding of product design and manufacturing was gained in the collaborative company. A novel maintenance method was defined based on three maintenance tasks and its functions. The key components of the method are a knowledge maintenance process (KMP) and a knowledge maintenance template (KMT). The maintenance method was evaluated based on four case study experiments and the results were incorporated to enhance the method.

1.2 Aims and Objectives

Aim:

The aim of this research was to explore and investigate the methods and techniques in manufacturing knowledge maintenance. This research defines a suitable method for maintenance of manufacturing knowledge such that it can be shared across design and manufacturing engineering disciplines.

Objectives:

a) To explore and identify the key maintenance tasks and its functions for an improved way of maintaining the manufacturing knowledge.

b) To define a novel manufacturing knowledge maintenance method based on the identified tasks.
c) To define a knowledge maintenance template for the representation of manufacturing information and knowledge.
d) To define a knowledge maintenance process and the actors involved for the performance of maintenance functions.
e) To design and build case studies for the experimental evaluation of the manufacturing knowledge maintenance method.
f) To test and evaluate the results achieved.

The above objectives give a high level view of the research work reported in this thesis. The details of the main research issues and the novel aspects of this research are explained in chapter 4.

1.3 Research Scope and Background

This research explores the maintenance of the manufacturing knowledge already captured in a knowledge base by keeping it up to date over a period of time. Manufacturing knowledge provides a very wide area for exploration and this research does not focus the whole range of manufacturing knowledge. The scope of the research is focused upon on the machining knowledge associated with turbine blades. Although other manufacturing knowledge influences the manufacturing of the blades, machining was considered to provide a sufficiently broad scope. Moreover the scope of the project was further refined to that of High Pressure (HP) Trent X-tra Wide Body (XWB) turbine blades.

This research scholarship grant was awarded by the Engineering and Physical Sciences Research Council (EPSRC). The work was part of SAMULET **(**Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies) project. This research was done in association with Rolls-Royce and focused on the machining of XWB HP turbine blades. The work of the research project was carried out by a Research Associate (Dr. Esmond Urwin) and by the author (Saravana Govindan), the focus of the former is on knowledge modelling and building up a knowledge base, whereas the latter's focus is on knowledge maintenance to provide a continuous improvement of knowledge base.

Figure 1-1 illustrates the research background of the project work. Knowledge modelling determines the capturing, structuring and representation of the knowledge. Knowledge maintenance provides a flexible environment to keep the knowledge up to date by adding new knowledge and by modifying existing knowledge.

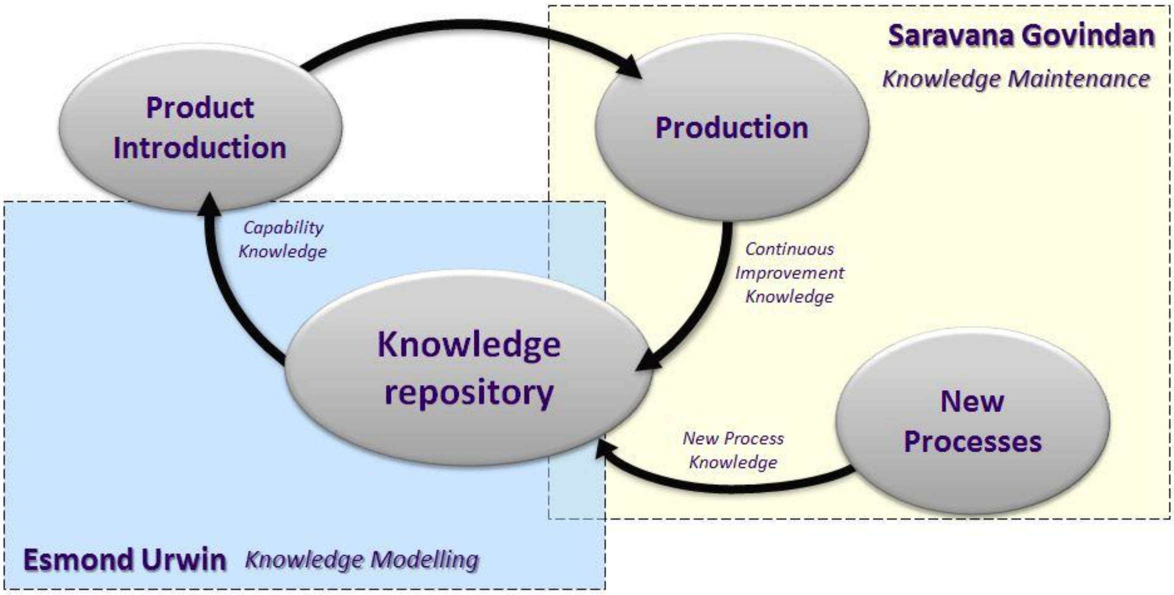


Figure 1-1: SAMULET 5.6.1 Research Background

The main objective of this whole research work is to define suitable method for the capture and maintenance of best practice manufacturing knowledge in an integrated, structures and accessible way such that it can be shared across design and manufacturing engineering disciplines.

1.4 Research Methodology

1.4.1 Introduction

This section explains the research methodology adopted in this research in detail. The choice of which research method to employ is dependent upon the nature of the research problem. (Morgan and Smircich, 1980) argued that the actual suitability of a research method derives from the nature of the social phenomena to be explored.

According to Creswell (2008), the knowledge claims, the strategies, and the method, all contribute to a research approach that tends to be more quantitative, qualitative or mixed. Based on the research context, the qualitative research method was found to be perfectly suitable. Among the strategies for the qualitative approach, the Grounded Theory (GT) method and case study method were chosen due to the iterative and exploratory nature of the research. Four iterative case studies were conducted for the evaluation of the method and a theory was developed based on the analysis of gathered data and information.

The detailed development of research method is explained in following subsections. Section 1.4.2 explains the research environment the research methods used. Section 1.4.3 details the case studies developed for this research. A summary is provided in section 1.4.4.

1.4.2 Research Environment

This research was based upon following main question, that being:

Within a commoditized approach how the manufacturing knowledge should be maintained?

A commoditized approach implies that the manufacturing methods for a range of parts remain largely consistent and that as a consequence, the manufacturing knowledge related to the commodity is worthy of capture as it can be reused in the design of other related parts in the commodity range.

When assessing the best approach to take for methodological development of the context at hand, it must be assessed for its key properties and then these must be weighed against whether the research approach rationale is a quantitative or qualitative one (Galliers, 1991).

Based on the understanding of the research context, the qualitative method approach (Creswell, 2008) was chosen. Due to the exploratory manner the research lent itself to a case study approach (Zhang *et al.*, 2009). To suit the research study and allow for development of theory during the data collection period, the Grounded Theory (GT) method (Glaser and Strauss, 1967; Turner, 1981) was found to be a perfect fit for the deductive and iterative nature of the proposed research. Linked with this, a number of case studies were created and undertaken to collect the necessary data and information for the purposes of analysis and deduction of the knowledge maintenance method. All these approaches collectively provided rich contextual viewpoints upon the phenomenon under study. The following section explains qualitative research method and its two key strategies (Case Study, Grounded Theory) in detail.

1.4.2.1 Qualitative Research Method

According to Anderson and Aydin (2005), the goal of qualitative research understands issues or particular situations by investigating the perspectives and behaviour of the people in these situations and the context within which they act. To accomplish this, qualitative research is conducted in natural settings and uses data in the form of words rather than numbers. Qualitative data are gathered primarily from observations, interviews and documents, and are analysed by a variety of systematic techniques. This approach is useful in understanding causal processes and in facilitating action based on the research results. In this research, the key properties of the research context were assessed in choosing the best approaches for the development of research methodology. Based on the understanding of the context and considering the research environment the best fit was a qualitative method with a logical viewpoint.

The strengths of qualitative research methods lie in their usefulness for understanding the meaning and context of the phenomena studied, and the particular events and processes that make up these phenomena over time, in real-life, natural settings (Maxwell, 2012). According to (Bitsch, 2005) the areas of application of qualitative approaches include: (a) the description and interpretation of new or not well-researched issues; (b) theory generation, theory development, theory qualification, and theory correction; (c) evaluation, policy advice, and action research; and (d) research directed at future issues. All these areas are applicable to this research and hence a qualitative method is used.

1.4.2.2 Case Study Approach

According to Yin (2008), 'case' refers to an event, an entity, an individual or even a unit of analysis. It is an empirical inquiry that investigates a contemporary phenomenon within its real life context using multiple sources of evidence. Case studies can involve either single or multiple cases, and numerous levels of analysis (Yin, 2008). Case study has been commonly used in social science fields like sociology, industrial relations and anthropology even though generally was considered an underutilised strategy.

Due to the exploratory manner of this research, a case study approach was chosen from the qualitative method. The case study approach allows us to retain the holistic and meaningful characteristics associated with organisational and managerial processes (Zhang *et al*., 2009). Case studies typically combine data collection methods such as archives, interviews, questionnaires and observations. The evidence may be qualitative (e.g., words), quantitative (e.g., numbers), or both. All these data collection techniques were used in this research, but the main techniques were interviews and questionnaires. Since this research is based on qualitative method, the evidences are in the form of words. In this research four iterative case studies were conducted for the evaluation of the knowledge maintenance method developed.

1.4.2.3 Grounded Theory

Grounded theory is a methodology of developing theories that are grounded in systematically gathered and analysed data. Data collection, analysis, interpretation and theory development proceed interdependently and iteratively. The Grounded theory (GT) method was found to be an effective methodology for the deductive and iterative nature of the research thesis (Glaser and Strauss, 1967; Turner, 1981). It suited well in this research for the development of theory through the analysis of knowledge captured.

Research questions were prepared based on the research statements, to understand more about the phenomenon under study. The questions were formulated so that they give the author the flexibility and freedom to explore the phenomenon in depth (Corbin and Strauss, 1990; Glaser, 1978). The data and information were generally collected by using interviews, observations, and from existing written documents (Chenitz and Swanson 1986; Corbin and Strauss, 1990; Glaser, 1978).The grounded theory literature (Chenitz and Swanson, 1986; Corbin and Strauss, 1990; Glaser, 1978) emphasizes the need to combine many data collection methods, however in this research interviews are mainly used as method for data collection.

The data collected were analysed simultaneously to determine the theoretical shape and to orient further collection of data. In this research, this approach was considered important for the development of theory. During the analysis, knowledge maintenance categories were identified and developed in terms of their properties and dimensions. It was developed through a process involving the generation of basic categories to describe features of the data and constant comparisons between cases, instances and categories.

According to Glaser (1978) there are essential factors to evaluate grounded theory. The theory must fit, have relevance and it must work. Fit refers to the categories of the theory that have a connection to the data. In this research, the results were validated by a group of expert engineers identified from the collaborative company. It was examined based on how it fits with current organisation process.

1.4.3 Case Study Development

The main focus of this research is to explore and define methods to support the maintenance of manufacturing knowledge. The manufacturing knowledge associated with XWB (X-tra Wide Body) High Pressure (HP) Turbine Blades (TB) was chosen for the development of the case study. To understand more about the research context and to know how blades are designed and manufactured, the data collected from the sponsor company were used. Aligned with this, a number of information sources were required so as to enable convergence of evidence (Zhang *et al*., 2009).The data sources for this case study were documents, drawings, interviews, observations and physical artefacts.

Interviews were used as the primary data gathering instrument in this research. A semi-structured interview was prepared, where the questions were carefully designed to provide adequate coverage for the purpose of the research. Major questions were developed in the form of a general statement which was then followed by a sequence of sub-questions for further probing. The questions were then piloted to the expert engineers identified from TB manufacturing, TB design, knowledge management and manufacturing communication. These engineers were selected from different departments based on their expertise in product, process and domain knowledge. Engineers were informed in advance to plan for the interviews. Based on their feedback necessary corrections were made and re-examined.

Four iterative case studies have been performed for the evaluation of knowledge maintenance method. Based on the case study results, a novel knowledge maintenance method was developed and different roles of people within the organisation who act on these methods were identified. The GT method was used to refine the research question and propositions as the study progressed. Utilising this method, the research methodology was improved for better knowledge maintenance.

1.4.4 Summary

The research methodology used in this research was explained in this section. The research environment and the research methods used were explained in the sub sections. Four iterative case studies experiments were performed (explained in chapter 6) for this research and based on the experimental results a novel knowledge maintenance method (explained in chapter 4) was defined for the XWB HP turbine blade.

1.5 The Structure of the Thesis

The structure of the thesis is organised into following seven chapters,

Chapter 1 provides the introduction to the research work, outlines the aims, objectives, research scope, and environment. It also explains the research methodology in detail.

Chapter 2 presents a comprehensive literature review of subject areas of related work. It provides an overview to knowledge management, modeling and maintenance of manufacturing knowledge and explains the main tasks of knowledge maintenance. It highlights the knowledge maintenance research gaps and current issues.

Chapter 3 discusses about the details of industrial investigation done on manufacturing knowledge maintenance in association with Rolls-Royce, Derby, UK. It explains the BPMN activity modeling done during the exploration phase of the research, relationships between manufacturing, design & inspection features, feature knowledge relationships and various knowledge sources identified.

Chapter ***4*** discusses the author's concept for a novel method for manufacturing knowledge maintenance to support knowledge sharing in product design and manufacture. This chapter also forms the base for the contents explained in of chapter 5 and 6.

Chapter 5 describes the detailed perspective of knowledge maintenance method against its key elements. All the key elements involved in the development of the maintenance method are explained.

Chapter 6 explains the four iterative case studies conducted for the experimental evaluation of maintenance method. As a result of these evaluations a novel method for maintain the machining knowledge of XWB HP turbine blade was defined.

Chapter 7 discusses the contribution of this research reported in this thesis. It presents the discussion of the major research issues explored as well as conclusions and the important recommendations of further work.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

This chapter presents a state-of-the-art literature review in the field of manufacturing knowledge maintenance. The individual sections present the main topics researched, related to the thesis. It also identifies the research gap and provides the justification for this research.

The literature review is divided into five sections. The section 2.2 provides an introduction to knowledge management. It includes the definition of data, information and knowledge and their differences. It explains the different types of knowledge. The section 2.3 details the use of knowledge management systems (KMS). The sub sections details the KM models, tools and technology and also explains the role of KMS in Product Lifecycle Management (PLM). The section 2.4 explains the concepts in manufacturing knowledge modeling and knowledge maintenance. The sub sections details the main aspects of manufacturing knowledge sharing. The section 2.5 explains knowledge maintenance and its processes. The section 2.6 provides the summary of the literature review and explains the research gaps.

2.2 Knowledge Management

2.2.1 Definition of KM

Knowledge Management (KM) means a systematic and organised attempt to use knowledge within an organisation to transform its ability to store and use knowledge to improve performance (KPMG, 1998). Another common definition is that KM is the collection of processes that govern the creation, dissemination, and leveraging of knowledge to fulfil organisational objectives it is an emerging set of principles, processes, organisational structures, and technology applications that help people share and leverage their knowledge to meet their business objectives. KM is not an end in its self. It is also fundamentally about sharing knowledge and putting that knowledge to use (Gurteen, 1999).

Jarboe and Alliance (2001) defined the general purpose of KM as, " It is a set of techniques, tools and activities focused on helping organisations capture and communicate their resources, tacit and explicit perspectives and capabilities, data, information, knowledge and maybe wisdom (competence)”. In a nutshell, the KM is the overall task of managing the processes of knowledge creation, storage and sharing and related activities.

KM is a mechanism that facilitates critical organisational process to support: a)innovation, the generation of new ideas, and the exploitation of the organisation’s thinking power; b) capturing insight and experience; c) the reuse sources of know-how and expertise; d) fostering collaboration, knowledge sharing, continual learning; e) improve the quality of decision making (Levett and Guenov, 2000)

KM is not a product in itself, or a solution that organisations can buy off the shelf or assemble from various components. It is a process implemented over a period of time, which has as much to do with human relationships as it do with business practice and information technology (Benjamins *et al*., 1998).

As Davenport and Prusak (2000) stated, knowledge is not something new; it has always been used and exchanged within the organisations. According to them, “what is new is to recognize knowledge as a corporate asset and to understand the need of managing it and involving it with the same care given when obtaining the value of other more tangible assets”. That is why organisations need to look for more structured approaches to KM in a way to make its members aware of the importance of organizing resources in order to obtain the value of knowledge.

Knowledge creation, utilization and management of knowledge are the core of the new product development process and are becoming the primary source of sustainable competitive advantage in an era characterized by the short product life cycles, dynamic markets and complex processes (Ramesh and Tiwana, 1999).The development of systems to assist in managing knowledge has been a topic of considerable interest and to capture, reuse, maintain and transfer knowledge are essential elements of such systems (Prasad, 2000; Staab *et al*., 2000). This is why it is important to move towards the definition and understanding of types of knowledge in the role of information systems in managing knowledge (Li and Gao, 2003)

According to last definitions it can be observed that innovation, knowledge models, creation, transfer, maintain and reuse are strong fundamentals of KM. However it is important to emphasize differences between data, information, and knowledge to determine manufacturing knowledge structures.

2.2.2 Data, Information and Knowledge

The concepts of knowledge, information and data are closely related. Although distinct, these three abstract concepts are often confused. As commonplace as the confusion of data and information is the confusion of knowledge and information, nurtured even by the prominent thinkers, who themselves pioneered the idea of information-based organisations (Kock *et.al*., 1996).

Knowledge is a complex and multifaceted concept and several different authors have studied the knowledge in KM, however they found relevant differences between data, information and knowledge (Guerra-Zubiaga *et.al.*, 2006). So it is important to explain the concepts of data, information and knowledge at the beginning. Figure 2-1 explains the connection between data, information and knowledge.

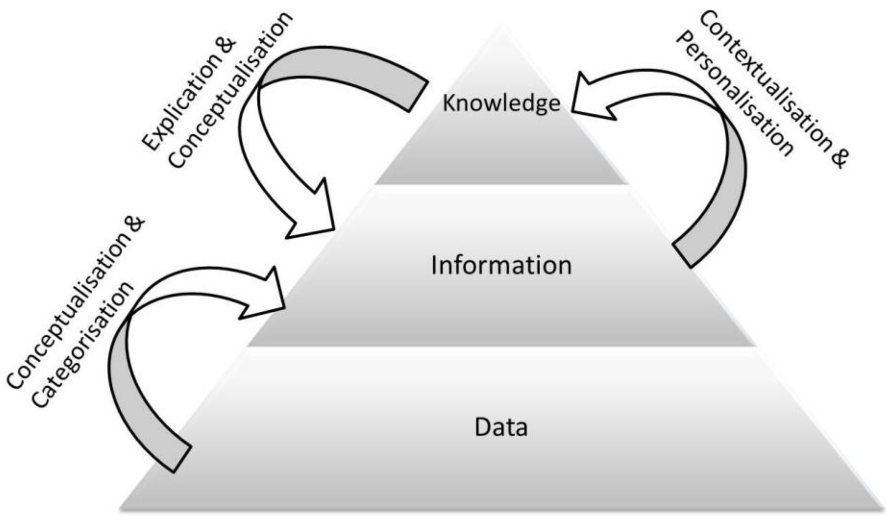


Figure 2-1: Data, Information, and Knowledge (Redrawn from Zimmermann *et al.*, 2002)

2.2.2.1 Data

Data is raw. Data relates simply to words or numbers, the meaning of which may vary, and is dependent on the context in which it is used (Harding and Popplewell, 1996). Data are simply symbols with no context and no relationships.

Davenport and Prusak (2000) pointed out that data are objective facts, presented without any judgement or context. It simply exists and has no significance beyond its existence. It can exist in any form, usable or not. It does not have meaning of itself. Data are patterns with no meaning; they are input to an interpretation process, i.e. to the initial step of decision making (Aamodt, 1995).

2.2.2.2 Information

Information is data that is structured or titled in some way so that it has a particular meaning (Harding and Popplewell, 1996). Information is interpreted data. Information is data with meaning; it is the output from data interpretation as well as the input to, and output from, the knowledge-based process of decision making (Aamodt, 1995).

Data becomes information when it is categorised, analysed, summarised and placed in context. Information is data that has been given meaning by way of relational connection. This "meaning" can be useful, but does not have to be. Data endowed with relevance and purpose forms the information. Information is data that is structured or titled in some way so that it has a particular meaning (Guerra-Zubiaga, 2004).

2.2.2.3 Knowledge

Knowledge is much more difficult to define because it has so many possible interpretations. For example, knowledge is information with added detail relating to how it may be used or applied (Harding and Popplewell, 1996)

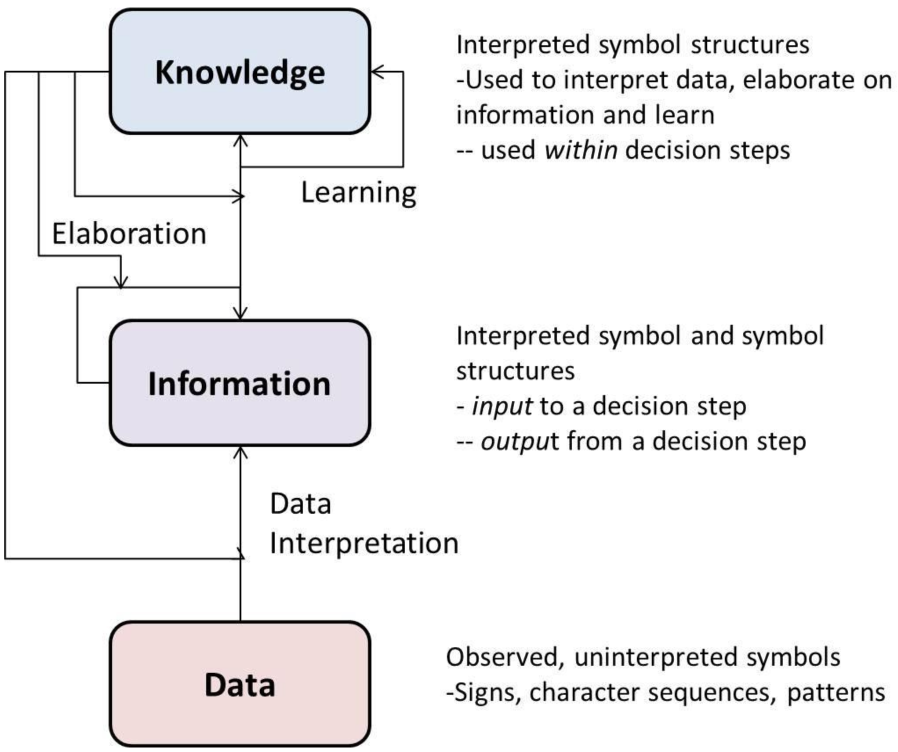


Figure 2-2: The Data-Information-Knowledge model (Redrawn from Aamodt and Nygard, 1995)

Aamodt and Nygard (1995) stated ‘Knowledge is learned information; Knowledge is information incorporated in an agent's reasoning resources, and made ready for active use within a decision process; it is the output of a learning process’.

They have also summarized the following knowledge roles and it is illustrated in figure 2-2:

- To transform data into information - referred to as data interpretation
- To derive new information from existing - referred to as elaboration
- To acquire new knowledge - referred to as learning

Knowledge is increasingly considered the most important asset of organisations and companies, especially within the service sector of knowledge-based industries. This knowledge, experiences and know-how of companies is stored and capitalized in order to be shared and so to become the intellectual capital (Cabrita and Vaz, 2007)

Knowledge has been implicitly managed, as long as work has been performed. Knowledge is now the cause rather than the effect of such transformations, particularly when it is systematically organised to be purposeful. Since many argue that the more developed world is evolving into a knowledge based economy (Beijerse, 1999; Drucker, 2002; Wiig, 1997), the new application of knowledge today is to knowledge itself, i.e. meta-knowledge (Laszlo and Laszlo, 2002). Hence the essence of KM is to manage knowledge about knowledge.

Knowledge is defined as including all the factors that have the potential to influence human thought and behaviour and that sometimes allow the explanation, prediction, and control of physical phenomena. This is a very broad definition and includes factors such as skills, intuition, organisational culture, reputation, and codified theory. All the factors, which are contained within the definition, may be placed on a spectrum of knowledge, which runs from tacit (uncodified) knowledge at one extreme to explicit (codified) knowledge at the other (Hall and Andriani, 2003).

Apart from Data, Information and Knowledge the other important concepts in this category is Intelligence and Wisdom. But this research focused mainly on knowledge and going to the level of wisdom is beyond the scope of work.

2.2.3. Types of Knowledge

Nonaka (1991) considers the transfer and the creation of knowledge, given among the three types of knowledge: explicit, tacit and implicit. There are three main types of knowledge used in a manufacturing environment: explicit, tacit and implicit (Guerra-Zubiaga and Young 2007).

2.2.3.1 Explicit Knowledge

Explicit knowledge is a formal and systematic type of knowledge consisting of basic facts and storable document sets (Nickols, 2000). It is objective and rational, and is captured in storable documents such as texts, tables, formulas, diagrams and product specifications. It can be represented through procedures, tables and graphs (Guerra-Zubiaga and Young 2008).

According to Hall and Andriani (2003) explicit knowledge is knowledge that has been captured in a code, or a language that facilitates communication. In its most advanced state, explicit knowledge is contained in codified theory, which not only explains why things work but also enables the prediction of the outcome of novel phenomena.

Tacit Knowledge Approach	Explicit Knowledge Approach
Knowledge *is personal in nature* and very difficult to extract from people.	Knowledge *can be articulated and codified* to create explicit knowledge assets.
Knowledge must be transferred by *moving people* within or between organisations	Knowledge can be *disseminated (Using information technologies*) in the form of documents, drawings, best practices etc.
Learning must be encouraged by *bringing the right people together* under the right circumstances.	Learning can be designed to remedy knowledge deficiencies through *structured, managed, scientific processes.*

Table 2-1: Tacit vs. Explicit Knowledge (Redrawn from Sanchez, 2004)

2.2.3.2 Tacit Knowledge

Tacit knowledge consists of personal relationships, practical experience, and shared values. The representation of tacit knowledge may include patterns, storytelling, video clips and sketches. Implicit knowledge is represented by text (Guerra-Zubiaga *et al.*, 2006) Tacit knowledge is subjective and cannot be articulated but it refers to well tested knowledge and follows a format (Guerra-Zubiaga, 2004)

Hall and Andriani (2003) described tacit knowledge as the knowledge acquired by experience and allows the prediction of previously experienced phenomena. He also identified the disadvantages of tacit knowledge and stated why organisations strive to make the possessed knowledge explicitly,

- The organisation is not ‘‘internally vulnerable’’ to knowledge being lost when employees leave and take their personal knowledge with them.
- The knowledge, which the organisation possesses, can be disseminated to large numbers of employees over large distances and applied to a wide range of applications.
- Theory, which allows the simulation and operation of ‘‘what if’’ scenarios and which will indicate appropriate corrective action to be taken when things go wrong, exists

Nonaka & Takeuchi (1995) stated that tacit knowledge is just transferable with an entire system that supports this exchange. Examples of this knowledge are personal beliefs, perspective, mental models, ideas and ideals, all of which can be grouped and represented on a sketch. The experience and training of a person are also part of the tacit knowledge that can be transferred to another person. For example, by watching a video clip, it is possible that a person learns by imitation. Nonaka (1991) develops some of the knowledge transfers and creations: tacit to tacit, explicit to explicit, tacit to explicit and explicit to tacit. It was found that only in the tacit–tacit relationship does a complete transfer of tacit knowledge exist.

The acquisition of tacit knowledge takes place through observation, imitation and practice, and the most efficient way to transfer or store tacit knowledge is through the use of sketches, video clips, story-telling and pattern. The work presented by (Guerra-Zubiaga, 2004) shows a successful implementation of the use of sketches, video clips, storytelling and patterns as tacit knowledge representation.

2.2.3.3 Implicit Knowledge

Implicit knowledge is the type of knowledge that has not yet been articulated; it is implied by or inferred from observable behaviour or performance of another person. Implicit knowledge has a bridge property that links together the explicit and tacit components used as a link in a knowledge management system (Nickols, 2000)

Implicit knowledge can then be defined simply as knowledge that is not explicit. But implicit knowledge, as it is considered here, is closer to `knowing that' than to `knowing how.' In cases of implicit knowledge, a proposition or rule is known, but this is not available to the knower for verbal report. In the absence of verbal report, an attribution of implicit knowledge must be supported by other kinds of empirical evidence. But more fundamentally, we need some account of what it is for a subject to possess knowledge but to be quite unable to make it explicit (Dienes and Perner, 1999).

This research focuses on keeping the knowledge up to date for an existing knowledge base (KB), so the type of knowledge is always explicit. However other types of knowledge have to be considered equally while building up the KB, but when the KB is already developed then the type knowledge available will be always explicit.

2.3. Knowledge Management Systems

Automation of manufacturing processes to improve the productivity of manufacturing industry. Advances in manufacturing control, applications of artificial intelligence and new communication software, along with advanced technologies in computing hardware, enable factory designers to model and implement fully automated and integrated manufacturing systems (Weber and Moodie, 1989).

2.3.1 Knowledge based Systems

Many companies are building knowledge management systems (KMS) in order to manage organisational learning and business know-how. The main purpose of such a policy is to help knowledge workers to create important business knowledge, to organize it, and to make it available whenever and wherever it is needed in the companies (O'Brien and Marakas 2006). Facing a tremendous amount of data on a daily basis, enterprises only use IT to integrate each division of various tools, such as intranet, data warehouse, electronic whiteboard, artificial intelligence and expert systems so that the jumbled business data is well-organized and more integrated (Khandelwal and Gottschalk, 2003)

The new product development in large companies, operating for instance in automotive and aerospace sectors, is supported by Knowledge-Based Engineering (KBE). KBE in industry is mostly used to automate design processes and to integrate knowledge and experience from different departments (Liening and Blount, 1998), for example, in the design and manufacture domain the generative technology of knowledge-based tools enables companies to create product definitions which incorporate the intuitive knowledge (experience) of designers and engineers about design and manufacturing processes (Kochan, 1999).The main claimed benefit of KBE lies in its ability to aid rapid product development in a collaborative way for increased productivity.

2.3.2 KM Models, Tools and Technology

2.3.2.1 KM Models

There are three broad categories of KM models, identified by (McAdam and McCreedy, 1999)

a) Knowledge Category Models
b) Intellectual Capital Models
c) Socially Constructed Models of KM

Knowledge Category Models*:*

These types of model categorize knowledge into discrete elements. One of the most renowned KM models fits into this category, the Knowledge Spiral model by Nonaka and Takeuchi, (1995). This model is shown in its simplest form in figure 2-3.

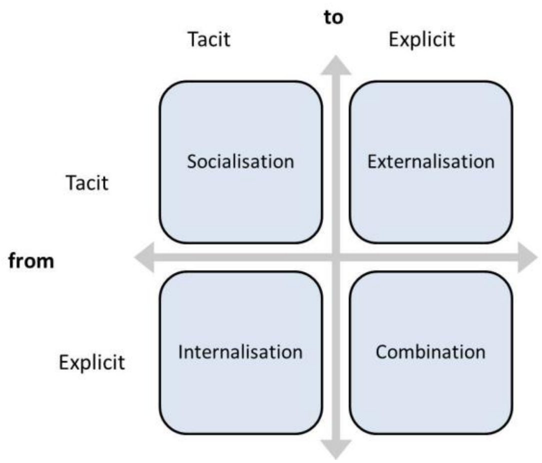


Figure 2-3: Knowledge Spiral Model (Adapted from Nonaka & Takeuchi, 1995)

This model presents a high level conceptual representation of the knowledge dimensions, namely tacit and explicit knowledge. The model makes a number of assumptions, namely,

1. Tacit knowledge can be transferred through a process of socialization (everyday comradeship) to become the tacit knowledge of others

2. Tacit knowledge can become explicit knowledge through a process of externalisation (formalizing a body of knowledge)

3. Explicit knowledge can be transferred into tacit knowledge in others through a process of internalization (translating theories into practice)

4. Explicit knowledge can be transferred to explicit knowledge in others through a process of combination (combining existing theories)

One criticism of the model is that knowledge transfer in organisations is much more complicated and convoluted than this simple matrix suggests. The model also assumes a desegregation of tacit and explicit knowledge; often this is not the case.

Another example of a knowledge category model is that of (Boisot, 1998), as shown in figure 2-4. Boisot's model considers knowledge as, codified or uncodified, diffused or undiffused, within an organisation. Boisot uses the term 'codified' to refer to knowledge that can be readily prepared for transmission purposes (e.g. financial data). The term 'uncodified' refers to knowledge that cannot be easily prepared for transmission purposes (e.g. experience). The term 'diffused' refers to knowledge that is readily shared while 'undiffused' refers to knowledge that is not readily shared.

Codified	**Proprietary Knowledge**	**Public Knowledge**
Uncodified	**Personal Knowledge**	**Common Sense**
	Undiffused	**Diffused**

Figure 2-4: Knowledge Category Model (Redrawn from Boisot, 1998)

There are a number of parallels between Nonaka's model and that of Boisot. For example, Nonaka's categorization of explicit and tacit knowledge has a degree of correspondence with Boisot's reference to codified and uncodified knowledge. Also, in both models the horizontal dimension relates to the spread or diffusion of knowledge across the organisation. However, Boisot's model suffers the same limitations as Nonaka's model in that codified and uncodified are but two discrete categories of knowledge. Also, the idea of diffused knowledge is rather general and it is not clear if it includes incorporating knowledge within the organisation, as well as disseminating it.

Intellectual Capital Models

(Brooking, 1997) suggests that KM is actively concerned with the strategic outlook and operational tactics required for managing human centered, intellectual assets. KM from this standpoint is seen as leveraging Intellectual capital (IC) (Drucker, 1992), or as recognising or rediscovering assets that the organisation are not using to full potential, ultimately employees. As these approaches imply that the key areas of KM are the management of IC it is worth reviewing a typical IC model. The model shown below is the Intellectual Capital model adopted from (Chase, 1997; Roos and Roos, 1997).

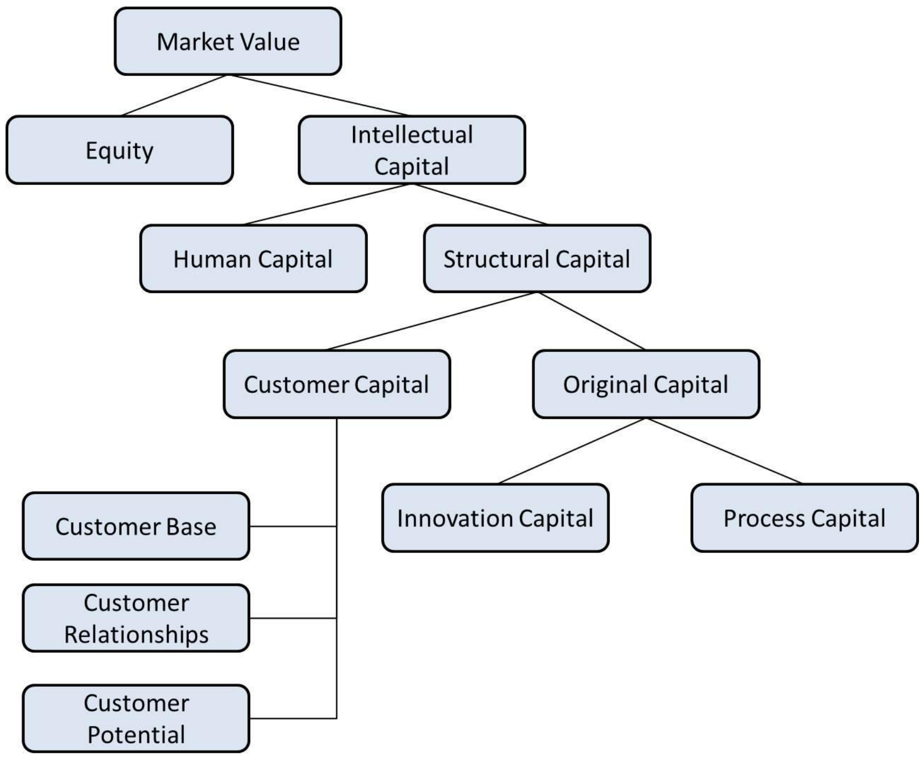


Figure 2-5: Intellectual Capital Model of KM (Redrawn from Chase, 1997)

One problem that can be associated with this model is the adoption of a scientific approach to knowledge. This is evident through the classification of knowledge as a commodity linking it to organisation capital. This view of Intellectual Capital ignores the political and social aspects of KM. The IC model also assumes that KM can be decomposed into objective elements rather than being a socio-political phenomenon. This is similar to the Nonaka and Takeuchi (1995) approach.

Socially Constructed Models of KM

This group of models assumes a wide definition of knowledge viewing it as being intrinsically linked within the social and learning processes of the organisation. There is a large area of commonality between these types of models and those models seeking to represent the Learning Organisation and Organisational Learning (Scarbrough *et.al*., 1999).

KM is concerned with the construction, capture, interpretation, embodiment, dissemination and use of knowledge. These components are represented in (Demarest, 2001) Knowledge Management model, shown over page.

The social view of knowledge is concerned with the social and learning processes within an organisation. This approach to knowledge construction considers inequality, conflict, domination, subordination and manipulation influences as well as more traditional behavioral questions associated with efficiency and motivation (Alvesson and Willmott, 1996). Thus social knowledge construction is a dynamic process of contextuality rather than the assimilation of a body of facts.

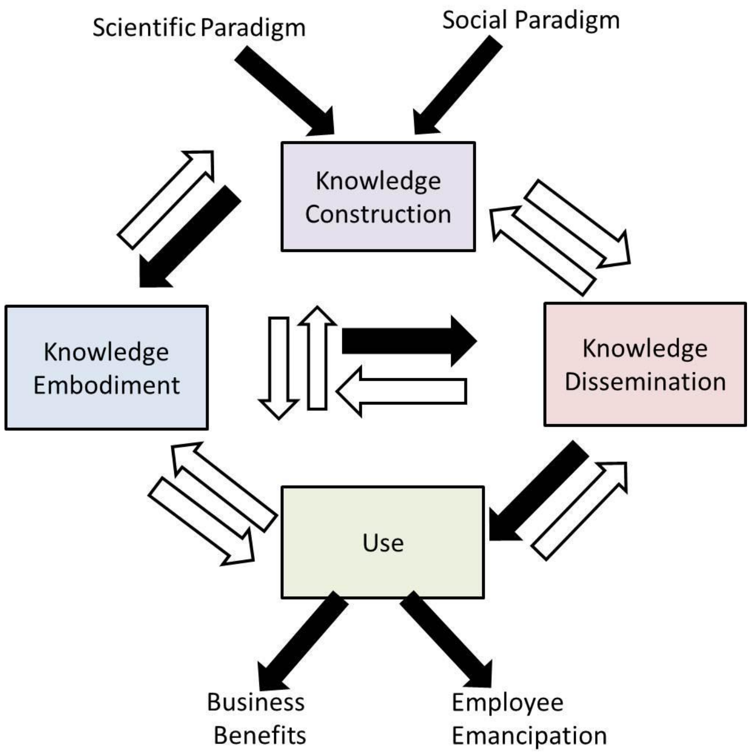


Figure 2-6: Demarest's Knowledge Management Model (Redrawn from McAdam and McCreedy, 1998)

The model depicted in figure 2-6 shows that knowledge construction is not limited to scientific inputs through explicit programmes but includes a process of social interaction. The implications of this wider concept of knowledge construction must be reflected in the embodiment/dissemination of knowledge as part of the organisation's KM approach. There is little point in widening the concept of knowledge construction only to limit the embodiment and dissemination techniques used or to force existing techniques onto new knowledge. Attempting to do so will lead to disappointing results, frustration and a negative view to Knowledge Management caused by the mismatch between conception and application. Knowledge usage must also be reflected via the knowledge initiatives installed in the organisation.

2.3.2.2 KM Tools

According to Davenport and Prusak (2000) and Abecker *et al*., (1998) if the tools and technology is correctly designed and implemented, will effectively support KM. For instance, some of them can favor knowledge integration between individuals and organisations.

(Garavelli *et.al*., 2002) has stated some technologies can enable the knowledge of an individual or a group to be extracted, structured, and used by other members of the organisation. Their most valuable aims are the extension of the knowledge span, the increase of knowledge transfer speed, the support to knowledge codification. For instance, some applications based on multimedia technologies, on advanced databases, on groupware technologies, and on the Internet, have been considered quite effective in supporting KM.

KM should be supported by a collection of technologies for authoring, indexing, classifying, storing, contextualizing and retrieving information as well as for collaboration and application of knowledge. A friendly front-end and a robust back-end are the basic necessities of a software tool for knowledge management. Below are the examples of various tools available for knowledge management as discussed by (Lindvall *et.al*., 2003).

Document and Content Management:

In terms of knowledge management, the documents that organisations produce represent their explicit knowledge. New knowledge can be generated from documents. Document Management systems enable explicit-to-explicit knowledge conversion.

Microsoft SharePoint (www.microsoft.com/Sharepoint) is an example for document management system. It supports larger workgroups which often require formal publishing processes and the ability to search for and aggregate content from multiple data repositories and file formats.

Collaboration Services:

Very often employees need to collaborate and communicate, especially when they work in an environment that is distributed in time and space. Knowledge conversions supported by this category are mainly tacit-to-tacit, which occur, for example, when two or more users communicate using chat tool or an instant messenger.

Microsoft Live Meeting (http://office.microsoft.com) is an example of this type of tool which connects employees by providing a computer based communication channel. Sometimes communication may be synchronous and asynchronous.

Data and Knowledge Discovery:

The goal of this category of tools is to generate new knowledge from existing data, information and knowledge bases. Examples of this type of tool include visualization and data mining, as well as analysis and synthesis tools.

Autonomy VoiceSuite (http://www.autonomy.com) analyses multimedia content and transcribes it into text, identifies and ranks the main concepts within it, and automates personalized information delivery over the internet, or by using other digital channels such as mobile phones, or PDAs.

Knowledge Portals:

Knowledge workers use many different computer-based information sources (manufacturing activities, inventory levels, customer orders). These information sources need to be integrated and accessed through a common, yet personalized, interface. Portals create a customized single gateway to a wide and heterogeneous collection of data, information and knowledge.

IBM WebSphere (www.ibm.com) allows employees, partners and customers to interact with documents, applications and services and one another. It hosts the personalized and community portal pages, enterprise-wise document directory and web-based administration.

2.3.2.3 KM Technology

To an organisation, the primary goal of knowledge management systems is to identify the valuable knowledge that resides within employees and disseminate it throughout the organisation. However, experience suggests that this seemingly straightforward process is in practice fraught with difficulties (Empson, 1999; Wang, 2002)

In their study on knowledge management projects in organisations, Davenport and Prusak (2000) identified six types of technology for knowledge management and highlight the shortcomings of each approach (see Table 2-2). Basically, they argue that most Information Technology (IT) based "Knowledge Management systems" are merely sophisticated and efficient mechanisms for filing and disseminating information. Systems similar to the "yellow pages" business directory, identifying who knows what within a company, simply provide information about where knowledge resides. They further point out that, currently, there is still no "right" technology for knowledge management. (Tan and Platts, 2004)

Technology	Features	Shortcomings
Expert Systems (ES)	Typically concentrated on managing narrow domains of knowledge such as configurations of computers or the diagnosis of a particular type of disease.	ES need to be supported by other related highly structured systems and because of these, it is difficult to maintain and add knowledge – as the knowledge domains needs to be fairly stable
Artificial Intelligence (AI)	Great expense and amount of time to capture a relatively small amount if human expertise	Difficult to embed tacit knowledge in AI
Case based Reasoning (CBR)	Knowledge about a particular domain is expressed as a series of problem.	Case construction and modification are somewhat complex and require
Neural Network	Requires a large quantity of data (quantitative) and a high powered computer	User must be knowledgeable of the system
Notes	Knowledge in textual databases is indexed on the basis of keywords and their proximity in the text	These are relatively shallow aspects of the knowledge, and it can be difficult to extract knowledge in search queries on this basis
Web	Using publishing tool ?(HTML) to capture information, store it, and allow broad access	Users are confounded with lots of information and have problem judging the knowledge that is being provided

Table 2-2: Knowledge Management Technologies (Adapted from Davenport and Prusak (2000)

The technologies supporting the main functions of Knowledge Management systems (KMS) are well suited to Zack (1999) classification of knowledge management technologies as shown in table 2-3.

Distributive (Integrative) Technology	Data Warehousing (and Data Mining tools) Document Management Systems Electronic Publishing Information Retrieval Systems Search Engines Intelligent Agents Enterprise Information portal (i.e Corporate Intranet) Decision Support Systems Business Modeling systems
Collaborative (Interactive) Technology	Message or Email Groupware Knowledge Mapping Tools Enterprise Information Portal (i.e Corporate Intranet) Web based Training Helpdesk Applications Decision Support Systems Workflow Systems

Table 2-3: Classification of Knowledge Management Technologies (Redrawn from Zack (1999))

The need for negative-feedback control systems (Figure 2-7) in manufacturing operations has been recognized for many years. Indeed, failure to adopt such practices contributed to the failure of many early materials requirements planning (MRP) implementations. To monitor and improve manufacturing processes, therefore, there are a number of accepted techniques to aid fault diagnostics and to guide improvements based on quality measures (Beroggi and Aebi, 1996; Duffy, 1995; Hamada *et.al.*,1993; Kepner and Tregoe, 1997).

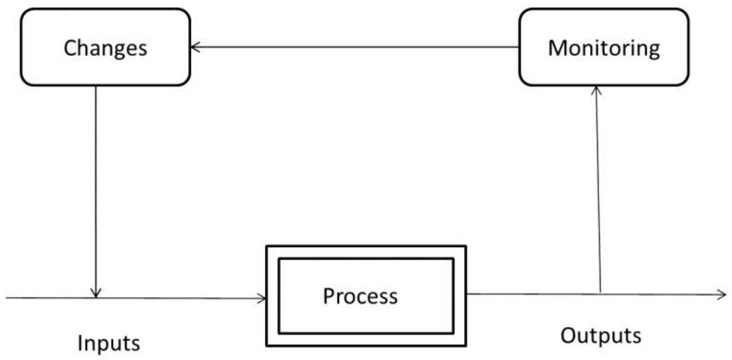


Figure 2-7: Negative Feedback Process Control

In some industries and enterprises, these principles have been automated, offering greater speed and accuracy of data capture and analysis (Tannock *et al.*, 1992).These are described by sector 1 in Figure 2-8, as organisations using simple processes to operate within stable markets (Puttick, 1990).

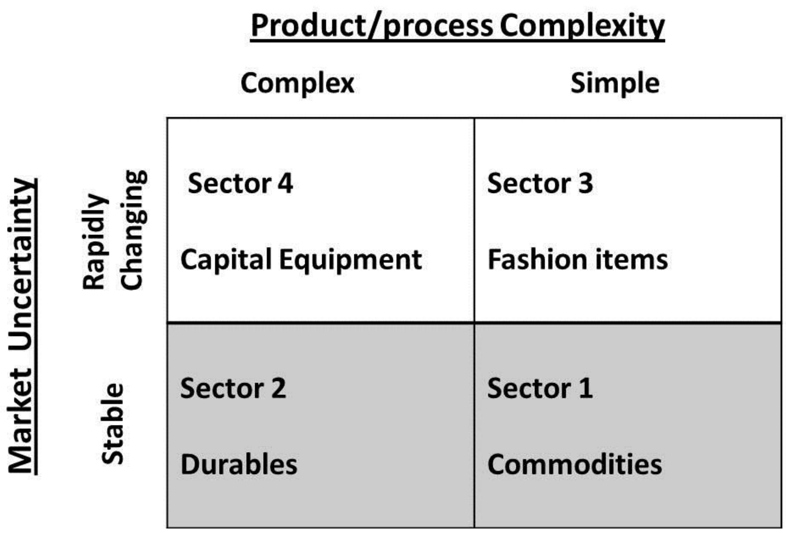


Figure 2-8: Manufacturing Industry Sectors (Redrawn from Puttick, 1990))

In such organisations, process efficiency becomes the major factor that determines competitiveness. This area has seen the highest adoption of expert system technology, because the processes are easily understood and remain relevant for some time, and the efficiency benefits significantly affect competitiveness (Johnson *et al.*, 2008). Therefore, the justification for expert system development is provided, outweighing the usually high cost of extracting and codifying rules or cases governing process capability (Jain and Mosier, 1992).

In general, many small and medium-sized enterprises may be considered within categories 3 and 4, because they have less protection against competition than the large, capital-intensive process industries, and so have to change their products and processes more often in order to maintain their competitive position. Over the last decade, the reduction in the cost of computer technology has placed process monitoring and analysis equipment within the grasp of many medium-sized manufacturing enterprises. Although expert systems are not a viable process control solution for medium-sized manufacturing enterprises, as can be seen in Figure 2-9 such systems are only one aspect of the wider knowledge management discipline (Wiig, 1997) and many other knowledge management technologies exist that may be applicable to support continuous improvement (Beckett *et.al*., 2000).

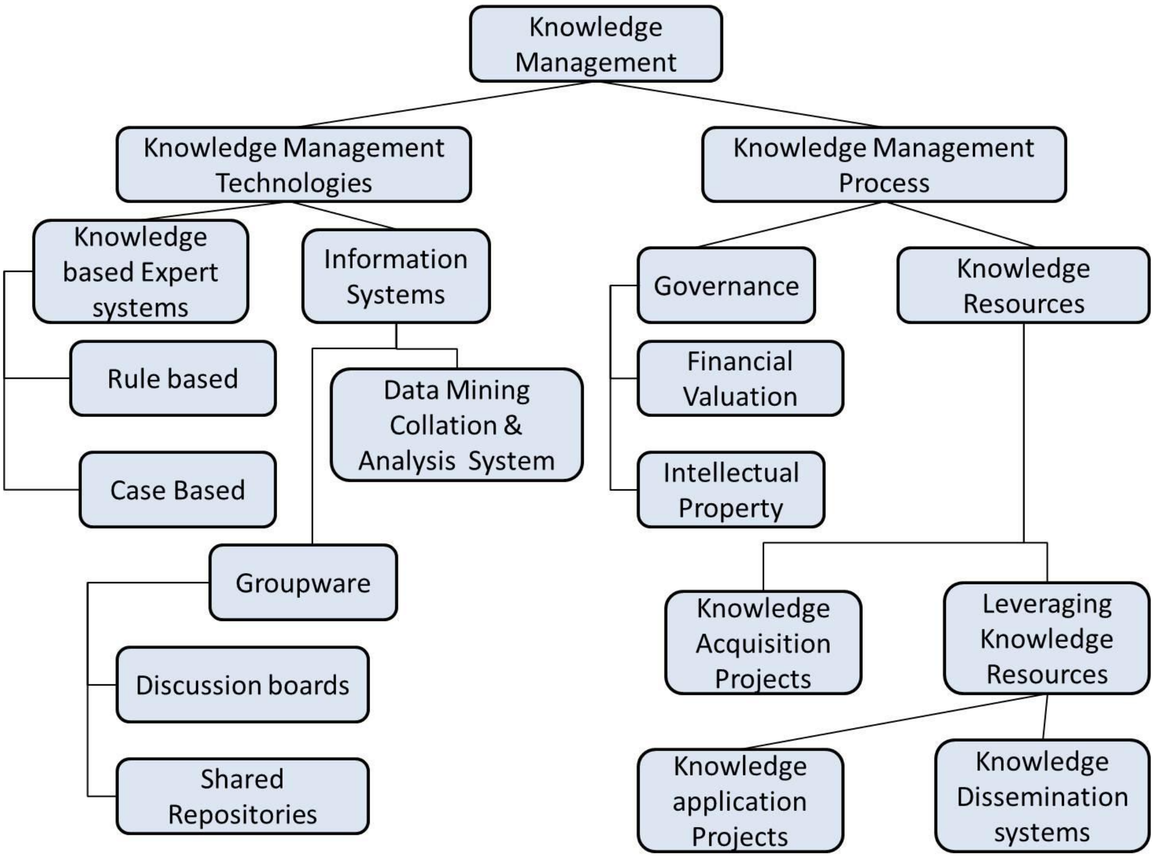


Figure 2-9: Knowledge Management Processes and Enabling Technologies

2.3.3 Product Life Cycle Management

People often describe Product Lifecycle Management (PLM) as a technology. It is more appropriately described as a strategy for making companies more innovative and productive by applying a number of technologies. These tools enable manufacturing companies to capture, use, and build upon the intellectual property created by design and manufacturing engineers, and to do so all the way from the concept of a product to the very end of its life (Hakola and Horning, 2004).

A few years ago, it became apparent that manufacturing companies needed technology to capture essential data, usually embodied in engineering activities and documentation, to make it available when required to those who needed it, and still to keep it secure. Computer Aided Design (CAD) using engineers complained that the hardest part of their jobs was finding data they needed. They had to search through files, load pictures of models, and hunt for the right one. That difficulty extended through the enterprise, where manufacturing engineers needed to design and build tools based on similar data, and non-engineering people, such as financial department people trying to figure out cost data on a particular configuration, dealt with similar problems.

To solve those problems and replace frustration with efficiency, PLM needs to leverage design data by making it more available for collaboration and use across the extended enterprise. By doing so, it brings together design engineers, manufacturing engineers, maintenance engineers, and non-engineering personnel and departments, who manage material requirements, cost, sales and marketing – and extends data creation to include manufacturing. PLM also ensures that if any single individual should leave the enterprise, his or her knowledge remains.

PLM is about more than product design. To be competitive in the current world economy, companies need a PLM strategy centred on an integrated product model that incorporates manufacturing data. To enable such a system, the company needs a software infrastructure – a layer that interfaces with the operating system. PLM applications come next, and these break down into two layers – a pure application layer and a layer of common components that apply across PLM, where configuration and document management belong, those things typically thought of as PDM applications.

While PLM offers a range of tools to support the business including the ability to manage workflows, the heart of an effective PLM system is the database at its core. The issue then is how to structure the databases at the heart of PLM in order to ensure all users have access to effective information support. The importance of product models has long been recognized in providing a core of product information to support decisions (Krause *et al.*, 1993).

Minimising the time of the product development phase and ensuring effective support for the service phase of the product lifecycle is a long standing problem (Ming *et al*., 2008; Sudarsan *et al.*, 2005). This is partly due to the lack of communication between different actors involved during the product lifecycle (Tang and Qian, 2008).

Further (Young *et.al.*, 2007) suggests that the support for product development activities can be improved if the manufacturing methods of all previously manufactured products have been organised in a product lifecycle management (PLM) system to be accessed by designers and manufacturing engineers. PLM is a key technology to support the communication between actors (Guerra-Zubiaga *et al.*, 2006; Stark, 2005). Present PLM systems provide the communication management functions; however, they are limited in supporting communication beyond the level of metadata as well as a certain level of geometrical information (Ming *et al.*, 2008).

The figure 2.10 illustrates the framework of a product life cycle representation. It highlights in particular two Unified Modelling Language (UML) class structures which start to provide contexts for manufacturing knowledge sharing. The first is for manufacturing capability models which can be used to build a representation of an enterprise's manufacturing ability. The second is a product model representation which goes beyond typical representations of product characteristics such as geometry and product architecture, to include other key classes relating to product purpose and views which enable life cycle contexts to be captured (Young, 2005).

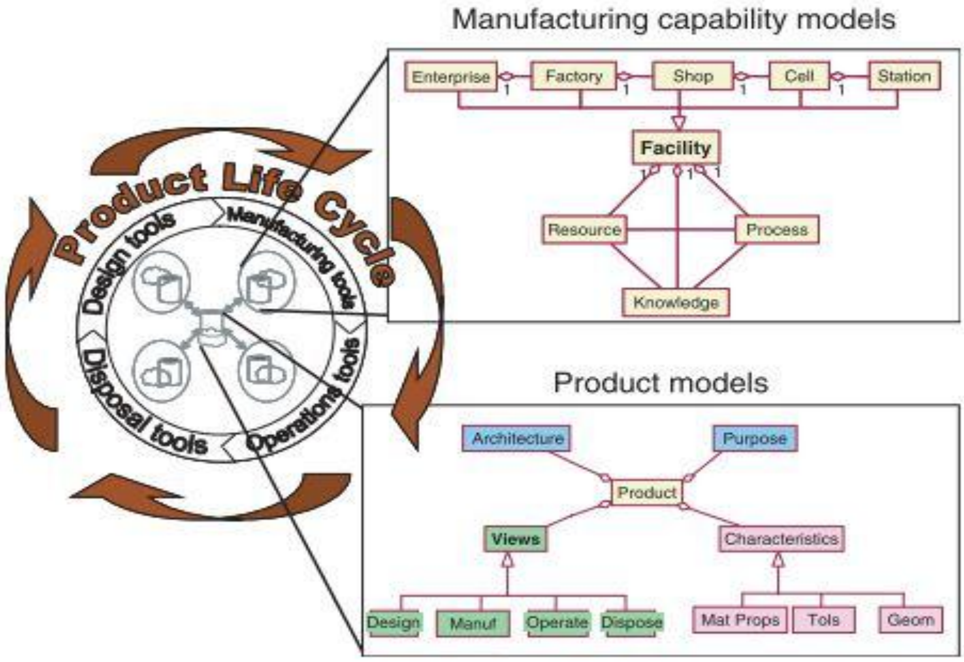


Figure 2-10: Product Information and Manufacturing contexts in the Lifecycle (Redrawn from Young, 2005)

However, given the design, manufacture, operation and disposal aspects of the life cycle it is also important to support decisions with non-product specific information focused on each of these areas of the life cycle. For example, the manufacturing area of the life cycle should be able to offer support on manufacturing process capability and information on suppliers with resources capable of meeting specific capability requirements (Young *et al.*, 2007).

The importance of a manufacturing model is that it not only provides a common source of information to support design decisions, but it focuses the core competencies of the business so that as new understanding is generated during product manufacture, the model can be updated for future benefit. It therefore provides a clear integration link between PLM as a provider of manufacturing information and shop floor manufacturing systems in terms of data collection and feedback. (Young *et al.*, 2007)

2.4. Modeling and Maintenance of Manufacturing Knowledge

Nowadays manufacturing businesses are moving towards knowledge intensive manufacturing. The key to knowledge intensive manufacturing is to extend the scope of the product manufacturing knowledge sharing and reusing. Abilities to share and reuse manufacturing knowledge are the primary requirements in developing manufacturing knowledge management system (Zhou and Dieng, 2004).

The world keeps changing at an ever-increasing pace, so knowledge must keep up with this changing world because knowledge models the world in a manner which permits decisions to be made. This might appear at first sight an easy process – data storage is cheap, so just keep adding to the knowledge base. But let us see what has happened to the Web from a certain perspective in that it has continued to grow without limits and there is relatively little that is removed from it. We all suffer the consequences of this infinite process of addition. Hence the knowledge maintenance is very important for the effective KM.

The subsections under this topic discusses about the main areas in manufacturing knowledge sharing. The first subsection begins with an introduction to manufacturing knowledge and ends with stressing the importance of knowledge maintenance

2.4.1 Definition of Manufacturing Knowledge

Manufacturing companies utilise large amounts of knowledge to manufacture products and apply manufacturing knowledge to develop products according to customer requirements and to offer competitive prices. Over time, the combination of new technologies, product innovation and experience of workers has improved the manufacturing knowledge used to produce articles and, as a consequence, this collective knowledge has expanded. To improve product development decisions and to obtain a competitive advantage, an important aim for manufacturing companies is to retain, transfer and improve their own manufacturing knowledge (Beckett *et al.*, 2000).

The success of any manufacturing company depends upon its ability to keep their orders flowing. With the usage of knowledge management systems, manufacturers are able to share their knowledge both internally and externally. In an international manufacturing environment where knowledge is created and disappears dynamically, the ability to capture and share knowledge is becoming more critical. The cost of knowledge creation in new product and process developments, human resources, lost opportunities and market share, is escalating. The capability of turning an individual's tacit knowledge into explicit organisational knowledge helps Japanese companies to win major market share. Few realise, however, that the new knowledge created is not that new and may have existed somewhere in the organisation before.

2.4.2 Manufacturing Modeling

A Product Model may be defined as an information model, which stores information related to a specific product (Molina and Bell, 1995). Product Model paradigm has slowly been extended with time, for instance, through the inclusion of additional dimensions such as product family evolution (Sudarsan *et al.*, 2005). On the other hand, a Manufacturing Model is said to be a common repository of manufacturing capability information, whose use is justified in the way the relationships between all manufacturing capability elements are strictly defined (Liu and Young, 2004).

Manufacturing model is defined as an information model that identifies, represents and captures the data, information and knowledge describing the manufacturing resources, processes and strategies of a particular enterprise. This enables the provision of the necessary manufacturing information for the support of manufacturing decision-making in the concurrent design of products. It has been strongly influenced by the work of other researchers (Kimura, 1991; Al-Ashaab, 1994).The manufacturing model has become an important element of the enterprise modeling process as it captures and represents the information describing the manufacturing resources of an enterprise. The concept of manufacturing models evolved from the efforts of various industries and research groups to build information models for their particular applications (Bjorke and Myklebust, 1992; ESPIRIT, 1993)

A manufacturing model representing this core manufacturing capability is just as important as any product model from the manufacturing perspective of the life cycle. A manufacturing model should identify process and resource specifications, potential methods of manufacture and best practice for manufacturing (Young, 2005).

To design an integrated information system, we need to understand how each manufacturing function operates and how it relates to other manufacturing functions. An integrated information system also requires coordinated solutions to data management problems for individual applications as well as for the exchange of data between these applications. Since function and data are closely inter-related in the integrated system, it is necessary to represent these functions and the data in a single integrated information model (Yeol Lee and Kim, 1998).

In order adequately to represent the capability of a manufacturing facility, the data structures of the manufacturing model should be composed and organized in a manner that facilitates the communication of manufacturing information. Additionally, it must support both generic and specific representations in particular manufacturing enterprises. Finally, it must be able to capture the manufacturing information at different levels of functionality, i.e. from different perspectives. (Molina and Bell, 1998)

2.4.3 Manufacturing Knowledge Sharing

Knowledge sharing within an enterprise (e.g. among different areas, departments, plants, different players in a virtual company etc.) is related to a number of fundamental and specific problems such as acceptance by employees and motivation issues, ontology problems, correlation of different types of knowledge, treatment of experience based and often incomplete and/or ill-structured knowledge etc. Management of tacit knowledge including its capturing, maintenance and sharing over different areas is still not efficiently solved in industrial practice. For example, a typical problem is how to ensure maintenance and continuous update of knowledge systems by employees themselves – missing an efficient maintenance leads to a relatively short life time of the systems for the sharing of knowledge in manufacturing companies, i.e. these systems are quickly becoming non-useful, because the knowledge included becomes obsolete. (Fischer and Stokic, 1999)

The problem in manufacturing companies is very often that the knowledge is available, but it is not used either because it is not well structured, or because employees are not aware of its existence or trained to properly uses it in their daily work. Communities of Practice are often built horizontally (e.g. over design departments of large companies) but rarely vertically (e.g. between planning and shop-floor areas, including employees with different levels of expertise etc.)

Due to the specific problems of the manufacturing industry regarding KM, many powerful and generic KM tools and methods available at the market do not meet the needs of the manufacturing enterprises. It may be concluded, that many unresolved problems and many specific issues related to KM in manufacturing industry, ask for a further development/enhancement of methodologies and ICT (Information and Communication Technologies) tools to reflect these specific needs (Fischer and Stokic, 1999).

Guerra-Zubiaga and Young (2006) stated the importance in defining the suitable knowledge structures in the creation of these decision support systems. Due to the significant volume of knowledge generated in the manufacturing and design stage, there is a need to create structures and methods that readily manage and maintain the knowledge to: (a) assure the long-term use of such systems and (b) improve the company's competitiveness (Guerra-Zubiaga, 2004). Next section describes knowledge maintenance in more detail.

2.5 Knowledge Maintenance

Maintenance is the science of controlling change in a software system. Knowledge maintenance is the science of controlling change in a KBS. More precisely: Knowledge maintenance is the process of reflecting over some knowledge based system in order to handle a new situation (Menzies and Debenham, 2000).

The knowledge being used and stored should stay current; hence, the implementation of "knowledge maintenance" concepts can be a solution. Knowledge maintenance means the practice of updating the types of knowledge within a manufacturing knowledge structure. It includes the update of the rule criteria used for making decisions.

As with many physical assets, the value of knowledge can erode over time. Since knowledge can get stale fast, the content in a KM program should be constantly updated, amended and deleted. The relevance of knowledge at any given time changes, as do the skills of employees. Therefore, there is no endpoint to a KM program. Like product development, marketing and R&D, KM is a constantly evolving business practices.

Birchall and Tovstiga (2002) evaluate the element of the knowledge analysis as the processes by which knowledge is managed in the company, that is, how it is generated, identified, stored, disseminated, used and discarded. Knowledge bases generalize relational databases by including not only base facts and integrity constraints, but also deductive rules. Using these rules, new facts (derived facts) may be derived from facts explicitly stored. Among other components, knowledge bases include an update processing system that provides the users with a uniform interface in which they can request different kinds of updates, i.e. updates of base facts, updates of derived facts, updates of deductive rules and updates of integrity constraints.

In general, several problems may arise when updating a knowledge base (Abiteboul, 1988) (Kowalski, 1992). Perhaps the best-known problem is that of integrity constraints checking. An integrity constraint is a condition that a knowledge base is required to satisfy at any time. Integrity checking is the process of verifying that a given base update (a set of insertions and/or deletions of base facts) satisfies the integrity constraints. If some constraint is violated, then the update is rejected; otherwise the update is accepted. Efficient integrity checking methods have been developed for relational and deductive databases. The problem has also been studied for full, first-order logical databases (Teniente and Olivé, 1995).

An alternative way to deal with integrity constraints is integrity constraints maintenance, which is a process that also starts with a given base update and the integrity constraints but now, if some integrity constraint is violated, an attempt is made to find a repair, that is, an additional set of insertions and/or deletions of base facts to be added to the base update, such that the resulting base update satisfies all integrity constraints. In general, there may be several repairs and the user must select one of them. Eventually, no such repair exists, and the base update must be rejected (Teniente & Olivé, 1995).

Geissbuhler & Miller (1990) introduced a "knowledge library" model used for knowledge base maintenance (KBM). Typically, an expert desiring to update of a piece of knowledge goes through five steps: checking it out, updating it, checking it back in, verifying the update, and compiling it for specific applications. "KB librarians" orchestrate these steps and maintain the consistency and currency of the knowledge base. Librarians have an overall view of the state of KBM, keep track of which KB segments are being updated, and teach users how to follow maintenance guidelines. They are also responsible for setting an expiration date on knowledge items and to contact their authors for revisions.

During the check-out step, the user discusses with the librarian the nature of the update: potential conflicts with work in progress are detected, nomenclature and formatting issues are resolved, then the relevant piece of knowledge is checked out. The check-in step involves a technical review of the update by the librarian, and its integration in the knowledge base using tools that enforce consistency rules: error logs as well as easily readable renditions of the updated knowledge are sent to the expert for corrections and verifications. A test environment is also available to check complex logic. Once formally signed-off by the expert and the librarian, the updated knowledge base is made available to the production applications.

Guerra-Zubiaga (2004) represented the knowledge maintenance model in Manufacturing Facility Information and Knowledge Model (MFIKM). The knowledge maintenance life cycle starts when new information or knowledge is identified. However, knowledge transformations are important to update explicit, tacit, and/or implicit knowledge. An important element in the transformation is the definition of the knowledge type that will be used to store the new knowledge within the MFIKM. In the case of new information, it is necessary to find the location of the original information according to the MFIKM and then replace old information with new. The figure 2-11 explains the MFIKM knowledge maintenance lifecycle.

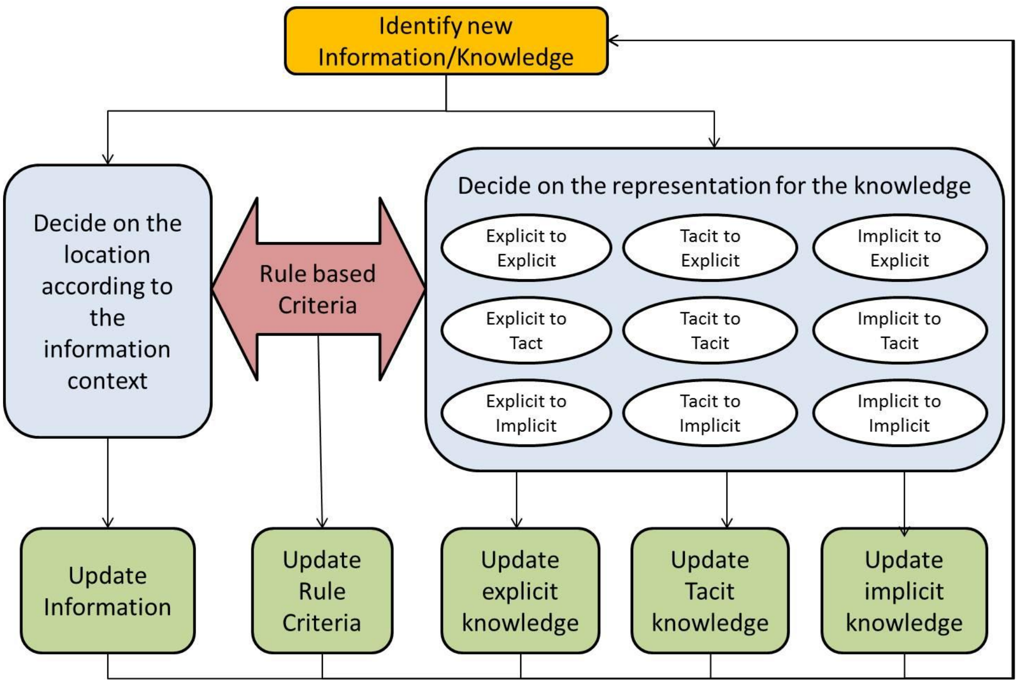


Figure 2-11: A Manufacturing Model to Enable Knowledge Maintenance in Decision Support Systems (Redrawn from Guerra-Zubiaga, 2004)

Knowledge is now seen as an integral part of the resources a business has, and as a key to maximising value and obtaining competitive advantage. The Advanced Knowledge Technologies project (www.aktors.org) has identified six challenges for the use of knowledge and the technologies involved in its management:

1) Acquiring knowledge
2) Modelling knowledge
3) Reusing knowledge
4) Retrieving knowledge
5) Publishing knowledge
6) Maintaining knowledge

As stated before, the review was focused on the sixth challenging 'Maintaining Knowledge' i.e. updating the knowledge repository dynamically and identifying parts which have become out of date. Nowadays it is widely assumed that knowledge is modelled and stored in structures called 'ontologies' which represent the 'shared conceptualisation' of a specific domain. Knowledge must be maintained and kept up to date in spite of where it is stored in ontology's, prepositional knowledge bases or simple databases.

Knowledge changes in a number of ways. There is always some knowledge to be added to the knowledge base, due to changes in the world or our understanding of it. There is always some knowledge to be removed from the knowledge base because it is out of date, untrue or merely irrelevant. There is some knowledge whose accessibility needs to be changed, i.e. it has become background knowledge rather than foreground knowledge.

According to (Brewster *et.al.*, 2003) knowledge maintenance activities could be categorized as follows,

a) Knowledge Acquisition: The addition of a proposition to the knowledge base.
b) Knowledge Realisation: The result of processing existing knowledge, and inferring new knowledge.
c) Knowledge Foregrounding: Certain events make a whole collection of information and knowledge come to the foreground
d) Knowledge Backgrounding: Certain events or non-occurrence of events (including the passage of time) makes items of knowledge less accessible, less available.
e) Knowledge Deletion: Knowledge is deleted from the knowledge base, because it is clearly out of date, false, no longer relevant, or not used for a certain period of time.

But for an effective maintenance of knowledge, the maintenance method should also include key activities such as Analysis, Classification, Storage, Validation and Presentation of Knowledge. These five activities are explained in the subsections below.

2.5.1 Analysis

The objective of the analysis of knowledge is to state the conditions that are individually necessary and jointly sufficient for propositional knowledge: knowledge that such-and-such is the case. Birchall and Tovstiga (2002) evaluate the element of the knowledge analysis as the processes by which knowledge is managed in the company, that is, how it is generated, identified, stored, disseminated, used and discarded. Oliveira (1996) proposes some of these processes: learning from past experiences; learning with others; learning with changes; learning by the performance analysis; learning by training; learning by contracting; and learning by searching (technology transfer – information coded in some way in which it needs to be understood, incorporated and registered).

Knowledge analysis has been carried out in different ways in different disciplines. Lin and Cheng (2010) have proposed Analytical Hierarchy Process (AHP) to evaluate the systematic design decision of door-shaped structure to improve final engineering designs. The approach uses the knowledge framework of a door-shaped structure for engineering knowledge classification. A classified hierarchical engineering knowledge audit was carried out via hierarchical analysis of the proposed systematic techniques. The hierarchical implementation of the knowledge classification audit included the structure type, structure subsystem, technique function, boundary condition, engineering principle method and limitations. Table 2.4 shows the keywords of technique and function for the door-shaped structure.

Technique	Function		
	Supportive structure	Light - weight	Strength requirement
Local reinforcement	Seam connecting plate, bracket, welding, river joint,..	Seam connecting plate, bracket, welding, stiffener,..	Seam connecting plate, bracket, welding, concentration,..
Arrangement change	Transverse, longitudinal, spacing, scantling, girder, stiffener	Transverse, longitudinal, spacing, scantling, geometry, loading, pattern, span,..	Transverse, longitudinal, spacing, scantling, shape, pillar,..
Material change	Density, high tensile steel, resistance load, support member,..	Density, aluminium, alloys, glass fibre, high tensile steel, minimum weight, material property,..	Density, high tensile steel, young's modulus, defection, stress..

Table 2-4: Keywords of technique and function for the door-shaped structure (Redrawn from Lin and Cheng, 2010)

Based on the relationships of hierarchical knowledge, this approach established relational engineering knowledge base. The approach adopted technical documents as representative of expert knowledge. Therefore, expert knowledge was retrieved from collected engineering technique and patent documents. This approach used a modified AHP that considered the ratios of the number of times related technical terms of different functions are mentioned in technical documents and patent. Via this modified AHP, this approach used the three techniques such as local reinforcement, as well as the three functions such as light-weight to establish a model for systematic calculation procedure.

Finally, based on the ratios of number of times these technical and functional terms occur, and according to the evaluation criterion of adjustment and revision of relationship between occurrence ratio and weighting value, the approach calculated the hierarchical relative importance values of different techniques under selected function. After the design evaluation of the door-shaped-structure using the modified AHP, the design decisions can be evaluated the applicability to design improvement, and a suitable structural design can be rapid determined using the general engineering principles and mesh model for finite element analysis.

2.5.2 Classification

Knowledge classification refers to the stage where the captured knowledge is categorized according to its level of hierarchy. While classification in knowledge representation is a longstanding area of research, most work has concentrated on the placement of concepts into a hierarchy or ontology (Schmolze and Lipkis, 1983) rather than the placement of entire axioms into a knowledge base. In this way, classification of knowledge into a hierarchical ontology is more similar to the classification of text documents into a hierarchy of classes. Using statistical rather than semantic methods in classification of documents is an approach with much significant previous work (Joachims, 1998; Koller and Sahami, 1997; McCallum *et al.,* 1998) Text classification tasks that involve categories arranged into a semantic hierarchy in particular are relevant to this task. In one previous approach (McCallum *et al*., 1998) a generative Bayesian model was used to predict the classification of text documents into a hierarchy. In this model, shrinkage is used to improve the performance of the model on smaller classes by utilizing the structure of the classes. The probability of placing a document in a given class is based not only on the statistics for that particular node in the class tree, but also on other nodes above it in the tree, thus “shrinking” the maximum likelihood estimate of a node towards that of its ancestors. Another approach to hierarchical text categorization is the so-called “Pachinko machine” (Koller and Sahami, 1997). In this type of algorithm, decisions are made starting at the root of the hierarchy, working down to the leaves.

There are various classification methods of knowledge. A key distinction made by the majority of knowledge management practitioners is Nonaka's reformulation of Polanyi’s distinction between tacit and explicit knowledge. The former is often subconscious, internalized, and the individual may or may not be aware of what he or she knows and how he or she accomplishes particular results. At the opposite end of the spectrum is conscious or explicit knowledge -- knowledge that the individual holds explicitly and consciously in mental focus, and may communicate to others. In the popular form of the distinction, tacit knowledge is what is in our heads, and explicit knowledge is what we have codified. Nonaka argued that a successful KM program needs, on the one hand, to convert internalized tacit knowledge into explicit codified knowledge in order to share it, but, on the other hand, it also must permit individuals and groups to internalize and make personally meaningful codified knowledge they have retrieved from the KM system.

Another common method for categorizing the dimensions of knowledge discriminates between embedded knowledge and embodied knowledge. These two dimensions, while frequently used, are not universally accepted. It is also common to distinguish between the creation of "new knowledge" (i.e., innovation) and the transfer of "established knowledge" within a group, organisation, or community. Collaborative environments such as communities of practice or the use of social computing tools can be used for both creation and transfer.

(Kai-Ji *et al.*, 2009) have proposed a method and its application for Business-Process oriented knowledge classification. In their method, Knowledge classification was based on pattern abstraction and matching. The procedure of classifying was translated into matching of knowledge pattern. By the semantic analysis of knowledge, if the dimension of knowledge was 0, that meant the knowledge can be eliminated. In their proposed method, they established contacts between knowledge and processes, matched the pattern of the knowledge with the knowledge pattern of process, classified the knowledge, and then keep it into the knowledge base.

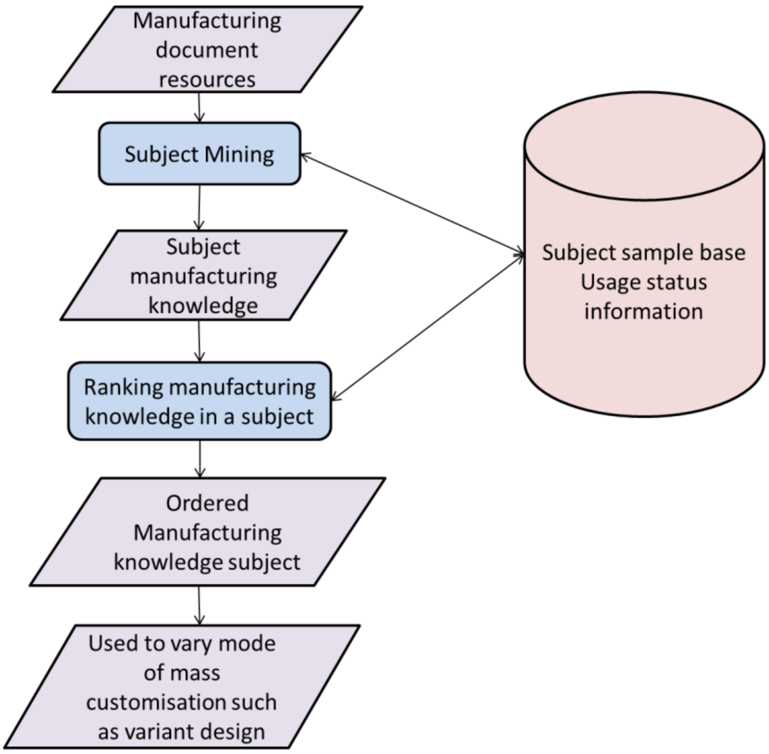


Figure 2-12: Knowledge Classification Concept (Redrawn from Zhao-yang *et al*., 2009)

(Zhao-yang *et al.*, 2009) have discussed the concept of Subject mining and Ranking for manufacturing knowledge classification in Mass Customization scenarios. The first step was to establish the manufacturing knowledge base with subject characteristic. Similar subject knowledge mostly had common solution space, so it was used to resolve the same type of problem. The second step was to rank the manufacturing knowledge within a subject based on its usage status and identify a sequence of potentially selection series for resolving a type of problem.

The operation of the mining and ranking was dependent on the availability of manufacturing documents about mass customization production. According to their concept for knowledge classification, manufacturing knowledge subject mining is a kind of binary classification problem. The subject mining process can be performed by using data mining and knowledge discovery technologies. This process mainly consists of sample knowledge training, analysing to unknown subject document and subject similarity analysis and classification. The whole flow is illustrated in figure 2-13.

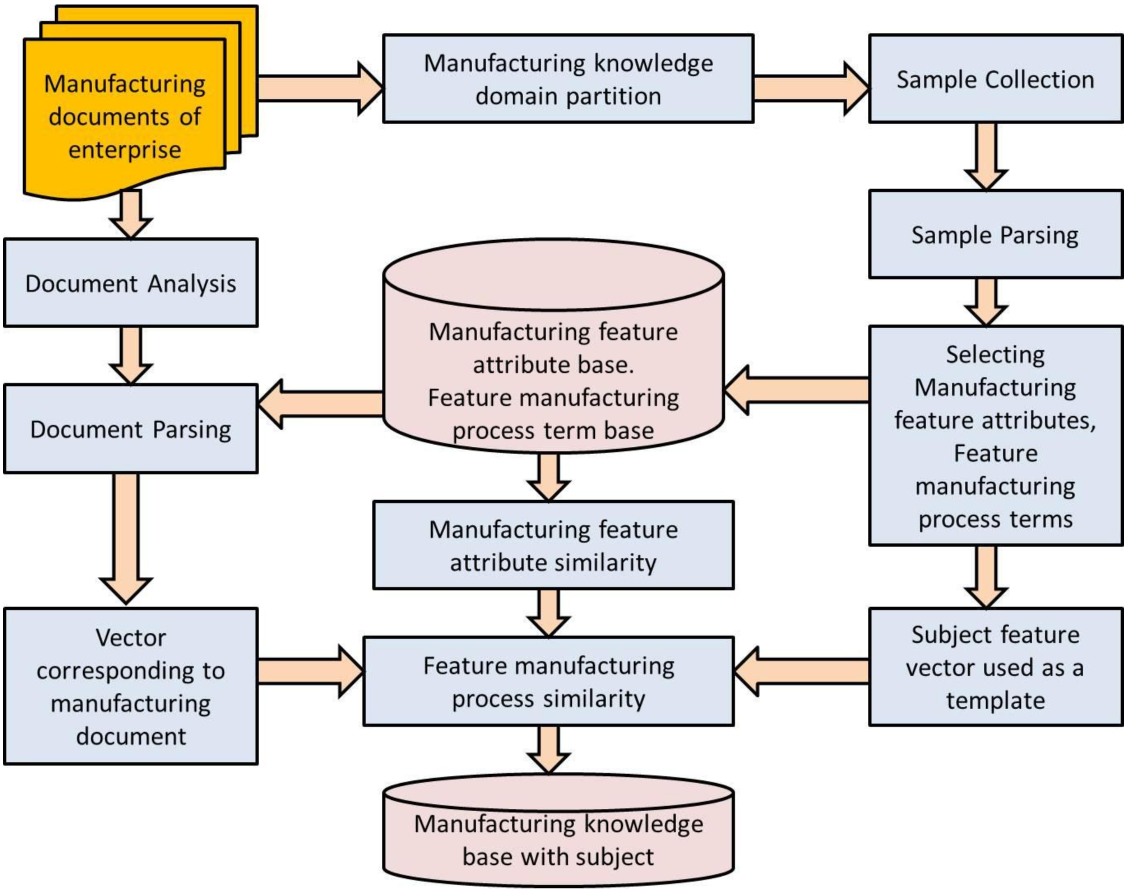


Figure 2-13: Flowchart of Subject mining of Manufacturing Knowledge

2.5.3 Storage

Data warehouses are the main component of KM infrastructure. Organisations store data in a number of databases. The data warehousing process extracts data captured by multiple business applications and organizes it in a way that provides meaningful knowledge to the business, which can be accessed for future reference. For example, data warehouses could act as a central storage area for an organisation's transaction data. Data warehouses differ from traditional transaction databases in that they are designed to support decision-making and data processing and analyses rather than simply efficiently capturing transaction data.

Knowledge warehouses are another type of data warehouse but which are aimed more at providing qualitative data than the kind of quantitative data typical of data warehouses. Knowledge warehouses store the knowledge generated from a wide range of databases including: data warehouses, work processes, news articles, external databases, web pages and people (documents, etc.). Thus, knowledge warehouses are likely to be virtual warehouses where knowledge is dispersed across a number of servers.

Databases and Knowledge bases can be distinguished by the type and characteristics of the data stored. While data in a database has to be represented in explicit form (generally speaking the information can only be extracted as it is stored in the system), the knowledge-based systems support generation of knowledge that does not explicitly exist in the database. In this way, the data in knowledge bases can be incomplete, fuzzy, and include a factor of uncertainty. The knowledge in the knowledge bases is stored based on rules, allowing a computer to make conclusions like: “if all vegetables are plants” and “if a tomato is a vegetable”, then “a tomato is also a plant”. In this way it is not necessary to store a list of all plants, or all vegetables, in order to get the answer to a question.

Data marts represent specific database systems on a much smaller scale representing a structured, searchable database system, which is organised according to the user’s needs. For example, a supermarket chain may wish to analyse a small, specific piece of information, such as – what quantity and type of beer is most consumed during the summer? In this case it is not necessary to process all data about all products in order to undertake this analysis.

Data repository is a database used primarily as an information storage facility, with minimal analysis or querying functionality. Content and Document Management Systems represent the convergence of full-text retrieval, document management, and publishing applications. It supports the unstructured data management requirements of knowledge management (KM) initiatives through a process that involves capture, storage, access, selection, and document publication. Content management tools enable users to organize information at an object level rather than in large binary objects or full documents.

2.5.4 Validation

Fundamentally, validation is attempting to identify whether all the possible cases are covered by the KBS. Alternatively in the sub-field of anomaly detection a system is analysed holistically to find structural anomalies, such as redundancies, conflicts or dead ends (Kusiak, 2002). To ensure that knowledge repositories contain high-quality knowledge, knowledge management research recommends that contributions to a repository undergo stringent validation processes.

A knowledge validation process begins when an employee submits a document containing a codification of some part of his or her knowledge, and ends when that contribution is either accepted for inclusion in a repository, or rejected. Validation cannot be performed automatically by the repository; instead, assessing quality requires the insights of peer reviewers or subject matter experts. To understand which perceptions of knowledge validation processes might play important roles in influencing individuals' contribution behaviors, the research began by reviewing the KM literature to determine the ways in which individuals' perceptions of these processes could vary (Davenport and Klahr, 1998; Marwick, 2001; Nick *et al.*, 2001) (Offsey, 1997; Zack, 1999). The preliminary findings were discussed with knowledge managers and knowledge contributors to identify the key characteristics that contributors are capable of observing and forming judgments about. This process converged on three such key characteristics:

1. The time lag between submission of a new contribution and a decision by a reviewer,
2. The extent to which contributors can observe the validation process in action, and
3. The restrictiveness (overall rejection rate) of the validation process.

Because each contributor will experience a unique set of interactions with a repository, his or her perceptions of the validation process along these three dimensions will vary. Perceptions are thus far more important in understanding contributors' behaviors than are any "actual" or "objective" measures of validation process characteristics. All employees who contribute to a knowledge repository are exposed to the process by which their contributions are validated, and are left with certain perceptions of how that process works.

Knowledge validation processes may occur in a highly transparent manner, whereby contributors are informed of the status and progress of contributions as they are reviewed and judged. There are two possible final outcomes of a validation process -acceptance or rejection. Based on their experiences with a validation process, contributors extrapolate to form general expectations about the likelihood that future contributions will be accepted or rejected (Szenberg, 1994). A restrictive validation process is a reliable signal of repository knowledge quality, as it indicates that the vast majority of contributions are not of sufficient quality to be accepted (Durcikova and Grap, 2009).

2.5.5 Presentation

Knowledge which is captured, analysed, classified and validated must be presented in some format for sharing and re use. Knowledge presentation much be done is such a way that it is easy to use within the manufacturing facility. There are several ways through which the knowledge can be presented for sharing. Some of the approaches are given below:

a. Communities of practice and intranets
b. Staff directories and expertise finders
c. Collaborative environments
d. Intranet-based knowledge tools

Communities of practice and intranets: The approach ‘communities of practice’ was developed by Wenger (1999) to explicitly recognise the importance of the less-formal knowledge sharing that occurs between peers, and within small groups. This has grown to be of major interest within the knowledge management community, and it has been used successfully within (and between) many organisations.

An intranet can play a valuable role in supporting the establishment and ongoing activities of a community of practice, including:

- Building a ‘home page’ for the community of practice,
- Providing a collaborative environment that can be used by community of practice members, especially those located in other departments.
- Offering a mechanism by which the output of the community of practice can be shared to the rest of the organisation

One of the key elements of a community of practice is that the group takes on the responsibility for the stewardship of the knowledge within their facility. Once captured, this knowledge can then be shared with other areas of the manufacturing and design that may face the same challenge, or stored for future use.

Expertise and knowledge: Listing the specific expertise, skills and knowledge of an engineer enables searches to be made for sources of knowledge.

Collaborative environments: Knowledge management must occur on three levels within a manufacturing facility:

- **Organisation:** knowledge that is critical to all engineers throughout the manufacturing facility. This need is typically met by standard corporate intranet content, such as policies and procedures.

- **Team or business unit:** information that is shared within a team, and is not of general interest to others within the organisation.
- **Personal:** knowledge, skills and expertise needed by an individual engineer.

Intranet-based knowledge tools: A number of interesting new technologies have surfaced in the last few years which have a strong focus on knowledge presentation. Some of the approaches are:

- **Weblogs:** It is an online diary created by one or more engineers based on the knowledge.
- **K-logs:** Knowledge logs, like weblogs but used within an organisation.
- **Wikis:** ultra-lightweight content management system, developed primarily in the open-source world

2.6 Summary

Knowledge management (KM) has become an increasingly important area of research, but there are a number of challenges facing its use in this area, including knowledge acquisition, knowledge modeling and knowledge maintenance. The literature review is mainly focused on the problem related to knowledge maintenance.

Knowledge maintenance refers to making use of existing "discovered" knowledge. Instead of emphasizing a radical break-through, several manufacturing companies take a simpler route for knowledge management. Depending on business objectives, the organisations choose to imitate and replicate existing knowledge. Though this process saves lot of time in maintaining the past and existing knowledge, there is always a need to maintain the manufacturing knowledge obtained from new processes and tools.

The past decade has seen recognition of the importance of Knowledge Management (KM). The growth of interest in KM is due to the recognition that commercial assets lie in the tacit knowledge of the workforce rather than in the bricks, mortar and equipment, the traditional means of valuing corporate assets. Furthermore, the rapid turnover of staff in many modern institutions has led to recognition of the need to manage corporate knowledge in a more effective manner. Even more important has been the fact that we live in a period of information surfeit due to the Web – terms such as 'information overload' or 'infosmog' are common. This necessitates an effort to turn excessive information into focused knowledge, in the AI sense of 'knowledge as usable information' (Kieron, 2002) and manage the knowledge more efficiently.

2.6.1 Critical Analysis of Research Gap

There are a number of different methods by which knowledge maintenance has been performed to date**.** Teniente and Olivé (1995) proposed a method for updating knowledge bases while maintaining their consistency based on deductive conceptual models. The kind of updates handled by the method are: updates of base facts, view updates, updates of deductive rules, and updates of integrity constraints. Also this method is based on events and transition rules, which explicitly define the insertions and deletions induced by a knowledge base update. However this method only focuses on maintaining the consistency of knowledge using a relational database, but there is still a need to investigate other important maintenance functions such as knowledge value, credibility and knowledge life which are essential for effective knowledge maintenance.

Menzies and Debenham (2000) put forward an expert system for knowledge maintenance based on artificial intelligence. They explored the representation of connections between knowledge by using three different knowledge approaches which are 1) Logical 2) Procedural and 3) Network. While their work focused on maintenance by modeling dependencies using the three approaches they were not concerned with the specific interdependencies between product design and manufacturing knowledge which are fundamental for an effective knowledge maintenance method in the context of this thesis.

Craw *et al.*, (2001) proposed a case based knowledge maintenance for the case based reasoning system. Their research focused on the optimisation of the parameters and feature selections/weights for the indexing and nearest-neighbour algorithms used by Case Based Reasoning (CBR) retrieval. Although knowledge retrieval is important for knowledge maintenance, however there is a need to define a knowledge maintenance system which provides a flexible environment for add new knowledge and modify an existing knowledge in the KB. How this could be done was not covered in their work but is an important aspect of this thesis.

Guerra-Zubiaga (2004) proposed a knowledge maintenance method based on knowledge structures and their relationships. His method was illustrated in figure 2-11. This is perhaps the most relevant work done on manufacturing knowledge maintenance because it is specifically focused on manufacturing knowledge and its maintenance. However although he defined structures based on knowledge types there is still a need to define methods which capture the range of maintenance tasks that are needed for the effective continuous update and management of the manufacturing knowledge. The research reported in this thesis focuses on such maintenance tasks and the critical functions they require in order to provide effective knowledge maintenance.

The maintenance methods researched by these authors are all related to the provision of improved computational support for knowledge maintenance without giving clear evaluation of the people involved or the roles that they must perform and the responsibilities that they must take. The provision of this understanding is just as important for a paper based approach as it would be for a computational approach and the former has been explored in this thesis.

Based on the review of literature the key areas of importance for knowledge maintenance have been identified as the types of knowledge, the knowledge maintenance functions, the functions specific for knowledge analysis and finally the maintenance methodology to be used. Each of these is described in turn in the following paragraphs.

a) **Knowledge Types:**

   Guerra-Zubiaga (2004) identified the need for clear knowledge structure and understanding of the types of knowledge to be maintained. While there is some discussion on types of knowledge, generally two are identified: tacit and explicit. Procedures, tables and graphs are examples of explicit knowledge representations; text, patterns, sketches, storytelling and video clips are tacit knowledge representations. The underlying structure is important for the effective organisation and retrieval of the knowledge.

b) **Knowledge Maintenance functions:**

   Maintenance functions play an important role in Knowledge Maintenance. It is essential to determine the Knowledge Maintenance functions which need to be performed for the effective management of an existing knowledge base. Borysowich (2010) proposed maintenance functions such as quality assurance, integrity checking, archiving old and outdated information and assessing the impact of changes made on existing knowledge. However there are other important Knowledge Maintenance functions such as knowledge filtering, relevancy checking, criticality ranking and verification and validation of completeness which should be taken into consideration.

c) Key functions for knowledge analysis:

Knowledge analysis is an important part of knowledge maintenance. This is the process of analysing knowledge based on its usefulness, weaknesses and appropriateness (Sierhuis and Clancey, 1997). There are number of knowledge analysis functions which are significant for knowledge maintenance. Some of the key functions are the dynamic nature of knowledge (McInerney, 2002), the types of knowledge (Guerra-Zubiaga, 2004), the value of knowledge (Reich, 1995) knowledge usage (McCarthy and Aronson, 2001) and consistency (Teniente and Olivé, 1995). However credibility of knowledge, degree of comprehensiveness, technical relevancy, long-term needs, and data duplication are also important functions which should be included in a knowledge maintenance method.

CHAPTER 3 - AN INDUSTRIAL INVESTIGATION INTO MANUFACTURING KNOWLEDGE MAINTENANCE

3.1 INTRODUCTION

This chapter explains the detailed industrial investigation done on manufacturing knowledge maintenance in the collaborative company. There are five main sections in this chapter. Section 3.2 explains the process activity modeling done during the exploration phase of the research work and its outcome. Section 3.3 provides the definition of the feature and explains the relationship between the manufacturing feature, the design feature and the inspection feature used in this research. Section 3.4 explains the feature and knowledge relationship structure created for this research work. Section 3.5 explores the various knowledge sources identified during the industrial investigation. A summary for this chapter is presented in section 3.6.

All the values and knowledge defined in this chapter are modified away from the real values to ensure that no sensitive information is held with the thesis.

3.2 ACTIVITY PROCESS MODELING

It is important to understand the processes and stages that the design engineers and manufacturing engineers undertake, but also to realise the current state-of-the-art ways of engineering a turbine blade that exist within the collaborative company. This was accomplished by the development of the Integration Definition Function Modeling (IDEF0) and Business Process Modeling Notation (BPMN) models within the first phase of the Samulet 5.6.1 project. The purpose of this activity was to set out the preliminary modeling work that was undertaken on the manufacturing processes used for turbine blades within the company. IDEF0 was used for mapping information flow and activity decomposition, and BPMN for mapping the time based interactions between processes.

These two different modeling methods were used to record and map out the activities, information flows and decision points that take place within the design and manufacture of turbine blades within the Turbine Blade Facility (TBF). The combination of these two methods provided a comprehensive approach to modeling business processes. These process models were analysed to understand the information needs of design engineers and what information manufacturing engineers currently hold. The IDEF0 and BPMN models contain the following aspects:

- A developed current ‘As-Is’ model of the turbine blade manufacturing function processes and information flows. This comprises of BPMN process model.
- A listing and description of the main information flows that was modelled within the ‘As-Is’ models.

However these models were not included in the thesis, since they contains the confidential information of the collaborative company.

Activity Modeling Outcome:

The analysis of the activity and process models resulted in identifying the critical categories of manufacturing information and knowledge which should be captured in a knowledge repository. The identified categories are tooling information, process capability, manufacturability information, manufacturing part information, method of manufacture and design for manufacture rules. These six categories are further explained in section below.

The analysis also indicated the need for design for manufacture rules to be stipulated and supplied. There was a need to develop a system that can deliver reliable information, which is easily and readily available on demand to engineers. The information supplied from the system has to be up to date, correct, precise and credible.

3.2.1 Information and Knowledge Categories

The six key areas of information and knowledge that exist within the Turbine Blade Facility (TBF) for design and manufacturing functions are listed in the figure 3-1. These were derived from the work of mapping process and information flows within the TBF. This relates to both turbine blade Design and Manufacturing Engineering.

These categories are:

1. Tooling Information: information about standard tools (sizes, diameters, etc.) and information about jigs, fixtures and inspection tooling used by manufacturing.

2. Process Capability:

- Machine Process Capability: information about tolerances, surface finish, and other aspects of machine and process capabilities (e.g. CMM machines).
- Manual Process Capability: information about the manual process e.g. welding, what can be achieved, what limits exist and what is needed by the welders. This can also apply to the human aspects of machine setup and operation.

3. Manufacturability Information: information about machine working envelopes (tool working angles, tool access, etc.) and problems of manufacturability (e.g. lessons learned).
4. Manufacturing part information: information about what is needed by manufacturing engineers to be able to achieve the intended design.
5. Method of Manufacture: information about the manufacturing processes used / to be used and the order they are executed in.
6. Design guidelines: this is an amalgam of the above information categories but also includes manufacturing knowledge about do’s and don’ts, lessons learned and manufacturing engineers’ needs and wishes.

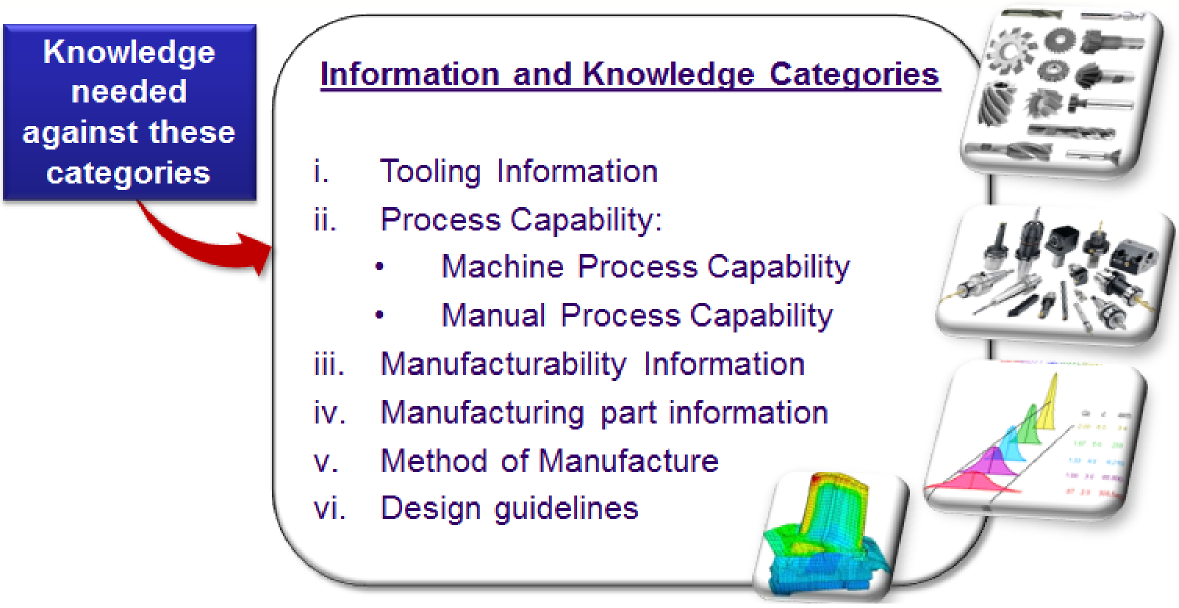


Figure 3-1: Information and Knowledge Categories

These six information and knowledge categories identified were important for both design and manufacturing engineering in TBF. However two key decisions were taken to help focus and simplify the research being undertaken. This was partly due to the wealth of information that was available to the researchers, thus allowing clarity and precision to be gained from the approach.

(i) The first key decision was to choose two of the Information and Knowledge Categories. These were:

- Tooling Information
- Process Capability

(ii) The second key decision was to target specific component features to better understand the information and knowledge relationships between design, manufacturing and inspection. Hence two simple manufacturing features of a turbine blade were chosen to focus upon in the first instance.

The first decision enabled a clear cut plan of action to gather and assess two types of information and knowledge. This allowed focusing upon some of the more detailed aspects to better understand the information and knowledge relationships and ensure the approach was achievable. The second allowed the research to concentrate in depth upon two features of a turbine blade so as to study, derive and map out the relationships between design and manufacturing viewpoints, information and knowledge. This brought about a full understanding of the context, language, requirements and aspects involved in the process of development and manufacture of a specific turbine blade.

For the understanding of the tooling and process capability information used within the design and manufacturing processes, two specific XWB HP blade features were chosen for the study. These were the Leading Edge Seal Tip and Trailing Edge Seal Tip. The associated manufacturing and design aspects with these features were investigated in depth which are explained in sections below

3.3 Feature Relationship

It is important to understand the information and knowledge relationships between design, manufacturing and inspection features. These relationships are complex and the underlying manufacturing knowledge is hard to elicit, hence these relationships need to be formalised first. The below sections explains the three different types of features and its relationship.

3.3.1 Definition of a Feature

Feature' is a word that can be used to represent many different things to many different people. Different engineers from different domains apportion vastly contrasting meanings to the word, hence it was important to understand and relate three specific feature viewpoints of the chosen case study product together.

Shah *et.al.* (1990) defined four requirements that a feature should fulfil.
A feature:

- has to be a physical constituent of a part (component).
- should be mappable to a generic shape.
- should have engineering significance.
- must have predictable properties.

Topology and/or non–geometry related information can often not be defined as part of the feature.

3.3.1.1 Manufacturing Feature

Manufacturing features are normally decreased from the manufacturing stock in terms of subtractive volumes, and they are conveniently connected with manufacturability analysis and process planning activities such as the configuration of work piece holding, choice of machine and cutting tools, and planning of the machining operations.

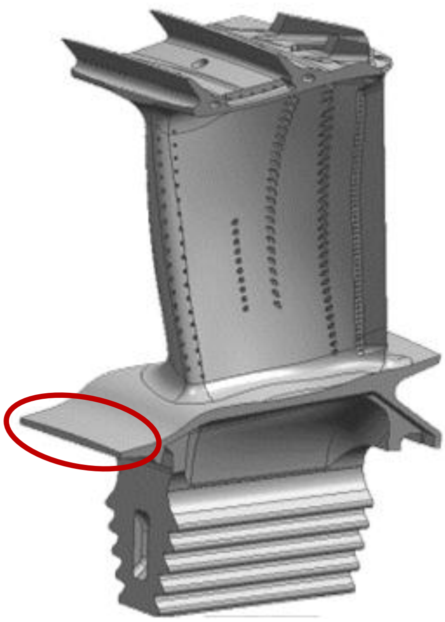


Figure 3-2: Manufacturing Feature – Root Leading Edge Seal Tip (Courtesy of Rolls-Royce)

A manufacturing feature is used to describe the manufacturing information of the part. Different manufacturing domains require different feature representations. Some of the properties that are available in manufacturing features are assembly method, manufacturing process and tolerances. A manufacturing feature can be defined as a form feature. Among manufacturing features, the one of the important feature are the machining features. The Figure 3-2 shows the manufacturing feature root leading edge seal tip of a XWB high pressure turbine blade. This feature is manufactured by series of machining operations.

3.3.1.2 Design Feature

Design is an integral part of any product or process. Designers go through a number of processes to achieve the final specification from an initial list of requirements known as a design brief. The designers solve problems through the design search space by a process of divergence and convergence to the eventual solution. Several iterations are undertaken to find a solution. Final communication of a design is often in the form of drawings and depending on the complexity of the design, a full scale model of the artifact could be made.

Figure 3-3 illustrates the design feature diagram of root leading edge seal tip of a XWB high pressure turbine blade. Based on the figure, the root leading edge seal tip has four dimensional capabilities marked as W, X, Y, and Z. The design engineer calls this feature as sealing fin. This is a critical design feature because it determines the gap between adjacent blades. It increases airflow, cooling width and the performance of the blade. The designers are interested in achieving the four dimensional capabilities associated.

3.3.1.3 Inspection Feature

An inspection feature will have a measurement to be inspected. The features are most generally inspected by an organized examination. It involves the measurements and tests applied to certain characteristics in regard to an object or activity. The results are usually compared to specified tolerance for determining whether the feature meets the dimensional capability.

In figure 3-3, the four dimensional measurements (W, X, Y and Z) are the inspection features of root leading edge seal tip. Coordinate Measuring Machine (CMM) is used for measuring the physical geometrical characteristics of the inspection features.

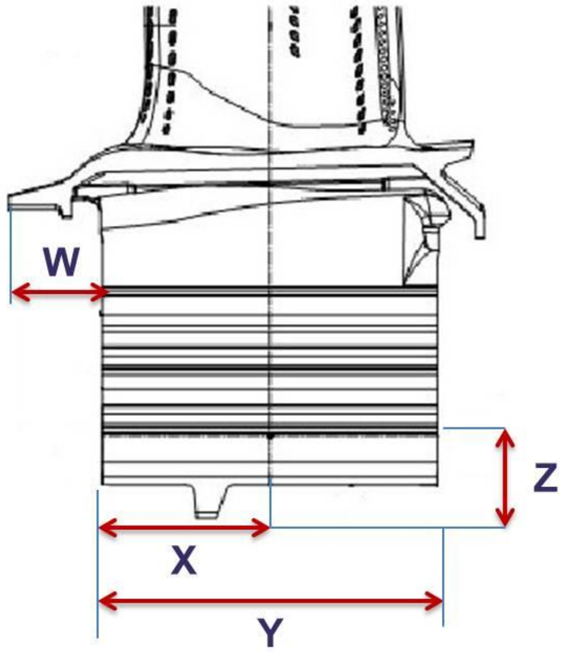


Figure 3-3: Design Feature – Root Leading Edge Seal Tip

For the purposes of this research the following are the definitions of a feature for each of the three viewpoints:

a) ***Manufacturing Feature:*** A manufacturing feature is a shape produced by a discreet manufacturing operation.
b) ***Design Feature:*** A design feature is a shape that performs a specific function.
c) ***Inspection Feature:*** An inspection feature is a discreet measured point or dimension.

3.4 MANUFACTURING FEATURE KNOWLEDGE RELATIONSHIP

The feature relationship structure is important for the better understanding of information and knowledge relationships between design, manufacturing and inspection features. In this research the feature relationship structure was created by Esmond Urwin. The below sections explain the structure created to describe the feature and knowledge relationship.

3.4.1 Knowledge Relationship Structure

The Feature Knowledge Relationship Structure (FKRS) is presented in figure 3-4 is based on UML model defined by (Urwin *et.al.*, 2011). The FKRS was used to explore the key decisions that were made during the new product development process between design and manufacturing to elicit the information and knowledge that is used and needed by engineers to facilitate the process. It sets out some of the main aspects that are involved in the design and manufacturing of a turbine blade.

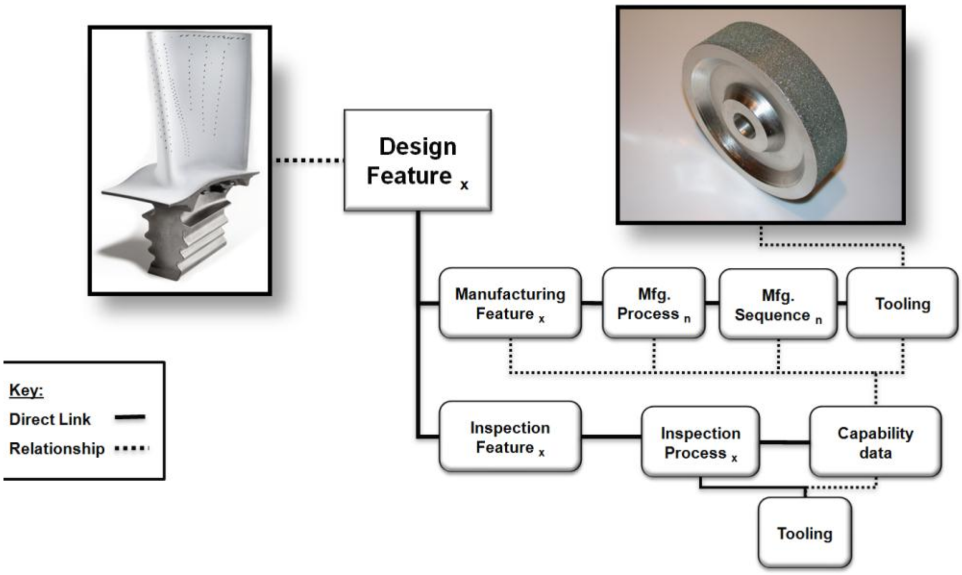


Figure 3-4: The Feature Knowledge Relationship Structure (Adapted from Urwin *et al.,* 2011)

From the information and knowledge mapping activities a Feature Knowledge Relationship Structure (FKRS) was developed. This model explicitly stated the relationships between design feature, a manufacturing feature and an inspection feature. The FKRS set out the derived relationship view between these three different types of features. There were different types of information and knowledge that can be associated against each of these. Hence by explicitly modelling and stating these relationships the FKRS allowed the information and knowledge to be linked between entities.

The first of these entities was the design feature, this is the product part that is being developed and represents the design engineering point of view. The second was the manufacturing feature, this is part of the manufacturing perspective about the product that is being manufactured. Related to this were the manufacturing process and the associated tooling used to produce the feature. The third was the inspection feature, which again has an associated inspection process, tooling and resultant capability data.

Each design feature has a number of dimensions that need to be measured, these constitute inspection features. Measurements are taken to validate that the manufacturing operations are capably producing the specified design feature for a given tolerance. A design feature to inspection feature relationship is one to many, whilst the design feature to manufacturing feature relationship is a many to many relationship. Aligned with a manufacturing feature is a manufacturing process which is employed to realise the feature which in turn uses manufacturing tooling. Accordingly an inspection feature employs an Inspection process to generated Capability Data and uses Inspection Tooling. The Capability Data relates to the Manufacturing Feature, Manufacturing Process, Manufacturing Tooling and Inspection Tooling.

3.4.2 Application of FKRS

To understand more about the FKRS applicability, it was assessed based on the two chosen manufacturing features. Figure 3-5 is a specific instantiation of the feature relationship structure; it is for the Root Leading Edge Seal Tip of a XWB HP blade. It illustrates the specifics for each of the items within the generic feature relationship structure. For example the design feature name is stated against the picture of the actual design drawing of the feature. The manufacturing feature five letter acronym is then stated with the associated manufacturing grinding operation number and the specific sequence number where the feature is created in the grinding machine. Related to this is the actual engineering drawing of the tooling associated with the grinding operation for the given feature. The instances of the inspection features have been populated. For this design feature there are three inspection features, each of which has a specific inspection process an associated inspection program and resultant capability data.

This structure was developed by accessing the numerous different bits of information produced by design and manufacturing and relating them to each other. This specific example is used to explore the key decisions that are made during the new product development process between design and manufacturing to elicit the information and knowledge that is used and needed by engineers to facilitate the process.

It sets out some of the main aspects that are involved in the design and make of a XWB HP turbine blade. It directly relates a design feature to both a manufacturing feature and an inspection feature. A manufacturing feature has a manufacturing process, a manufacturing sequence and tooling associated with it. Whilst an inspection feature has an inspection process and capability data that has been generated associated with it. The dotted lines show the attributed influences between the items. This formalises three specific viewpoints and sets out the relationships of how design and manufacturing relate to any given turbine blade feature. By explicitly stating this and using it to explore the underlying information and knowledge associated with a given feature, it will help develop a basis for relating information and knowledge. The FKRS was used to define the knowledge maintenance template (KMT) which is later explained in the chapter 4 and 6.

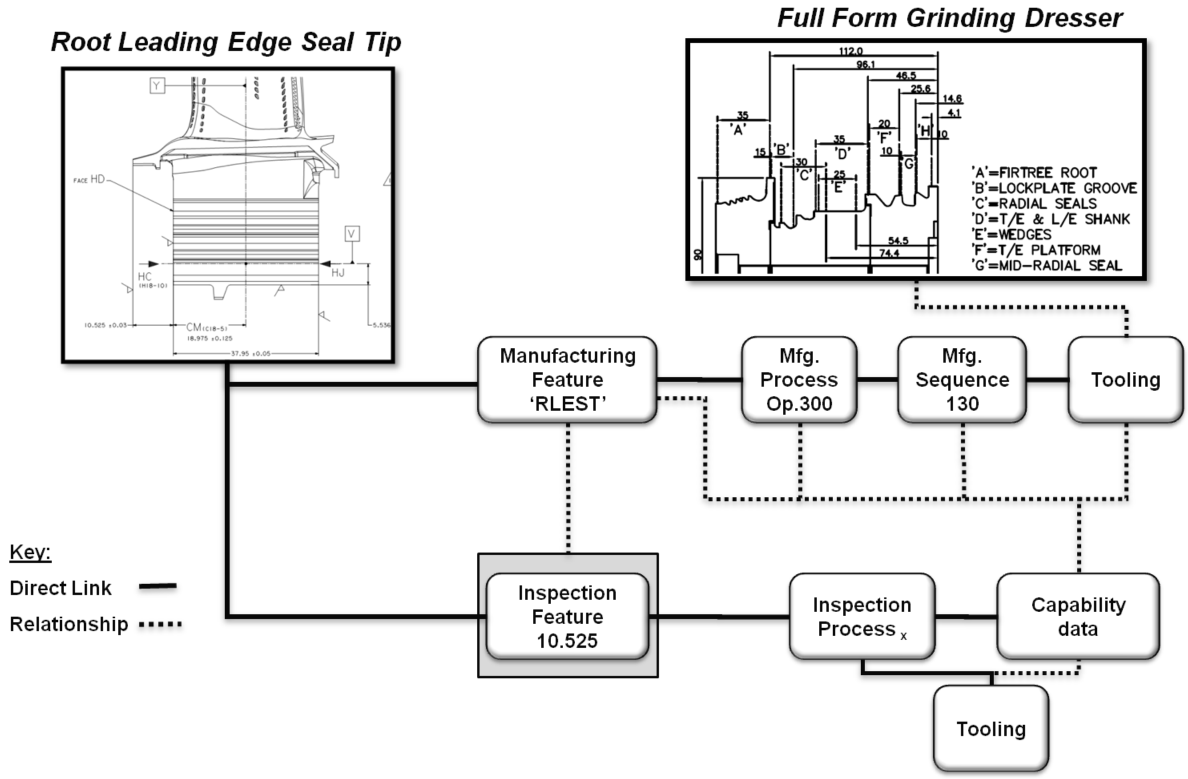


Figure 3-5: Knowledge Relationship Structure

3.4 Manufacturing Information and Knowledge

As mentioned earlier, to understand more about the manufacturing information and knowledge, following two manufacturing features of XWB HP turbine blade were chosen,

1. Root Leading Edge Seal Tip (RLEST)
2. Root Trailing Edge Seal Tip (RTEST)

These two features are also called as Sealing fin/Lock Plate. Based on the understanding of the design requirements, the inspection features associated with these two features were identified. The method of manufacture (MoM) of these two features was explored and the manufacturing sequence and operation were identified. Based on this exploration the manufacturing information and knowledge associated with RLEST and RTEST were identified. Figure 3.6 illustrates the root leading edge seal tip and its key inspection feature and the figure 3.7 illustrates the root trailing edge seal tip and its key inspection feature.

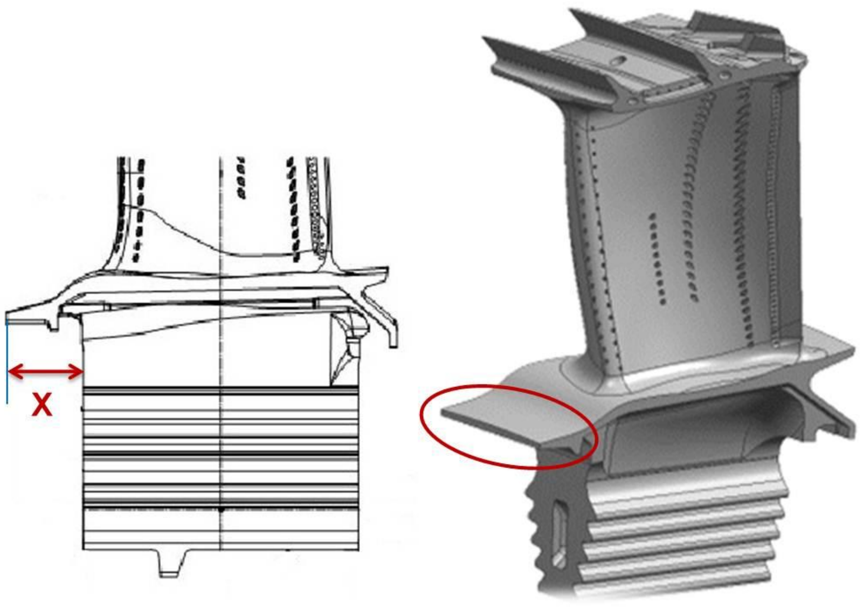


Figure 3-6: Inspection Feature - Root Leading Edge Seal Tip (Courtesy of Rolls-Royce)

The main inspection features 'X' and 'Y' are associated with the design feature and its relationship to the datum point by way of the firtree.

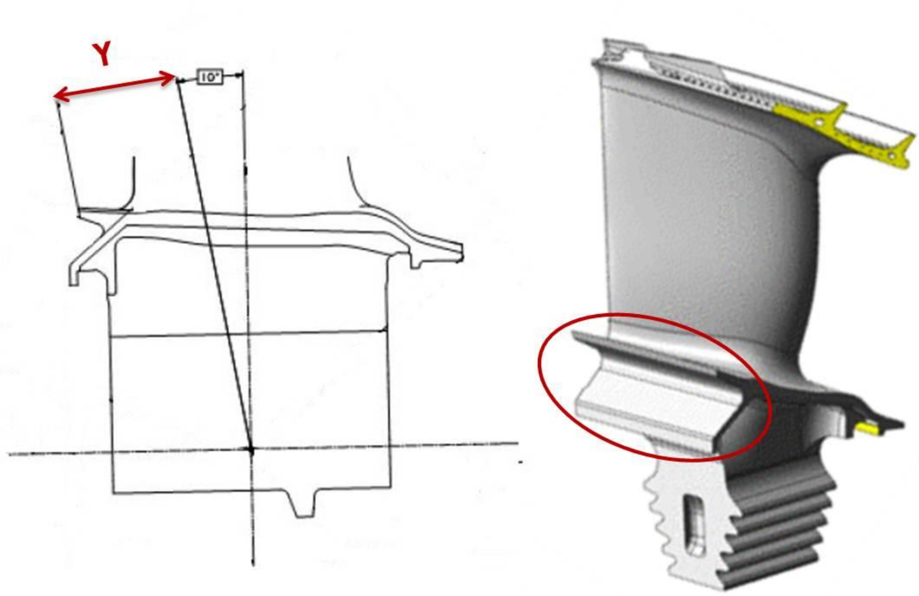


Figure 3-7: Inspection Feature - Root Leading Edge Seal Tip (Courtesy of Rolls-Royce)

For each manufacturing feature the design engineers want to know the knowledge associated with following categories,

- Manufacturing process capability
- Manufacturing tooling knowledge.

For each inspection feature the design engineers want to know the knowledge associated with following categories,

- Capability information (surface finish capability, dimensional capability, etc.)
- Tooling information (standard sizes, constraints, etc.)

Based on the above categories, the manufacturing and inspection knowledge associated with these two features were elicited from the engineers. This knowledge includes all the associated processes, modus operandi, methods of manufacture and key decision points, which are explained in the upcoming sections (values and knowledge defined are modified from the real values).

3.4.1 Manufacturing Process and Tooling Knowledge

As explained earlier, the two categories used for capturing manufacturing knowledge were manufacturing process knowledge and manufacturing tooling knowledge. The manufacturing process knowledge captured for Root Trailing edge seal tip and Root leading edge seal tip are listed below,

Root trailing edge seal Tip - Manufacturing Process Knowledge:

- No fixture constraints
- No inspection constraints
- Angled faces to be greater than 10˚, so grinding wheel is continuously dressed and not grinding on the side of the wheel.
- Radii to be no less than 5mm, risk of wheel breakdown.
- Data driven DfM, capability based on Trent 3000 equivalent information as same MoM adopted.
- MoM, this feature is also used subsequently as an engraving face therefore certain considerations must be accounted for like the stylus to ensure sufficient surface area can be engraved.

Root leading edge seal Tip -Manufacturing Process Knowledge:

- No fixture constraints
- No inspection constraints
- Flat faces, therefore produced by a flat wheel no concerns.

- MoM, this particular face later acts as a location face for the grinding of the leading edge lock plate groove, therefore a tighter tolerance is reflected on the finish part drawing to maintain the position of the leading edge lock plate groove.
- The root leading edge seal tip is used as a location face for the machining of the leading edge lock plate groove
- Due to the tighter tolerance the accuracy is built into the dresser and the leading edge shank and leading edge seal tip are ground together with the same single wheel

Root Trailing Edge and Root Leading Edge - Tooling Knowledge

The manufacturing tooling knowledge is common for both Root Trailing edge seal tip and Root leading edge seal tip.

- For op300 the tooling constraint is the tang clamp which influences the type of machining features acceptable to manufacturing. This largely impacts the firtree as these features get closest to the tang clamp.

3.4.2 Inspection Process and Capability Knowledge

The two categories used for capturing inspection knowledge were inspection process knowledge and inspection capability knowledge. The inspection process knowledge is common for both Root Trailing edge seal tip and Root leading edge seal tip.

Root Trailing Edge and Root Leading Edge – Inspection Process Knowledge:

The inspection method for op300 is reasonably flexible as the CMM probe has more or less full access to the whole of the blade. The only constraint with the CMM probe is that it can only rotate 10˚ from the horizontal plane (see illustration in figure 3-8). It is also worth noting that the CMM probe can only rotate in 5˚ increments which can affect how the probe approaches the inspection surface, ideally it would approach perpendicular to the surface.

Root Trailing Edge and Root Leading Edge – Inspection Knowledge:

While the root trailing edge and leading edge are inspected by CMM in process dimensionally for size, a further inspection of the form is carried out by shadow graph. A light source is shone on the blade which then projects the shape of the form through a mirror onto the shadow graph and detects any breakdown of the form.

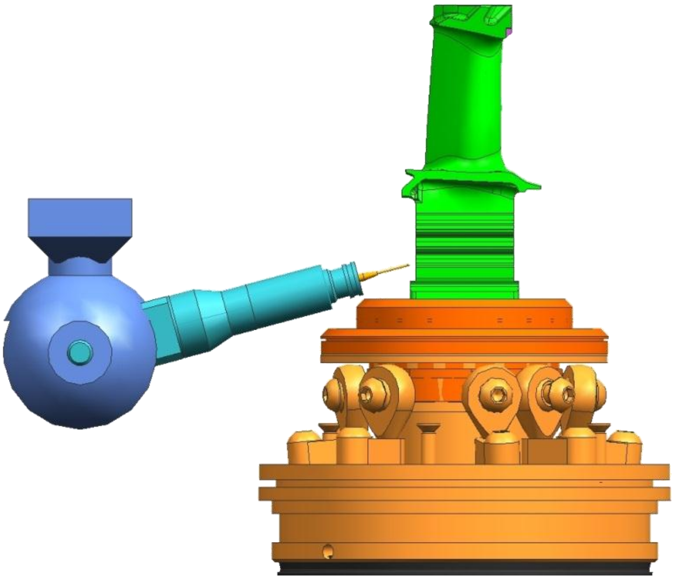


Figure 3-8: Inspection Process using CMM (Courtesy of Rolls-Royce)

Root Trailing Edge – Capability Information:

The capability information of the inspection features are measured by Cp, Pp, Cpk, and Ppk values

- Cp = Process Capability
- Cpk = Process Capability Index
- Pp = Process Performance
- Ppk = Process Performance Index

The capability of processes is defined by a couple indices called Cp and Cpk. Cp tells how capable the process is. If there is more of variation in the process then it is not capable. Reduction in variations will improve your Cp value. Cpk tells how centred our process is. Pp is used measure the performance of the process. Ppk is used to verify the whether the process is capable to meet requirements.

Figure 3.9 illustrates the capability information of root trailing edge seal tip. This graph is drawn by MeasurLink (tool for real-time data acquisition and analysis) based on the mean values received from CMM. For each inspection feature, a similar graph is drawn by MeasurLink to determine the Cp, Pp, Cpk, and Ppk values. By using these values the process capability information for every inspection features are checked.

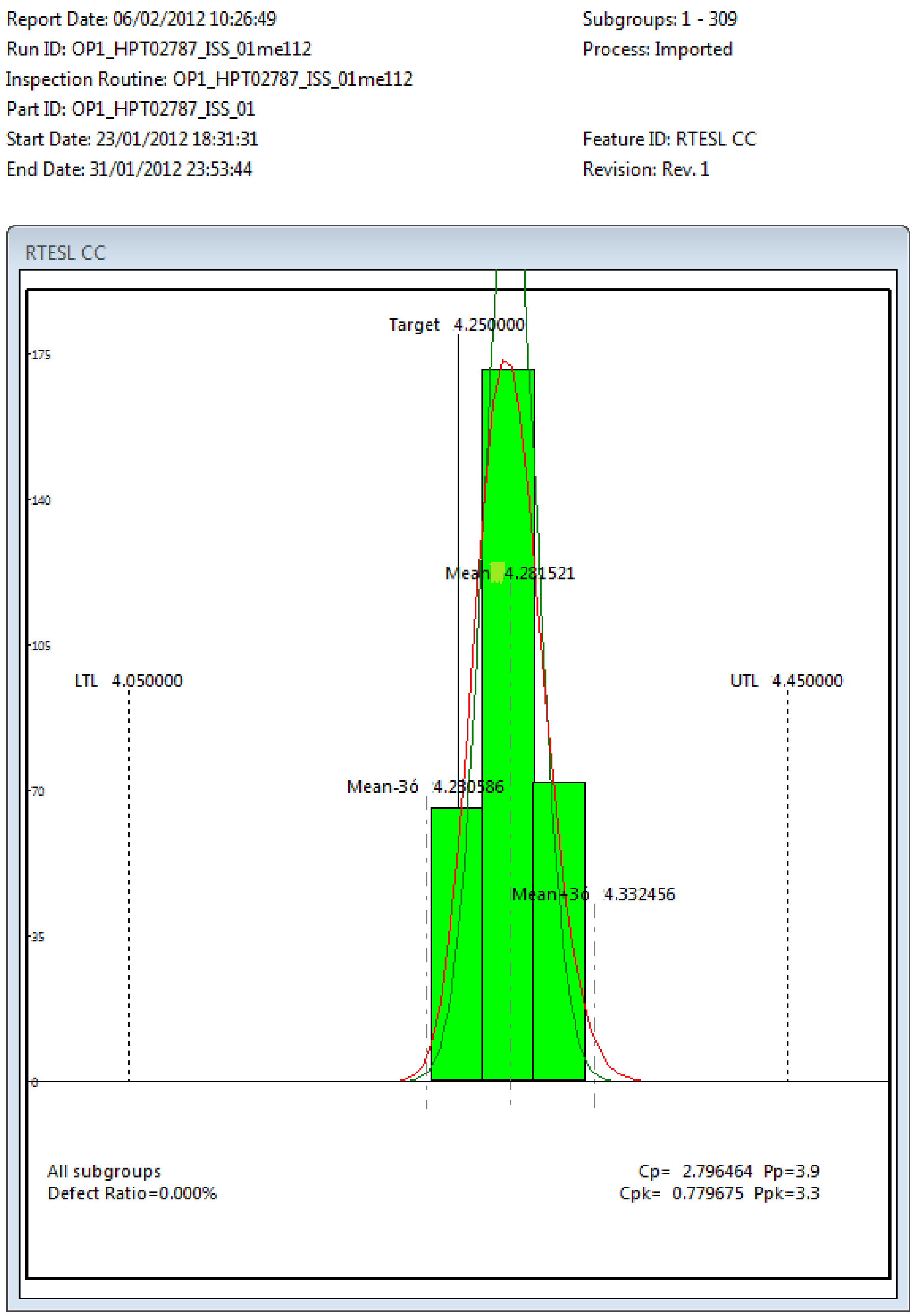


Figure 3-9: Capability Information – Root Trailing Edge (Courtesy of Rolls-Royce)

3.5 Knowledge Sources

The final important activity done during the industrial investigation is identifying the valid knowledge sources. It is important to identify potential sources of knowledge that exist in the Turbine Blade Manufacturing Facility. This activity helped to answer the following two questions,

1. What is the source of new knowledge?
2. What are factors that change the existing knowledge?

A detailed study was conducted in TBF to identify all the available knowledge sources for design engineers. Figure 3-10 shows the various knowledge sources identified during the industrial investigation. These sources were identified based on the discussion with manufacturing and design engineers. Some of these sources are not the exact knowledge source but they are knowledge documents, where the knowledge identified is stored in different forms and names. The knowledge sources are available in different data forms such as drawings, reports, intranet and word documents. All the identified sources are reviewed by the design engineers and based on their feedback correction were made.

The key knowledge sources from the list are communication sheets, tooling specifications, component family templates, capability data and technical reports. These five knowledge sources are used by design engineers to make decisions. This knowledge source identification process helped to understand the company's current knowledge sharing process and knowledge usage. These knowledge sources were used in determining the credibility of the knowledge which is explained later in the chapter 5 (section 5.7.1).

Knowledge Source	Data Forms	Comments
Manufacturing Engineer - Verbal	Verbal	Inconsistent
Manufacturing Engineer - Email	Email	Inconsistent
Manufacturing Engineer - Comm. sheet	Comm. sheet in response to design request	Ought to be associated to specific part number or family
Capability data	Capability data in response to design request	Snapshot in time
Cost model output	Cost data	May be used to compare the cost of different manufacturing methods
Tooling CAD Model	CAD Model	Model to show tooling/clearances or to demonstrate manufacturing sequence
Existing Comm. Sheet	Comm. sheet (from other projects)	May not be applicable or quality controlled.
Lessons Learnt Log	Intranet database: http://www.capability.rolls-royce.com/lessons/	Targets specific issues.
Components	Visual inspection/surgery or parts by design	To assess visual standard of parts
Risk Assessment	Risks recorded during risk review	Reflect opinion
Technical Report	Report	E.g. Design definition report, manufacturing report
FAIR (First article inspection report)	Report	Only available after first parts manufactured and inspected. Could be useful to look at FAIR's from similar parts
Non-conformance	Concessions	From similar parts – may reveal areas of non-conformance for improvement.
Engineering Drawing	Engineering Drawing	From similar parts – shows historical tolerancing
Design Scheme Drawing	Engineering Drawing	From similar parts – shows design intent

Figure 3-10: Knowledge Source and Data Forms

3.6 SUMMARY

This chapter explains the detailed industrial investigation done on manufacturing knowledge maintenance in association with the collaborative manufacturing company.

The section 3.2 explained the analysis of the activity process modeling. This analysis resulted in identifying the critical categories of manufacturing information and knowledge which should be captured in a knowledge repository. Out of the six categories identified only two were chosen for the better understanding of research phenomenon under study. Two manufacturing features were chosen to understand the information and the knowledge associated based on the two knowledge categories.

The section 3.3 provided the definition for the manufacturing, design and inspection features and explains the relations between them. The section 3.4 explains the importance of the feature relationship structure developed for this research project. This structure provided the better understanding of information and knowledge relationships between design, manufacturing and inspection features. The application of FKRS on the Root Leading Edge Seal Tip of a XWB HP blade was explained.

The section 3.5 explained the manufacturing and inspection knowledge captured for the two manufacturing features 1) Root Leading Edge and 2) Root Trailing Edge under the two knowledge categories 1) Tooling knowledge and 2) Process Capability. The knowledge capturing process for the two features helped in understanding the research environment. The final section explores the various knowledge sources identified during the industrial investigation. From this list the key knowledge sources were used in defining the maintenance method for knowledge filtering, which is explained in Chapter 5.

CHAPTER 4 - AN OVERVIEW OF A NOVEL METHOD FOR MANUFACTURING KNOWLEDGE MAINTENANCE

4.1 INTRODUCTION

The purpose of this chapter is to expose the author's concept for a novel method for manufacturing knowledge maintenance which supports knowledge sharing in product design and manufacture. The literature review identifies the gaps in understanding knowledge maintenance and identifies a need to define suitable methods for the maintenance of manufacturing knowledge. A novel method for manufacturing knowledge maintenance is explained in this chapter through four sections.

Section 4.2 proposes the author's novel knowledge maintenance method, which explains the importance of knowledge maintenance tasks and knowledge lifecycle maintenance process. It also details the knowledge analysis tasks and functions identified in this research. Section 4.3 details knowledge analysis maintenance method and its key components which are knowledge maintenance process and knowledge maintenance template. A summary of this chapter is then provided in section 4.4.

4.2 THE PROPOSAL FOR A NOVEL KNOWLEDGE MAINTENANCE METHOD

4.2.1 Knowledge Maintenance Tasks

Knowledge maintenance tasks are vital for effective knowledge management (KM). Several knowledge management tasks have been identified and proposed in the past, a number of which are believed in this thesis to also be necessary for effective knowledge maintenance. They are Knowledge Acquisition (Motta *et al*., 1990), Relevancy Checking (Godbout, 1999) Knowledge Filtering (Miyashita and Sycara, 1995), Criticality Ranking (Ermine *et al.*, 2006), Integration and Structuring (Abbott, 2004), Presentation and Output (Hussain *et al.*, 2004) and Verification & Validation (Preece, 2001).These tasks are important aspects of knowledge maintenance because they are essential for the development of maintenance process and for managing the knowledge lifecycle. Borysowich (2010) proposed four tasks for knowledge maintenance which are Quality Assurance, Integrity Checking, Archiving Old and Out-dated Data and Assessing Impact of Modification. All these tasks are also important and should form a part of knowledge maintenance. The combinations of these 11 tasks are illustrated in figure 4-1, which are believed here to be a necessary set and should be performed at regular intervals to update and maintain a manufacturing knowledge base.

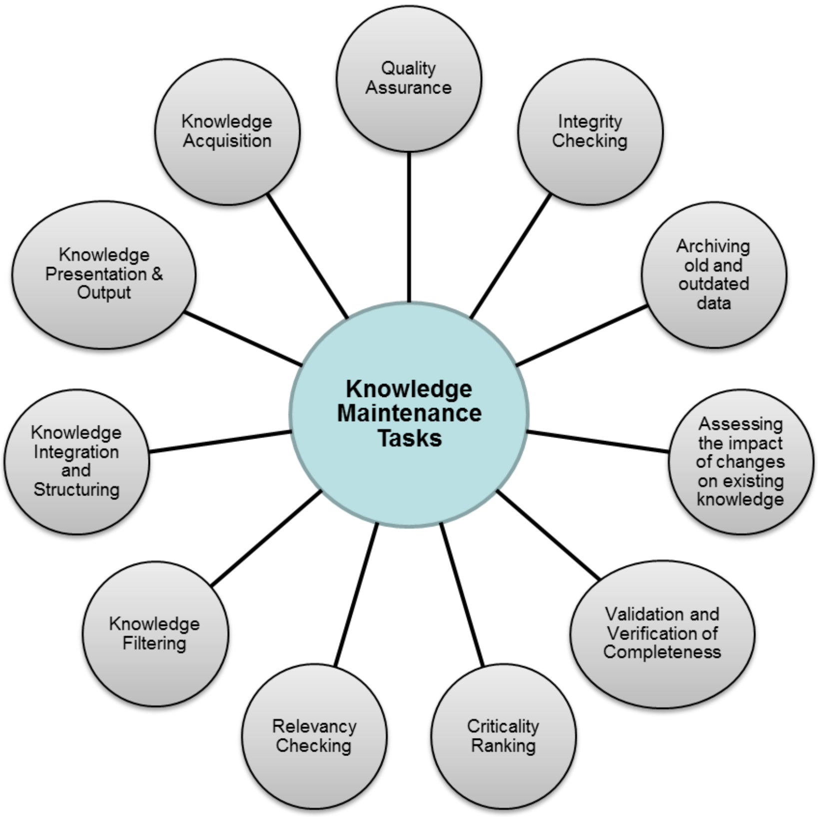


Figure 4-1: Knowledge Maintenance Tasks

4.2.2 Maintenance Process for Knowledge Lifecycle

Knowledge management (KM) consists of processes that facilitate the application and development of organisational knowledge, in order to create value and to increase and sustain competitive advantage (Carlucci *et al.*, 2004). Several KM processes have been proposed in the recent past. Oluic-Vukovic (2001) outlines five steps in the knowledge processing chain: gathering, organizing, refining, representing, and disseminating. This model covered the complete range of activities involved in the organisational knowledge flow. Awad and Ghaziri (2004) encapsulated a KM model consisting of four steps as capturing, organizing, refining and transferring. However the conceptual framework of KM provided by (Bouthillier and Shearer, 2002) provided a more complete analysis of organisational knowledge flow. As shown in figure 4-2 their framework comprises of six basic tasks: discovery of existing knowledge, acquisition of knowledge, creation of new knowledge, storage and organisation of knowledge, sharing of knowledge, use and application of knowledge.

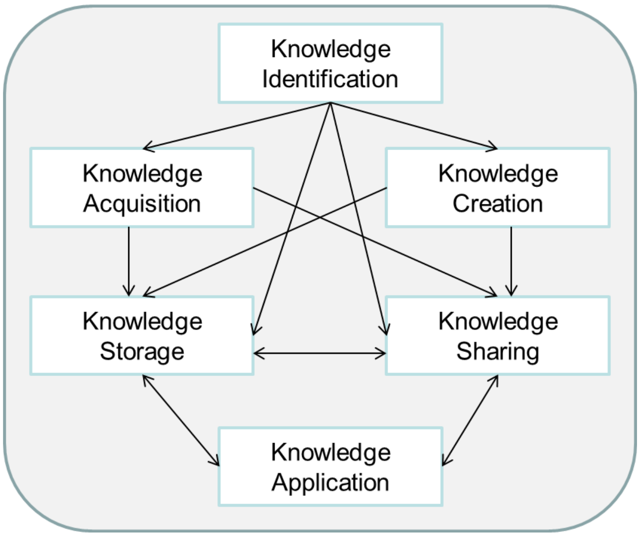


Figure 4-2: Conceptual Framework: Knowledge Management Processes ***(adapted from Bouthillier and Shearer, 2002)***

This framework has been used here as the initial basis for the maintenance process for knowledge lifecycle explored in this research. A knowledge lifecycle provides an efficient approach to manage various stages in knowledge development. However their framework needs to be extended to include other important knowledge maintenance processes which are knowledge analysis, knowledge classification and knowledge update. These maintenance processes are essential for managing the knowledge lifecycle. By grouping the maintenance tasks based on these processes forms an effective maintenance process for knowledge lifecycle.

Guerra-Zubiaga (2004) proposed the structures and relationships within the manufacturing model to support knowledge maintenance. However there is a need to define a maintenance process which relates to the range of maintenance tasks as these are of critical importance for the continuous improvement of knowledge to keep it up to date. This research focuses on such maintenance tasks and its critical functions, which are required to provide effective knowledge maintenance. The following definitions are provided to differentiate a maintenance function, task, process and method;

- ***Function:*** An activity which needs to be done.
- ***Task:*** Consists a set of functions which needs to be performed for its completion

- ***Process:*** Consists of a sequence of tasks which needs to be performed to provide an expected output.
- ***Method:*** Consists of a sequence of processes which needs to be followed to solve the problem.

Figure 4-3 illustrates the novel maintenance process proposed for managing the knowledge lifecycle. This maintenance process consists of key tasks that should be performed for the continuous improvement of knowledge. Out of eleven maintenance tasks identified in the previous section only seven were considered in this research. The remaining four tasks were left out due to the following reasons. Quality assurance was not included because relevancy checking, knowledge filtering and integrity checking tasks indirectly verify the quality of the knowledge. Archiving old and outdated knowledge was not considered as a separate task but as a sub function in maintaining consistency of the knowledge during knowledge modification. Knowledge acquisition was not considered because knowledge capturing and modeling was focused separately in this research by Dr. Esmond Urwin (explained in chapter 1). Assessing impact of knowledge modification was not included as separate maintenance task but considered as an additional responsibility of the Technical Leaders to verify during the knowledge review which is later explained in the section 4.3.1.

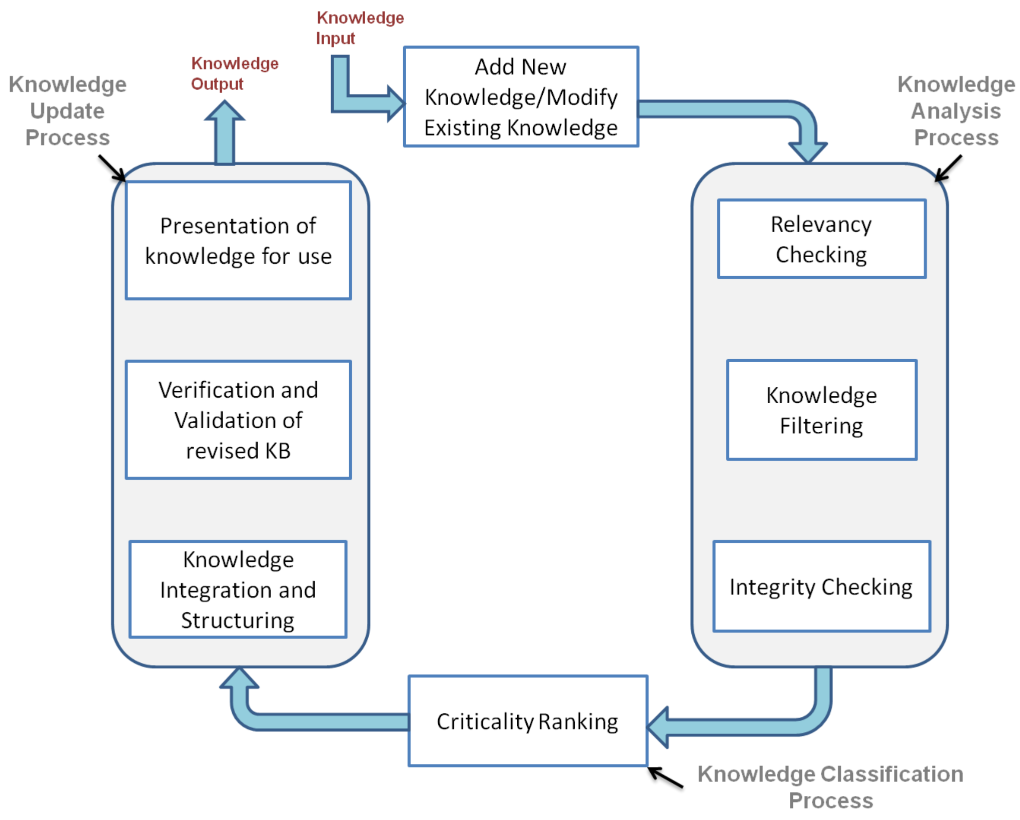


Figure 4-3: Maintenance Process for Knowledge Lifecycle

The knowledge lifecycle process comprises of three processes 1) Analysis process, 2) Classification process and 3) Update Process. The analysis process includes three tasks which are relevancy checking, knowledge filtering and integrity checking. The classification process is based on criticality ranking task. The final update process consists of three tasks which are knowledge integration and structuring, validation and verification, and presentation of knowledge. In this research a maintenance task is defined as an activity which needs to be performed.

4.2.3 Knowledge Analysis Tasks and Functions

As shown in figure 4-3, all the three processes consist of one or more maintenance tasks which are important for the effective knowledge maintenance. However the emphasis of this research is on the knowledge analysis process because it determines the quality of the knowledge, which is an important aspect of knowledge maintenance. The knowledge analysis process is more vital because it determines the correctness of the knowledge entered. According to (Sierhuis and Clancey, 1997) it is the process of analysing knowledge based on its usefulness, weaknesses and appropriateness. The analysis process is explored by identifying knowledge functions for each of the three maintenance tasks which are Relevancy Checking, Knowledge Filtering and Integrity Checking. Figure 4-4 illustrates the knowledge analysis process proposed and the functions identified for the three tasks. These functions identified in this research, provide the basis by which the three knowledge maintenance tasks are achieved.

Several knowledge management functions have been identified and proposed in the past, a number of which are believed in this thesis to also be necessary for effective knowledge maintenance. They are dynamic nature of knowledge (McInerney, 2002), the value of knowledge (Reich, 1995) checking credibility of knowledge (Andrews and Delahaye 2002), knowledge life (Holsapple and Joshi 2004) data duplication (Lup Low *et.al.*, 2001), knowledge usage (McCarthy and Aronson, 2001), technical relevancy (Schulz and Jobe, 2001), and consistency (Teniente and Olivé, 1995). Guerra-Zubiaga (2004) proposed knowledge type as a knowledge maintenance function. However based on the evaluation long-term needs, accuracy, acceptability and applicability are also important maintenance functions for performing knowledge analysis. All these thirteen functions are important and should form a part of knowledge analysis process. These functions are classified into three groups 1) Relevancy Functions, 2) Filtering Functions and 3) Integrity Functions based on their performance and association with the maintenance tasks.

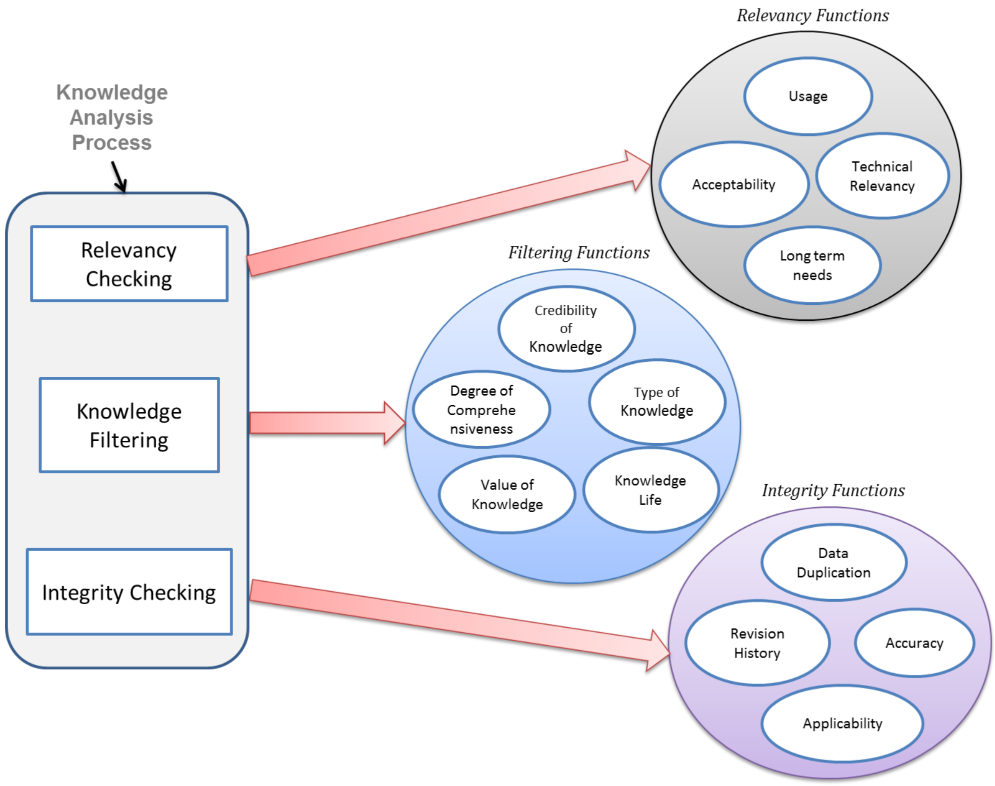


Figure 4-4: Knowledge Analysis for Maintenance

4.3 Knowledge Maintenance Method

There are different methods by which knowledge maintenance has been performed in previous research. Teniente and Olivé (1995) proposed a method for updating knowledge bases while maintaining their consistency based on deductive conceptual models. Menzies and Debenham (2000) put forward an expert system for knowledge maintenance based on artificial intelligence. Craw *et al*. (2001) proposed a case based knowledge maintenance for the case based reasoning system. However these methods rely on computational support and a major tenet of the research reported in this thesis is that knowledge needs to be maintained whether or not it is in a computational form.

The maintenance functions identified for knowledge analysis tasks are used in the development of the maintenance method. Four iterative case studies were conducted for exploring the knowledge analysis maintenance method. As a result of these evaluations, out of thirteen functions proposed only eight maintenance functions were included in the knowledge analysis maintenance method. They are technical relevancy as a relevancy function; credibility of knowledge, knowledge value, knowledge type and knowledge life as the filtering functions; revision history and applicability as the integrity functions. The remaining five functions which are usage, long term needs, acceptability, degree of comprehensiveness and accuracy were included in determining the value of the knowledge.

The key components of the knowledge maintenance method are a Knowledge Maintenance Process (KMP) and a Knowledge Maintenance Template (KMT). A knowledge maintenance process identifies the roles and responsibilities of the actors for the performance of knowledge maintenance functions. The knowledge maintenance template represents the information and knowledge attributes.

4.3.1 Knowledge Maintenance Process (KMP)

According to (McKeen & Staples, 2001), knowledge management and knowledge managers are organisational phenomena. The knowledge managers are those key individuals charged with the task of making knowledge management successful. Based on this, there is need to identify key persons in an organisation for the performance of knowledge maintenance process.

Yeol Lee and Kim (1998) stated that, a knowledge professional is an individual who knows how to organise knowledge into systems and structures that facilitate the productive use of knowledge resources. Similarly in this research a knowledge controller role was established to facilitate the interaction between the other actors and to control the knowledge maintenance functions. Three other actors were identified based on the evaluation of the knowledge analysis maintenance method. They are Engineer, Technical Leaders and Commodity Leader. The actions performed by the four actors are explained briefly below,

Engineer - Inputs the knowledge into the knowledge management system and initiates the knowledge ADD / MODIFY process.

Technical Leaders - Verifies the knowledge and provides feedback to the Engineers for modification.

Commodity Leader - Owns the whole maintenance process and is responsible for the approval of the knowledge documents.

Knowledge Controller - Enables the interaction between the Engineers, Technical Leaders & Commodity Leaders and controls all the knowledge maintenance functions.

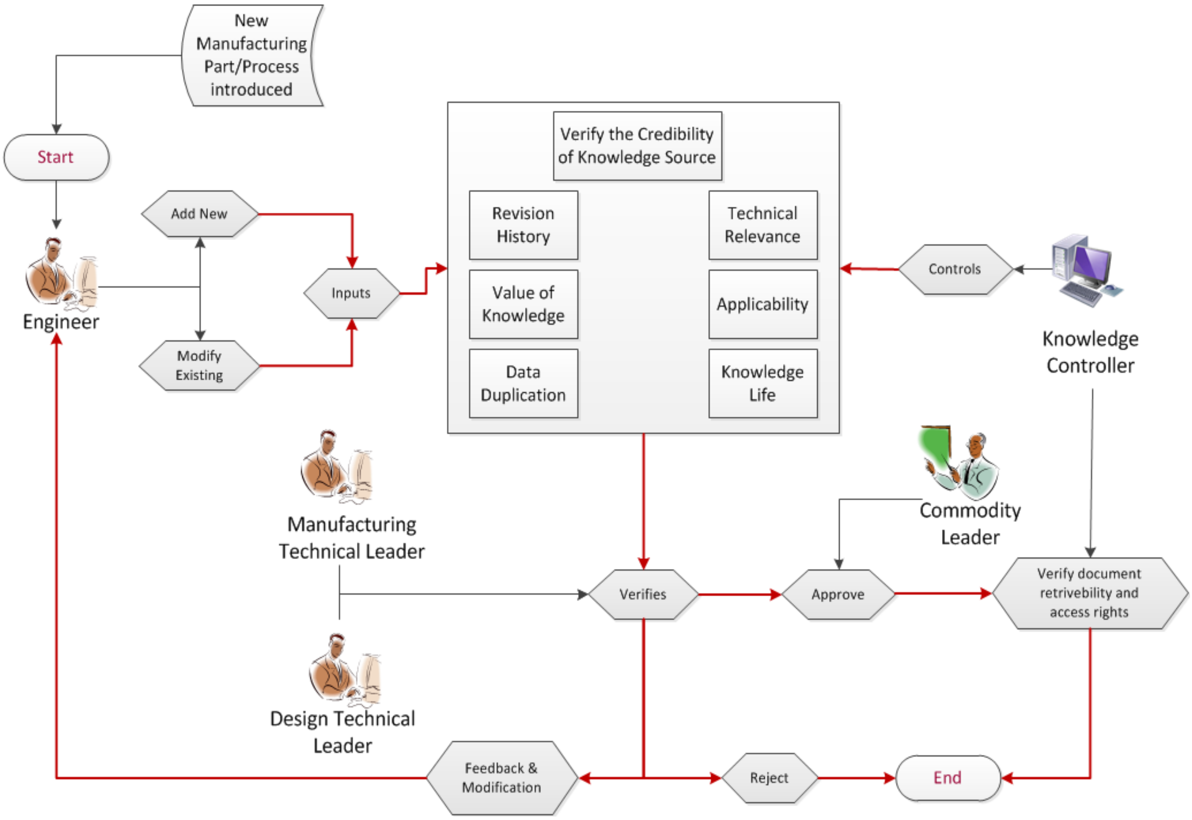


Figure 4-5: Knowledge Maintenance Process

Figure 4-5 illustrates the detailed knowledge maintenance process which includes four actors and seven maintenance functions. In a manufacturing environment, when a new part or process is introduced it will trigger a change in the existing knowledge or provides an opportunity to add the new knowledge. This trigger initiates the maintenance process.

A knowledge maintenance template was created utilising and extending the Feature Knowledge Relationship Structure (FKRS) developed by Urwin *et.al.*, (2012). This template includes all the eight maintenance functions illustrated in figure 4-5. This template is used by the engineer to generate knowledge documents by adding new knowledge or modifying an existing knowledge. The detailed explanation of roles and responsibilities of the four actors are explained later in section 5.5.1

4.3.2 Knowledge Maintenance Template (KMT)

A knowledge maintenance template provides simple capture and maintenance of manufacturing knowledge, so that it can be shared with design engineers. The template allows relevant manufacturing knowledge to be captured in specific maintenance fields. It also explicitly states the relationships between the different manufacturing, design and inspection features.

Figure 4-6 illustrates the manufacturing knowledge maintenance template. It consists of different sections which are used to represent the following seven maintenance functions,

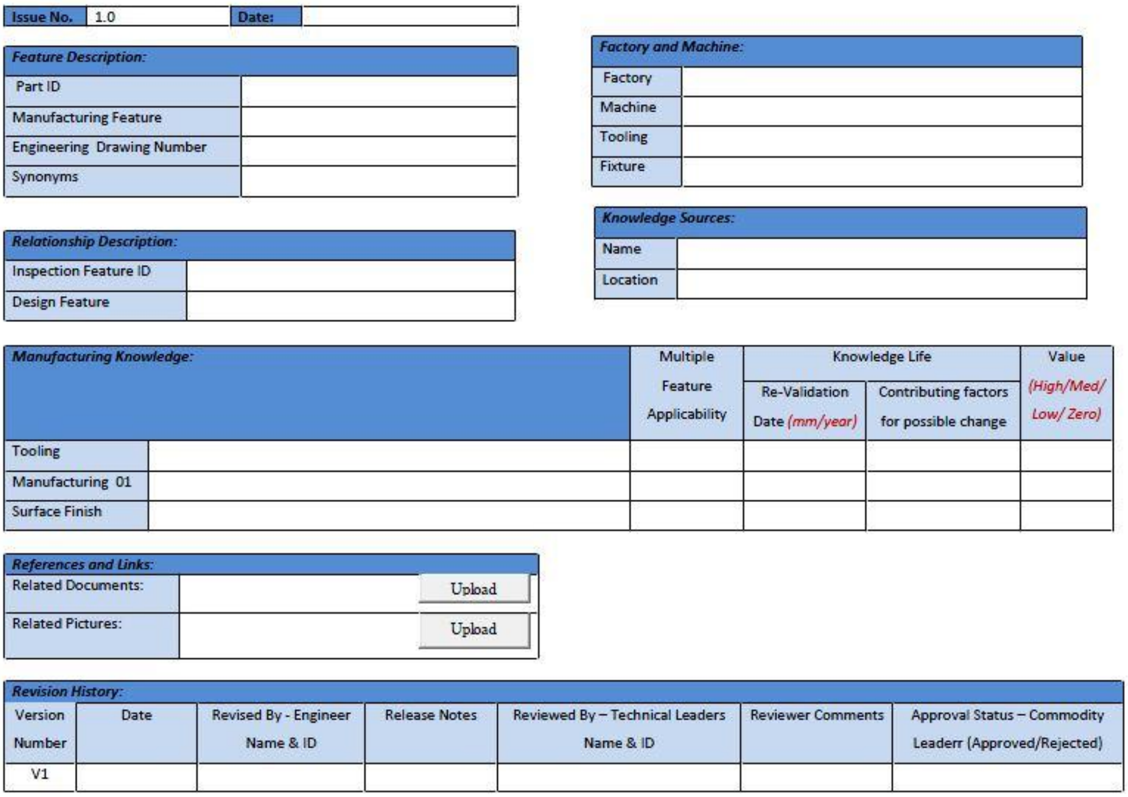


Figure 4-6: Knowledge Maintenance Template

(1)Technical Relevancy

Technical relevancy is established by the Engineer populating the relevant knowledge in each of the fields of the template. The structure of the documents has been defined such that the knowledge captured is technically relevant. It is important that all sections of the documents should be filled by the Engineer, for proper knowledge capture and maintenance.

(2)Credibility of Knowledge

This function helps to identify the source of the knowledge entered. Knowledge source information is captured for the purpose of knowledge filtering. For the captured knowledge, the original source must be known to validate the credibility of knowledge and also to seek future clarifications. By measuring the credibility of the knowledge source ineffective knowledge can be filtered. A valid knowledge source list has been prepared and the Engineer has to select the valid source while entering the knowledge. The knowledge source list will be reviewed periodically.

(3)Multiple Feature Applicability

Multiple feature applicability function captures the information of manufacturing features within a part which use the same knowledge. This process of capturing provides clarity about the relations between different manufacturing features. The Engineer lists out all the other manufacturing features which use the same knowledge.

(4)Knowledge Life

Knowledge changes over the period of time. Knowledge life maintenance function captures the validity time for the knowledge entered. The knowledge life is entered by the Engineer in the form of knowledge re-validation date and the contributing factors for the possible knowledge change.

(5)Data Duplication

Before entering the knowledge the Engineer has to review the existing knowledge and the previously rejected knowledge to avoid duplication.

(6)Value of Knowledge

Knowledge value function identifies how valuable the captured knowledge is corresponding to the design engineer. Knowledge value is measured based on five parameters which are usage, long term needs, acceptability, degree of comprehensiveness and accuracy. The knowledge captured is rated as High, Medium or Low by the Engineer's based on the five parameters and the Technical Leader's verifies the rating.

(7)Revision History

The integrity of the knowledge is checked by maintaining the revision history of the knowledge. A revision history field is created which captures all the activity done in the knowledge document. This log will contain all details about the changes made to the knowledge. It provides the details about the Engineer, Technical Leaders and Commodity Owner who have worked on this document. The changes are captured in the form of release notes with reviewer's comments.

4.4 SUMMARY

This chapter discusses the author's concept for novel manufacturing knowledge maintenance method. As mentioned in chapter 1, one of the main objectives of this research was to identify the key tasks for manufacturing knowledge maintenance. The literature review aided in identifying several important knowledge maintenance tasks, which were considered to suit this research. A novel maintenance process that consists of key tasks that should be performed for the continuous improvement of knowledge has been defined. In the maintenance process, the emphasis was given to knowledge analysis because it determines the quality of the knowledge, which is an important aspect of knowledge maintenance. After examining each task three tasks were identified to be the part of knowledge analysis, which were relevancy checking, knowledge filtering and integrity checking. The maintenance functions associated with these three tasks were identified. Based on these maintenance functions a novel knowledge maintenance method (KMM) was defined. The two key components of the methods were the knowledge maintenance process (KMP) and the knowledge maintenance template (KMT). The seven maintenance functions, credibility of knowledge source, technical relevance, knowledge value, knowledge life, data duplication, revision history and applicability, implemented in KMT and KMP provides an effective knowledge maintenance method.

The KMP defines four actors for the proper execution knowledge maintenance activities. It also details the knowledge analysis tasks & functions identified in this research. The KMP provides a flexible environment to add new knowledge and to modify existing knowledge in the knowledge base. The roles and responsibilities of the actors in the KMP for the performance of knowledge maintenance functions have been defined. The four main activities performed by the actors in the KMP are input, control, verify and approve. The execution of these activities by the key actors forms the basis of the maintenance process.

The KMT developed for the representation of information and knowledge, provides a simple and easy way of capturing the manufacturing knowledge. The maintenance fields created in KMT provides specific categories to enter the details of the knowledge, which are important to keep the knowledge up-to-date. The detailed development of the knowledge maintenance method is explained in chapter 5 and the methods to perform each function are explained in sections 5.6, 5.7 and 5.8.

CHAPTER 5 - A DETAILED DEVELOPMENT OF THE KNOWLEDGE MAINTENANCE METHOD

5.1 INTRODUCTION

This chapter describes the detailed perspective of knowledge maintenance method against its key elements. Chapter 4 provided a high level explanation of author's concept for a novel method for manufacturing knowledge maintenance; this chapter provides a detailed explanation of all the key elements involved in maintenance method. This chapter consists of nine sections.

Section 5.2 details all the knowledge maintenance tasks identified and explains the initial knowledge maintenance flowchart established using the tasks. It also details the six stages of knowledge maintenance represented in the flowchart. Section 5.3 details the maintenance process flow to manage the knowledge lifecycle and the three knowledge maintenance process (*Analysis, Classification, and Update*) associated with it. Section 5.4 explains the knowledge analysis process and three knowledge maintenance tasks *(Relevancy, Filtering, and Integrity*) focused in this research. Section 5.5 explains the definitions of the actors involved in the process. Section 5.6 details the relevancy checking task and defines the method to establish technical relevancy. Section 5.7 explains, knowledge filtering based on the credibility of knowledge source, knowledge value, knowledge life, knowledge type and data duplication. Section 5.8 explains integrity checking task and the sub sections explain the methods identified for data duplication and maintaining consistency. Section 5.9 explains the novel knowledge maintenance method defined based on the knowledge analysis tasks and its functions. The two main components of the method are Knowledge Maintenance Process (KMP) and Knowledge Maintenance Template (KMT) which are explained in the subsections. A summary of this chapter is then provided in section 5.10.

5.2 EXPLANATION OF THE KNOWLEDGE MAINTENANCE TASKS

As explained in chapter 4, following knowledge management tasks have been identified and proposed in the past literature, which are believed to be necessary for knowledge maintenance.

Quality Assurance:

Quality of knowledge is an important factor for knowledge management process because the knowledge is used in problem solving, decision support and innovation (Soo *et al*., 2002). Quality assurance checks the consistency and completeness of the knowledge (Pipino *et.al*., 2002). Criteria for quality of knowledge in knowledge management systems are timeliness, accuracy, completeness, consistency and relevance (Tongchuay and Praneetpolgrang, 2008). In general, quality assurance verifies whether the quality requirements of the knowledge are fulfilled or not. In this research, quality assurance was not considered as a separate knowledge maintenance task because relevancy checking, knowledge filters and integrity checking tasks indirectly verify the quality of the knowledge.

Integrity checking:

Integrity checking is a key task to make sure that no incorrect knowledge is entered into the knowledge repository. Integrity checking is necessary to prevent data duplication or multiple entries in the knowledge base (Bry *et.al.*, 1991). Consistency checking of the knowledge base will support the knowledge integrity (Preece & Shinghal, 1994). In this research, integrity checking task is used for verifying the accuracy, data duplication, applicability and consistency of the knowledge.

Archiving old and outdated knowledge:

Old and outdated knowledge should not be deleted but be archived, because it enables the history of the knowledge to be maintained. In this research, archiving old and outdated knowledge is not considered as a separate task but as a sub function for maintaining consistency of the knowledge during knowledge modification. When the knowledge is modified the old knowledge will be archived which is explained later in section 5.8.1

Assessing impact of changes made to existing knowledge:

Whenever an existing knowledge is modified, there is a need to access the impact and verify the changes made. This task has to be carried out every time during knowledge modification. It is also applicable for every change in the Knowledge Base (KB), a quick check on key functionalities of KB should be conducted and verified. In this research, assessing the impact of changes made to existing knowledge is not considered as a separated maintenance task but it was included as one of the responsibilities of the Process Leaders to verify it during the knowledge review (explained in section 5.5.1).

Validation and Verification of Completeness:

Validation and Verification of completeness is performed to make sure that the output of the KB is consistent. Completeness checks are performed to test if the KB is able to give outputs to all reasonable inputs, the output knowledge should be meaningful and provide a solution to the user's problem or query. In this research, validation and verification of completeness is not considered as a separate task, but it was included as one of the responsibilities of the Process Leaders to verify for every knowledge modification (explained in section 5.5.1).

Criticality Ranking:

Criticality ranking helps to classify the knowledge based on its criticality. The rankings are assigned based on its importance, safety and performance to product, process and resources. In this research, criticality ranking is not considered as a separate task and the classification of knowledge is established through knowledge value (explained in section 5.7.2).

Relevancy Checking:

The decision to retain or to reject knowledge depends mainly on the perception of the relevance of the information in the immediate context. According to Godbout (1999), the initial factor determining which pieces of general information will be assessed is the relevancy of that information to the receiver. People will be more attentive to information related to their areas of interest or to the problem which currently draws their attention. Any irrelevant and unwanted information has to be rejected and should not be entered into the KB. In this research, relevancy checking task is used for verifying the knowledge usage, technical relevancy, acceptability and long term needs.

Knowledge Filtering:

Knowledge filtering ensures completeness and correctness of the knowledge entered in the KB. The process of filtering determines the value and credibility of the knowledge to the receiver (Godbout, 1999). Unfiltered knowledge is harmful because it is an unwanted addition to a KB and deteriorates the KB performance (Miyashita and Sycara, 1995). In this research, knowledge filtering task is performed based on credibility of knowledge, knowledge type, knowledge value, knowledge dynamism and degree of comprehensiveness.

Knowledge Integration and Structuring:

Knowledge integration is an aspect of knowledge management because it is an important task for developing organisational intelligence. Processes of knowledge assimilation and structuring, and the ways in which it is integrated can assist with innovation and competitive intelligence for an organisation (Abbott, 2004). In this research, knowledge integration and structuring was not considered as a separate knowledge maintenance task, since it was defined and established during knowledge capturing.

Knowledge Presentation and output:

Knowledge sharing requires the presentation of knowledge in the best format and appropriate for the user. The knowledge which is presented in an effective manner, improves knowledge sharing with communities seeking the enhancement of their existing knowledge and skills. To support knowledge sharing, the knowledge presentation creates an environment, which facilitates engineers share their knowledge. In this research knowledge presentation and output was not considered as a separate knowledge maintenance task, since it was defined and established during knowledge capturing.

Knowledge Acquisition:

The most popular principle in knowledge based systems states that the performance of an expert system critically depends on the amount of knowledge embedded in the system. The combined activity of eliciting, interpreting and organizing the knowledge acquired from the expert is called knowledge acquisition (Motta *et.al.*, 1990). As mentioned earlier in chapter 1, knowledge acquisition was established during knowledge modeling and was not considered as a separate maintenance task.

5.2.1 Knowledge Maintenance Flowchart

The knowledge repository is the core of the knowledge management system. The quality of the knowledge in the knowledge repository determines the effects of knowledge reusing and sharing. If the knowledge in the knowledge repository contains irrelevant information, the knowledge retrieval and knowledge sharing will affect (Zack, 1999). Even worse, if some of the knowledge is incorrect, it will inevitably mislead future decision makings and operations in an organisation. If an incorrect piece of knowledge provided by unqualified personnel enters into a knowledge repository, it may cause fatal disasters when someone else wants to use it in the future. Without a control in knowledge maintenance process, the quality of knowledge cannot be guaranteed.

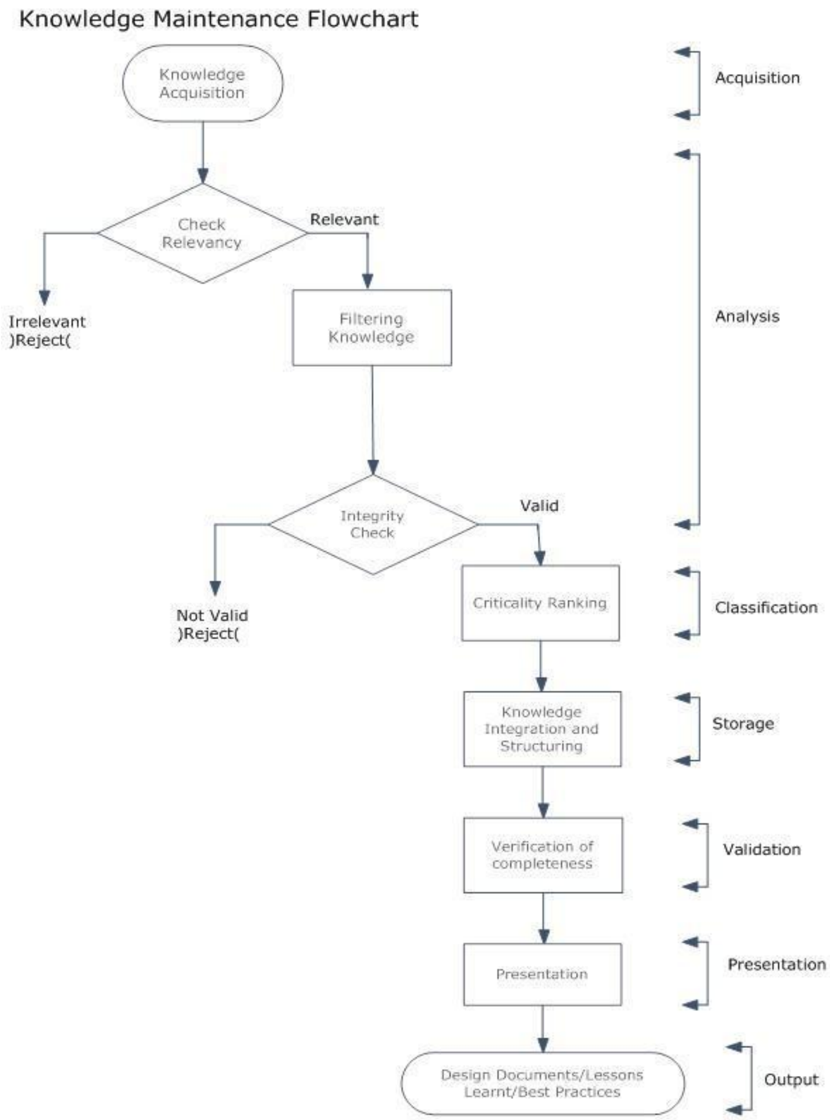


Figure 5-1: Knowledge Maintenance Flowchart

Flowcharts are commonly used to represent a process flow (Vasudevan *et al.*, 2008). In this research, for the schematic representation of knowledge maintenance process, a flowchart was developed as shown in figure 5-1. This flowchart illustrates the sequence of maintenance tasks that are performed for the effective maintenance of KB. In the flowchart, the maintenance tasks identified are represented in six knowledge maintenance stages, which are Knowledge Acquisition, Knowledge Analysis, Knowledge Classification, Knowledge Storage, Knowledge Validation and Knowledge Presentation & Output. Each stage has its own functionality and it consists of one or more knowledge maintenance tasks. To keep the knowledge up to date, the captured knowledge goes through all the six maintenance stages and its associated tasks.

5.2.1.1. Acquisition:

The first stage of the maintenance process is knowledge acquisition. Knowledge acquisition is the process of acquiring knowledge from a human expert (or group of experts) and using the captured knowledge to build knowledge based system (Smith, 1996). There are various techniques of acquiring the knowledge from the expert, but it is mainly performed by interacting with the expert. These can be broken down into four main approaches as shown in Table 5-1.

Direct Approaches	The knowledge engineer interacts directly with the expert to obtain an explanation of the knowledge that the expert applies in the work
Observational Approaches	The knowledge engineer observes the expert in the performance of the task
Indirect Approaches	The expert is not encouraged to try and verbalize his/her knowledge and the knowledge engineer uses other methods to elicit the information
Machine-based Approaches	Elicit knowledge through use of either knowledge-engineering languages or through induction from databases of domain examples

Table 5-1: The main approaches to knowledge acquisition

In this research, direct approaches are used for the acquisition of knowledge. The knowledge is captured by interacting with the expert engineer directly. Various formal and informal interviews are conducted with expert engineers for knowledge acquisition. The knowledge is also captured from an already existing knowledge source even if the representation of the knowledge is different. However knowledge acquisition was not explored in this research, since it was part of knowledge modeling.

5.2.1.2 Analysis

One of the most difficult stages in building Knowledge Based Systems (KBS) is that of organizing the knowledge gained from human experts and other sources into a coherent, unambiguous structure of the domain. There are at present no generally accepted or well established guidelines for achieving such a goal for Knowledge maintenance. Currently, the knowledge engineer through sheer hard work and intuition produces a loose collection of ideas, descriptions and procedures which she/he then purports to be an analysis of the domain knowledge. Such methods are not systematic and often seem to be no more than ad hoc (Ferrari and Toledo, 2004). Hence, there is a need for a methodological approach to Knowledge Analysis. Thus, there are three important maintenance steps identified for knowledge analysis in this research. They are a) Relevancy checking, b) Knowledge filtering and c) Integrity checking. There are a number of functions which are significant for knowledge analysis, but the key functions with respect to the three maintenance steps which are explained in section 5.6.1.

5.2.1.3 Classification

Classifications of knowledge enable researchers and practitioners to generalize, communicate, and apply the findings easily (Vessey *et al*., 2005). There are many approaches to the process of knowledge classification such as hierarchies (Kwasnik, 2000), text knowledge classification (Kai-Ji *et al*., 2009), ontology classification (Masters *et.al*., 2007). Each kind of classification process has different goals and each type of classification scheme has different structural properties as well as different strengths and weaknesses in terms of knowledge representation and knowledge discovery. In this research knowledge classification refers to the stage where the analysed knowledge is categorized according to its level of criticality. The three ranking types are identified as high, medium and low. This knowledge classification process helps the user to focus more on high critical knowledge and meeting its requirements.

5.2.1.4 Storage

The storing of knowledge is important in knowledge maintenance. Storage of knowledge involves the keeping of intellectual assets in a form that promotes its preservation, retrieval and utilization (Walsh and Ungson, 1991) (Miyashiro, 1996). The storage of knowledge should promote both informal, i.e. process oriented knowledge and formal, i.e. codified knowledge. Such repositories should be structured around functions, locations, business-process objectives and learning needs of construction organisations (Kululanga and McCaffer, 2001). The storage mechanism should be designed to support data processing, decision-making and to conduct further analysis. For an effective maintenance, the knowledge storage must be done based on knowledge integration and structuring. Knowledge integration is the process of synthesising multiple knowledge into a common model. Knowledge structuring optimise the structure in which the knowledge is stored for better knowledge retrieval. However in this research the knowledge storage was not explored as knowledge maintenance process, but it was considered for knowledge modeling and capturing.

5.2.1.5 Validation

Knowledge validation is to verify the knowledge based on the end user requirements. According to Laurent (1992) the validation process is a composition of two kinds of tasks:

– Activities that intend to verify the structural correctness of the KB (verification),

– Activities that intend to demonstrate the KB ability to verify correct conclusions (evaluation)

To ensure that knowledge repositories contain high-quality knowledge, knowledge management research recommends that any contributions to a repository undergo stringent validation processes (Durcikova and Grap, 2009). The validation should be done by including both verification and evaluation methods. The entire KB should be tested with trial knowledge and by performing several test cases. These test cases should be created based on the end user perspective. In this research the validation and verification of the knowledge was performed by the actors assigned, which is explained later in the section 5.5.1.

5.2.1.6 Presentation & Output

The final stage is knowledge presentation, where it is presented to the end user to understand and use the knowledge. Presentation knowledge facilitates communication and it is concerned with the method of delivery of knowledge (Hussain *et al*., 2004). Knowledge presentation must be done so that it can be used within the organisation.

Knowledge sharing requires the presentation of knowledge in best format and appropriate for the user. The knowledge which is presented in an effective manner, improves knowledge sharing with communities seeking the enhancement of their existing knowledge and skills. To support knowledge sharing, the knowledge presentation creates an environment, which facilitates engineers share their knowledge. In this research the knowledge presentation was not explored further, but it was considered for knowledge modeling and capturing.

5.3 Knowledge Maintenance Process

The six stages identified in knowledge maintenance flowchart are assessed based on the research environment and its applicability. A maintenance process for knowledge lifecycle was defined as shown figure 4-3. The knowledge lifecycle comprises of three processes namely, Analysis, Classification and Update. The analysis process includes relevancy checking, knowledge filtering and integrity checking, the classification process is based on criticality ranking and the update process includes knowledge integration & structuring, validation & verification and presentation of knowledge.

Knowledge Analysis Process:

As shown in the figure 5-1, the second stage of the knowledge maintenance flowchart is knowledge analysis. Knowledge analysis consists for three maintenance tasks which are Relevancy checking, Knowledge filtering and Integrity checking. During the development phase of the research, knowledge analysis was identified as the most important process in knowledge maintenance, because it determines the quality of the knowledge. Hence this research focused on defining a knowledge maintenance method based on knowledge analysis tasks and its functions. The key maintenance functions with respect to the three maintenance tasks are identified, which are later explained in section 5.4.

Knowledge Classification Process:

Knowledge classification is used to classify the acquired knowledge. During the initial stage stages of the research, the classification was defined based on the knowledge criticality. Criticality ranking was given to the knowledge based on its priority and importance. Three ranking types defined were High, Medium and Low. This classification of the knowledge helps the engineer to concentrate more on highly critical knowledge and focus to meet the specifications exactly.

High criticality indicates that the knowledge is critical to safety, frequently applied and high importance. Medium criticality indicates knowledge less critical to safety, performed occasionally and influences job performance. Low criticality indicates knowledge is only remotely significant in ensuring safety, rarely applied in a performance context, has little influence on job performance, or is of minimal importance. However during the later stages of the research, based on the case study evaluations the knowledge classification was established using knowledge value instead of criticality. This is explained later in the section 5.7.2.

Knowledge Update Process:

The third stage of the maintenance life cycle is knowledge update process. The update process consists of three stages such as knowledge storage, knowledge validation and knowledge presentation. The knowledge passes through these three stages to complete the update process. The three stages of the update process are explained below.

Knowledge storage is done based on knowledge integration and structuring. The knowledge integration focuses more on synthesising and the understanding of the knowledge from different perspectives. Knowledge structuring optimises the structure in which the knowledge is stored for better knowledge retrieval.

The next task is knowledge validation, where the knowledge is validated based on the end user requirements. The validation is done by proper testing and verification methods. The entire KB is tested with trial knowledge and the validation is done by performing test cases. The test cases are created based on the end user perspective.

The final task of the update process is knowledge presentation, where the knowledge is presented to the end user to understand the knowledge. Knowledge sharing requires the presentation of knowledge in formats appropriate for the people. The knowledge which is presented in an effective manner, improves knowledge sharing with communities seeking the enhancement of their existing knowledge and skills. However knowledge update process was not explored in this research, since knowledge analysis was considered to provide a sufficiently broad scope for this exploration.

5.4 Knowledge Analysis for Maintenance

As mentioned earlier, the emphasis of this research is on the knowledge analysis process because it is important to have the accurate and relevant knowledge. The knowledge analysis process, as proposed, consists of three tasks: a) Relevancy checking, b) Knowledge filtering and c) Integrity checking. A range of functions associated with these three tasks have been identified which are shown in figure 5-2.

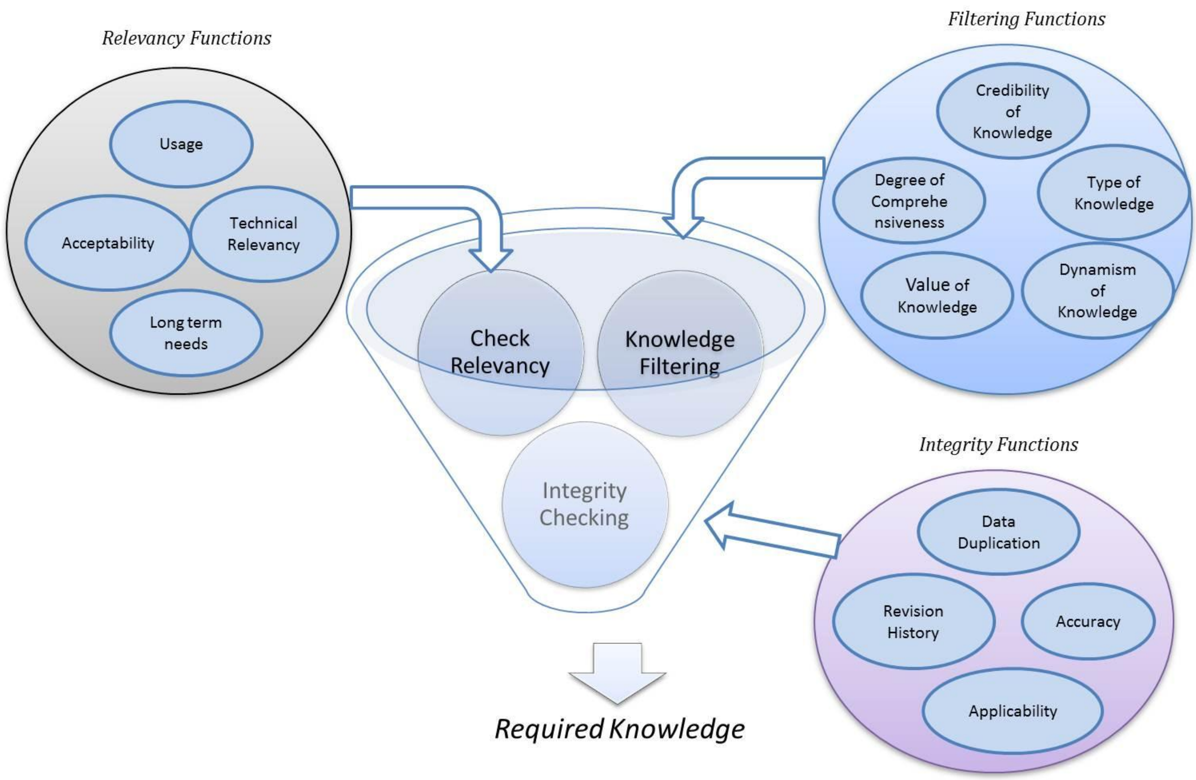


Figure 5-2: Knowledge Analysis for Maintenance

5.4.1 Relevancy Checking

The knowledge acquired should be checked for its relevancy before further processing. This is done on the basis of various relevancy functions identified. Knowledge usage checks the usefulness of knowledge. Acceptability checks whether the acquired knowledge is adequate to satisfy the requirements. Technical relevancy verifies whether the knowledge is technically relevant to the work. Long term need function checks whether the captured knowledge satisfies the future needs.

Out of these four functions, only technical relevancy was identified to define a method to check the knowledge relevancy. Technical relevancy was chosen because, irrelevant knowledge may create overload in a knowledge repository and results in undue processing time when a person tries to retrieve a particular knowledge from the repository. This function helps to organise the captured knowledge in a technically relevant level which will make the usability of knowledge easier. Other functions usage, acceptability and long term needs are used as attributes for determining the knowledge value which is explained later in the section 5.7.2.

5.4.2 Knowledge Filtering

Knowledge filtering functions are used to filter out the unwanted knowledge. The credibility of knowledge is used to make sure the correct knowledge is entered to the knowledge base. This function determines the credibility of knowledge by identifying the credibility of knowledge source. The original source of the knowledge must be known to validate knowledge or to seek any clarifications.

The knowledge life captures the knowledge validity, which changes over a period of time. With new processes, technologies and expansion of existing processes in a manufacturing facility, the knowledge is often recaptured, reassessed and modified. So this function identifies all the contributing factors for the knowledge change, which are essential to keep the knowledge repository up to date. In this research knowledge life is used to capture the validity of knowledge and the contributing factors for possible knowledge change.

Capturing and processing a less valuable knowledge leads to extra effort in knowledge maintenance and more space in knowledge repository. So it is necessary to find if the knowledge is valuable at initial stages. The value of knowledge checks value of the identified knowledge with respect to the knowledge users. In this research knowledge value is used to classify the knowledge in to three types which are high, medium and low.

Knowledge type identifies whether the captured knowledge is explicit or tacit. Explicit knowledge is a formal and systematic type of knowledge consisting of basic facts and storable document sets. Tacit knowledge consists of personal relationships, practical experience, and shared values. Identifying the type of knowledge is necessary for analysis and processing of knowledge.

Degree of comprehension function is used verifies the level of understanding of the knowledge by the users. This enables the users to understand the captured knowledge easily.

Out of the five functions credibility of knowledge, knowledge life and knowledge value are identified for the development of the maintenance method. Knowledge type was initially considered in the method, however based on the evaluations it was decided not to be included. Degree of comprehension is also not considered, but it was included as one of the attributes for determining the knowledge value which is explained in section 5.7.2.

5.4.3 Integrity Checking

Integrity checking functions are used to maintain knowledge reliability. Data duplication prevents the duplication of knowledge. It is performed to make sure that the knowledge is not duplicated in the KB. The consistency of the knowledge can be maintained by capturing the revision history of every knowledge change. A revision history is created to capture all the activity done by actors in the knowledge maintenance method. A record is made in the revision history for every change done to the knowledge. This enables to maintain the information about all the changes done to the knowledge. Accuracy checks the correctness of the written knowledge and keeps it free from errors. Applicability provides an option to link multiple features using the same knowledge. This function also provides an understanding about the relations between different manufacturing features.

Apart from accuracy, all the other three functions revision history, applicability and data duplication were considered for the development of maintenance method. Accuracy was not considered as a separate function but used as an attribute for providing the knowledge value rating.

5.5 MANUFACTURING KNOWLEDGE MAINTENANCE METHOD

As explained in chapter 4, the two key components of the maintenance method are the knowledge maintenance process (KMP) and the knowledge maintenance template (KMT). The KMP uses four actors for the performance of the key maintenance activities. The activities performed by the actors respectively are ***Engineer - Input***, ***Technical Leaders - Verify***, ***Commodity Leader - Approve*** and ***Knowledge Controller - Control***. In this research two technical leaders, one each from manufacturing and design departments are part of this knowledge maintenance process.

The knowledge maintenance process is initiated by the engineer by adding new knowledge or by modifying the existing knowledge in the knowledge base. The manufacturing technical leader verifies whether the manufacturing knowledge is captured accurately from the manufacturing processes and tooling. The design technical leader verifies whether the captured knowledge can be used by the design engineer. The commodity leader approves the knowledge maintenance process. All the seven maintenance functions are controlled by the knowledge controller.

5.5.1 Actors Definition

Engineer:

Engineer inputs the knowledge into the knowledge management system, initiates the knowledge add / modify process. This person is from the manufacturing department who has worked on the particular manufacturing feature or process. The functions performed by an Engineer are,

- Capture the knowledge by following the standard templates.
- Knowledge written should be easily understood by staff members
- Provide the initial classification of knowledge and be respectful of copyrighted information.
- Ensure the knowledge article remains up-to-date.
- Verify data duplication of knowledge.

Technical Leaders:

Technical Leaders are similar to subject matter experts who are proficient in particular manufacturing/design process. Two technical leaders, one each from manufacturing and design departments are part of this knowledge maintenance process. The manufacturing technical leaders verify whether the manufacturing knowledge is captured accurately. The design technical leaders verify the captured knowledge based on the design engineers use. The Technical Leaders performs following functions,

- Review knowledge as requested by the Engineer.
- Verify the knowledge against the maintenance functions.
- Confirm the classification of the knowledge article.
- Provide the feedback to the engineers for modification
- Reject the inaccurate and unusable knowledge.
- Review the knowledge templates, knowledge sources and knowledge maintenance process.

Knowledge controller:

Enables the interaction between the Engineer and Technical Leaders and controls the knowledge maintenance functions. The functions performed by knowledge controller are as follows,

- Facilitate the environment for capture and maintenance of knowledge.
- Ensure that the knowledge is classified correctly.
- Determine the review process required for the knowledge article.
- Ensures that the Knowledge Maintenance Process is followed.
- Recommend improvements to the knowledge maintenance process.
- Verify the documents retrievability and access rights.

Commodity Leader:

Commodity Leader owns the whole maintenance process and is responsible for the approval of the knowledge documents. The commodity leaders performs following functions,

- Facilitate the environment and resources for capture and maintenance of knowledge.
- Approves the knowledge documents.
- Ensures that the Knowledge Maintenance Process is followed and Sign off the documents.
- Recommend improvements to the knowledge maintenance process.

5.6 Relevancy Checking

Relevancy checking prevents irrelevant knowledge entering the KB. In this research knowledge relevancy is established by capturing the knowledge according to the taxonomy developed. This taxonomy was created based on the feature relationship defined in chapter 3. The method for establishing relevancy checking is explained in the subsections below.

5.6.1 Technical Relevancy

As explained in section 3.3, the feature knowledge relationship structure (FKRS) was defined during the industrial investigation of this research. This relationship enables to link the manufacturing feature with the corresponding design and inspection feature. Also this relationship uses two knowledge categories, process capability and tooling for capturing the knowledge. The FKRS was used in developing the taxonomy, based on this a method for establishing the relevancy checking of knowledge was defined.

To achieve technical relevancy, knowledge taxonomy was implemented based on the hierarchy of components in a manufacturing facility as shown in the figure 5-3. It begins with

Part ID of the manufacturing feature and links with design and inspection features. These links form the feature relationship between design, manufacturing and inspection. The knowledge associated with the manufacturing feature is captured in the form of manufacturing process and tooling. Similarly the knowledge associated with the inspection feature is captured in the form of inspection process and tooling.

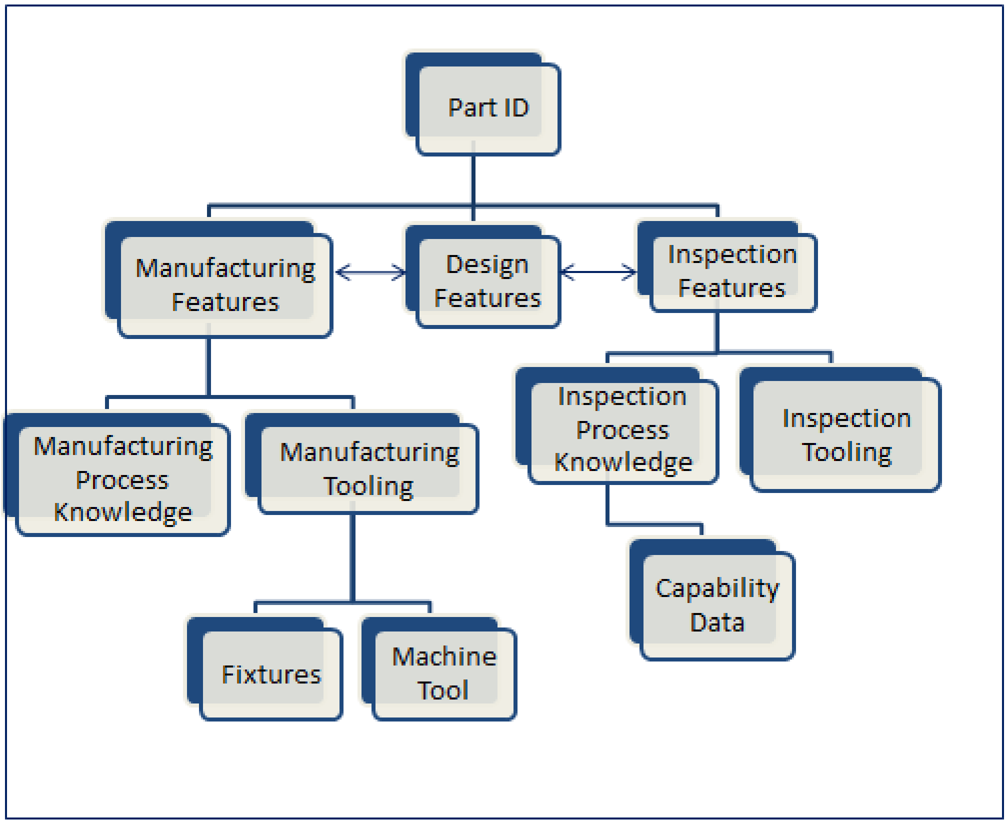


Figure 5-3: Hierarchy to achieve Technical Relevancy

Technical relevancy is established by the engineer populating the relevant knowledge in each of the fields of the template. The structure of the documents has been defined to capture all the technically relevant categories, it is important that all sections of the documents are completed. Whenever new knowledge is entered or existing knowledge is modified, it should be done within the specific fields based on this hierarchy. The technical leaders verify whether the knowledge entered is technically relevant to the categories and they also verify the knowledge taxonomy defined. The knowledge controller defines the taxonomy and it will be referred whenever the technical relevancy process is performed. The method for relevancy checking is shown in figure 5-4.

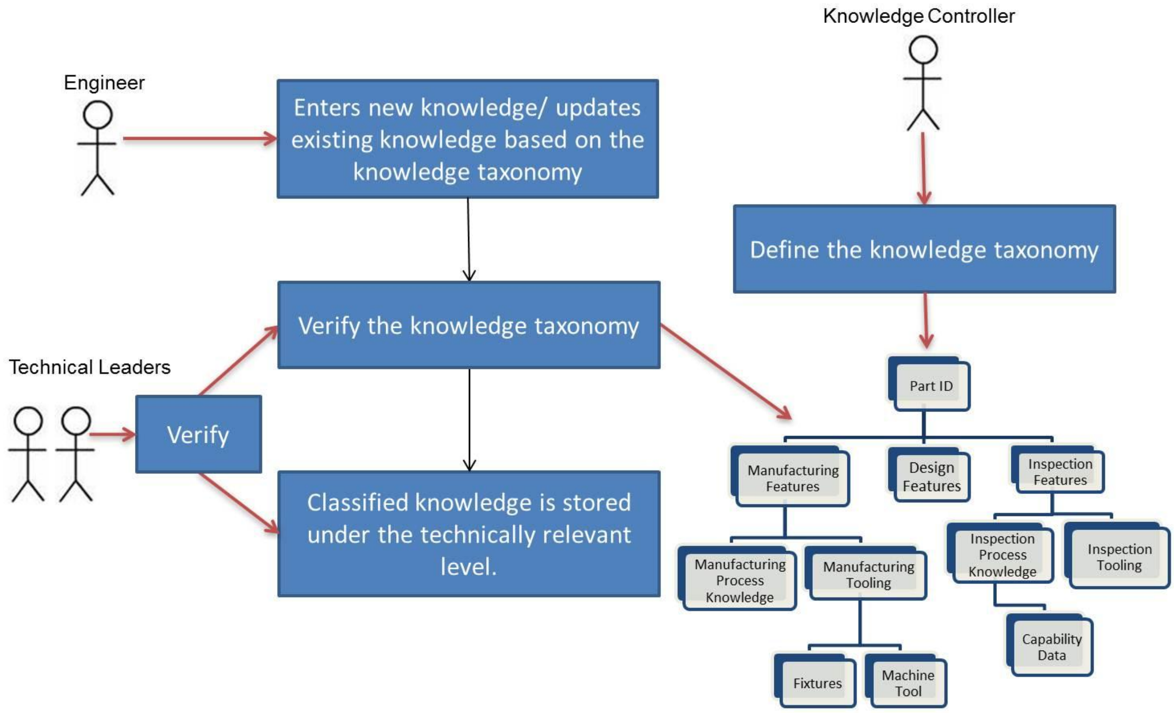


Figure 5-4: Technical Relevancy Checking

5.7 Knowledge Filtering

Knowledge filtering task prevents unwanted knowledge entering the KB. In this research knowledge relevancy is established by using four functions, credibility of knowledge source, knowledge value, knowledge life and data duplication. Knowledge type function was initially considered, but based on the evaluations it was decided not to be included. The methods for establishing knowledge filtering by using four maintenance functions are explained in the subsections below.

5.7.1 Credibility of Knowledge Source

This function helps to identify the source of the knowledge entered. For the captured knowledge, the original source must be known to validate or to seek future clarification. By measuring the credibility of the knowledge source ineffective knowledge can be filtered. As explained in chapter 3, interviews were conducted with engineers to identify the list of valid knowledge source (refer table 3-1). From the list, key knowledge source which engineers use to make decisions were identified, they are Communication Sheets, Tooling specification, Component Family Template, Technical Reports and Capability Data. This knowledge sources were considered more credible when compared to other sources identified. This source list is maintained by the knowledge controller and it is reviewed periodically by the technical leaders.

The engineer has to select the valid knowledge source from the list while adding new knowledge or modifying existing knowledge. The technical leaders have to verify the credibility of the knowledge based on its source and approves it. If the knowledge entered doesn't have a valid source, then the technical leaders can reject the knowledge. The knowledge controller has to keep the knowledge source up to date. Whenever new valid sources are identified, it has to be reviewed with technical leaders before using it for knowledge filtering. The method for filtering knowledge based on credibility of knowledge source is shown in figure 5-5.

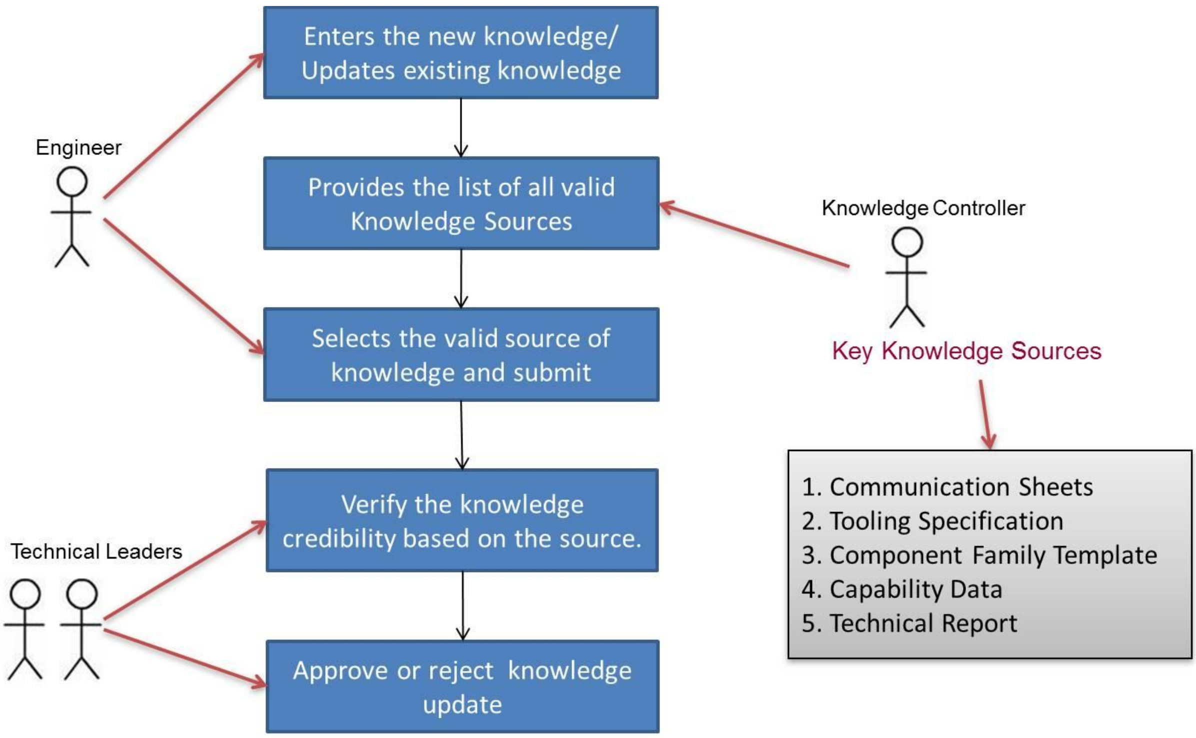


Figure 5-5: Credibility of Knowledge Source

The knowledge source details are captured in two fields,

1. The **name** of the knowledge source. Enter the source name from the valid knowledge source list. (e.g.) GQP C.4.7 Manufacturing technical package Component Family Template

2. The **location** of the knowledge source. It can be a webpage address or the location of shared folder. (e.g.) www.rrps-capability.rolls-royce.com/pi/module-index.htm

During the initial stages of the research it was decided to establish a credibility rating based on the importance of the knowledge source. The ratings were identified as High, Medium and Low. However based on the experimental evaluations, it was decided not to include credibility rating for the classification of knowledge source.

5.7.2 Knowledge Value

Knowledge value function uses the value rating to filter out the invalid knowledge entering KB. The knowledge value is determined based on five attributes, which are usage, acceptability, long term needs, accuracy and degree of comprehensiveness. The initial knowledge value is entered by the engineer and the technical leaders review the knowledge and verify the knowledge value rating. The four value parameters are High, Medium and Low. The definition of these four rating are

- High – Mandatory (no tolerance)
- Medium – Mandatory but can be leveraged. Tolerance accepted (Only at certain conditions)
- Low – Useful to confirm but not mandatory
- Zero – No Value (Invalid)

The method for filtering knowledge based knowledge value is shown in figure 5-6.

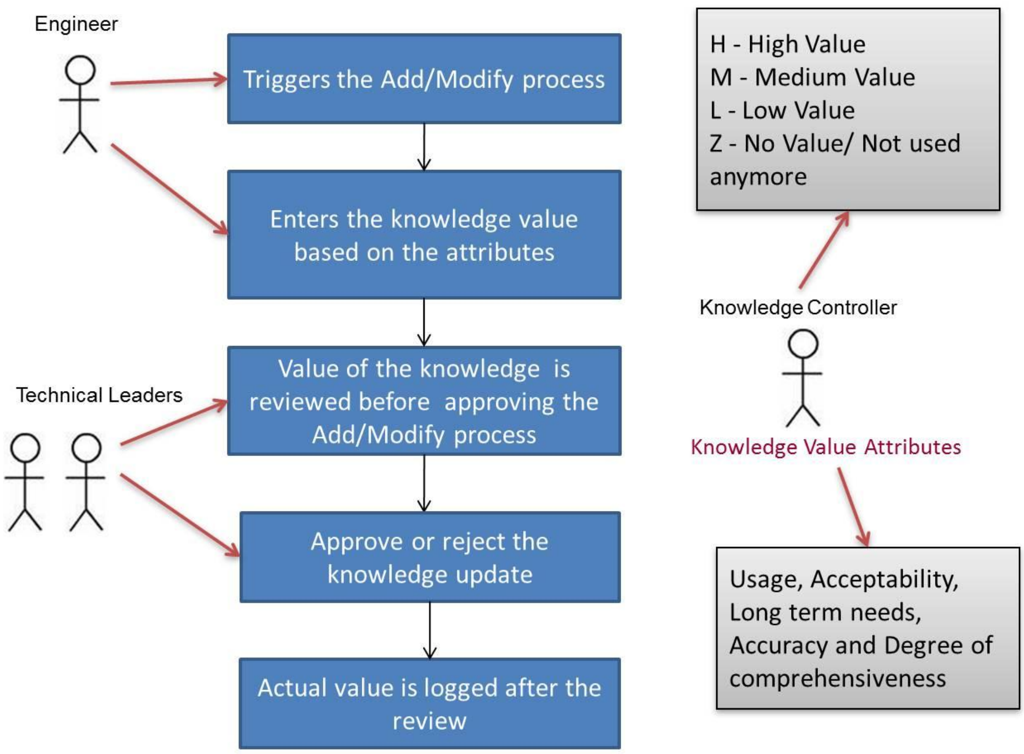


Figure 5-6: Knowledge Value

The knowledge controller has to define the knowledge value parameters and the attributes used to determine the value. During the knowledge review the technical leaders can enter the knowledge value as 'Zero' if the knowledge is invalid or no longer used. The knowledge with value zero will be removed from the list and it will be archived. Value 'Zero' can be used only by technical leader during the review process

5.7.3 Knowledge Type

Type of knowledge can be categorised as explicit/ tacit and the identification is helpful for the document analysis. The Engineer while entering knowledge has to mention its type in the required field. The technical leaders review the knowledge and verify the knowledge type. The type of knowledge is entered as Explicit (E) or Tacit (T).

- Explicit (E) – Explicit knowledge is a formal and systematic type of knowledge. Knowledge captured as simple texts, tables, procedures, formulas, graphs, diagrams, product specifications.
- Tacit (T) - Tacit knowledge consists of personal relationships, practical experience, and shared values. The representation of tacit knowledge may include patterns, storytelling and video clips.

The method for filtering knowledge based knowledge type is shown in figure 5-7.

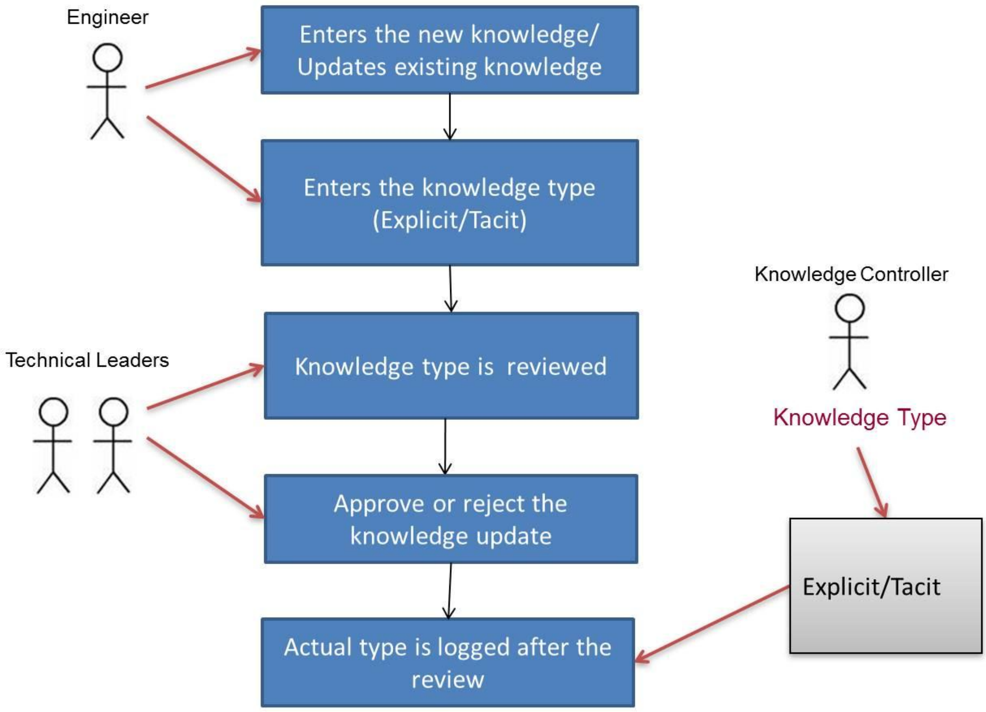


Figure 5-7: Knowledge Type

Knowledge type function was initially considered in establishing the knowledge filtering, however based on the experimental evaluations it was decided not to be included (explained in Chapter 6).

5.7.4 Knowledge Life

Knowledge life changes over the period of time. Knowledge life provides the knowledge validity time. The knowledge life is entered by the Engineer in the form of knowledge re-validation date and the contributing factors for the possible change. Enter the date on which the knowledge should be reassessed for its validity. The date shall be entered in month and year format (mm/year), (e.g.) 04/2012.

- Enter the details of the key contributing factors to reassessment and potential change of knowledge. (e.g.) Makino AXX Grinder is replaced by Makino AYY Grinder. The manufacturing rules associated with AXX will be changed.

The revalidation date provides the exact time for updating the knowledge, which enables the engineer to revisit the knowledge at specific time. The technical leaders verify the validation date and the contributing factors. The knowledge controller defines the parameters for measuring the knowledge change. The method for filtering knowledge based knowledge life is shown in figure 5-8.

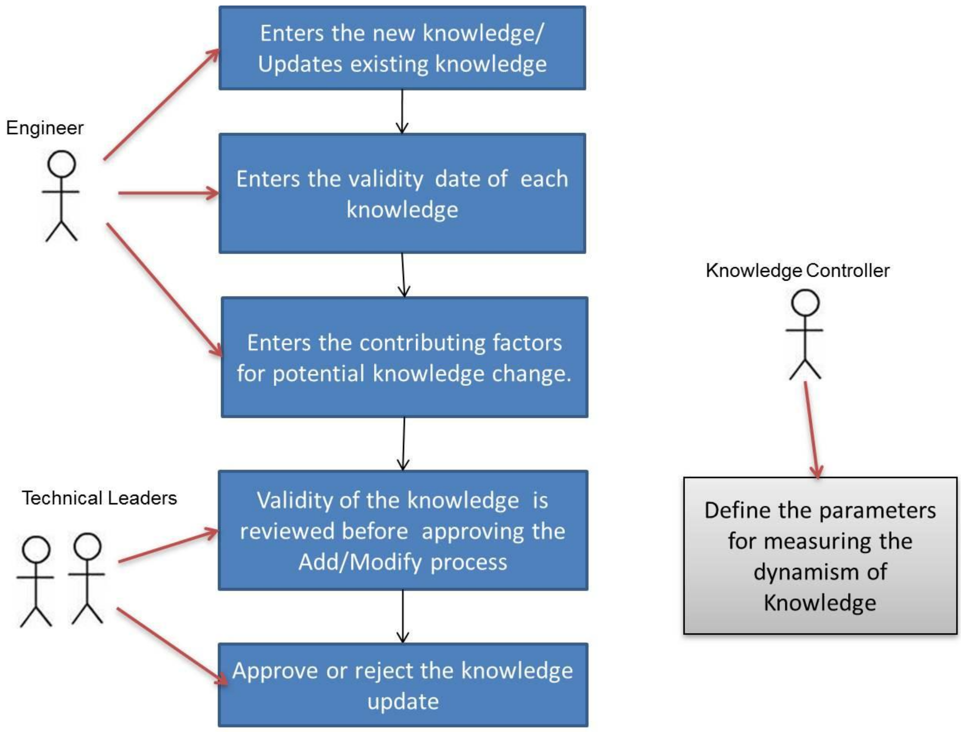


Figure 5-8: Knowledge Life

5.8 Integrity Checking

Checking the integrity of the knowledge plays an important part in knowledge maintenance. In this research, the method for checking the integrity of knowledge is defined based on three maintenance functions, which are 1) Prevent Duplication, 2) Revision History and 3) Applicability.

5.8.1 Data Duplication

Before entering a new knowledge or updating existing knowledge, the engineer has to review the existing knowledge and the previously rejected knowledge to avoid duplication and also to minimise knowledge verification time. Data duplication is self-triggered and carried out by the engineer who enters knowledge in the KB.

Every time a new knowledge is entered, it is verified against the existing knowledge and previously rejected knowledge to see if the knowledge is redundant. When the existing knowledge is modified, it is verified against the other existing knowledge and previously rejected knowledge to avoid duplication. If the review shows that the knowledge already exists, it will be rejected by the engineer and then knowledge update process is stopped. If not, the knowledge proceeds to next step. The technical leaders verify again whether the knowledge is not duplicated and approves the knowledge addition or modification. The method for checking the integrity of knowledge based data duplication is shown in figure 5-9.

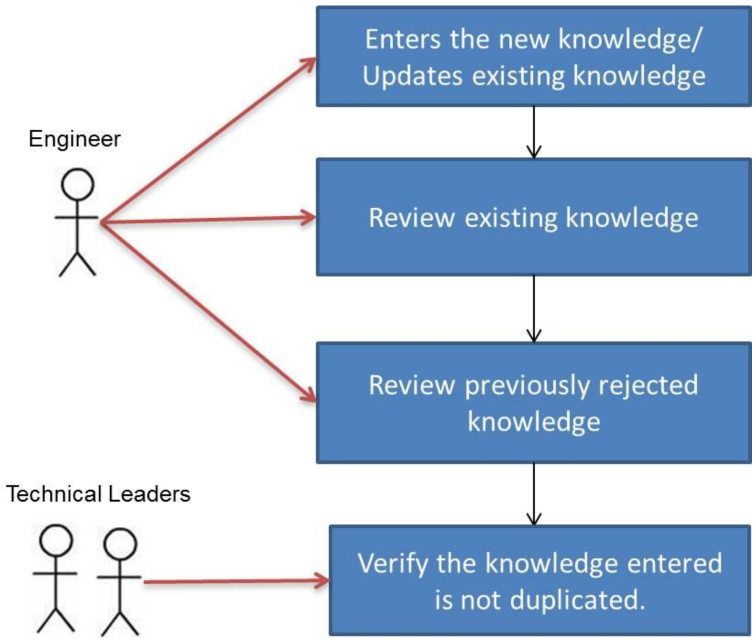


Figure 5-9: Data Duplication

5.8.1 Revision History

The consistency of the knowledge is checked by maintaining the revision history of the knowledge. A revision history field is created which captures all the activity done in the knowledge documents. This log will contain all details about the changes made to the knowledge. This ensures that the changes made to the knowledge are consistent and available for reference.

The knowledge controller creates revision history table to capture the knowledge change and activities done in knowledge documents. The Engineer fills the version number, date and release note and submits for the technical leader's approval. The release note contains all the changes made to the knowledge and the reasons for knowledge change. The Technical leaders verify the knowledge change based on the release notes and updates review status, comments and approve knowledge update. The commodity leader approves and signs off the knowledge documents after ensuring the knowledge maintenance process have been followed correctly. The method for establishing the revision history of knowledge is shown in the figure 5-10.

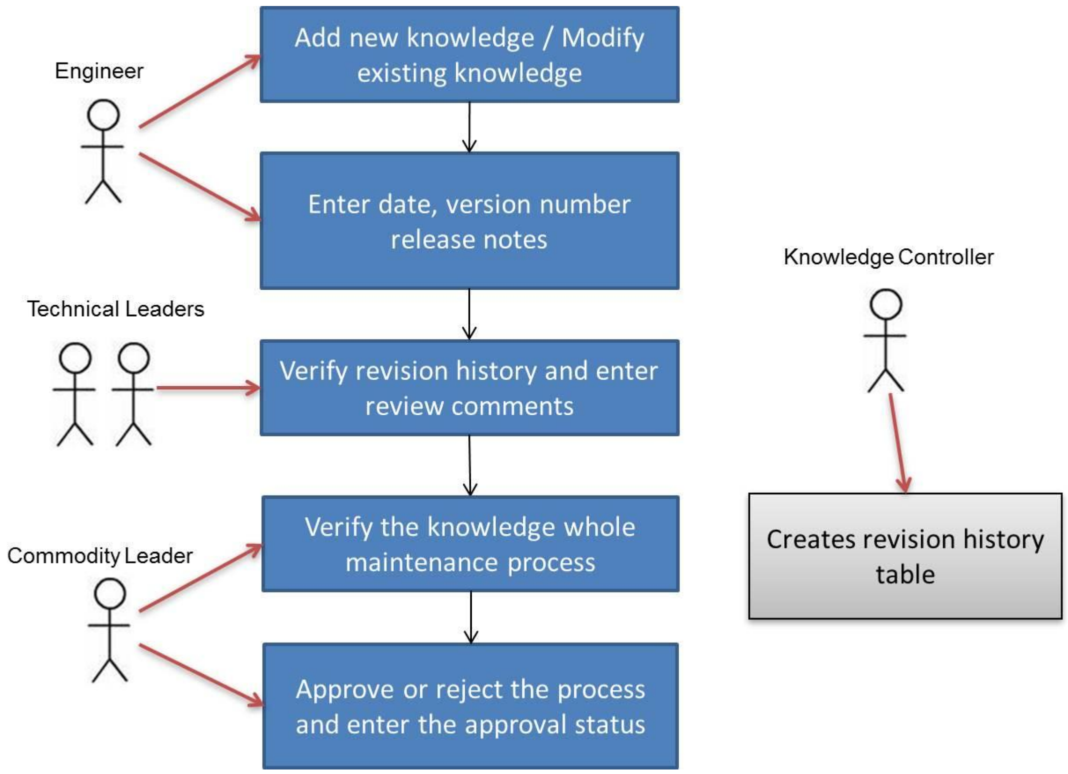


Figure 5-10: Revision History

5.8.2 Knowledge Applicability

Knowledge applicability function captures all the other manufacturing features which use the same knowledge. This process of capturing the applicability of knowledge to multiple features provides clarity about the relations between different manufacturing features. While entering knowledge, the engineer has to list out all the other manufacturing features which use the same knowledge.

- Enter the name of other features if the same knowledge can be applied. (e.g.) Root Leading Edge Seal Tip. Document Reference no: XXXXX

The knowledge controller defines the parameters for capturing the multiple feature applicability. The Technical leaders verify the knowledge applicability to other manufacturing features and approve knowledge update. The method for checking the knowledge applicability is shown in figure 5-11.

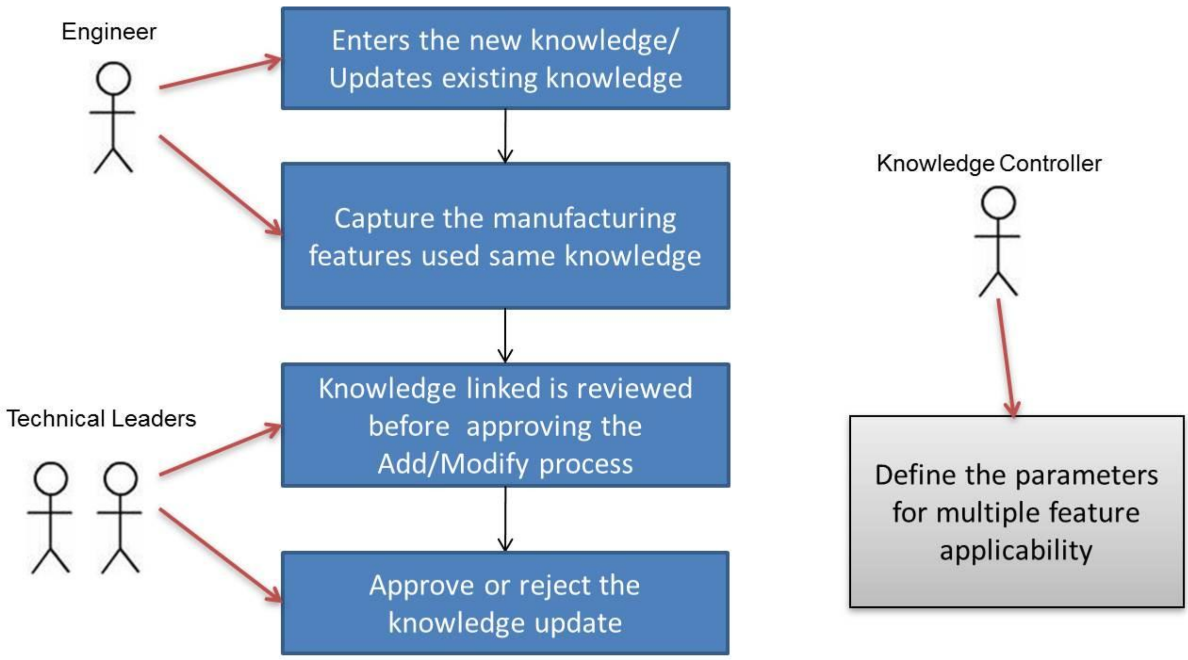


Figure 5-11: Applicability

5.9 Knowledge Maintenance Method

A knowledge maintenance method was defined based on three maintenance tasks, check relevancy, knowledge filtering, and integrity checking. The seven maintenance functions used were credibility of knowledge source, technical relevance, knowledge value, knowledge life, data duplication, revision history and applicability. The key components of the maintenance method were the Knowledge Maintenance Process (KMP) and the Knowledge Maintenance Template (KMT). The seven maintenance functions were implemented in the KMT and the KMP, which provides an effective knowledge maintenance method. The below sections explains the KMP and the KMT.

5.9.1 Knowledge Maintenance Process (KMP)

A knowledge maintenance process flow was developed using seven maintenance functions as illustrated in chapter 4 (figure 4-5). Five different actors were identified to perform the maintenance process; they were Engineer, Manufacturing Technical Leader, Design Technical Leader, Commodity Leader and Knowledge Controller. The four main activities performed by the actors respectively were Engineer - Input, Technical Leaders - Verify, Commodity Leader -Approve and Knowledge Controller - Control.

The Start process in the KMP is triggered when a new manufacturing part to process is introduced. The process flow begins when an engineer adds a new knowledge or modifies an existing knowledge in the KB. The knowledge has to be entered based on seven maintenance functions. Two technical leaders, one each from manufacturing and design departments are part of this knowledge maintenance process. The manufacturing technical leader verifies whether the manufacturing knowledge is captured accurately, based on two knowledge categories (processes and tooling). The design technical leader verifies the captured knowledge based on the designers usage. Based on the feedback from the technical leaders review, the engineer updates the knowledge and resubmits for the verification. After verifying knowledge, the technical leaders submit the documents to commodity leader for approval. The commodity leader owns the whole maintenance process and is responsible for the approval of all the knowledge documents. The commodity leader enters the approval status and sign of all the knowledge documents. The individual process for the performance of seven maintenance functions are defined and controlled by the knowledge controller. The knowledge controller verifies the document retrievability and access rights to make sure only authorised person’s uses knowledge document. This provides security and avoids mishandling of knowledge documents.

The KMP provides a flexible environment to add new knowledge and to modify existing knowledge in the knowledge base. The actor's and their activities based on seven knowledge maintenance functions provide effective route knowledge maintenance.

5.9.2 Knowledge Maintenance Template (KMT)

The knowledge document template was developed to allow the quick and simple capture and representation of manufacturing and inspection knowledge. The KMT uses the feature knowledge relationship structure (FKRS) to maintain the knowledge defined in chapter 3. The maintenance fields created in KMT provides specific categories to enter the details of the knowledge, which are important for the knowledge to be kept up-to-date. The KMT was defined based on seven maintenance functions as shown in chapter 4 (figure 4-6). It contains following sections,

Feature Description: Contains the aspects relating to a manufacturing feature. These being the part family, the feature name, its associated drawing number and any synonyms that are associated with a feature.

Relationship Description: This states the relationships that exist between a given manufacturing feature, the associated design feature and inspection feature.

Factory and Machine: Provides information about the factory that the specific manufacturing feature is made in, the type of machine used, the tooling and fixtures used and the relevant inspection routine.

Knowledge Source: Knowledge source information is captured for the purpose of knowledge filtering. A valid knowledge sources list has been prepared and the Engineer has to select the valid source while entering the knowledge.

Manufacturing Knowledge: This section states the knowledge associated and the considerations that must be taken into account when manufacturing the specific feature. These can be a set of rules to adhere to, reasons why certain tolerances can or cannot be met and other environmental or modus operandi aspects that influence manufacturing engineers routines.

When the knowledge is entered the corresponding knowledge maintenance fields, Multiple feature applicability, Knowledge life, and Value has to be updated.

Revision History: This section contains the information about all the changes done to the knowledge document. It includes the details about the Engineer, Commodity Owner who worked on the document. The change history is captured in the form of Release notes and Reviewer comments.

5.9.3 Actors Interaction with KMT

5.9.3.1 Engineer:

Engineer inputs knowledge and creates a knowledge document. This person is from the manufacturing team, who has worked on the particular manufacturing feature for which he creates the knowledge document. The engineer enters information in the following maintenance fields

Knowledge Source

For knowledge capturing, original source of knowledge must be known to validate its credibility and to seek future clarifications. *Enter the name and the location of the knowledge source.*

Knowledge Source:	
Name of the Source	
Location	

Figure 5-12: Knowledge Source in KMT

		A	B		C
Manufacturing Knowledge:		Multiple Feature Applicability	Knowledge Life		Value *(High/Med/ Low/ Zero)*
			Re-Validation Date *(mm/year)*	Contributing factors for possible change	
Tooling					
Manufacturing 01					
Surface Finish					

Figure 5-13: Maintenance Fields in KMT

Multiple Feature Applicability (A)

Multiple feature applicability captures all the other manufacturing features which use the same knowledge. This process of capturing provides clarity about the relations between different manufacturing features. The Engineer has to list out all the other manufacturing features which use the same knowledge. *Enter the manufacturing feature name and its knowledge document reference number.*

Knowledge Life (B)

Knowledge life changes over the period of time. Knowledge life provides the time of which the knowledge will be valid. The knowledge life is entered by the Engineer in the form of knowledge re-validation date and the contributing factors for the possible change. *Enter the reassessment date and the contributing factors for the knowledge reassessment.*

Knowledge Value (C)

Knowledge value identifies how valuable the captured knowledge is corresponding to usage, acceptability, long term needs, degree of comprehensiveness and accuracy. The knowledge value is rated as High / Medium / Low by the Engineer. *High – Mandatory, Medium – Mandatory but can be leveraged under specific circumstances, Low – Need to confirm but not mandatory*

Revision History:						
Version Number	Date	Revised By - Engineer Name & ID	Release Notes	Reviewed By – Technical Leaders Name & ID	Reviewer Comments	Approval Status – Commodity Owner (Approved/Rejected)
V1						

Figure 5-14: Revision in KMT

Revision history

It contains all the changes made in the knowledge document. Maintaining a revision history ensures that the every knowledge change is recorded consistently. Different fields are created to capture all the activity performed by the actors in the knowledge documents. *The Engineer fills the version number, date, release notes.*

5.9.3.2 Technical Leaders:

Knowledge review is performed by the Technical leaders similar to subject matter experts who are proficient in particular manufacturing/design process. Two technical leaders, one from manufacturing team and another from design team forms a part of knowledge review process.

- The manufacturing technical leader reviews the technical content of knowledge captured.
- The design technical leader reviews the knowledge based on its usage.

Knowledge Value

During the knowledge review the technical leaders can enter the knowledge value as 'Zero' if the knowledge is invalid or no longer used. The knowledge with value zero will be removed from the list and it will be archived. *Zero – Invalid knowledge*

Revision history

During the knowledge review the technical leader verifies the information entered in all the maintenance fields. *Enters the review status and comments.*

5.9.3.3 Commodity Leader:

Commodity Leader owns the whole maintenance process and is responsible for the approval of the knowledge documents.

Revision history

The commodity leader approves and signs off the knowledge documents after ensuring the knowledge maintenance process have been followed correctly. *The commodity leader enters the approval status (Approved/Rejected).*

5.10 SUMMARY

This chapter describes the detailed perspective of the knowledge maintenance method against its key elements. There are eight main sections reported in this chapter.

Section 5.2 detailed the knowledge maintenance tasks identified. A knowledge maintenance flowchart was established using the tasks which details the six stages of knowledge maintenance represented in the flowchart. Section 5.3 detailed the maintenance process flow to manage the knowledge lifecycle. The three main knowledge maintenance process (*Analysis, Classification, and Update*) associated with it are identified. Although knowledge classification and update are important in process for knowledge maintenance, the emphasis of the research is on knowledge analysis process because it determines the quality of the knowledge. Section 5.4 explained the knowledge analysis process and three knowledge maintenance tasks *(Relevancy, Filtering, and Integrity*) focused in this research. Relevancy task prevents irrelevant knowledge entering KB, filtering tasks prevents unwanted knowledge entering KB and the integrity tasks maintenance the consistency of knowledge in the KB. The maintenance functions associated with three maintenance tasks were explained.

Section 5.5 explained the actors involved in the maintenance process. The actors identified are the Engineer, Technical Leader, Commodity Leader and knowledge controller. The roles and responsibilities of the actors for the performance of maintenance functions are defined. Section 5.6 details the relevancy checking method based on technical relevancy function. Section 5.7 explains, knowledge filtering method based on the credibility of knowledge source, knowledge value and knowledge life. Section 5.8 explains integrity checking method based on data duplication, revision history and applicability. Section 5.9 explains the novel knowledge maintenance method defined based on the knowledge analysis tasks and its functions. The two main components of the method are the Knowledge Maintenance Process (KMP) and the Knowledge Maintenance Template (KMT).

CHAPTER 6 - EVOLUTION OF KNOWLEDGE MAINTENANCE METHOD BASED ON FOUR CASE STUDIES

6.1 INTRODUCTION

This chapter explains the four iterative case studies conducted for the evaluation of novel knowledge maintenance method (KMM) discussed in chapter 4. These case study evaluations were performed to improve the efficiency of the KMM. As a result of these evaluations, the novel knowledge maintenance method was defined.

Section 6.1 explains Case Study 1, which details the assessment of an initial Knowledge Maintenance Method (KMM) based on two manufacturing features of a XWB HP Turbine Blade. The results were evaluated based on the feedback from a group of expert engineers. Section 6.2 explains Case Study 2, which was based on the application of the KMM to a fully defined Turbine Blade. The evaluation was conducted based on the feedback received from the same group of expert engineers that performed the initial evaluation. Section 6.3 details Case Study 3, in which the KMPF and KMT produced as a result of Case Study 2 were further evaluated by conducting informal interviews with a different group of senior experts. Section 6.4 focuses on Case Study 4, which details the evaluation of the KMPF and KMT by performing a comparison study with an existing knowledge management method implemented for Process Failure Mode Effect Analysis (PFMEA). A summary of this chapter is then provided in section 6.5.

6.2 CASE STUDY 1

As explained in Chapter 3 (Section 3.4), two manufacturing features of XWB HP blade (Leading edge seal tip and Trailing edge seal tip) were chosen for the initial understanding of the relationship between design, manufacturing and inspection features. Based on the feature relationship structure, information and knowledge associated with two manufacturing features were captured under the following two categories,

(1). Manufacturing Process Knowledge
(2). Tooling and Inspection Knowledge

The following research objectives were set to understand more about the knowledge associated with the two manufacturing features under these two categories,

- Explore the method of manufacturing for features below and understand the manufacturing sequence in manufacturing operation (OP300)
  - *Root Trailing Edge Seal Tip (110)*
  - *Root Leading Edge Seal (130)*

  (OP 300 is a manufacturing operation number. 110 and 130 are the manufacturing sequence number)
- Focus on the following inspection feature, to understand the dimensions and inspection process:
  - *Leading Edge Root Seal to Shank*
  - *Trailing Edge Root Seal to Point P*
- Prepare a semi structured interview questionnaire to extract the knowledge from the engineers.
- Look at the factors that change the knowledge and develop a knowledge maintenance method.

Based on the these objectives following questions were prepared, in order to conduct interviews with the expert engineers,

(1). In what ways do you store the knowledge?

(2). How do you keep knowledge up to date?

(3). What are the factors that result in potential knowledge change?

The questions were formulated such that they give freedom to explore the research problem in depth (Glaser, 1978; Strauss & Corbin, 1990). A semi-structured interview questionnaire was prepared as shown in Appendix A, these questions were carefully designed to provide adequate coverage for the purpose of the research. The questions were developed in the form of a general statement which was then followed by a sequence of sub-questions for further probing.

A semi structured interview was conducted with a key range of expert engineers. Five expert engineers were identified from TB manufacturing, TB design, knowledge management and manufacturing communication. These engineers were selected from different departments based on their expertise in product, process and domain knowledge. Engineers were informed in advance to plan for the interviews. Each expert engineer spent 2 to 4 hours (approx) for the evaluation of the maintenance method. Based on these interviews the manufacturing knowledge was captured and the key issues associated with maintaining the knowledge were identified.

The information and knowledge collected were analysed simultaneously, it helped to determine the important knowledge maintenance tasks and functions based on the research environment. This simultaneous analysis also helped to develop the interview questions and to identify the key persons for conducting the interviews. Figure 6-1 illustrates the maintenance functions identified for the three knowledge analysis tasks.

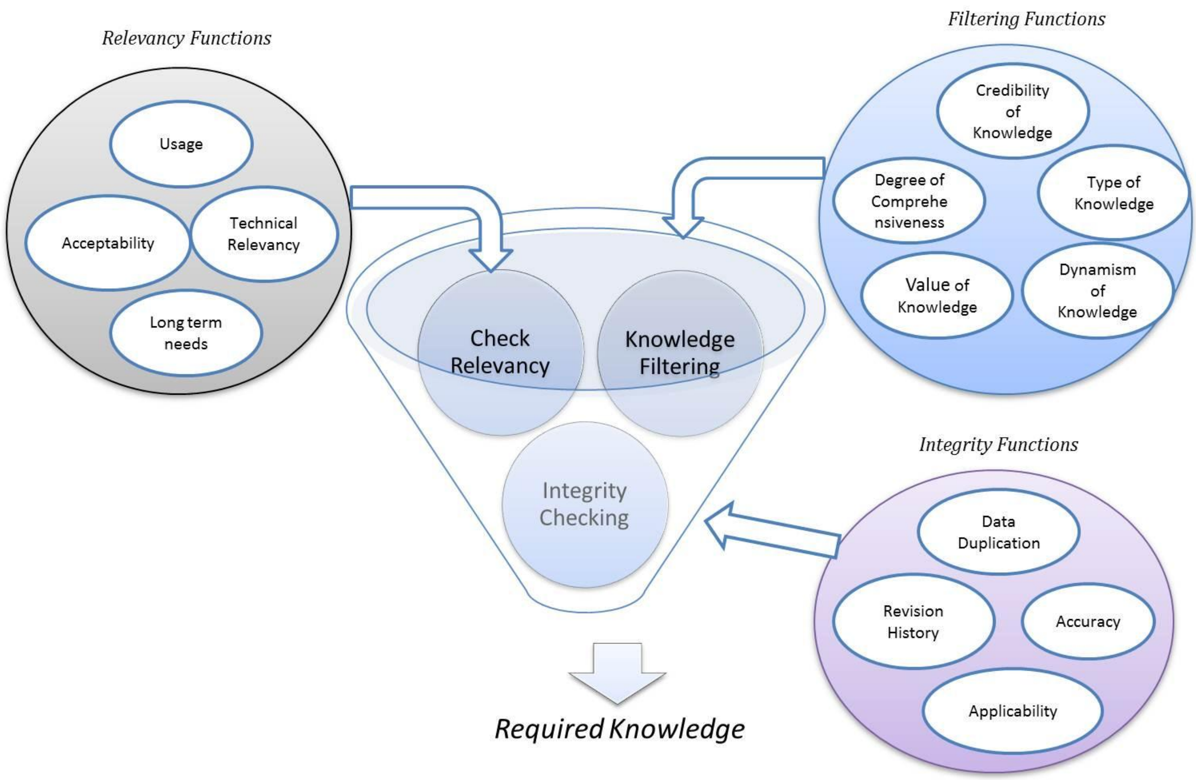


Figure 6-1: Knowledge Analysis Tasks and Functions

Four knowledge analysis functions were chosen out of thirteen functions for the initial development of the knowledge maintenance method. These functions were chosen based on their importance in context with the research environment. They were technical relevancy as a relevancy function, credibility of knowledge as a filtering function and data duplication & maintain consistency as integrity functions. The technical relevancy function is used to verify whether the knowledge is technically relevant. The knowledge credibility function is used to filter out the invalid knowledge entering the knowledge base. Data duplication function is used to verify whether the entered knowledge is not redundant and consistency of knowledge is established by maintaining a revision history of all the changes made to the knowledge. Figure 6-2 illustrates the knowledge analysis functions identified for the initial development of maintenance method.

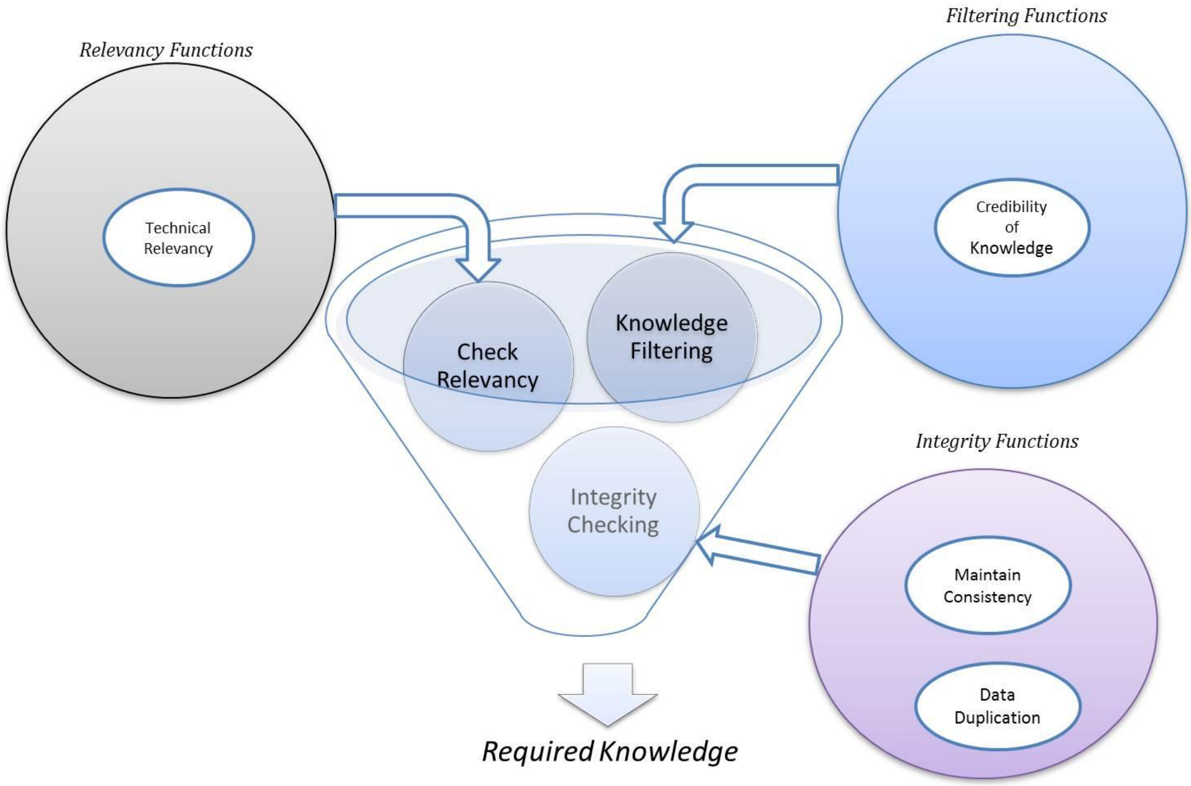


Figure 6-2: Knowledge Analysis Functions evaluated in Case Study 1

6.2.1 Initial Knowledge Maintenance Method

An initial knowledge maintenance method was proposed based on these four maintenance functions as shown in figure 6-3. The three actors involved in the process are Engineer, Process Owner and Knowledge Maintenance System. The actions performed by the three actors are – Input, Verify and Control respectively.

The process flow begins when an engineer adds a new knowledge or modifies an existing knowledge in the KB. Four maintenance functions used for the initial development of the method were technical relevancy, knowledge credibility, data duplication and maintain consistency. The technical relevancy function enables the knowledge to be entered in specific fields based on the feature relationship structure. The credibility function is used to verify the knowledge credibility based on the knowledge source.

The third function is data duplication, where the duplication of the knowledge is checked. Consistency is maintaining by recording the change history which captures all the changes made to the knowledge. The knowledge controller defines the maintenance method using the four functions and enables the interaction between the engineer and the process owner. The Process owner reviews and approves the knowledge based on the maintenance method defined. He can also reject the knowledge update if the knowledge entered is not according to the maintenance functions.

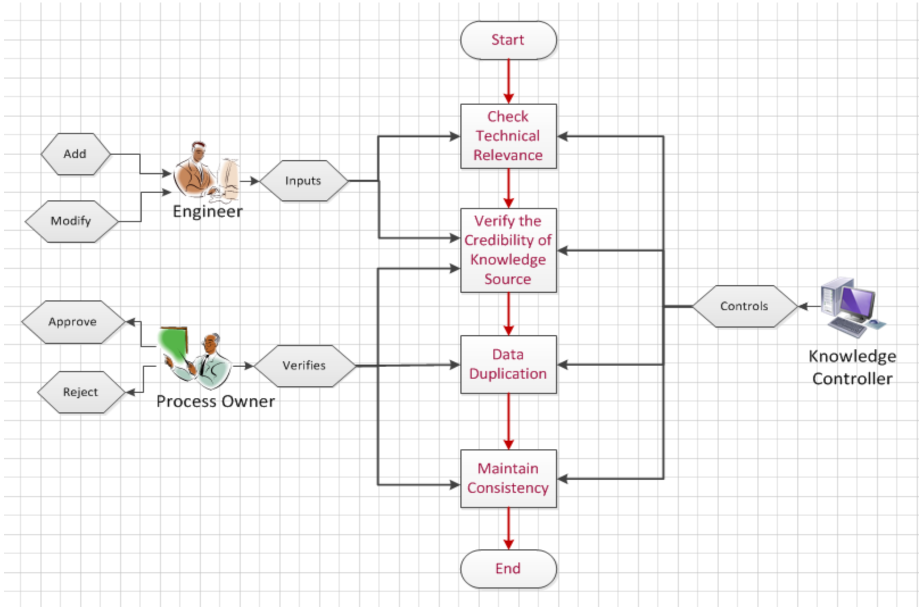


Figure 6-3: Initial Knowledge Maintenance Process developed in Case Study 1

To evaluate the initial knowledge maintenance method, interviews were conducted with the same group of expert engineers identified earlier. Each expert engineer spent 2 to 4 hours (approx) for the evaluation of the maintenance method. Following questions were asked to them to evaluate the method,

(1). Is the method effective?

(2). Any improvements to the method?

(3). Do the actor's roles fit with organisation process?

Conclusions:

Based on the interview feedbacks from the expert engineers, following key points were taken forward for conducting the Case Study 2,

- Need to develop and refine the method further to improve the effectiveness.

- Need to consider the implications of the method, by including the full set of function identified for knowledge analysis.
- Evaluate the method with other manufacturing features of the turbine blade.

Limitations:

- The KMM was assessed only based on two manufacturing features of a turbine blade. It has to be applied to the other manufacturing features of a turbine blade.
- The KMM was evaluated only based on the feedback from a group of expert engineers. No other evaluation method was used.

6.3 Case Study 2

Second case study was based on the application of the KMM to a fully defined Turbine Blade. The following six manufacturing processes associated in the manufacturing of a XWB HP turbine blade are,

1. Machining/Grinding (Stage 1)
2. Die Sinking
3. Film Cooling
4. Welding
5. Machining/Grinding (Stage 2)
6. Coating and Polish

This research was conducted through exploring the machining knowledge of turbine blades associated with stage 1 of machining/grinding. Although other manufacturing process knowledge largely influences the manufacturing of the blades, stage 1 machining was considered to provide a sufficiently broad scope for this exploration. The 25 manufacturing features associated with machining (stage 1) process were chosen for the exploration. This approach helped to understand the knowledge relationships between design, manufacturing and inspection features.

Based on the feature relationship structure, an initial knowledge document template was created (shown in figure 6-4) for the purpose of knowledge elicitation. This template was developed to allow the quick and simple capture and representation of manufacturing and inspection knowledge.

Issue No.		Date:	

Feature Description:	
Part ID	
Manufacturing Feature:	
Manufacturing Drawing Number	

Relationship Description:	
Inspection Feature ID:	
Design Feature:	
Design Drawing Number	

Factory and Machine:	
Factory	
Machine	
Tooling	
Fixture	
Inspection Routine	

Manufacturing Knowledge:	
Fixtures:	
Tooling	
Manufacturing Rule 01:	
Manufacturing Rule 02:	
Manufacturing Rule 03:	
Surface Finish	

References and Links:	
Related Documents:	Upload
Related Pictures:	Upload

Issue Governance:			
COP Author:	No Constraints	Approver:	

Figure 6-4: Knowledge Document Template

6.3.1 Knowledge Analysis Functions and Attributes

One of the main conclusions of case study 1 is to analyse the implications of the method, by including the full set of function identified for knowledge analysis. Hence in case this study, all the functions identified for the three maintenance tasks were explored.

<u>*Relevancy Checking*</u>

The knowledge acquired should be checked for its relevancy before further processing. Out of these four functions identified, only technical relevancy was chosen to define a method to check the knowledge relevancy. This function helps to organise the captured knowledge in a technically relevant level which will make the usability of knowledge easier. Other functions usage, acceptability and long term needs are considered as attributes, to determine the knowledge value.

Knowledge filtering

Filtering functions are used to filter out the unwanted knowledge. The credibility of knowledge is used to make sure the correct knowledge is entered to the knowledge base. This function determines the credibility of knowledge by identifying the credibility of the knowledge source. The knowledge life captures the knowledge validity, which changes over a period of time. This function identifies all the contributing factors for the knowledge change, which are essential to keep the knowledge repository up to date. Capturing and processing less valuable knowledge leads to extra effort in knowledge maintenance and more space in the knowledge repository. The value of knowledge checks value of the identified knowledge with respect to the knowledge users. Knowledge type identifies whether the captured knowledge is explicit or tacit. Degree of comprehension is used to verify the level of understanding of the knowledge. The knowledge captured should be easy to understand by the end users, this function enables to verify it.

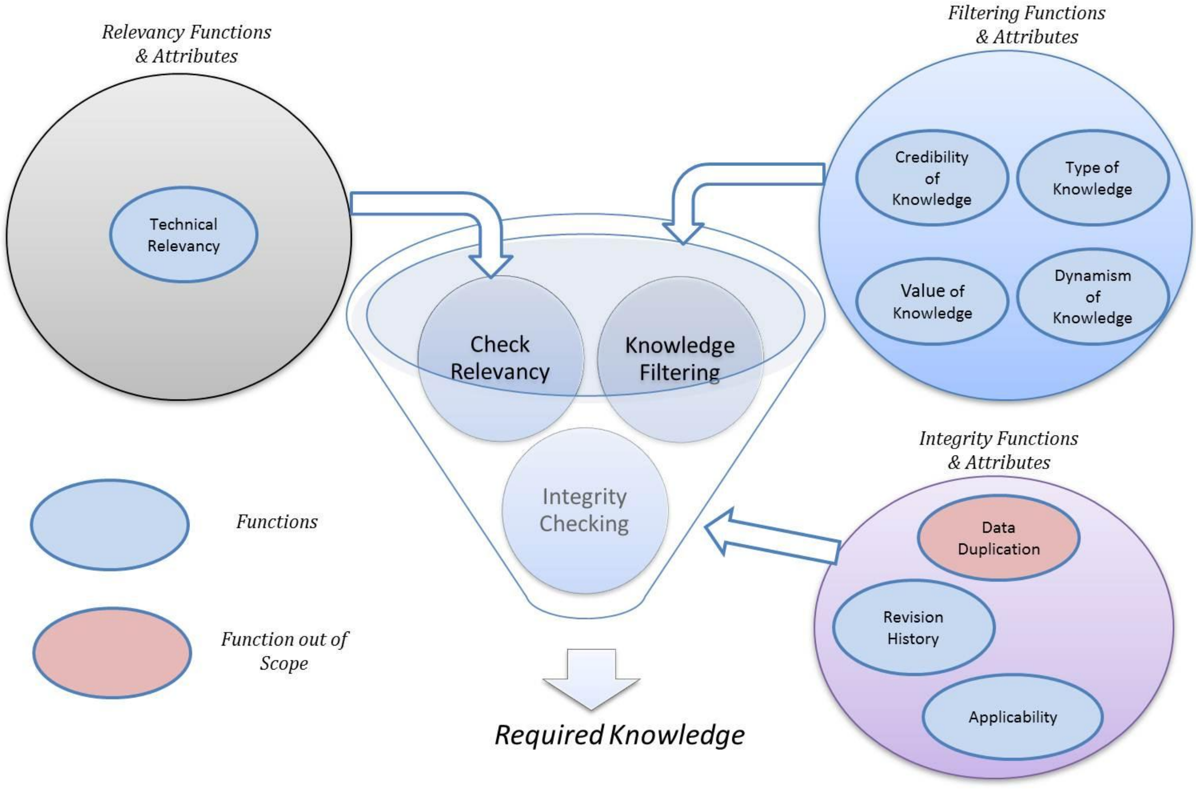


Figure 6-5: Knowledge Maintenance Functions evaluated in Case Study 2

Out of the five functions credibility of knowledge, knowledge life, knowledge value and knowledge type are identified for the development of the maintenance method. Degree of comprehension is not considered as a separate function, but it was included as an attribute to determine the knowledge value.

Integrity Checking

Integrity checking functions are used to maintain knowledge reliability. Data duplication prevents redundancy of knowledge. The consistency of the knowledge can be maintained by capturing the revision history of every knowledge change. A revision history is created to capture all the activity done by actors in the knowledge maintenance method. Accuracy checks the correctness of the written knowledge and keeps it free from errors. Applicability provides an option to link the multiple features using the same knowledge. Apart from data duplication and accuracy, the other two functions revision history, and applicability were considered for the development of the maintenance method. Data duplication was not considered, since it requires a computational support. Accuracy was not considered as a separate function, but it was included as an attribute to determine the knowledge value.

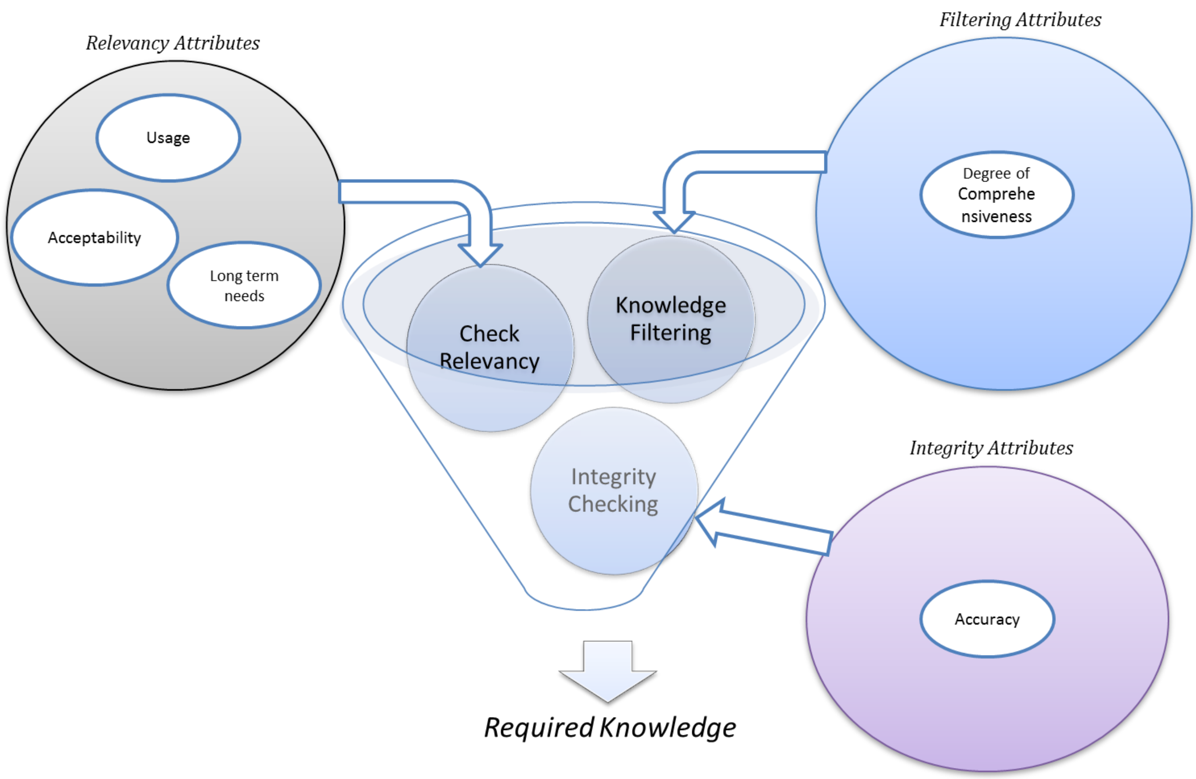


Figure 6-6: Knowledge Maintenance Attributes identified in Case Study 2

After analysing thirteen functions only seven functions were considered to be more suitable for this research environment. Based on the investigation the seven knowledge maintenance and five attributes associated with the three maintenance tasks were identified. Figure 6-5 illustrates the knowledge analysis functions and figure 6-6 illustrates the knowledge analysis attributes.

6.3.2 Knowledge Maintenance Method

A knowledge maintenance process was developed with the seven maintenance functions. The three actors identified in Case study 1 were used to perform the maintenance process. The process flow begins when an engineer adds a new knowledge or modifies the existing knowledge in the knowledge maintenance system. The process owner verifies and approves the knowledge maintenance process. All the seven maintenance functions are controlled by the knowledge controller.

The evaluation was conducted based on the feedback received from the same group of expert engineers that performed the initial evaluation. A revised knowledge maintenance method (KMM) was produced based on the evaluation results, which extended the functions and attributes of the KMM. The two main components of the KMM are the Knowledge Maintenance Process (KMP) and Knowledge Maintenance Template (KMT).

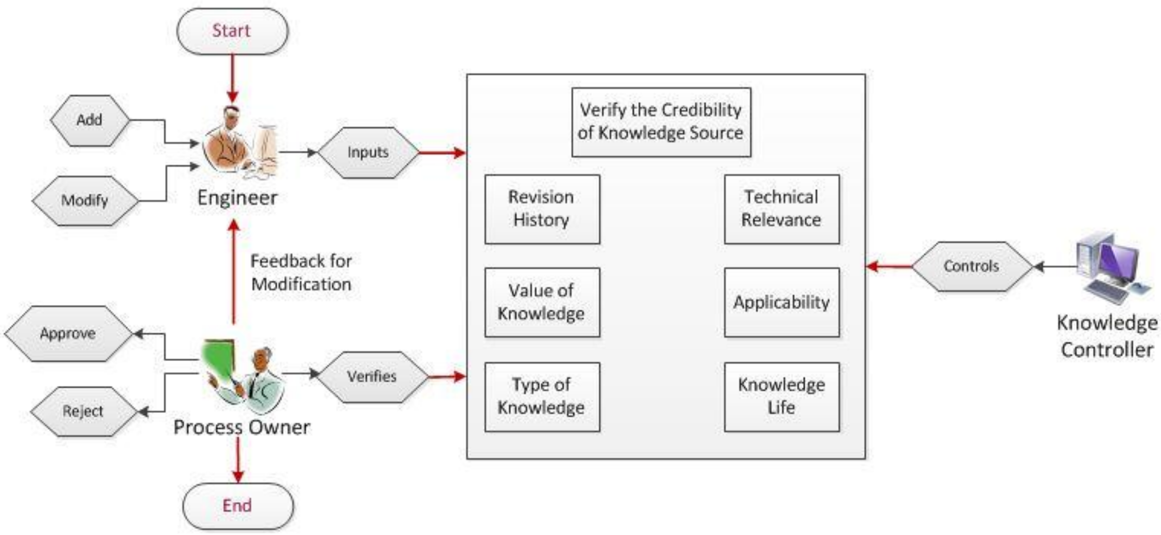
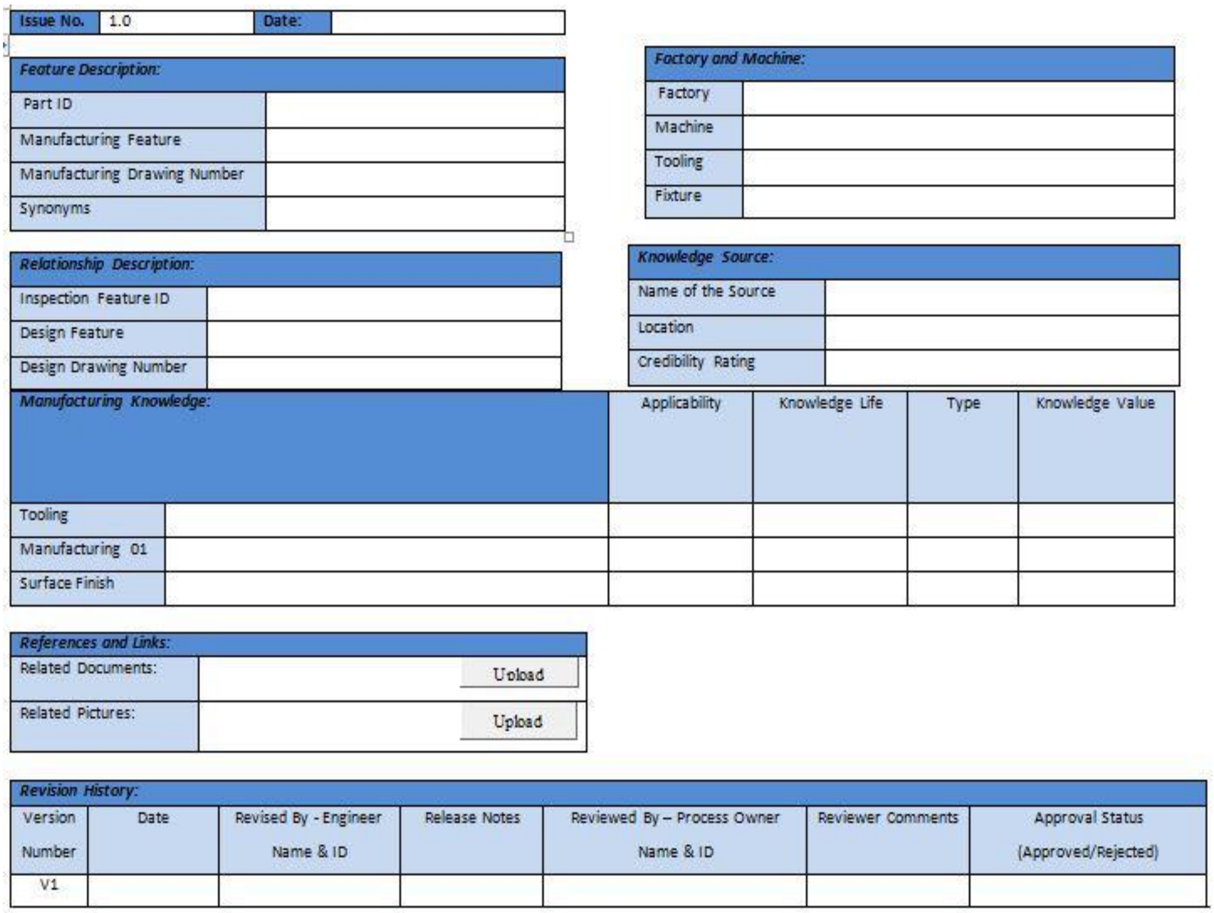


Figure 6-7: Knowledge Maintenance Process developed in Case Study 2

A new Knowledge Maintenance Process (KMP) was defined based on seven functions as illustrated in figure 6-7 and a new Knowledge Maintenance Template (KMT) was defined based on the knowledge document template as shown in figure 6-8.



Issue No.	1.0	Date:	

Feature Description:	
Part ID	
Manufacturing Feature	
Manufacturing Drawing Number	
Synonyms	

Factory and Machine:	
Factory	
Machine	
Tooling	
Fixture	

Relationship Description:	
Inspection Feature ID	
Design Feature	
Design Drawing Number	

Knowledge Source:	
Name of the Source	
Location	
Credibility Rating	

Manufacturing Knowledge:		Applicability	Knowledge Life	Type	Knowledge Value
Tooling					
Manufacturing 01					
Surface Finish					

References and Links:		
Related Documents:		Upload
Related Pictures:		Upload

Revision History:						
Version Number	Date	Revised By - Engineer Name & ID	Release Notes	Reviewed By – Process Owner Name & ID	Reviewer Comments	Approval Status (Approved/Rejected)
V1						

Figure 6-8: Knowledge Maintenance Template developed in Case Study 2

Conclusions:

- A new knowledge maintenance method was defined and the key components of the method are the KMP and the KMT.
- A KMP was defined based on seven maintenance functions and a KMT was defined based on the knowledge document template.
- The role and responsibilities of actors in the knowledge maintenance process (KMP) was defined.
- The next stage of the research work is to finalise the maintenance methods and decide on the experimental approach to evaluate the methods.
- To test and refine the method based on the comparative experiments.

Limitations:

- The KMP and KMT were assessed only based on the manufacturing features on a XWB HP turbine blade. It was not applied to different types of turbine blades.
- The KMP and KMT were again evaluated based on the feedback from the same group of expert engineers. It has to be evaluated by different group of expert engineers.

6.4 Case Study 3

One of the limitations of case study 2 is the maintenance method were evaluated by same group of expert engineers. Hence in the case study 3, the KMP and KMT were further evaluated by conducting informal interviews with a different group of senior experts. Five different experts engineers were chosen with roles in Turbine Blade (TB) design, TB manufacturing, knowledge management and manufacturing communication. Each expert engineer spent 4 to 6 hours (approx) for the evaluation of the maintenance method. The feedback from each engineer was analysed and used to update the KMP and KMT.

A semi structured interview questionnaire was prepared with an emphasis on following three key points,

(1). Effectiveness of the maintenance method
(2). Structure and layout of KMT
(3). Practicality of KMP
(4). Improvements
(5). Implementation in Industry

The results of the informal interview led to the following results,

Effectiveness of KMP

- Needs more clarity in when the engineer has to start the knowledge maintenance process.
- KMP needs an additional process to check the access rights of the actors to access the documents.
- Different actors have to be used for knowledge verification and approval. Same person should not perform both verification and approval process.

Effectiveness of KMT

- There is no Part ID, it should be modified to Part Family
- Manufacturing drawing number is not exists only engineering drawings are used as manufacturing drawings.
- Design drawing number field has to be removed, since design drawing number and engineering drawing number are same.

Structure and layout of the knowledge maintenance template

- The structure and layout of the KMT is considered good and no changes are requested.

Usefulness of the maintenance process

- The credibility rating is provided for the whole documents, but it should be identified for each individual knowledge element.
- The credibility rating classification is not useful, since the knowledge is already classified based on its value.
- Capturing knowledge type is not useful, since all the knowledge entered is explicit.

Improvements

- The knowledge sources should be kept shared for both design and manufacturing engineers use.
- Need to revalidate and approve the knowledge document after every single knowledge modification.

Implementation in Industry

- Need to prove the value of the knowledge maintenance (e.g.) reduction in effort, less number of meetings, increase in engineer's efficiency.
- Evaluate the method based on business needs.
- Need to schedule the workload of engineers to keep them actively involved in knowledge maintenance process.

This experimental evaluation helped to identify the key areas to improve the knowledge maintenance method. Based on the above results a few important changes were made within the KMT and the KMP. An extensive and efficient knowledge maintenance method was defined, better than originally envisaged. The modified maintenance process and template were explained in next section.

6.4.1 Modified Knowledge Maintenance Process

Based on the feedback, it was understood that the same person can not perform both verification and approval process. The knowledge maintenance process explained in figure 6-8 has been modified and a new actor was introduced to approve the process. The role of process owner was removed and replaced with technical leaders for knowledge verification. A new actor 'commodity leader' was introduced for knowledge approval. Two technical leaders were introduced, one each from manufacturing and design departments are part of the new knowledge maintenance process. The manufacturing technical leader verifies whether the manufacturing knowledge is captured accurately from the manufacturing processes and tooling. The design technical leader verifies the captured knowledge based on the designers usage.

One of the feedbacks was to provide more clarity in when the engineer has to start/trigger the process in the KMP. Based on this an updated Start process was established to have proper trigger for KMP. The engineer has to add new knowledge and create knowledge document whenever new manufacturing part or process is introduced.

Another feedback highlighted that, KMP needs an additional process to check the access rights of the actors to access the documents. Based on this a new process to check the access rights of key actors to the documents is added and this is performed by the Knowledge Controller.

Based on the feedback, capturing knowledge type is considered not useful, since all the knowledge entered in the KMT is explicit. Although both explicit and tacit knowledge were used in the manufacturing industry, when it is entered in the template all the knowledge becomes explicit. Due to this knowledge type function was removed from the KMP and the KMT.

Figure 6-9 illustrates the updated knowledge maintenance process. The roles and responsibilities of two new actors are explained briefly below.

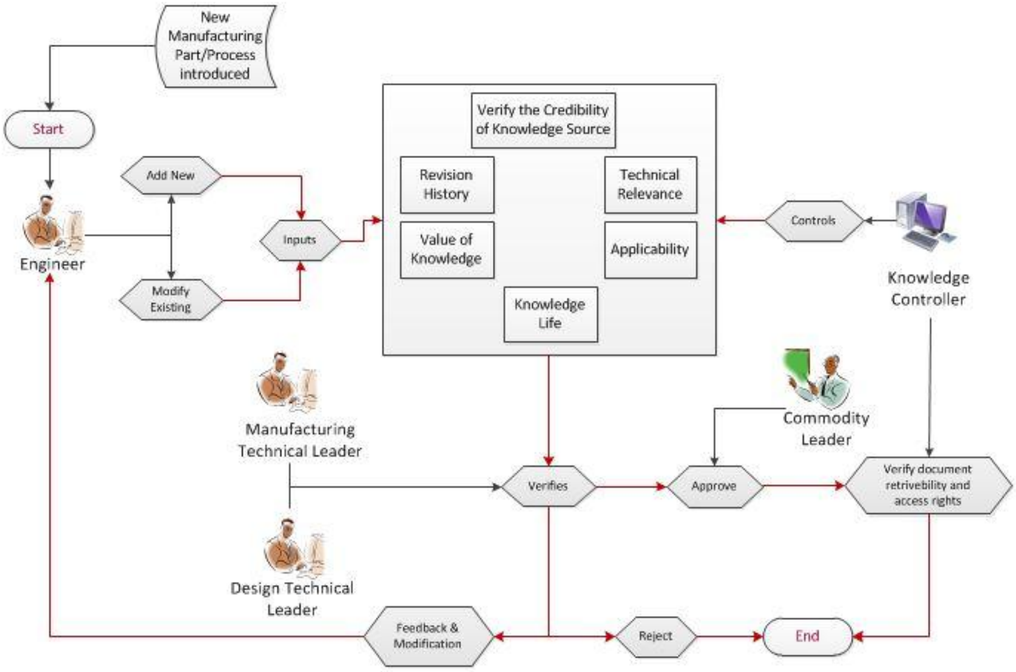


Figure 6-9: Knowledge Maintenance Process developed in Case Study 3

Technical Leaders - Technical Leaders are similar to subject matter experts who are proficient in particular manufacturing/design process. Two technical leaders, one each from manufacturing and design departments are part of this knowledge maintenance process. The manufacturing technical leaders verify whether the manufacturing knowledge is captured accurately. The design technical leaders verify the captured knowledge based on the designers usage. The Technical Leaders performs following functions,

1. Review knowledge as requested by the Engineer.
2. Verify the knowledge against the maintenance functions.
3. Confirm the classification of the knowledge article.
4. Provide the feedback to the engineers for modification.
5. Reject the inaccurate and unusable knowledge.
6. Review the knowledge templates, knowledge sources and knowledge maintenance process.

Commodity Leader - Commodity Leader owns the whole maintenance process and is responsible for the approval of the knowledge documents.The commodity leaders performs following functions,

1. Facilitate the environment and resources for capture and maintenance of knowledge.
2. Approves the knowledge documents.

3. Ensures that the Knowledge Maintenance Process is followed and Sign off the maintenance process.
4. Recommend improvements to the knowledge maintenance process.

6.4.2 Modified Knowledge Maintenance Template

Based on the feedback, the following changes have been made to the KMT,

- Under feature description section, manufacturing drawing number was replaced with engineering drawing number.

- The engineers have to provide the revision number while entering the engineering drawing number

- The Part ID in feature description section was modified to Part Family, since no ID exists.

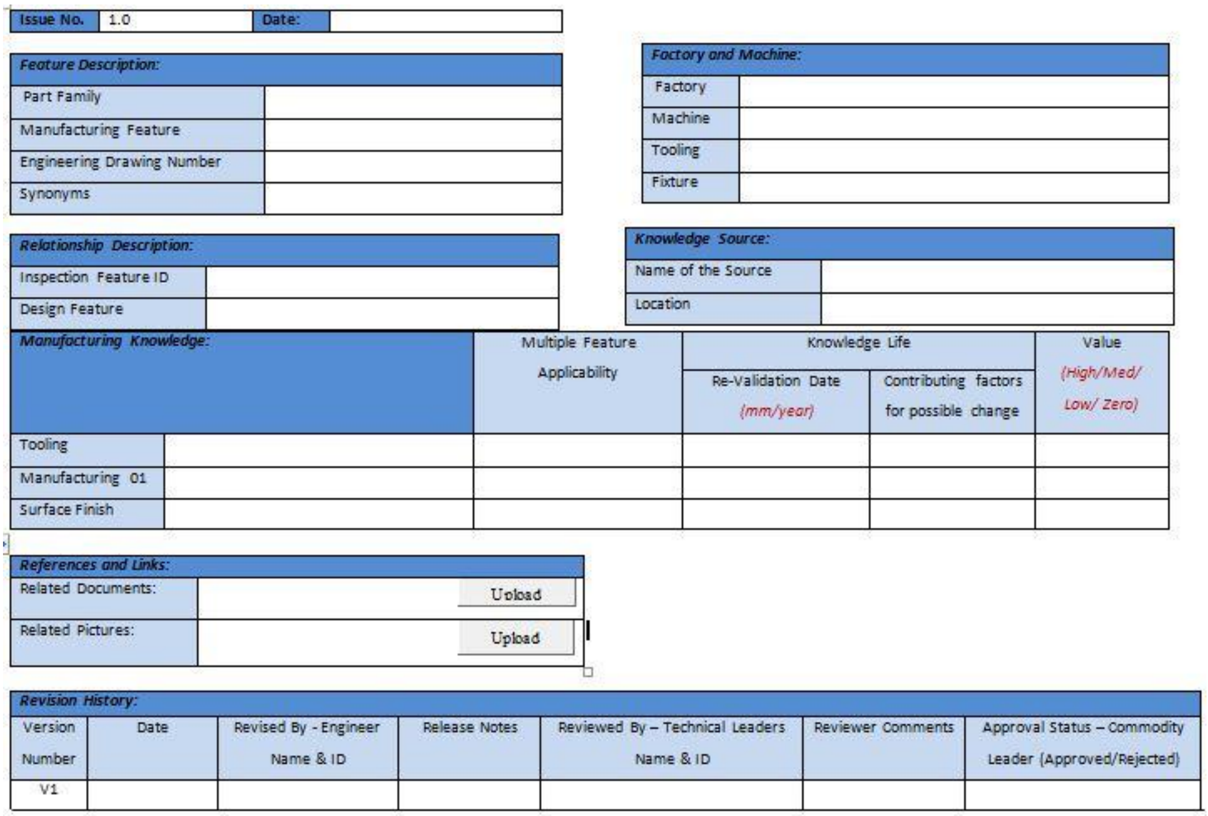
- Under relationship description section, design drawing number was removed, since design drawing number and engineering drawing number are same.

- The knowledge type function was considered not useful and the fields to capture knowledge type were removed.

- The credibility rating field was removed and the knowledge classification was established based on the knowledge value.

- In the revision history section process owners were replaced with technical leaders and commodity leader for knowledge verification and approval.

Based on the evaluation, the revised template consisting of seven maintenance functions was defined. The figure 6-10 illustrates the updated knowledge maintenance template.



Issue No.	1.0	Date:	

Feature Description:	
Part Family	
Manufacturing Feature	
Engineering Drawing Number	
Synonyms	

Factory and Machine:	
Factory	
Machine	
Tooling	
Fixture	

Relationship Description:	
Inspection Feature ID	
Design Feature	

Knowledge Source:	
Name of the Source	
Location	

Manufacturing Knowledge:		Multiple Feature Applicability	Knowledge Life		Value (High/Med/ Low/ Zero)
			Re-Validation Date (mm/year)	Contributing factors for possible change	
Tooling					
Manufacturing 01					
Surface Finish					

References and Links:		
Related Documents:		Upload
Related Pictures:		Upload

Revision History:						
Version Number	Date	Revised By - Engineer Name & ID	Release Notes	Reviewed By – Technical Leaders Name & ID	Reviewer Comments	Approval Status – Commodity Leader (Approved/Rejected)
V1						

Figure 6-10: Manufacturing Knowledge Maintenance Template developed in Case Study 3

<u>Conclusions:</u>

- The KMP and KMT produced as a result of Case Study 2 were further evaluated by conducting informal interviews with a different group of senior experts and an improved knowledge maintenance method (KMM) was defined.
- Based on the evaluation an updated KMT was produced for the better representation of information and knowledge.
- An updated KMP was defined which identifies the roles and responsibilities of the key actors for the performance of KM functions. A new role called 'Commodity Leader' was introduced for the knowledge approval.

<u>Limitations:</u>

- The KMP and KMT were assessed only based on the manufacturing features on a XWB HP Turbine Blade. It was not applied to other types of turbine blades or different manufacturing part.
- Although the KMP and KMT were evaluated based on the feedback from the different group of expert engineers, other evaluation methods apart from feedback mechanism has to be explored.

6.5 Case Study 4

One of the main limitations of the previous three case studies was that apart from feedback mechanism no other evaluation methods were explored. For the further evaluation of maintenance method defined, a different case study to examine the real time applicability was required. Due to this, the case study 4 focused on the evaluation of the KMP and KMT by performing a comparison study with an existing knowledge management method implemented in a different manufacturing facility. A knowledge management method developed for Process Failure Mode Effect Analysis (PFMEA) provided an option to do that. A detailed study was conducted, by comparing the PFMEA knowledge management method with the KMP and KMT defined.

This case study focused on the evaluation of KMP and KMT by performing a comparison study with the knowledge management methods developed in a different manufacturing facility for PFMEA.

6.5.1 Comparison study with PFMEA Knowledge Management Method

A detailed study was conducted, to get answers for the following questions.

(1). *How PFMEA knowledge is kept up to date?*

(2). *What is the knowledge maintenance method/process used?*

(3). *What are the roles and responsibilities of the persons involved in a PFMEA process?*

(4). *How far the knowledge maintenance method developed fits with the PFMEA Process?*

The PFMEA knowledge management process identified for the comparison study is shown in the figure 6-11. This process is illustrated based on the context of knowledge maintenance process established for DFM. The process flow starts when an Engineer in a shop floor adds a new knowledge in Live PFMEA Controller. The knowledge entered gets stored automatically in the PFMEA database which is controlled by the System Engineer. The System Engineer interacts with the Process Leader to verify the knowledge entered by the Engineer. The role of Process Leader is to verify the knowledge entered by the Engineer and provide modification feedback to the System Engineer. The System Engineer updates the incorrect knowledge based on the feedback received and keeps the database up to date. When the Engineer wants to use the knowledge already exists in the database, he can retrieve it by using the search function available in the PFMEA Live controller. This process will not involve System Engineer and Process Leader.

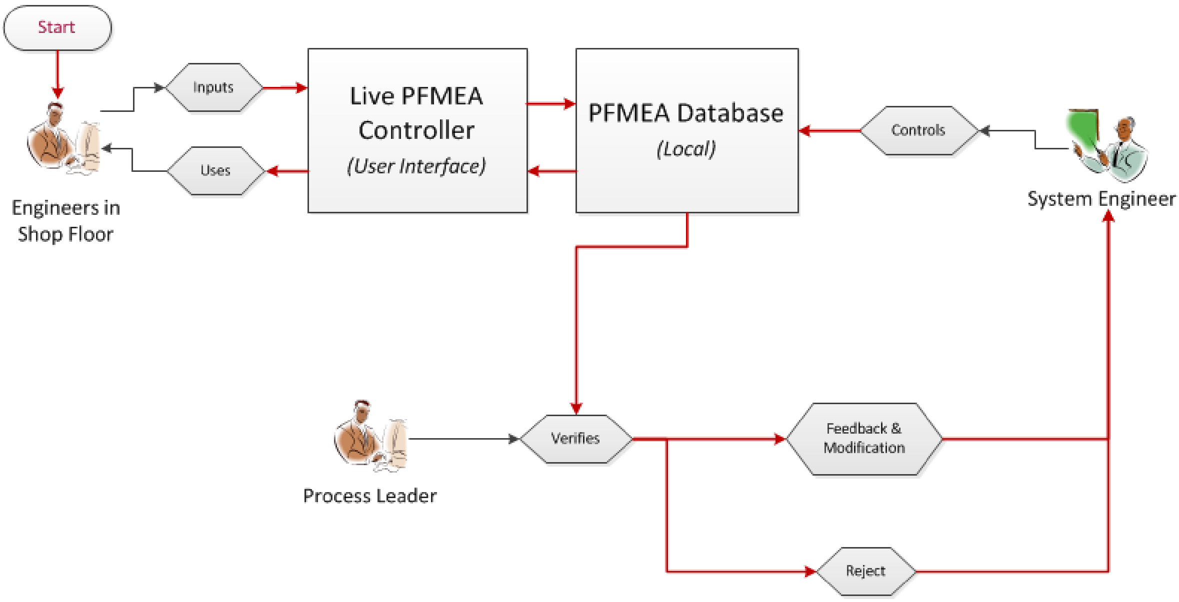


Figure 6-11 : PFMEA - Knowledge Management Process

A detailed comparison study was conducted between the KMP and the PFMEA knowledge management process based on the maintenance functions used. The results are shown in the table 6-1,

__Similarities:__

- The PFMEA KM process is controlled by a System Engineer whose roles and responsibilities are almost similar to that of Knowledge Controller.
- The knowledge is verified by the Process Leader which is similar to the roles performed by Technical leaders.

__Differences:__

- The modification of knowledge and the revalidation of RPN is done by System Engineer not the Engineer who entered the knowledge.
- Since it is a live document there is no need for sign off approval and the role of Commodity Leader is not required.

Maintenance Functions in KMP	Maintenance Functions used in PFMEA	Reasons
Credibility of knowledge Source	N/A	The knowledge is entered directly by the Engineers in shop floor, hence capturing knowledge source and verifying credibility is not applicable
Technical Relevance	YES	The knowledge entered by the Engineers are considered as technically relevant.
Value of Knowledge	YES	Value is captured in the form of RPN.
NO	Data Duplication	Data duplication is performed manually by using key word search. It is not included in KMP.
Revision History	N/A	Revision history is not applicable, since it is live document..
Knowledge Life	NO	Knowledge validity and factors that change the knowledge is not captured.
Types of Knowledge	N/A	All the knowledge entered is explicit, hence capturing knowledge type is not applicable.
Applicability	N/A	The knowledge captured is specific for particular process and it can't be applied for other process.

Table 6-1: Maintenance Functions Comparison

Limitation of PFMEA Method:

- The revalidation date and factors for possible knowledge change are not captured in PFMEA KM process

Limitation of Knowledge Maintenance Method:

- A process to avoid duplication of data is essential and the function must be included in the maintenance process.

As a result of this evaluation, it was found that the knowledge maintenance method established for DFM is generally applicable to the maintenance of PFMEA knowledge but that the data duplication function that had been removed from the KMM was reinstated. The data duplication function is performed by the engineer while entering the knowledge. Before entering a new knowledge or updating existing knowledge, the engineer has to review the existing knowledge and the previously rejected knowledge to avoid duplication and also to minimise knowledge verification time. An updated knowledge maintenance process was defined as illustrated in chapter 4 (figure 4-5) and also an updated KMT was defined as shown in chapter 4 (figure 4-6).

Based on the results the Knowledge Maintenance Process (KMP) and Knowledge Maintenance Template (KMT) was evaluated, revised and implemented for the XWB HP turbine blade.

The implementation consists of applying the knowledge maintenance process to complete knowledge documents (using the knowledge maintenance template) for the full range of machining features on the XWB HP turbine blade. It provides full coverage of machining and inspection knowledge for the blade.

Conclusions:

- Date duplication function which was not considered earlier is included in the knowledge maintenance method (KMM).
- The knowledge maintenance process and the knowledge maintenance template were modified based on evaluation results.
- An effective KMM which details the functions that need to be considered for successful knowledge maintenance was developed.

Limitations:

- The KMM was assessed only based on the manufacturing features on a XWB HP Turbine Blade. It was not applied to other types of turbine blades or different manufacturing part.
- The applicability of KMP to other industrial environments was not explored, the actors and their roles needs to be investigated.
- The applicability of the method to a different company or a supply chain unit (SCU) was not explored.

6.6 Summary

The four iterative case studies conducted for the evaluation of novel knowledge maintenance method (KMM) was explained in this chapter. These case study evaluations were performed to improve the efficiency of the KMM.

Case study 1 focused on knowledge associated with two manufacturing features of a XWB HP turbine blade. A structured interview questionnaire was prepared based on the research questions and the interviews were conducted with a key range of expert engineers. These engineers were identified from TB manufacturing, TB design, knowledge management and manufacturing communication. Based on these interviews the machining knowledge was captured and the key issues associated with maintaining the knowledge were identified.

Several important knowledge maintenance tasks were considered to suit this research. Three of these tasks were considered more important, which were relevancy checking, knowledge filtering and integrity checking. Knowledge maintenance functions and attributes associated with these three tasks were identified but only four functions were used in defining the initial Knowledge Maintenance Method (KMM). The KMM includes three actors for the proper execution knowledge maintenance activities. This maintenance method was evaluated by the expert engineers and based on their feedback necessary corrections were made.

Second case study was based on the application of the initial KMM to a fully defined Turbine Blade. The evaluation was conducted based on the feedback received from the same group of expert engineers that performed the initial evaluation. A revised KMM was produced based on the evaluations results. The two important components of the method were Knowledge Maintenance Process (KMP) and Knowledge Maintenance Template (KMT). Based on the further evaluation, some important changes were made to the KMP which extended the knowledge maintenance functions and attributes identified in Case Study 1. A new KMT has evolved to capture the key attributes.

In case study 3, the KMP and KMT produced as a result of Case Study 2 were further evaluated by conducting informal interviews with a different group of senior experts from TB manufacturing, TB design, knowledge management and manufacturing communication. As a result of this evaluation, an updated was produced for the representation of information and knowledge. Also an updated KMP was produced which identifies the roles and responsibilities of the actors for the performance of knowledge maintenance functions.

Case Study 4 focused on the evaluation of the KMM by performing a comparison study with an existing knowledge management method implemented for Process Failure Mode Effect Analysis (PFMEA). A detailed study was conducted, by comparing the PFMEA knowledge management process with KMM based on the maintenance functions used. As a result of this evaluation, it was found that the KMM is generally applicable to the maintenance of PFMEA knowledge. The data duplication function that had been removed from the KMM was included.

As a result of these evaluations, the novel knowledge maintenance method was defined. The maintenance method comprising the Knowledge Maintenance Process (KMP) and the Knowledge Maintenance Template (KMT) provides an effective route to knowledge maintenance. Three maintenance tasks check relevancy, knowledge filtering, and integrity checking was considered for successful knowledge maintenance of the XWB HP turbine blade. The seven maintenance functions, credibility of knowledge source, technical relevance, knowledge value, knowledge life, data duplication, revision history and applicability, implemented in the KMT and the KMP provides an effective knowledge maintenance method.

The KMT developed for the representation of information and knowledge, provides a simple and easy way of capturing the manufacturing knowledge. The KMP provides a flexible environment to add new knowledge and to modify existing knowledge in the knowledge base. The four main activities performed by the actors in the KMP are input, control, verify and approve. The execution of these activities by the key actors forms the basis of the maintenance process. The knowledge maintenance method has been evaluated based on four iterative case study experiments and the results were incorporated to enhance the method.

CHAPTER 7 - DISCUSSION, CONCLUSION AND FURTHER WORK

7.1 INTRODUCTION

This research work documented in this thesis has investigated a novel task based maintenance method to support knowledge maintenance in a manufacturing facility. This research has explored the use of knowledge analysis task and its functions to support manufacturing knowledge maintenance. The maintenance method was iteratively developed and evaluated based on four case study experiments and the results were incorporated to enhance the method. This was achieved through five research objectives, as outlined in chapter 1.

This chapter discusses the contribution of this research reported in this thesis. Section 7.2 compiles the overall understanding and provides a discussion of the major research issues. Section 7.3 provides the concluding remarks to this work and section 7.4 proposes important recommendation of further work.

7.2 DISCUSSION

7.2.1 Knowledge Sharing between Design and Manufacture

An approach was taken to work closely with a manufacturing company to answer the following questions,

1. What are the processes of knowledge sharing between design and manufacturing disciplines?
2. How can the knowledge be kept up to date?

Based on these questions, semi structured interviews were conducted with the design and manufacturing engineers in a manufacturing company. The assessment of interviews has provided a better understanding of the knowledge sharing process between design and manufacturing. Although there are Integrated Project Team (IPT) meetings conducted which involve design and manufacturing teams, there is a need for knowledge sharing outside these meetings. There is a necessity for easily accessible, timely and accurate manufacturing knowledge by the design engineers. For this purpose there are many informal interactions happening between the design and manufacturing engineers. These interactions occur throughout the new product introduction process. Hence a lot of knowledge needed by both design and manufacture teams are acquired in an informal manner, this leads to insufficient and inaccurate knowledge. If the manufacturing engineer is not available to answer the design engineer queries, then he has to wait which results in time consuming process. To address these issues, an accessible knowledge base with up to date manufacturing knowledge is needed. Hence a knowledge maintenance method is important to ensure that any knowledge supplied to design is current and up-to-date. The maintenance method should also determine what knowledge is new, what needs to be modified and what can be archived. This will allow quicker and better design to manufacture of a given product.

7.2.2 Scope of the applicability of the maintenance method

The manufacturing knowledge model represents and captures the data, information and knowledge describing the manufacturing resources, processes and strategies of a particular enterprise. This enables the provision of the necessary manufacturing information for the support of manufacturing decision-making in the concurrent design of products. The understanding of knowledge modeling and its representation is important because it provides a basis for effective knowledge maintenance. But a good knowledge maintenance method should be independent of any particular knowledge modelling method and should work with all of them. This research was focused on maintaining the knowledge already captured and was not looking at maintaining the knowledge that exists in people's head. A novel knowledge maintenance method has been defined and the key components of the method are a knowledge maintenance process (KMP) and a knowledge template (KMT). KMP is people based where the activities are performed by specific persons. KMT is paper based and the knowledge is documented using it.

This research was conducted through exploring the machining knowledge of turbine blades. Although other manufacturing process knowledge largely influences the manufacturing of the blades, machining was considered to provide a sufficiently broad scope for this exploration. Hence the maintenance method defined in this research is currently limited to machining knowledge and the approach should be explored for other manufacturing process such as casting and forging in the future. These manufacturing processes are also important and they provide manufacturing knowledge for design decisions. Although the knowledge maintenance template will need to be different, the same knowledge maintenance process should be applicable to other manufacturing processes. However this would need to be confirmed through further experimentation. One key aspect that would be likely in the KMT to change is the feature relationship structure used.

In a manufacturing facility there are a wide range of information and knowledge that needs to be structured and captured before being maintained. Critical categories of machining knowledge which should be captured in a knowledge repository have been identified as process and tooling. Other categories such as design guidelines, manufacturing part information, method of manufacture, and manufacturability information were identified but they were not included in this research. The KMT has to be modified to include these categories and the methodology is currently not applicable. Hence further work is needed to extend to fit these categories in the maintenance method.

7.2.3 Feature based knowledge relationships

To establish an effective knowledge sharing and maintenance process in a manufacturing facility it is important to understand the relationship between a manufacturing, design and inspection feature. The study of the information and knowledge used to design and manufacture the XWB HP turbine blade brought about the creation of the Feature Knowledge Relationship Structure. This is a key aspect for the comprehension of how different items of knowledge and information relate to each other between the different engineering domains for turbine blades.

A Feature Knowledge Relationship Structure (FKRS) explained in Chapter 3, was developed from the information and knowledge mapping activities. The model explicitly stated the relationships between the three different types of features that had been studied. The FKRS sets out the derived relationship view between a design feature, a manufacturing feature and an inspection feature. There are different types of information and knowledge that can be associated against each of these. Hence by explicitly modelling and stating these relationships the FKRS allows the information and knowledge to be linked between entities.

Although turbine blades are complex parts, the relationship between manufacturing, design and inspection features are well defined, hence the turbines blades were chosen to establish FKRS. The knowledge maintenance template (KMT) uses the FKRS to maintain the knowledge, hence defining the feature relationship is critical for knowledge maintenance. It is believed that the FKRS created is broadly generic for maintaining the machining knowledge of other turbine blade, this needs further work to confirm. For other components the feature relationship will not be the same and this will need to be defined.

7.2.4 Knowledge Maintenance Method Requirements

As explained earlier, the knowledge associated with the manufacturing of turbine blades was used as a basis for the exploration of maintenance method. The two main components of the maintenance method are Knowledge Maintenance Process (KMP) and Knowledge Maintenance Template (KMT). The potential areas of for the applications of KMP and KMT under different categories are explained below,

Applicability of KMP:

The four main activities of KMP defined in this research are input, control, verify and approve. The execution of these activities by key actors identified forms the basis of the maintenance process. The KMP is generic with respect to the actors used, however appropriate persons must be selected for the proper execution of maintenance process. Also the KMP is applicable even if persons in different roles are used, but the four activities must be performed by appropriate persons who are considered as experts.

KMP can be applied to different domains other than manufacturing, but there is a need to identify the key domain experts to execute the four activities. Also the KMP is applicable even if the environments for knowledge capture are different, i.e., apart from the template approach it can be used for database or web based approaches. However both of these approaches have not been explored in this research.

KMP is broadly applicable to a different Supply Chain Unit (SCU), however the four activities have to be performed and the process flow defined should be followed. Also the KMP can be applicable to different companies other than aerospace, but the key experts in an organisation have to be identified to perform these four activities and the maintenance process flow must be defined based on the knowledge capturing environment. All these approaches have to be explored and further work is needed to confirm the applicability of KMP.

Applicability of KMT:

KMT was defined based on the FKRS to maintain knowledge. It consists of different sections and fields, which were created based on the seven knowledge analysis maintenance functions.

As explained in chapter 4, these seven functions were defined based on three key maintenance tasks, which are relevancy checking, knowledge filtering and integrity checking.

KMT is generic with respect to the actors used, however appropriate persons must be selected for the proper execution and maintenance knowledge documents created. The KMT is applicable even if persons in different roles are used, but the knowledge maintenance activities must be performed by appropriate persons who are considered as experts.

KMT can't be applied to different domains other than manufacturing, since it is manufacturing feature based and has been defined only for the maintenance of machining knowledge. The template approach can be extended to other domains, but there is a need to define the knowledge relationship structure and the applicability of maintenance functions. However this is not explored in this research and needs further work. The KMT is not applicable if the environment for knowledge capturing is different and it can be used only if the knowledge is maintained in document format. So the KMT can't be used for database or web based approach.

7.2.5 Evolution of knowledge maintenance method

As explained earlier, due to the exploratory nature of this research, the case study approach was identified as a best fit for experimental evaluation. In this research four iterative case study evaluations have been performed for the development of knowledge maintenance method.

In the first three case studies, the knowledge maintenance method was evaluated by group of expert engineers. These expert engineers were chosen form different departments within manufacturing facility. Based on their feedbacks important changes were made to the Knowledge Maintenance Process (KMP) and the Knowledge Maintenance Template (KMT). Although this feedback mechanism provided an effective approach for the development of maintenance method, other evaluation methods were not explored during the first three case studies. The KMP and KMT were assessed only based on the manufacturing features of a XWB HP Turbine Blade. The maintenance method focused on the machining knowledge of the turbine blade, the applicability of the method to different manufacturing process was not explored. Also the method was not explored by applying to a different type of turbine blades or a different manufacturing part.

Case study 4 was initiated in order to explore a different evaluation approach other than the feedback mechanism. It focused on the evaluation of the KMP and KMT by performing a comparison study with an existing knowledge management method implemented for Process Failure Mode Effect Analysis (PFMEA). As a result of this evaluation, it was found that the knowledge maintenance method is generally applicable to the maintenance of PFMEA knowledge. However the application of KMP and KMT to a different domain other than manufacturing or a different company has not been explored in this research.

7.2 Novelty of the work

This thesis presents a novel task based maintenance method for manufacturing knowledge, ensuring that knowledge already captured in a knowledge base, is properly organised and kept up-to-date. The method is defined for maintaining machining knowledge, which supports knowledge sharing in product design and manufacture. The key components of the method are a Knowledge Maintenance Process (KMP) and a Knowledge Maintenance Template (KMT).

The KMT is created based on the Feature Knowledge Relationship Structure (FKRS) which uses the knowledge maintenance functions identified. The maintenance functions identify the key characteristics of knowledge which needs to be kept up to date for effective knowledge maintenance. A KMP provides a flexible environment to add and modify the knowledge, with five key actors identified as Engineer, Manufacturing Technical Leader, Design Technical Leader, Knowledge Controller and Commodity Leader. The roles and responsibilities of these actors for the performance of knowledge maintenance functions are defined.

7.3 Conclusions

The following set of conclusions have been drawn from the discussion,

- It has been shown that a novel task based knowledge maintenance method comprising the Knowledge Maintenance Process (KMP) and the Knowledge Maintenance Template (KMT) provides an effective route to knowledge maintenance. Three maintenance tasks, check relevancy, knowledge filtering, and integrity checking have been considered for successful knowledge maintenance of the XWB HP turbine blade.

- The KMT developed for the representation of information and knowledge, provides a simple and easy way of capturing the manufacturing knowledge. The maintenance fields created in KMT provides specific categories to enter the details of the knowledge, which are important to keep the knowledge up-to-date.

- The KMT uses the feature knowledge relationship structure (FKRS) to maintain the knowledge; hence defining the feature relationship is critical for the other specific applications of KMT.

- The seven maintenance functions, credibility of knowledge source, technical relevance, knowledge value, knowledge life, data duplication, revision history and applicability, implemented in the KMT and the KMP provides an effective knowledge maintenance method.

- The KMP provides a flexible environment to add new knowledge and to modify existing knowledge in the knowledge base. The roles and responsibilities of the actors in the KMP for the performance of knowledge maintenance functions have been defined.

- The four main activities performed by the actors in the KMP are input, control, verify and approve. The execution of these activities by the key actors forms the basis of the maintenance process.

- The knowledge maintenance method has been evaluated based on four iterative case study experiments and the results were incorporated to enhance the method.

7.4 Recommendations for Future Work

The following points are the main recommendations,

- The approach has been totally focused upon turbine blade machining, for future work it would be beneficial to study different products from other business units to determine the wider applicability of the approach. Also the applicability of the method to different manufacturing facilities or to a different manufacturing part has to be explored.

- This research has defined a knowledge maintenance method based on knowledge analysis tasks and its functions. The method includes three knowledge analysis maintenance tasks and seven maintenance functions. However there is to a need to explore additional maintenance tasks and functions related to knowledge classification and knowledge update.

- The applicability of the maintenance method to the range of turbine blades has to be explored. However the KMP can be broadly applicable as it is people based, but the KMT is applicable only if same manufacturing features and methods were used.

- The applicability of the method to a different company or a supply chain unit (SCU) has to be explored. Based on the environment the maintenance tasks and its functions have to be investigated, and the knowledge relationship structure has to be redefined.

- The actors and their roles and responsibilities in the knowledge maintenance process (KMP) were defined based on the engineers in case-study company. In order to apply the KMP to other industrial environments, the actors and their roles needs to be investigated.

Publications

✓ Saravana P. Govindan., and Robert I.M. Young, 2011. Manufacturing Knowledge Maintenance, Proceedings of 1st International Conference in South Asia on "Global Manufacturing Systems & Management".

✓ Saravana P. Govindan., and Robert I.M. Young, A Manufacturing Knowledge Base Maintenance Method, International Journal of Computer Integrated Manufacturing (Submitted for review on August 2012, minor review comments received on March 2013)

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APPENDIX A –SAMULET 5.6.1 Knowledge Maintenance Questionnaire (Case Study 1)

Q-1: What is your role in TBF?

Q-2: What are your main responsibilities (day to day activities)?

Q-3: Currently in what ways do you store the knowledge gained (TBF)?

Q-4: How do you update (maintain) the stored knowledge?

Q-5: Based on your experience, specify the critical knowledge for below manufacturing sequence in OP300 in terms of Tooling and Capability.

OP300 - Mfg Sequence	Knowledge Categories		Factors change the knowledge
	Tooling	Capability	
Root Trailing Edge Seal Tip (110) Root Leading Edge Seal (130)			

Q-6: Based on your experience, specify the critical knowledge for below manufacturing feature in terms of Tooling and Capability.

Manufacturing Features	Knowledge Categories		Factors change the knowledge
	Tooling	Capability	
RTESG (Root Trailing Edge Seal Groove)			
RLEST (Root Leading Edge Seal Tip)			

Q-7: What are the key knowledge associated with the below inspection features?

Inspection Features	Knowledge Associated	Factors change the knowledge
Leading Edge Root Seal to Shank		
Trailing Edge Root Seal to Point P		

Q-8: With related manufacturing/design, what sources of knowledge do you use to keep yourself up to date?

	Often	Sometimes	Rarely	Never	Don't know
Documents					
Discuss with Expert					
Intranet					
Training/Workshop					
Database					
Knowledge base					
World Wide Web					
Other (describe)					

Q-9: What is the critical information/knowledge you want to know from manufacturing/design engineering related to Leading & Trailing Edge?

Q-10: From your point of view, what is the key feature in manufacturing/designing a Turbine Blade?

Q-11: List the priority for knowledge management and maintenance activities in RR-TBF that you believe would have the greatest impact on improving manufacturing performance, enhancing efficiency and reducing costs.

Q-12: Do you have any other comments related to this research?

APPENDIX B – Knowledge Maintenance Case Study (PFMEA)

Case Study Aim:

Evaluate the knowledge maintenance method by comparing with the knowledge management method developed for PFMEA.

Current Status:

- A knowledge maintenance method has been developed and is being implemented for the XWB HP turbine blade. The key components of the method are a Knowledge Maintenance Process Flow (KMPF) and a Knowledge Maintenance Template (KMT).
- The evaluation of the Knowledge Maintenance Method (KMM) to date is based on a single case study. For the further evaluation of the KMM a different case study is required, knowledge maintenance in PMFEA provides an option to do that

Questions:

1. How PFMEA knowledge is kept up to date?
2. Any knowledge maintenance method used?
3. What are the roles of following persons in a PFMEA process?
    - Engineer
    - Developer
    - Facilitator
    - Action Owner
    - FMEA Owner

PFMEA Template – Check Understanding

Before conducting the case study, the PFMEA template was studied and the understandings were presented to the Engineer. Following assumptions were made before conducting the comparison study, *Process Failure Mode Knowledge* *Process Controls and Results*

Current Process Controls for:																						
Process Step Number	Classification	Process Details	Potential Failure Mode	Potential Failure Mode Effect	SEV	Potential Failure Mode Cause	7M's / Fishbone cause category	OCC	Prevention of potential failure cause	Detection of potential failure mode occurrence	DET	RPN	Recommended Improvement/Corrective Actions	Action Owner	Target Completion date	Responsible Business Department	Actual Improvements/ Corrective Actions Implemented	Actual Completion Date	SEV	OCC	DET	RPN

Figure: PFMEA Template

Two Knowledge Categories:

- Process Failure Mode Knowledge
- Process Controls and Results

Actors Involved:

PFMEA actors matched with the knowledge maintenance process (KMP) actors

- Local Expert - IPT Engineers & Developers???
- System Manager - Facilitator???
- Commodity/Process Lead - PFMEA/Action Owner???
- Technical Lead - Use Case Lead???

Maintenance Scope:

What changes are in scope?

- Process,
- Tooling
- Material
- New RPN value for every change
- …

APPENDIX C – Sample Interview Results

Manufacturing Engineer Feedback:

- Need to identify commodity leaders in TBF, discuss with Product Introduction Chief and Manufacturing Process person.
- The roles of Commodity leaders are already defined and their responsibility is totally different.
- Need to change the name for Commodity Leaders
- It is difficult to manage 100’s knowledge documents developed just for Turbine blades.
- The knowledge documents can be combined in terms of process wise, which makes it more manageable
    - Grinding
    - Flimcool
    - Welding
    - Diesink
    - Coating
    - J&S
- Combine Manufacturing knowledge and Inspection knowledge into one single knowledge document.
- How ME captures all the knowledge associated with the feature, how to avoid crossovers of knowledge?
- Provide pictures for applicable manufacturing knowledge.
- Pilot the knowledge maintenance process, provide a worked example document and show the output to ME.
- Knowledge life – Reassessment date would be always the new product introduction date.
- Get feedback from new resource allocated. Contact - Rory King

Design Engineer Feedback:

- No manufacturing drawings and design drawings, it's the one drawing sheet called Engineering drawing
- Specify the revision of the drawing.
- Need to change manufacturing Part ID to Part Family
- For Multiple feature applicability – Define the criteria? How to choose if the feature is applicable?
- Provide examples for Explicit and Tacit Knowledge
- Knowledge Value feedback
  - ➢ High – Mandatory and process can't be changed (Deviation from this guideline requires new buy-off form the ME and new process development is necessary)
  - ➢ Medium – Process can be changed only for specific scope. (Consult ME if needs to be changed)
  - ➢ Low – Process can be changed, provide the consequences (e.g.) Cost Impact, Need of special tooling
- Guideline document can be changed as Introduction to Manufacturing Knowledge Maintenances Process.