The reuse of machining knowledge to improve designer awareness through the configuration of knowledge libraries in PLM

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Abstract: The nature of competition induces the need to constantly improve and perform better. For global aerospace manufacturers this is as timely an epithet as ever as market forces urge for more growth, better financial return and market position. The macroeconomic aspect is compounded by the growth of product complexity and the need for higher product quality, hence the drive to reduce waste places emphasis upon production costs and the need to improve product performance. This paper focuses upon a rapid development and deployment method that enables the capture and representation of machining knowledge so that it may be shared and reused by design engineers to accelerate the design-make process. The study and mapping of information and knowledge relationships are described and put forward as a lightweight ontology. From this a set of knowledge document templates were created to facilitate the capture, structuring and sharing of machining knowledge within a collaborative multidisciplinary aerospace engineering environment. An experimental pilot system has been developed to test and demonstrate that knowledge document templates can accelerate the sharing of machining knowledge within an industrial product lifecycle management environment. The results are discussed to provide a case for further development and application within the product domain.

Keywords: knowledge engineering, knowledge reuse, knowledge retrieval, structured knowledge documents, product lifecycle management.

1 Introduction

Market pressures being placed upon global aerospace manufacturers are ever increasing. Consolidation within the industry continues at a pace to account for over capacity aligned with investor pressure to derive value for money. Consequently companies must keep growing, improving and providing quality products and services. This also is important for customers who seek more efficient and environmentally aware products to develop future generations of aircraft. Additionally as products become more complex, product performance needs to be improved so that costs can be minimised and value maximised by suppliers. But how can this be achieved? One such way is to capture, structure and share knowledge in more effective ways so as to enable reuse and accelerate the design-make process, thereby reducing product development timescales, waste and costs.

Over the past few years there has been an emphasis placed upon the study and development of knowledge based systems to enable better knowledge management and reuse of that knowledge within manufacturing environments (Cochrane *et al*. 2009; Gunendran and Young

2010; Chungoora *et al*. 2013). There are some drawbacks to these approaches in that they can consume inordinate amounts of time to create a knowledge base and test it before they are even implemented within a commercial environment (Mohammed, May and Alavi 2008). The research outcomes presented in this paper were a part of the Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies (SAMULET) programme 5.6.1 'manufacturing knowledge reuse and maintenance' which focused on utilising rapid development and deployment document based Product Lifecycle Management (PLM) software solutions for knowledge management and sharing to facilitate quick and effective approaches that could be easily implemented. This was in an effort to enable design and manufacturing engineers to share their knowledge in a universal format that could be instantly employed at the intended point of use.

The academic literature points towards major research efforts focused upon the concepts of sharing and reusing design information and knowledge in collaborative environments (Hall 1999; Lynne 2001; Costa and Young 2001; Dani *et al.* 2006; Liu and Young 2007; Zdrahal *et al.* 2007; Ong *et al.* 2006; Baxter *et al.* 2007; Berkani and Chikh 2010; Reed *et al.* 2010; Mok *et al.* 2011). Additionally there are some good examples of sharing and reusing knowledge between the disciplines of design and manufacturing to facilitate multi context knowledge sharing (Young and Gunendran 2007, 2010; Chungoora *et al*. 2013). Nonetheless whichever perspective is taken it is still a complex and exacting challenge to address (Verhagen *et al.* 2011).

The range of knowledge sharing, retrieval and reuse approaches span from document based approaches, to the more complex and formal ontological and knowledge based systems approaches. Concerning document based approaches and in particular the subject of Structured Documents (SD) there are two ways in which documents can be structured, those being visible and invisible. The visible structuring of documents relates to the layout of document contents based upon graphical aspects (spacing, numbering, etc.) and the text aspects, thus grammar, syntax and organisational or hierarchical aspects of the data, information and knowledge being structured (headings, naming conventions, etc.). The invisible structuring of documents is associated with the electronic 'marking' of a document using metadata, by way of a computer language such as Standard Generalized Markup Language (SGML) and the much more widely adopted eXtensible Markup Language (XML) (Liu, McMahon and Culley 2008). With regard to the visible aspect of SD, Liu, McMahon and Culley (2008) cite this as a key research area that impacts upon information access performance.

As such there are few references to the use of an ontology to develop and format the visible structure of a document for its intended domain application. Brandt *et al*. (2008) have developed an ontological approach for the structuring of information and knowledge. This approach has been applied directly to the specification and structuring of documents for chemical engineering. The output of which is a generic document class with the ability to apply specific document classes where necessary. Related work manifests itself in the approach of Thirunarayan, Berkovich, and Sokol (2005), who have developed and applied an ontology to the structure of a document, which aids the definition of a document's layout and logical composition both for the extraction of text but also for the composition of new documents too. Somewhat differently, Wu (2009) sets out a document based approach to the management of information and knowledge using factoring and synthesising to structure and present information within a structured document format. Market reports, customer requirements and product information are meshed together based upon a set of criteria to develop new products. An ontology is not used to structure knowledge within the approach, what is put forward is a modular approach to information representation and presentation.

The main focus of research work carried out on Structured Document Retrieval (SDR) is on deriving ways in which documents can be more effectively managed and searched for, together with more efficient access to information within them, thereby enabling more functionality. This pertains to the electronic ‘marking up’ of a document by way of the addition of code (Goldfarb 1981). One of the first widely accepted mark up languages, that of SGML, has been applied in research to assess how documents could be made more functional (Francois 1996; Kim and Cho 2000). But as SDR approaches have matured the study and assessment of SGML has encountered the newer, simpler XML formalism (Salminen, Lyytikäinen, and Tiitinen 2000; Trotman 2004). Currently XML is the favoured formalism for the mark-up of documents in SDR research efforts (Tseng and Hwung 2002; Bae and Kim 2007; Martínez-González and de la Fuente 2007). Two often noted techniques are the Darwin Information Typing Architecture (DITA) and DocBook. These are both XML based formalisms for the authoring, production and delivery of technical documents. These can be incorporated into content management systems and be customised to output content in a number of formats.

The use and application of XML to mark-up documents is well portrayed by Reid *et al*. (2006a, 2006b) with the assessment of Best Entry Points (BEP) and relevant objects for the focused retrieval of document components. A number of classical literature texts were marked up for analysis, these were then analysed against different query categories. The work highlights the advantages of coding documents with XML, in that it can enable the searching of individual segments of text within a number of documents. By focusing on BEP for end users it was shown that these could be advantageous by streamlining and making search queries more efficient. However by the authors’ own admissions, the approach is highly complex with regard to encoding human criteria BEP accompanied by the characteristics of individual query categories.

de Campos *et al*. (2010) provide a good example of XML being used both as a mark-up language for the augmentation of document functionality, but also as a technological framework for the development of services to augment ‘frequent user requests’ by way of the XML path language. They set out a general methodology to enable an Information Retrieval (IR) system to process structured queries. They show that the application of their method for managing content and structure queries can significantly improve IR precision.

Portier *et al*. (2012) put forward an interesting perspective upon multi-structured documents, from which they propose a Multi-Structured Document Model (MSDM). It seeks to enable a document to be tagged using XML as the meta language for multiple purposes within one singular document, rather than create multiple documents for each individual tagging purpose which can cause redundancy. They apply the MSDM to medieval texts and assess it by way of Multi-X, an XML based formalism. The results were encouraging and illustrate how the model can enable a document to be tagged for a number of different purposes. One of the main drawbacks of the approach is that is can be quite complex for humans to tag and structure documents using the MSDM.

Other methods have been applied within the field of SDR, de Campos, Fernandez-Luna, and Huete (2004) set out the use of Bayesian networks and influence diagrams to form a retrieval model. They show that it is a novel way in which to identify and display SD components. Jouve *et al*. (2003) present a conceptual framework for document semantic modelling with an associated ontological extension which is set within the context of a legal domain, it is mooted that it may be applicable to other domains.

What can be seen throughout these approaches is that whilst the results reported show greater functionality, a considerable amount of time, effort and expertise has been utilised to develop the electronic and invisible aspects to influence SD approaches.

The opposite end of the spectrum for information and knowledge engineering presents approaches which focus upon the development and application of formal ontologies and knowledge based systems to support design decisions by supplying manufacturing knowledge (Young *et al.* 2007; Cochrane *et al.* 2008, 2009; Gunendran and Young 2010; Chungoora *et al*. 2013). All of these approaches aim to ameliorate the representation and supply of manufacturing knowledge to facilitate quicker and better design decision making and therefore enable reuse. Aligned with these are a number of approaches that focus upon the reuse paradigm but from a wholly design orientated viewpoint, with little reference to the production and manufacturing of the ensuing products (Ahmed 2005; Baxter *et al.* 2008; Boh 2008; Hunter *et al.* 2005; Zdrahal *et al.* 2007; Li and Ramani 2007; Afacan and Demirkan 2011). These look at the feedback of previous designs, both in terms of geometry and CAD information but also knowledge aspects too. It can therefore be deduced from these that there is heavy emphasis upon the need to derive and develop effective and applicable ways in which to reuse knowledge.

Ball *et al.* (2001) cite the problem of the accessing and retrieval of knowledge as a major issue when discussing and researching knowledge systems that pertain to the reuse of design and manufacturing knowledge. This is partly due to the specific nature of the context in which the knowledge is captured. In fact, Marsh (1997), McMahon, Lowe, and Culley (2004), Baxter *et al.* (2007), Robinson (2010) and Reed *et al.* (2010) state that somewhere between 10% to 30% of a designer's time is spent acquiring and providing information. To quote Teece (2000, 38) knowledge "is of little value if not supplied to the right people at the right time". Moreover Kankanhalli, Lee and Lim (2011, 111) put forward an interesting sociological perspective surrounding the use of knowledge systems and the motivational aspects of using such systems. They show within the limitations of the published study that the "perceived knowledge repository capability is positively related to knowledge reuse", thus the lesson that can be learnt is that not only does knowledge have to be well formatted, structured and presented, but the system within which it is stored, searched for and retrieved must be user friendly and easy to use itself to foster and promote knowledge reuse efforts. Hence whilst pursuing knowledge based system approaches is seemingly worthwhile and valid, such approaches can prove to be complex undertakings, consuming large amounts of time. Moreover they need disproportional amounts of effort to develop the systems that can share knowledge to allow reuse which in turn need time to be developed, tested and validated for use as professional pieces of software within high technology corporate environments.

Therefore approaches are still needed that can be developed and applied in short spaces of time, which allow the capture and representation of knowledge in a highly structured manner, that can be rapidly developed and deployed, are simple to use and effectively share knowledge between different engineering functions and multidisciplinary teams of engineers.

This paper reports a successful method for the capture, representation, sharing and reuse of information and knowledge. This is comprised of three parts, the first is a developed Feature Knowledge Relationship Structure (FKRS) UML model which describes the relationships between multi-context design and manufacturing knowledge. The second is two knowledge document templates, created for the capture and representation of machining and inspection knowledge. The third is the development, deployment and testing of an industrial scale experimental pilot system, utilising a Product Lifecycle Management (PLM) environment within a high technology aerospace company. These are all underpinned by a sound methodological research approach.

The academic significance of this work is that it provides an understanding of methods by which industrial users can exploit existing commercial PLM environments in order to capture and share manufacturing knowledge. Significantly this has been explored against a real world context of full scale part manufacturing knowledge and product designer requirements.

This paper is structured in the following manner. Section two sets out the methodological approach of the reported research. Section three focuses upon knowledge discovery and the derived feature knowledge relationship structure that was produced from the research together with the knowledge document templates that were developed as a result of the structure. Section four looks at the development of the knowledge library, its configuration and the developed experimental pilot system. The results of a set of end user trials are presented in section five with a discussion in section six of the important aspects brought about by the research. The paper is brought to a close with conclusions in section seven.

2 *Research approach*

The research reported herein was based around one research question: *'How can machining knowledge be captured and searched for so that design engineers can quickly and easily access it for design reuse?'*

The scope of the research was the machining of high pressure turbine blades within an industrial high technology aerospace manufacturing environment. Knowledge sharing and reuse functions were to be performed within the sponsor company's PLM environment. The context being studied and the phenomena within it were assessed to be rich with qualitative information. It was necessary to apply a research approach to enable it to be structured and centred on reasoning and critical thought. This led the authors to select research methods that were in line with a scientific and inductive viewpoint to derive ideas and theory (Galliers 1991, Finch 1986). As Sarantakos (1993) and Easterby-Smith, Thorpe and Lowe (1991) point out, a qualitative focus for research work often lends itself to the use of mixed methods with small samples being investigated in depth over time. Thus a mixed methods approach (Creswell, 2008) was employed to enable the combination of different and complex sources of information and knowledge.

A method that applies to the inductive point of view is that of Grounded Theory (GT). This method allows for constant and iterative comparison of data and information to allow theories and ideas to be formed over a period of time when studying phenomena (Glaser and Strauss 1967, Turner 1981, Martin and Turner 1986, Strauss and Corbin 1990). The researcher worked within the context, as per Glaser's (1978) criteria for GT to obtain data and information, but also expertise with which to assess and evaluate it. GT influenced the way in which the research was produced and the formation of a methodological approach as illustrated in Figure 1. This shows the main activities that were employed to understand such a domain and how to interpret the information and knowledge that was generated, used, shared and re-used to manufacture a given product.

The method chosen to enable a structured approach to the elicitation and capture of data and information was that of a case study which is useful for research within a contextually rich environment. A single case study was designed in line with Yin's (2009) well accepted method together with Neal, Thapa and Boyce's (2006) guide for case study evaluation. The case study had a single unit of analysis and was holistic in approach. A specific instance of a highly advanced, complex turbine blade was chosen to concentrate upon along with a number of key stakeholders that could provide valuable knowledge and insight. As per Flyvbjerg's (2011) discourse upon case study methodology and application, a number of different sources of information and knowledge were used from within the sponsor company, so as to alleviate any problems with bias and construct validity; but also to provide data triangulation and enable the convergence of evidence (Yin, 2009). GT was applied to understand and refine the research approach during the assessment of research data.

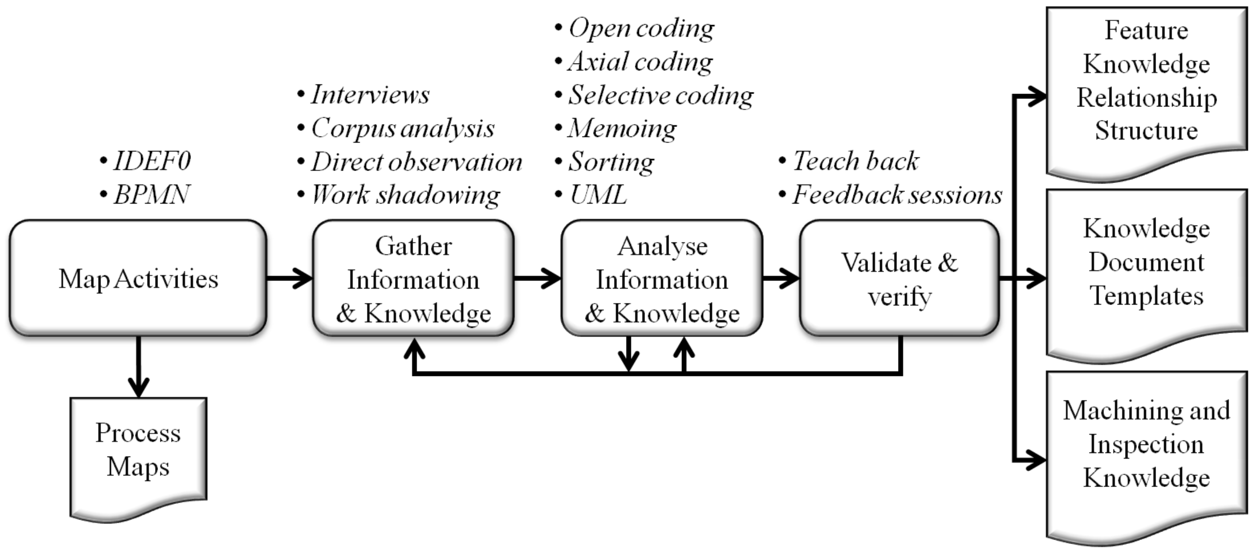

Figure 1. Methodological approach and applied methods

The primary steps to facilitate an answer to the question and to fully understand the context were to study the following items and aspects at the sponsor company. The Integration DEFinition 0 (IDEF0) and Business Process Mapping and Notation (BPMN) functional process mapping techniques were used for the context discovery. Both the design and manufacturing processes were studied to create maps of the functions, the information they used and where and when it flowed to and from. Once these maps had been created they were used to focus the research upon aspects requiring further study. These aspects were engineering drawings, plant and equipment, modus operandi and company culture. Additionally, time was spent interviewing, talking to and shadowing many engineers throughout the organisation. This was so as to understand the development processes and procedures used, what they actually did and how they recorded, stored and disseminated knowledge about design and manufacturing, both within their respective groups and between different groups and functions. The knowledge elicitation method of Cordingley (1989) and the Naturalistic Knowledge Engineer (NKE) method of Bell and Hardiman (1989) were applied during semi-structured interviews to aid the capture of information and knowledge. These in turn ameliorated the composition of the interview questions.

The multiple sources of information provided an excellent insight into the differences between the two communities, the type of the language they associated with and the words they ascribed to a particular turbine blade and feature set. Relationships between design and manufacturing information and knowledge were mapped out by applying the GT method. This consisted of open, axial and selective coding followed by memoing and sorting, as part of an inductive reasoning approach. There was a final process to verify what had been produced so that engineers (domain experts) from both design and manufacturing could agree and vouch for the completeness, consistency and accuracy of the relationship structure. This was achieved by using the teach back method (Cordingley 1989) on a one-to-one basis and formal feedback sessions with whole groups of design and manufacturing engineers, i.e. communities of interest.

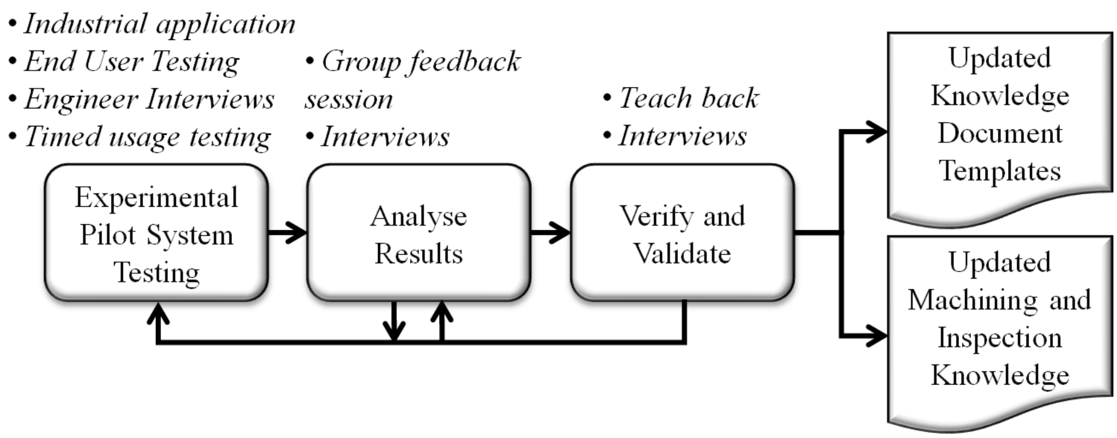

Figure 2. Application of the grounded theory approach to the experimental pilot system testing

In order to assess and test the developed experimental system, GT was again applied as seen in Figure 2. Two additional approaches were adopted, the first was that of a set of semi-structured interview questions aimed at eliciting and capturing qualitative feedback from a user group. This was done by way of a group feedback session from a number of design engineers at the sponsor company. The approaches of Stewart and Shamdasani (1990) and May (1991) were adapted for the purposes of the research and applied, those being (i) questions moved from the general to the specific and (ii) question order should be relative to importance of issues in the research. This allowed wide ranging and focused viewpoints and experiences to be captured. Secondly to capture quantitative feedback from engineers the Design of Experiments (DoE) methodology of Fischer (1926, 1947) was employed. Due to the nature of the sponsor company's business it was not possible to acquire independent measurements, hence a comparison approach was taken for the designed tests. This would establish baseline measurements to be derived from the first test to act as a control and then subsequent tests would be compared against that baseline.

3 Knowledge discovery

A key aspect of the research was to understand the different sources and uses of information and knowledge within the sponsor company. By employing the research methodology a wealth of different perspectives were mapped out from the design the manufacturing communities. Dependencies and time sensitivities were deduced utilising the mapping tools which allowed the different types of information and knowledge to be rated for importance and hence which aspects should be focused upon for the development of the research approach.

3.1 *Feature knowledge relationship structure*

From the information and knowledge mapping activities a Feature Knowledge Relationship Structure (FKRS) was developed. This model explicitly states the relationships between three different types of features that are used within the sponsor company.

'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 the three specific feature viewpoints of the chosen case study product together. For the purposes of this research the following are the definitions of a feature for each of the three viewpoints:

i. Design Feature: A design feature is a shape that performs a specific function.
ii. Machining Feature: A machining feature is a shape produced by a discreet machining operation.
iii. Inspection Feature: An inspection feature is a discreet measured point or dimension.

Machining features are created by utilising a defined machining process. This process consists of a sequence of manufacturing machines and machine tools, these are arranged into a specific order for each individual product dependent upon its size, shape and the individual features that have to be manufactured. Associated with this are the inspection features. Once a feature has been machined it is necessary to measure and inspect it so as to ascertain whether or not it was made correctly and to specification. Similarly an inspection feature has an inspection process which is a sequence of inspection machines and inspection tools again arranged specifically for individual products and features. The inspection process generates data from the individual feature measurements, this is used to form capability data which is used to assess product and process conformance against design intent and deduce how mature the machining process is.

Figure 3 illustrates the FKRS in Unified Modelling Language (UML) format to provide a lightweight formalised representation of the identified relationships, lightweight meaning in this instance a semi-formal logical representation of a theory using rules and constraints (Uschold and Gruninger 1996, 2004; Giunchiglia and Zaihrayeu 2007). The FKRS relates a design feature to a machining feature and an inspection feature, stating the cardinality of the relationships between the entities. The relationship between design and machining feature entities is many-to-many, between design and inspection entities it is a one-to-many and machining and inspection feature entities is also one-to-many. As the UML model in Figure 3 states, a machining feature has a machining process, which is utilised to produce a given feature, which, in turn, uses machining tooling, again the items used by the process to produce a feature. An inspection feature has an inspection process used to inspect a manufactured feature which uses inspection tooling to perform the procedure, this in turn produces capability data about the inspection feature being measured. Additionally an inspection feature has capability data, this has a one to one relationship, for each individual inspection feature there is a set of capability data associated with it.

The FKRS forms the basis for the sharing and interchange of information and knowledge between these different viewpoints and was therefore used to develop a method for capturing and representing machining knowledge. Whilst outside the scope of the research approach, other feature classes from different engineering activities could be considered when postulating upon a more holistic UML model that could represent through-life engineering viewpoints. Requirements engineering could be considered by linking requirement features to the FKRS design feature viewpoint. In additional later life cycle aspects such as assembly features, service or maintenance features and disposal features could be added to a through life model and linked to both the FKRS design and machining feature classes.

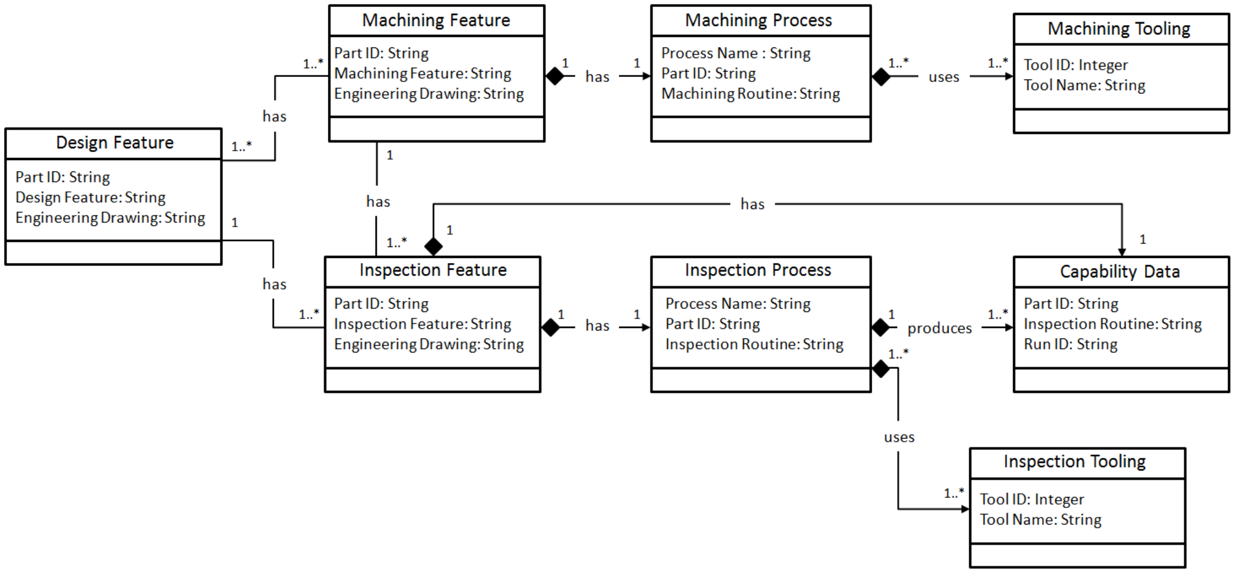

Figure 3. Feature Knowledge Relationship Structure

It is recognised that a great deal of research has been undertaken in the area of feature relationships and key feature attributes as seen from different viewpoints, e.g. design viewpoints and manufacturing viewpoints. Three good examples of this are Fenves *et al.* (2005), Gunendran and Young (2010) and Chungoora *et al.* (2013). Relationships between a design feature and a design function or design part family are explored by Chungoora *et al.* (2013). Within our industrial investigation the design engineers involved had a clear understanding of the functional relationships between the parts and the functional requirements of each part. Their need was to be provided with the manufacturing implications of the design decisions that they were making. Therefore the FKRS as defined in our work focused in detail on the manufacturing structure of the FKRS. As part of further research, it would be possible to extend and modify the FKRS relationships structures to include functional design aspects or in the case of assembly requirements to model the relationships between two or more parts.

3.2 *Knowledge document templates*

Three main routes for the development of the research project were considered and assessed as to which could provide a rapid development and deployment way in which to aid communication and the sharing of knowledge between manufacturing and design engineers. Formal knowledge based system and database approaches were thought to be too time consuming and could potentially be far beyond the reach of the timescales involved within the project. In the first instance a Microsoft FAST approach was pursued (Urwin *et al*. 2011), but after consultation with the sponsor company it was found that the sharing and reuse of information and knowledge within such an aerospace environment was considered to be a security risk. Aligned with this, version control of the documents with safety critical content could not be enforced, therefore the FAST approach was discontinued. As a consequence of these discounted approaches a different direction was deemed to be pertinent to the requirements of the project at hand. The approach taken was to develop a set of knowledge document templates utilising the FKRS UML structure. Whilst they were simple documents, they did in fact have the virtues of being developed using widely accepted, sound knowledge modelling techniques (IDEF, BPMN and UML). Moreover if needed they could be used to design databases utilising the represented UML structure. Additionally, the knowledge captured within them could be formalised to derive rule sets and hence form the basis of a knowledge based system.

The knowledge document templates were developed to allow the quick and simple capture and representation of machining and inspection knowledge. Figure 4 illustrates the first, that of a machining knowledge template. It had four main sections and was used to explicitly represent the following aspects:

i. Feature Description: aspects relating to a machining feature. Those being the part identification (ID), the feature name, its associated drawing number and any synonyms that were associated with a feature.
ii. Relationship Description: This stated the relationships that existed between a given machining feature, the associated design feature and inspection feature.
iii. Factory and Machine: Design engineers expressed the need for information about the factory that a specific machining feature was made in, the type of machine used, the tooling and fixtures used and the relevant inspection routine.
iv. Machining Knowledge: This section stated the machining knowledge about considerations that had to be taken into account when machining a specific feature. These could be a set of rules to adhere to, reasons why certain tolerances could or could not be met and other environmental or modus operandi aspects that might influence manufacturing engineers' routines.

The first two sections, those of Feature Description and Relationship Description represented the relationships between all of the viewpoints for which the document template utilised the constructs of the FKRS UML model. The third section, that of Factory and Machine was used to record extra information about the manufacturing aspects that were used to create a specific product. The fourth section within the template was used to represent knowledge captured from manufacturing engineers to impart to design engineers the constraints and difficulties they would have to address in order to achieve the manufacture of a specific feature for a given turbine blade.

Issue No.		Date:	

Feature Description:		
Part ID		
Machining Feature:		
Engineering Drawing Number:		
Machining Operation:		
Feature Shape:		
Synonyms:		

Relationship Description:	
Inspection Feature ID:	
Design Feature:	

Factory and Machine:	
Factory:	
Machine:	
Tooling:	
Fixture:	

Machining Knowledge:	
Tooling Rule 01:	
Machining Rule 01:	
Surface Finish:	

Figure 4. Machining knowledge template

The second knowledge document template concerned inspection knowledge and is presented in Figure 5. The first three sections of the template were changed due to the relationship perspective of the inspection document template and they explicitly state the inspection features. The fourth section was that of inspection tooling knowledge, this was used to capture manufacturing engineers' knowledge about what could and could not be achieved within a specific working environment and any rules that should be considered or adhered to. The fifth section illustrated represents capability knowledge. This captured the current machining capability that was achievable by a specific machining process within the sponsor company. Representing this allowed design engineers to instantly infer what could and could not be produced by the current method of manufacture for a given moment in time and thus, develop turbine blade features with the compliant tolerances.

Issue No.		**Date:**	

Feature Description:			
Part ID			
Inspection Feature:			
Feature Shape:			
Feature and Tool:			
Synonyms			

Relationship Description:		
Machining Feature:		
Design Feature:		
Engineering Drawing Number:		

Factory and Machine:	
Factory	
Machine	
Tooling	
Fixture	
Inspection Routine	

Inspection Tooling Knowledge:	
Inspection Access:	
Inspection Rule 01:	
Inspection Tooling:	

Capability Knowledge:			
Cp		Cpk	
Current Capability			

Figure 5. Inspection knowledge template

The purpose of the knowledge document templates was to capture and explicitly represent manufacturing engineers' knowledge about machining and inspection features in a structured manner. The aim was to share this valuable commodity at an earlier stage within the product development process to improve product performance and accelerate the design-make process by way of reducing time and effort needed to facilitate redesigns. As such the knowledge captured during semi-structured interviews as per the methodology set out in section 2, was unstructured free text. It did not have any syntactic or semantic formalisms applied to it. What had been captured was checked for consistency and correctness. The first stage for this process was to use the teach back method with individual manufacturing engineers to provide feedback upon the body knowledge. The second stage was to consult a group of design engineers and their domain viewpoints so as to translate the manufacturing engineering domain lexicon used to express the knowledge. This was a crucial stage, as much of the manufacturing engineering knowledge was focused upon their domain viewpoints. Design engineers wanted to know more about individual manufacturing and inspection processes to understand how the manufacturing environment could affect the design of a part and individual features. The third and final stage was to have the body of knowledge assessed and checked by a community of interest. This was comprised of experienced engineers from the design and manufacturing functions, their expertise was again crucial in the verification and validation of the knowledge that had been captured. In essence the populated knowledge documents templates were standard word documents that did not have any mark up language or other formalisms applied to them due to the constraints of the sponsor company.

4 Knowledge library configuration

The research at hand had been focusing on ways to facilitate the sharing of complex information and knowledge that could be rapidly developed and deployed. A decision was taken to concentrate upon a document template approach in part due to a need to apply the knowledge within the design process and enable a short implementation process. It was therefore necessary to develop an approach that would allow easy searching for, access to and retrieval of populated knowledge documents templates, without overly complex or lengthy development and implementation methods with which to facilitate those goals.

The knowledge library for the turbine blade that was studied was setup by applying the FKRS UML model to the captured explicit engineering knowledge, which is illustrated in Figure 6. This stipulates that specific knowledge documents will represent individual feature types for a given product.

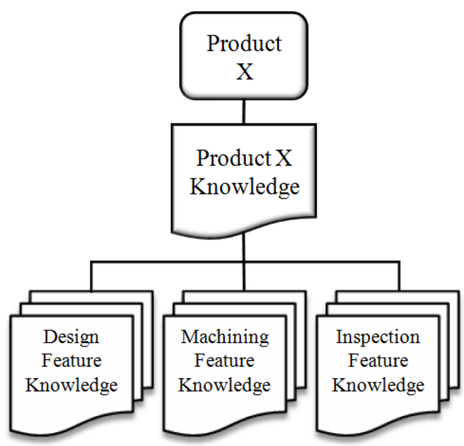

Figure 6. Product feature knowledge schema

4.1 *Product lifecycle management environment*

The sponsor company used an instantiation of a popular Product Lifecycle Management (PLM) software system. They are effective environments with which to organise, share and use information and knowledge whilst maintaining security and implementing version control.

The PLM environment held information for each of the individual products, but these were stored in a linear form and could be likened to silos of information. This prohibited the searching for and sharing of information between different products. For example to search for specific Product A information the search had to be undertaken within the Product A area of the PLM system, it was not possible to search for Product A information from within the Product B area, Figure 7 helps illustrate this.

To fit with the sponsor company’s modus operandi, a set of seventy two populated machining and inspection knowledge documents were uploaded onto the PLM server. It was agreed that these would form the knowledge base of an Experimental Pilot System (EPS), so that it could be tested and assessed.

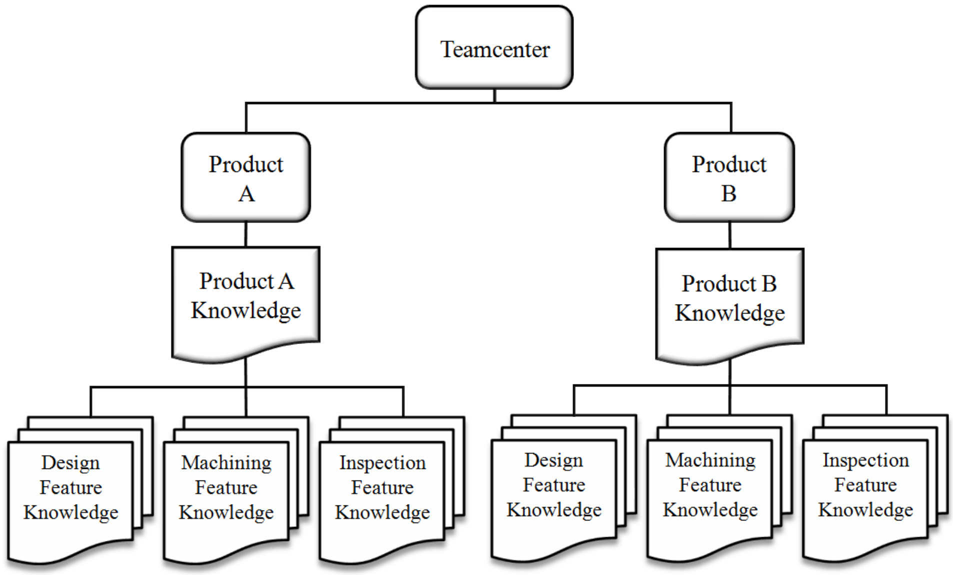

Figure 7. PLM knowledge storage schema

4.2 *Experimental pilot system*

One aspect of a PLM system is that it can be a somewhat time consuming task to search for information for large scale implementations. This can sometimes dissuade end-users from consulting the PLM system as the first port of call for product information and potentially using the system at all. Hence it was decided to develop an additional method to provide a quick, concise and user friendly interface to the documents stored within the PLM environment. This method would have to be compatible with and complimentary to the internal information technology systems at the sponsor company.

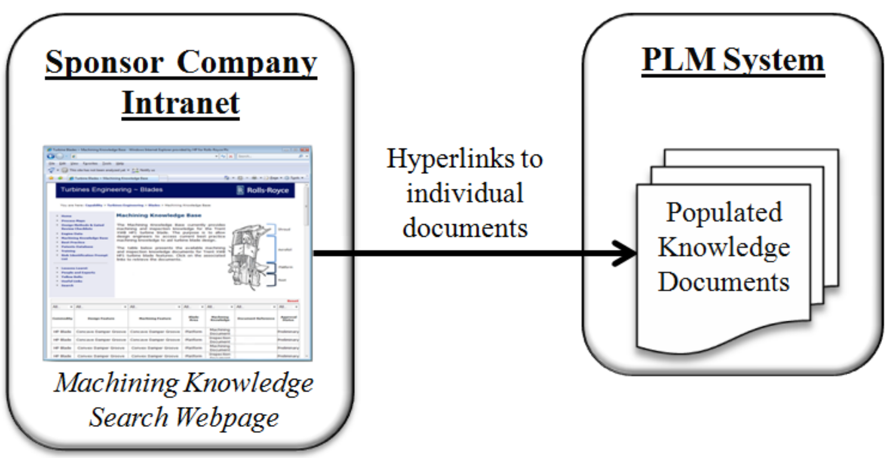

Figure 8. Experimental pilot system

The chosen method was that of a webpage to display the available machining knowledge and provide hyperlinks to the knowledge documents templates within the PLM system as shown in

Figure 8. The webpage was developed by interviewing design engineers (the intended end users) and manufacturing engineers, who would be responsible for providing and maintaining the knowledge within the documents. Additionally a mapping process was undertaken to map design feature names against machining feature names, as a host of different names were used to describe product features in the different engineering communities. Web editing software was then used to create the page, a table was inserted into the page to represent each of the different populated knowledge documents, accordingly each entry in the table was hyperlinked to the relevant document residing in the PLM system.

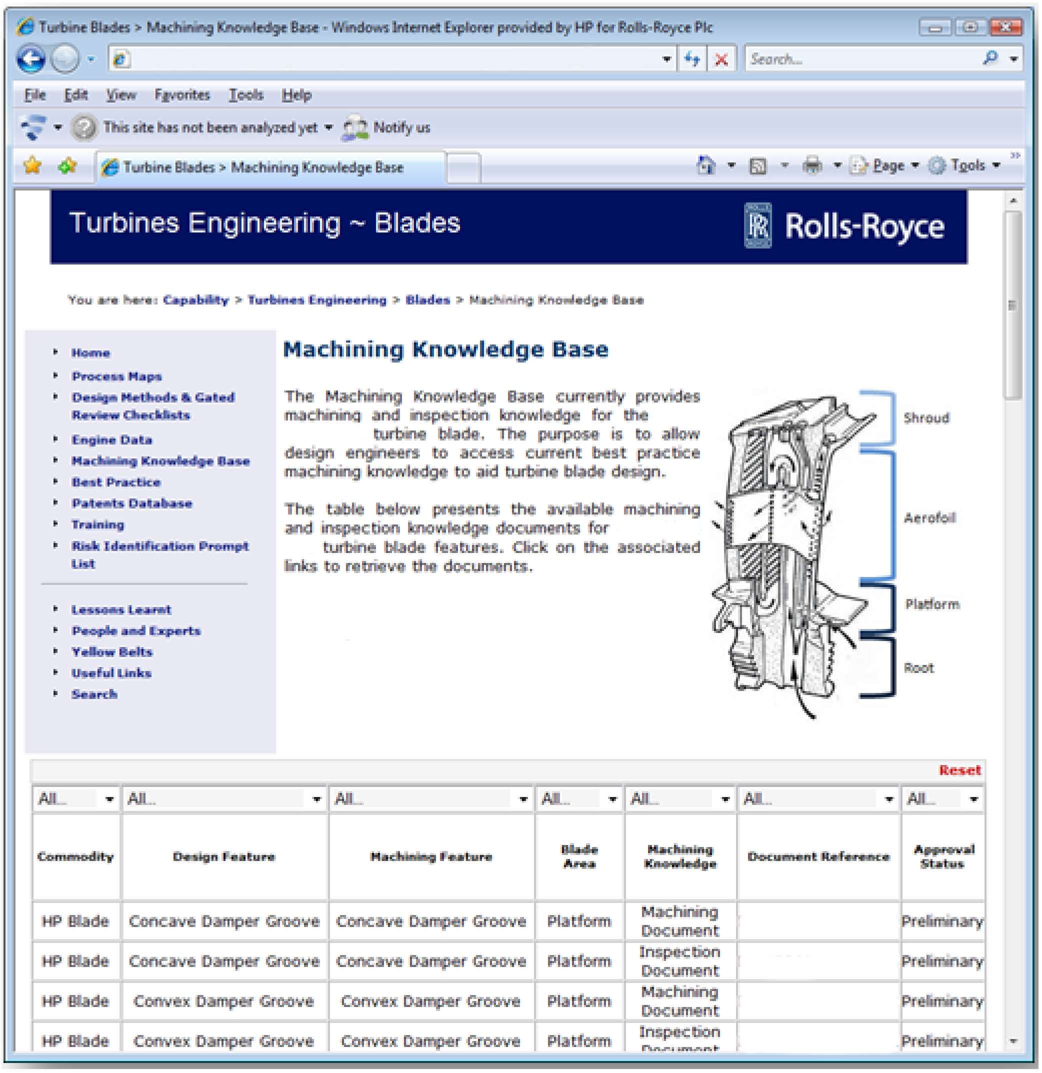

Figure 9. Machining knowledge base search webpage

Figure 9 depicts the developed webpage that presents a portal for access to populated knowledge documents within the PLM system. An illustration of a turbine blade was included to aid end users in determining the specific areas of a blade and to where product features have been assigned. The main part of the webpage is a table containing programmed hyperlinks to the populated knowledge documents, it has a number of columns to segregate the information. The first is that of commodity, this is to determine the type of commodity, in this instance as per Figure 9 it is a High Pressure (HP) turbine blade. The second and third columns relate to the features of the particular HP turbine blade. The second column is for design features and uses the design community naming convention for blade features, whereas the third column is for machining features, which uses the manufacturing community naming convention for blade features. It must be stated that as per the FKRS UML model in Figure 3, that there is not always a one to one relationship between design features and machining features. There are instances where a single design feature can encompass two or more machining features. Alternately a single machining feature can sometimes include two or more design features. Column four states the blade area that a specific feature relates to. Column five is for the type of knowledge documents, i.e. a machining knowledge document or an inspection knowledge document, as there will be one of each of these for each individual product feature. The sixth column is for the document reference hyperlinks, this contains directly programmed hyperlinks to the specific knowledge document templates within the PLM system. The seventh and final column is for the approval status of each of the knowledge document templates, stating whether they are preliminary and not officially signed off or they are approved and have been signed off for general use. The table within the webpage has a filter applied to each of the individual columns, for example end users can select an occurrence of a design feature to filter the table by. This enables a quick and easy search aspect to the webpage and a useful way in which to access the knowledge document templates within the PLM system. This combination of the webpage and PLM system formed the Experimental Pilot System (EPS).

5 End user trials

Designing, constructing and implementing an approach for the facilitation of knowledge sharing is all very well, but how good is such an approach? Feedback is important to ascertain the benefits of such a system, how useful it is and what improvements could be made. To this end a set of user trials were devised to elicit and garner feedback about the Experimental Pilot System. The deployment, use and assessment of the EPS within an industrial context was aided by application of the grounded theory methodological approach (see Figure 2). Feedback from industrial end users was utilised to initiate a number of iterations that enabled improvements to be made to the overall research output. The end user trials ran for a period of six weeks, whereby a group of design engineers were able to use the EPS within a live environment and apply it within their day-to-day industrial engineering tasks. The group consisted of eight experienced design engineers who were all domain experts, one of which was the team leader responsible for leading their work. The choice of group was made due to the fact that they were working on the turbine blade that was being studied by the authors. At the end of this assessment period a group feedback session was held where five main questions were asked to assess and evaluate the experimental system:

- (i) Ease of searching for the documents
- (ii) Ease of access to the documents
- (iii) Structure and layout of the knowledge document templates
- (iv) Usefulness of the knowledge
- (v) What could be improved

Data was gathered from the feedback session by way of note taking, with two researchers taking those notes. It followed a semi-structured approach so as to assess the five main questions but also to allow for freedom of expression by the design engineers. The answers were then collated and compared after the session and then presented back to the design engineers for them to validate the recorded responses.

5.1 *Ease of searching for the documents*

The design engineers were asked about the *'ease of searching for the documents'*. The answers to this question are split into two segments, the following answers were obtained:

- The EPS helped engineers quickly locate and find the document that they were looking for.
- The EPS filtering ability helped design engineers to focus upon the item they were searching for.
- The table within the webpage was well laid out and allowed engineers to see what documents were available for turbine blade machining knowledge.

A number of conclusions were reached:

(i) Using the EPS helped speed up the search for documents.
(ii) The filtering tool allowed engineers to quickly focus upon the document or feature they were interested in.
(iii) The EPS combined the additional security and version control aspects of the PLM system.

5.2 *Ease of access to the documents*

The design engineers were asked about the '*ease of access to the documents*', the following answers were obtained:

- The webpage interface was logically designed, simple and straightforward to use.
- Access to the documents was improved as the links were directly to the required document within the PLM system. The only problem with access was the time needed to log into the PLM system.

5.3 *Structure and layout of the knowledge documents templates*

Feedback from the design engineers about the '*structure and layout of the knowledge document templates*' pointed out a number of items:

- The structure of the documents was useful and logical. The inclusion of factory and machine information could help designers understand where a part was being made and what was being used to manufacture the part.
- The mapping of the design feature name to the machining feature name was not explicit enough as some engineers missed this during the use of the documents.

A conclusion was reached:

(i) Due to the fact the knowledge was feature based this meant that part knowledge was repeated for each feature. While no change to the structure of the documents was necessary there was a need to reorganise the assignment of where knowledge was stored. It was proposed to create a part level knowledge document to alleviate this issue.

5.4 *Usefulness of the knowledge*

A question about the '*usefulness of the knowledge*' within the knowledge document templates was asked. This was aimed at understanding how useful and applicable the knowledge was that had been elicited from manufacturing engineers and made explicit within the documents. The response was thus:

- The design engineers thought that what was contained within the documents was very useful. The information and knowledge covered the basic aspects of what should be considered when designing turbine blade features. The documents would be useful for novice designers to help understand basic machining aspects and constraints, likewise as a refresher for expert designers.

5.5 *Potential improvements*

A number of improvements and additions were suggested by the design engineers from the feedback session. These are listed against two of the questions used for the assessment. They are as follows:

5.5.1 *Ease of searching*

- The design engineers wanted to add a column in the webpage to indicate which machining process was used to create which feature.
- A map for feature names could be very useful, i.e. a taxonomy of words to relate naming conventions between the terms used to describe turbine blade features between the perspectives of design engineers and manufacturing engineers. This could be put into the part level documentation.

5.5.2 *Structure and layout of the knowledge document templates*

- The aspect of knowledge maintenance was of the utmost importance. It was imperative to set out an explicit and mandated knowledge maintenance process to keep the knowledge documents up-to-date and relevant. Roles and responsibilities had to be assigned within the design and manufacturing functions to fulfil this. Additionally when the documents are to be updated that they are not overfilled with excessive amounts of information. The updates must be concise and meaningful to all parties involved.
- The structure and setup of the PLM system was not optimised for the sharing of part family knowledge. Documents are stored relative to each individual project. The 'Product A' turbine knowledge document templates were stored within the 'Product A' project within the PLM system. It was therefore difficult to search between different products and commodities. In an ideal world an advanced search engine would be employed to search for the knowledge documents to get over these limitations.

5.6 *Timed testing results*

A number of tests were setup to assess and gauge the speed of the EPS and how it could influence the sharing of information and knowledge. As per the methodological approach in section two, a comparative Design of Experiments (DoE) approach was applied to the test question:

'*When searching for and accessing knowledge documents, what is the difference in speed between the established PLM system and that of the EPS'*, hence the following tests were devised:

- Test 1: Test searching and access of the knowledge document templates within the PLM environment only.
- Test 2: Test searching and access of the knowledge document templates using the developed Experimental Pilot System .

The DoE methodological approach used for the timed testing of the EPS is illustrated in Figure 10. The purpose of test one was to establish a baseline for further testing to be judged against. This would derive the times of the testing activities within a PLM environment only. Test two would then utilise the industrial EPS, that of the intranet webpage with direct access to documents within the PLM system. This would then ascertain the times of the different elements of the EPS. The results of test two could then be compared against the baseline created by test one to draw results accordingly.

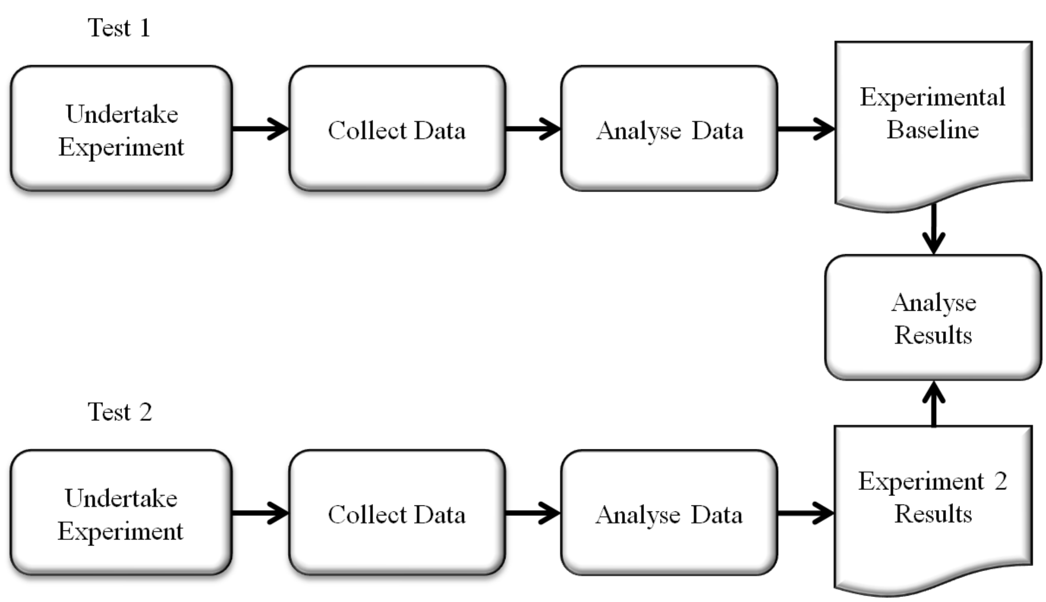

Figure 10. Experimental pilot system timed testing methodology

For each of the two tests, two activities were designed to be used to evaluate the speed of searching for and accessing the knowledge document templates.

- Activity A: Time to search for and locate turbine blade knowledge document templates. This would be measured in seconds to complete the activity and therefore would be a quantitative measurement.
- Activity B:Time to access & retrieve turbine blade knowledge document templates. This would be measured in seconds to complete the activity, again it would be a quantitative measurement.

Four end users were chosen to undertake the two designed tests, whilst a fifth end user was unavailable for the initial baseline testing, but available for the subsequent experiment two testing. All five end users were experienced engineers.

5.6.1 *Test 1: PLM system assessment*

The aim for the first test was to establish a baseline and act as a control for further testing. Activity A and B would assess the time taken to search for, locate and retrieve knowledge document templates within the PLM system. Times were recorded once the users were asked to begin Activity A and B.

The results that were recorded and obtained from test one are put forward in Table 1. These were used to form a baseline so that comparative assessment could be undertaken against test two. It was interesting to note that Activity A incorporated the PLM system login process. Although this login would take quite a bit of time the actual searching process would always generate a number of alternatives that had to be sifted through by the end user.

Table 1: Test 1 results

Engineer / **Activity**	**1**	**2**	**3**	**4**
A	351 seconds	407 seconds	289 seconds	507 seconds
B	32 seconds	57 seconds	112 seconds	65 seconds

5.6.2 *Test 2: Experimental pilot system assessment*

The aim for the second test was to assess how a different system setup, that of the experimental pilot system would compare against the baseline set in test one. As per the first test Activity A assessed the time taken to search for and locate the knowledge document templates but within the developed intranet webpage and not the PLM system. Activity B would then assess the accessing and retrieval of the knowledge document templates from within the PLM system, by way of clicking an EPS webpage hyperlink to gain direct access to the specific document needed. Times were recorded once the users were asked to begin Activity A and B.

The results that were recorded and obtained from test two are put forward in Table 2. It was noted during the testing that a large proportion of the time in Activity B within test two was taken up by the PLM system login process. Sponsor company network and server conditions could have affected these times, but this is a variable within the testing that is hard to deduce and measure.

Table 2: Test 2 results

Engineer / **Activity**	**1**	**2**	**3**	**4**	**5**
A	15 seconds	26 seconds	35 seconds	22 seconds	37 seconds
B	78 seconds	86 seconds	102 seconds	157 seconds	92 seconds

5.6.3 *Assessment of test results*

There is a marked difference between the data for Activity A between test one and test two. It can be clearly seen from Table 1 and Table 2 that time to search for and locate a knowledge document is greatly skewed in favour of the EPS and not the PLM system. This shows that the EPS improves the speed at which end users can locate knowledge documents.

The assessment of the data for Activity B between test one and test two seems to show some slight disparity between the two systems as depicted in Table 1 and Table 2. But it must be understood that accessing a document via an EPS webpage hyperlink in the webpage incurs the end user to login into the PLM system to allow access to the chosen knowledge document. This accounts for the majority of the time recorded for Activity B in test two.

If the average times of each of the Activities (A and B) assessed for the two tests are calculated, the following results are obtained:

- Test 1, Activity A mean time: 351 + 407+ 289 + 507 / 4 = 388.5 seconds
- Test 1, Activity B mean time: 32 + 57 + 112 + 65 / 4 = 66.5 seconds

Test 1 total average time = 455 seconds to locate and access a knowledge document within the PLM system.

- Test 2, Activity A mean time: 15 + 26 + 35 + 22 + 37 / 5 = 27 seconds
- Test 2, Activity B mean time: 78 + 86 + 102 + 157 + 92 / 5 = 103 seconds

Test 2 total mean time = 130 seconds to locate and access a knowledge document using the EPS.

These test results show that the experimental pilot system can speed up the process of location and access to knowledge documents. We recognise that network conditions outside our control could have influenced these results. However, the tests were conducted a further two times with similar results. We were not privy to the network organisation of the sponsor company and so cannot provide any further view on the overall accuracy of these time based results.

6 Discussion

The research presented herein has been concerned with a rapid development and deployment approach to the sharing and reuse of machining knowledge. This has involved knowledge elicitation, capture and structuring methods for knowledge reuse. The elicitation and capture of knowledge is a very time consuming activity and one that demands expertise and diligence. This is true regardless of the knowledge management approach taken, be it document based, ontological or a complex knowledge base. It is important therefore that if this effort is to be undertaken that the results of the effort is fully utilised. The approach presented in this paper is in the process of being developed for full scale use within the sponsor company.

A document based approach has the advantage that the design and population of templates can be relatively easy to do, additionally it can be quite simple to implement. Rather than a question of years, a document based approach can be deployed in a matter of months. One of the drawbacks of this approach is that the method of representing machining knowledge is less rigorous, design engineers are therefore required to have some understanding of manufacturing processes and knowledge. This is necessary so that inferences can made by applying machining knowledge for a given machining feature to a design feature and how this impacts upon intended parameters. The reason that the authors pursued a document based approach was primarily to fit within a document based PLM environment that was familiar to the design engineers and provided the information and knowledge security required by the sponsor company.

It has been recognised that the ability to tag sections of text within a document using XML based formalisms can be beneficial and provide a more modular breakdown of manufacturing knowledge. Microsoft FAST search had been used in conjunction with the research at the start of the project (Urwin *et al*. 2011), but due to the industrial constraints the research approach was modified.

For machining knowledge to be useful the relationships between the design, machining and inspection features had to be clear, concise and explicit. The Feature Knowledge Relationship Structure provided this, it represents a set of relationships between different product feature viewpoints. As such it provides a legitimate basis for the development of the knowledge document templates and applied sound knowledge modelling techniques (IDEF, BPMN and UML) to those documents. This brings flexibility to the approach by enabling a database or knowledge base to be derived from a set of fully populated knowledge documents at a later date.

The combination of the PLM system and the developed machining knowledge webpage into the Experimental Pilot System has been shown to provide useful benefit. It can simplify and quicken the location of and access to knowledge documents. Design engineers have provided valuable positive feedback that such a system does provide benefit in their day-to-day activities when manufacturing knowledge is needed for design tasks.

There are however the ever burgeoning problems of maintenance of the knowledge and the proliferation of document numbers over a period of time which can potentially obscure the simplicity of the current EPS system, its speed, accuracy and capability. The authors are aware of this and recognise the need for an effective maintenance capability. A paper describing a methodology to provide such a capability is currently under review.

7 Conclusions

The research presented within the paper has, in a preliminary form, answered the stipulated research question underpinned by a sound methodological research approach. Three constituent items have been developed to enable a rapid development and deployment approach to the sharing and reuse of machining knowledge within a commercial PLM environment. The FKRS UML model provides a lightweight ontological basis for the understanding and representation of the differing viewpoints of design, machining and inspection features. This is a necessary item if knowledge is to be understood and become meaningful between experts across different domains. Accompanying this, knowledge document templates have been created using the FKRS to fully represent the relationships between the viewpoints. These provide a universal format that is easily populated for design engineers to obtain machining and inspection knowledge for reuse within the design process. The third and final aspect is that of the developed experimental pilot system. It is essential that such knowledge can firstly be found and then accessed quickly and effectively. The results of the tests and feedback collected from design engineers have shown that utilising the experimental pilot system can provide quick and succinct access to these documents, whilst maintaining security and version control. The results have been very encouraging and our industrial partners are now in the process of implementing a full scale pilot study. Further work needs to be carried out to refine the approach for other types of commoditised parts.

The scope for possible further work is in the following directions:

(i) Devise a multiple case study approach to look at how different turbine blade types impact upon the FKRS. This can relate to machining part families and assess how the differences affect the knowledge applied and whether the FKRS can represent these.
(ii) Study different product types to ascertain how different relationships and levels of complexity impact upon the FKRS and how a document based approach can accommodate these.
(iii) Study different engineering domains, for example repair or assembly, to understand how they relate to products and what changes would be needed to represent these for both the FKRS and knowledge document templates. There would be potential to start working towards a through-life knowledge management viewpoint.

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Appendix

Notation

BEP – Best Entry Points
BPMN - Business Process Mapping and Notation
CAD – Computer Aided Design
DITA - Darwin Information Typing Architecture
DoE – Design of Experiments
EPS – Experimental Pilot System
FKRS – Feature Knowledge Relationship Structure
GT – Grounded Theory
HP – High Pressure
ID – Identification
IDEF - Integration DEFinition
IR - Information Retrieval
MSDM - Multi-Structured Document Model
NKE – Naturalistic Knowledge Engineer
PLM – Product Lifecycle Management
SAMULET - Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies
SD – Structured Documents
SDR – Structured Document Retrieval
SGML - Standard Generalized Markup Language

UML – Unified Modeling Language
XML - eXtensible Markup Language