UNIVERSITY OF SOUTHAMPTON
FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
School of Engineering Sciences

# Development and Evaluation of a Design Support System

by

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ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
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# DEVELOPMENT AND EVALUATION OF A DESIGN SUPPORT SYSTEM

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This thesis presents the development and evaluation of a knowledge-based Design System.

Despite the rise in Knowledge Management research and theories, there is insufficient evidence to conclude if Knowledge Management activities can increase business value. Furthermore, existing knowledge related research was found to insufficiently address the needs of Small to Medium Enterprises (SME).

The research develops and demonstrates a suitable knowledge strategy for a design and manufacturing SME faced with a potentially critical knowledge loss from a retiring expert and constrained business growth. The pivotal component of the strategy was the establishment of a codified knowledge base or 'Design System', containing product knowledge, best practice guidelines and bespoke design tools to support design knowledge reuse.

The system was successfully integrated into the business and a multi-faceted evaluative approach applied in a longitudinal study. The evaluation analysed a series of facets including, user behaviour, case studies and financial data. The study found that the Design System led to an increase in business value and successfully protected against knowledge loss.

The research therefore demonstrates a successful knowledge strategy that could be adopted by other SMEs and provides evidence of the benefit of knowledge-based systems in design and manufacturing.

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*Designer C*

**Rolls-Royce** Pro-Laser Technology

***Design System Phase One Testing – Feedback form***
*13th June 2007*

Name: *Designer C*

***The Design System***

*Please rate the design system in terms of :*
(Out of 5 whereby 1 would signify very little support and 5 a significant resource)

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| *Support provided by design system:* | ☐ | ✓ | ☐ | ☐ | ☐ |
| *Ease of use* | ☐ | ✓ | ☐ | ☐ | ☐ |
| *Content offered by design system* | ☐ | ☐ | ✓ | ☐ | ☐ |

Please detail the features most appreciated:

*Pictures of previous designs are very useful.*

Please detail features you feel you required:

*Drawings of features and mechanisms.*

Please detail the information or content you used the most:

*Pictures*

Please detail the information or content you required, but were not available:

Document Title: Design System Testing – Phase One: Feedback Form Date: 15/04/2010
Version: 2.0 Page .2

**Rolls-Royce** Pro-Laser Technology

***Case studies supplied***

| *Please rate the case studies in terms of :* | *1* | *2* | *3* | *4* | *5* |
|---|---|---|---|---|---|
| *The value of content supplied:* | ☐ | ☐ | ☐ | ✓ | ☐ |
| *The support provided w.r.t to the design task:* | ☐ | ☐ | ☐ | ✓ | ☐ |

Please detail the most valuable aspect of the case studies:

*Good simple part with enough variety to give multiple solutions.*

Please detail how you would improve the case studies:

*Find out what the welding requirements are (Two hemispheres).*
*Provide load data on the laser head (Gas loads).*

***Additional resources***

Please detail the most valuable resource provided:

*Jeff Bishop*

Please detail the resource most required:

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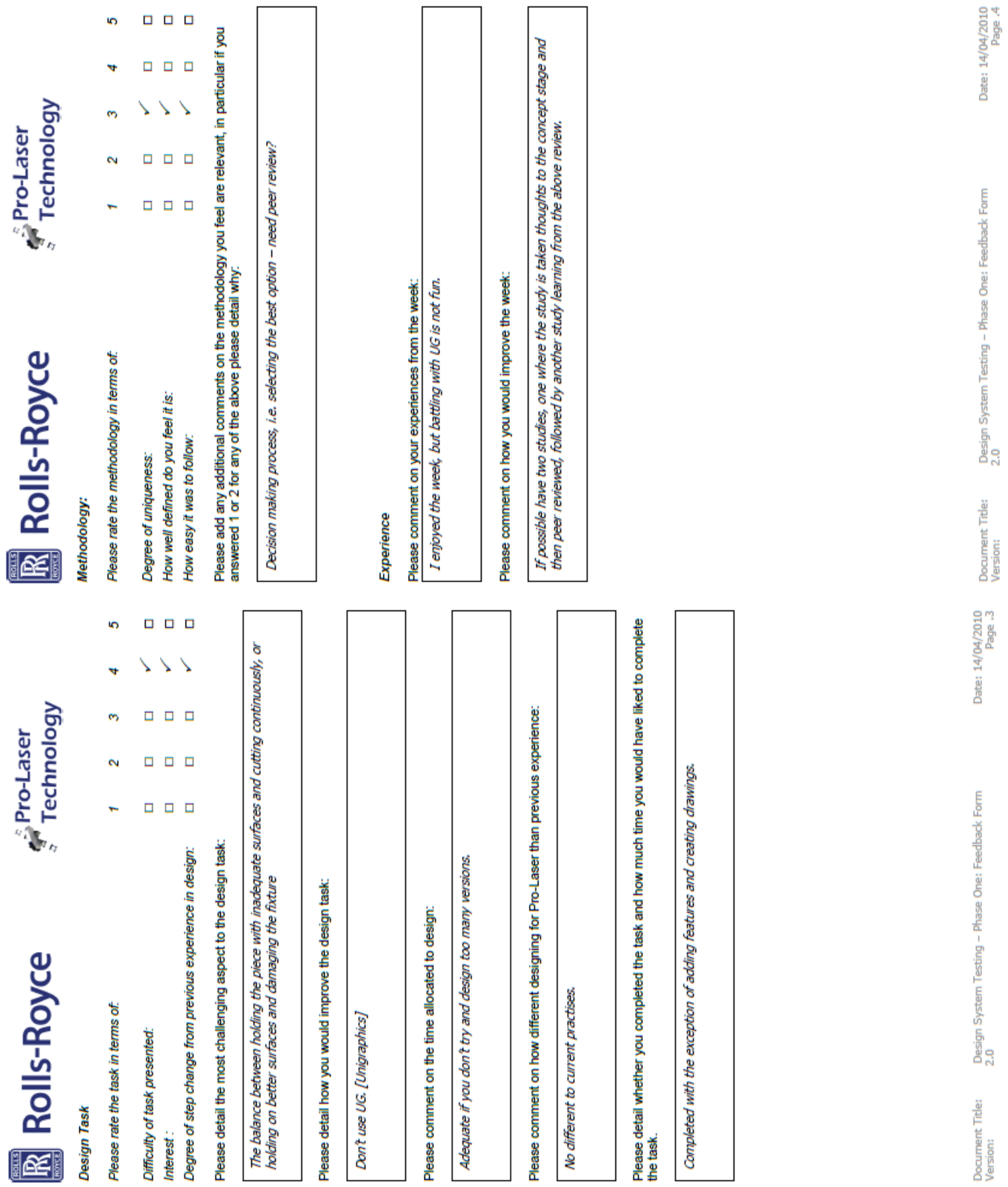

Rolls-Royce
Pro-Laser Technology

*Design Task*

| *Please rate the task in terms of:* | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| *Difficulty of task presented:* | ☐ | ☐ | ☐ | ✓ | ☐ |
| *Interest :* | ☐ | ☐ | ☐ | ✓ | ☐ |
| *Degree of step change from previous experience in design:* | ☐ | ☐ | ☐ | ✓ | ☐ |

Please detail the most challenging aspect to the design task:

*The balance between holding the piece with inadequate surfaces and cutting continuously, or holding on better surfaces and damaging the fixture*

Please detail how you would improve the design task:

*Don't use UG. [Unigraphics]*

Please comment on the time allocated to design:

*Adequate if you don't try and design too many versions.*

Please comment on how different designing for Pro-Laser than previous experience:

*No different to current practises.*

Please detail whether you completed the task and how much time you would have liked to complete the task.

*Completed with the exception of adding features and creating drawings.*

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Rolls-Royce
Pro-Laser Technology

*Methodology:*

| *Please rate the methodology in terms of:* | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| *Degree of uniqueness:* | ☐ | ☐ | ✓ | ☐ | ☐ |
| *How well defined do you feel it is:* | ☐ | ☐ | ✓ | ☐ | ☐ |
| *How easy it was to follow:* | ☐ | ☐ | ✓ | ☐ | ☐ |

Please add any additional comments on the methodology you feel are relevant, in particular if you answered 1 or 2 for any of the above please detail why:

*Decision making process, i.e. selecting the best option – need peer review?*

*Experience*

Please comment on your experiences from the week:

*I enjoyed the week, but battling with UG is not fun.*

Please comment on how you would improve the week:

*If possible have two studies, one where the study is taken thoughts to the concept stage and then peer reviewed, followed by another study learning from the above review.*

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# DECLARATION OF AUTHORSHIP

I, ***Nicholas Reed***, declare that the thesis entitled *"**Development and Evaluation of a Design Support System**"* and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as:

**Conference Papers:**

- REED, N., SCANLAN, J. & HALLIDAY, S. (2008) *Development of a Lightweight Knowledge Based Design System as a Business Asset to Support Advanced Fixture and Tooling Design*. Collaborative Product and Service Life Cycle Management for a Sustainable World.
- REED, N., SCANLAN, J., WILLS, G. & HALLIDAY, S. (2009) Providing value to a business using a lightweight design system to support knowledge reuse by designers. *International Conference on Engineering Design – ICED 09.* Stanford, USA.

**Signed:** ……………………………………………………………………..

**Date:**……………………………………………………………………………

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With the oversight of my main supervisor, editorial advice has been sought. No changes of intellectual content were made as a result of this advice. I am indebted to Gareth Hoskins, Jon Dewsbury and Alexandra Pope for their advice.

# GLOSSARY

## ABBREVIATIONS:

| | | |
|---|---|---|
| *BSC* | - | *Balanced Scorecard* |
| *CAD* | - | *Computer Aided Design* |
| *CAM* | - | *Computer Aided Manufacture* |
| *CBR* | - | *Case Based Reasoning* |
| *CNC* | - | *Computer Numerically Controlled* |
| *COP* | - | *Community of Practice* |
| *ESO* | - | *Evolutionary Structural Optimisation* |
| *FEA* | - | *Finite Element Analysis* |
| *IC* | - | *Intellectual Capital* |
| *KAMP* | - | *Knowledge Acquisition and Modelling Process* |
| *KBS* | - | *Knowledge Based System* |
| *KBV* | - | *Knowledge Based View of the Firm* |
| *KM* | - | *Knowledge Management* |
| *KPI* | - | *Key Performance Indicator* |
| *ME* | - | *Manufacturing Engineer* |
| *OS* | - | *Operating System* |
| *PDM* | - | *Product Data Management* |
| *PLM* | - | *Product Lifecycle Management* |
| *PM* | - | *Performance Management* |
| *QFD* | - | *Quality Functional Deployment* |
| *RBV* | - | *Resource Based View of the Firm* |
| *ROI* | - | *Return on Investment* |
| *SCM* | - | *Success Case Method* |
| *SME* | - | *Small to Medium Enterprise* |
| *SN* | - | *Skandia Navigator* |
| *SQL* | - | *Structured Query Language* |
| *TRIZ* | - | *Theory of Inventive Problem Solving* |
| *TS* | - | *Technical Specialist* |

## Definition of Terms:

### *Balanced Scorecard*

A strategic performance measurement system developed by Kaplan and Norton (1992) to complement traditional financial performance measures of firms (Kim, 2006).

### *Epistemology*

Of Greek origin, describing the theory or study of knowledge (Oxford English Dictionary, 2001)

### *Intellectual Capital*

"The sum of what everybody knows within a company and which gives it a competitive advantage" (Stewart, 1997).

### *Metrics*

Quantitative indices assigned to project attributes, such as complexity (Bashir and Thomson, 1999b)

### *Post-industrial*

"Occurring after or following on from the decline of the importance of manufacturing industry in the economy and society" (Oxford English Dictionary, 2001)

# Chapter 1

## Introduction

William Blake (1788) once wrote:

*"The true method of knowledge is in experiment"*

A relevant quote for the field of Knowledge Management [KM], in which field much is attributed but there remains little empirical evidence (Zack et al., 2009). The study presented here addresses the lack of experimentation in KM through the study of a software based Design Support System developed and trialled within a small design and manufacturing business.

This introductory chapter is intended to outline the key points of the research. The background and rationale behind the study is presented, together with the research aims and the statement of research. An overview is given of the approach taken and finally the chapter concludes with an illustration of the thesis structure.

### 1.1 Background and Motivation

It is broadly acknowledged that the post-industrial[1] economy is rapidly becoming the knowledge driven economy predicted by Bell (1974). Due to increased emphasis on innovation to provide a business's competitive edge (Swan et al., 1999, Levy et al., 2003, Milton et al., 1999), knowledge has now become the key asset in many companies relative to the diminishing primacy of capital and labour (Brint, 2001). Companies are becoming more aware of the role of knowledge in the market place and are looking for means to safeguard and maximise their intellectual property. The field of Knowledge Management is a relatively recent discipline that developed in the late 1980s in response to this need (Wiig, 1997b).

[1] Post-industrial: occurring after or following on from the decline of the importance of manufacturing industry in the economy and society (Oxford English Dictionary, 2001).

In recent years numerous studies have been completed, presenting theories and best practice approaches to Knowledge Management (Hahn and Subramani, 2000, Gruber and Russell, 1991, Hicks et al., 2002). Yet as highlighted by Lloria (2008), most of these studies are theoretical in nature and a review of the literature returns few conclusive studies that evaluate the effects of Knowledge Management in a company . In particular most studies are aimed at large multinational corporations (Davenport et al., 1997). There has been little study in support for Small to Medium Enterprises [SMEs] which, arguably, require as much or more support to manage their knowledge than larger companies, but have limited resources to invest (Pillania, 2008). Uhlaner at al. (2007) stated "Small firms often lack the financial investment capacity to make full use of new methods and innovations". There is a need, therefore, for a study to clearly identify and evaluate the effects of Knowledge Management on an SME and to conclude if indeed Knowledge Management represents a worthwhile investment by such companies.

Rolls-Royce plc understands the need for Knowledge Management and maintains its own Knowledge Management team (Cadas, 2001). Having launched a spin-off enterprise to further develop a non-core technology, the company initiated a research project to manage the knowledge activities of the enterprise and support its growth in the market place.

This provided an ideal case study to evaluate the impact of Knowledge Management activities on a business. The study benefits from a well-defined knowledge domain, a clear problem statement and strong company integration, with research beginning just four months into the company's life.

## 1.2 Research Aim

Research has been conducted to evaluate if a software-based design system was capable of providing value added support to novice designers by efficiently capturing and managing prior and existing design knowledge. The study has focused exclusively on knowledge activities supported by information technology in order to understand the most appropriate strategic use of information technology in business and engineering.

The study aims were to:

- Manage knowledge from the initial inception of the company but not necessarily the origins of technology.
- Develop a software-based design system to store and organise captured knowledge.
- Evaluate the impact and effect of the software-based design system on designers and the wider business.

These aims were met in part by the development of a software system to support design activities through the provision and capture of knowledge. Throughout the document this will be referred to as the 'Design System', the use of capitals distinguishing it from more generic systems.

## 1.3 Statement of Research

The statement of hypothesis was:

*"A Design System can provide value to a business by supporting knowledge re-use by designers"*

## 1.4 Research Approach

This study represents the conclusion of a four-year study, working with Rolls-Royce. The research can be separated into four distinct stages:

- Developing a thorough understanding of the design process and technology, trialling different approaches to knowledge capture and developing a rudimentary Design System.
- Investment in capturing and embedding knowledge into the Design System from the technical specialist.
- Development of the system, its role in knowledge re-use and its uptake in the business.
- Evaluation, in order to test for or against the hypothesis above.

## 1.5 Research Contributions

In completing the above aims and objectives, the research provides the following contributions to the field of Knowledge Management in Design:

1. A knowledge strategy was demonstrated suitable for an SME, highlighting the need for proactive management, a codified knowledge base and upfront knowledge capture using 'expert' interviews, discussed in Chapter 4.
2. The effect of individual 'inertia' against knowledge sharing was shown to be process driven and was reduced by aligning knowledge capture with existing design processes, discussed in section 5.3.
3. Design knowledge re-use was not found to reduce design and manufacturing time in a like-for-like study, but it was successful in reducing and avoiding errors, demonstrated in section 5.6.3.
4. The knowledge strategy was found to have supported an increase in business value (the gross margin and turnover both increasing). The results suggest this cannot be entirely a result of knowledge re-use, but rather better working practices. A Design System can therefore provide both process and product support.

In addition to this thesis, the research presented here has been published and presented in other forums, listed here:

**Publications**

- REED, N., SCANLAN, J. & HALLIDAY, S. (2008) *Development of a Lightweight Knowledge Based Design System as a Business Asset to Support Advanced Fixture and Tooling Design*. Collaborative Product and Service Life Cycle Management for a Sustainable World.
- REED, N., SCANLAN, J., WILLS, G. & HALLIDAY, S. (2009) Providing value to a business using a lightweight design system to support knowledge reuse by designers. *International Conference on Engineering Design – ICED 09*. Stanford, USA.

- REED, N., SCANLAN, J., WILLS, G. & HALLIDAY, S. *(Under review)* The Inertia Problem: Implementation of a Holistic Design Support System. *The Electronic Journal of Knowledge Management*
- REED, N., SCANLAN, J., WILLS, G. & HALLIDAY, S. *(Under review)* Knowledge use in an advanced manufacturing environment. *Design Studies*

**Conferences**

- Design, Computing and Cognition '08
  - 2 presentations, symposium and poster
- Concurrent Engineering '08
  - Presentation and paper
- ICED: 17th International Conference on Engineering Design '09
  - Presentation and paper

**Other**

Invited talk to Rolls-Royce DSE HighSpots - July 2010

## 1.6 Thesis Outline

The following thesis consists of 7 further chapters outlined below. The structure and relation of these chapters can be seen in Figure 1.

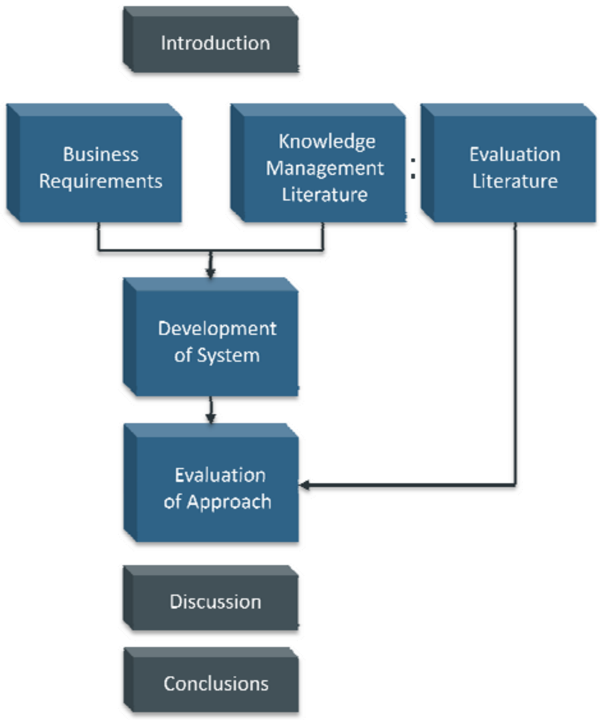



*Figure 1: Schematic structure of the thesis*

# Chapter 2

## Industrial Context

In order for a Knowledge Management strategy to be 'successful' – defined in this research as providing value to the business – it must be integrated with the organisational processes, human behaviour and commercial strategy of the company. Here, the business environment represents both the experiment and the subject to which this study stimulates and measures. In order to understand the research approach taken in later chapters it is necessary to understand this environment and its wider context.

Two factors are crucial to this study, first the relationship and distinction between the immediate business and the wider sponsor, and second the business aims and strategy of the spin off business. This chapter will provide a brief history and background of Rolls-Royce, the spin-off and a description of the business strategy established by the spin-off. An additional literature review is also provided to describe the technology supported by the knowledge activities, detailing the products produced and the manufacturing methods used.

### 2.1 A History of Rolls Royce plc

Rolls-Royce was established in 1904 through the combination of the eccentric Charles Rolls and the engineer Henry Royce. Rolls-Royce established itself as a maker of reliable and superior cars – Royce, single-handedly redesigning any component he could not acquire to a satisfactory standard (Rolls-Royce plc, 2004).

At the outset of World War I, the Home Office asked the company to produce aero engines. Initially it refused, but as the war progressed, Henry Royce realised that with war being fought in the air as well as on the ground, Britain's aircraft needed a reliable engine. Royce began designing, and by February 1915 an engine was on the test bed: this was to be the Eagle engine.

Following the war, the company focus returned to automobiles, but development and production of aero engines continued, leading to Royce's design of the famous Merlin engine. Royce died in 1933, but the engine went on to power the Spitfire in the Battle of Britain. It was the post-war Chief Executive Ernest Hives who marked the turning point in Rolls-Royce history, telling the board of directors that the future lay with the gas turbine.

In 1971 the company and brand was split, Rolls-Royce plc granting the use of the Rolls-Royce trademarks to the new "Rolls-Royce and Bentley Motors Ltd." while maintaining the right to utilise the brand in sectors other than the motor industry (Rolls-Royce plc, 2009).

Today the Rolls-Royce provides power systems for use on land, sea and in the air. It is a global company and currently employs around 39,000 people in 50 countries. It's primary market is civil aerospace and is the world's second largest manufacturer of gas turbines engines, with 54,000 turbines in service (Rolls-Royce plc, 2006b).

Rolls-Royce continually invests in new technologies, such as low emission engines and new manufacturing processes. The company maintains a network of links across the world, working with universities and dedicated research centres. Each year, together with these partners, the company invests around £885 million in research and development (Rolls-Royce plc, 2006b).

Rolls-Royce's technology strategy incorporates a 20 year period. Research projects fall into one of three categories, depending on the technology's readiness and time to market. Vision 5 consists of near term technologies applied to existing architectures, Vision 10 technology targeted at next generation systems, and Vision 20 step change or emerging technologies (Rolls-Royce plc, 2007).

The Manufacturing Technology group exists within Rolls-Royce to manage and support the development and implementation of mature manufacturing processes such as linear friction welding or near net shape processes. It is within this group that the research presented here operates.

## 2.2 Industrial Context of Research

In June 2006 Rolls-Royce Manufacturing Technology launched a project to develop and further a unique technology for the design and manufacture of fixtures and tooling, dubbed internally "Pro-Laser", as the technology utilises Profiled Laser cut sheet metal[2]. The project represents a Vision 5 project, demonstrating the aim to rapidly deploy the technology to market in the short to near term.

This section introduces the concepts and benefits of the technology, with particular focus on its reliance on knowledge. An overview of the business to date is given including an analysis of its growth and development.

### 2.2.1 Technology Overview

The unique technology represents a novel method of design and manufacture for fixtures and tooling. Using the high precision and repeatable manufacturing capability of a flat bed laser and a CNC press brake allows designers to embed product value early in the design. This allows highly accurate and repeatable products to be produced in typical lead times of weeks, shorter than conventional methods with lead times of months. An example fixture is shown in Figure 2.

[2] "Pro-Laser" is a working name for the venture. The name has no official capacity, as the project is still currently operated entirely within Rolls-Royce.

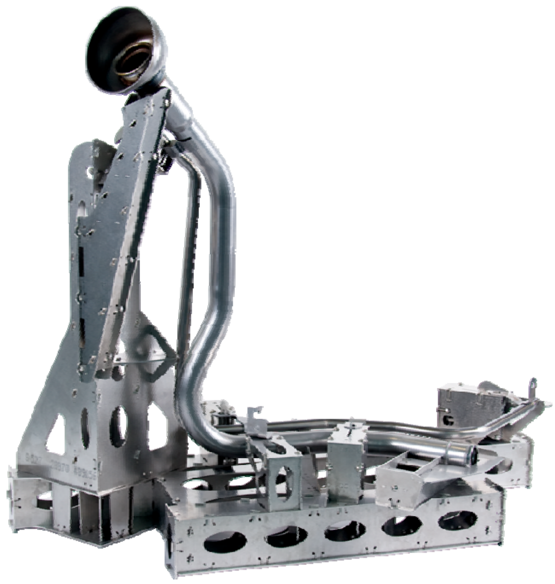


*Figure 2: Example fixture showing a typical fixture constructed from laser cut sheet metal*

This technology was developed over a period of many years by a single, highly experienced specialist during his design and production of fixtures and tooling for Rolls-Royce. However it was never significantly pursued by others. Consequently the majority of the expertise associated with the technology resides primarily as tacit knowledge within the Technical Specialist [TS] and a limited number of design engineers.

The nature of the technology and the use of modern manufacturing methods have the consequence of creating extremely knowledge-orientated products. That is, the majority of the 'value' exists in the design of the component, not in its manufacture. Because of the knowledge orientation of the technology the expert represents the most valuable asset to the development of the technology, but as the business began to grow he was placed in increasing demand. At the outset of this research it was known the specialist would retire in the near future, potentially causing a loss to the company of a vast proportion of intellectual expertise and knowledge. The specialist retired at the end of 2009.

### *2.2.2 The Current Business Environment*

The business is currently based in the Technology Centre, based at the Advanced Manufacturing Park (AMP) in South Yorkshire, UK. The park contains numerous centres such as the Boeing sponsored Advanced Manufacturing Research Centre. The Technology Centre contains both office and workshop space for research driven technology companies and the centre provides support to growing companies and emerging technologies (Oxford Innovation, 2009). The business occupies two offices and a large manufacturing space.

Currently the business consists of eight full time staff: a programme manager, the technical specialist, four designers and a workshop engineer. Additionally, in August 2009 a RROIPL (Rolls-Royce Operations India Pvt Ltd) employee was attached to the business supporting the further development of design tools.

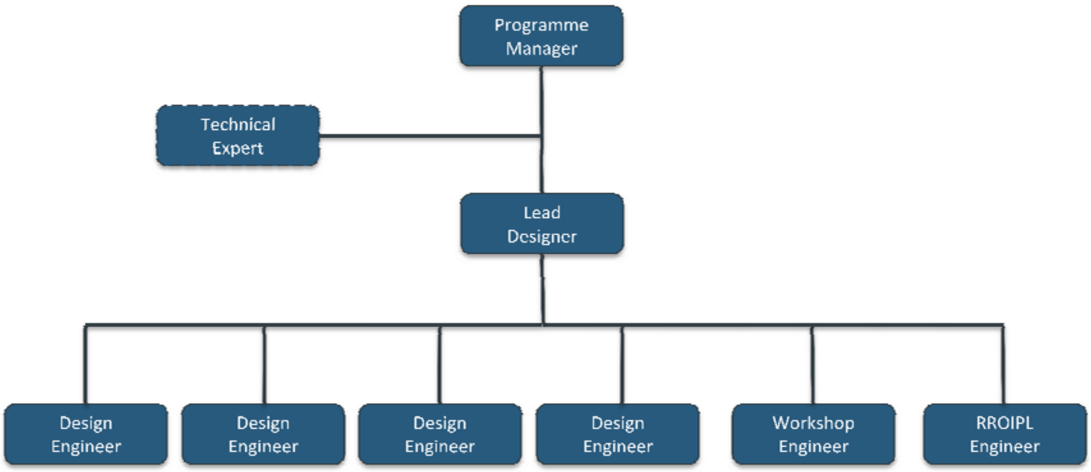



*Figure 3: Illustration of the employees associated with the Sheffield programme as of March 2009*

Using the European Commission guidelines on Small to Medium Enterprises [SME], the business is classed as a Micro enterprise, well within the SME classification (European Commission, 2003). Although the business continues to operate within Rolls-Royce (and not technically classed as independent), it operates as a distinct cost centre, independent of the main site and will be considered throughout this research to be an independent SME.

### 2.2.3 Business Capability

The business occupies a large manufacturing workshop equipped with a 2.2kW flat bed laser, Press Brake, CMM tools and a large selection of hand operated tools and equipment. To date, the workshop has been sufficient to produce all projects designed and developed by the team. Despite the large amount of activity and products produced, current manufacturing capability is adequate for the business and does not represent a bottleneck to the design and manufacture process.

### 2.2.4 The Business Growth

The Business was formally established in June 2006. Initially this consisted of the technical specialist, senior manager and four, half-time equivalent manufacturing engineers based out of the Rolls-Royce Hucknall site.

A plot of the number of employees over time, from the company's inception, is shown in Figure 4. The plot shows the total number of employees in red and the number of designers in blue (thus blue is a subset of red). The spike and dip around October 2007, represents the move from the four half-time equivalent engineers, to two full-time designers. An overlap with an incoming designer is the cause of the apparent discontinuity.

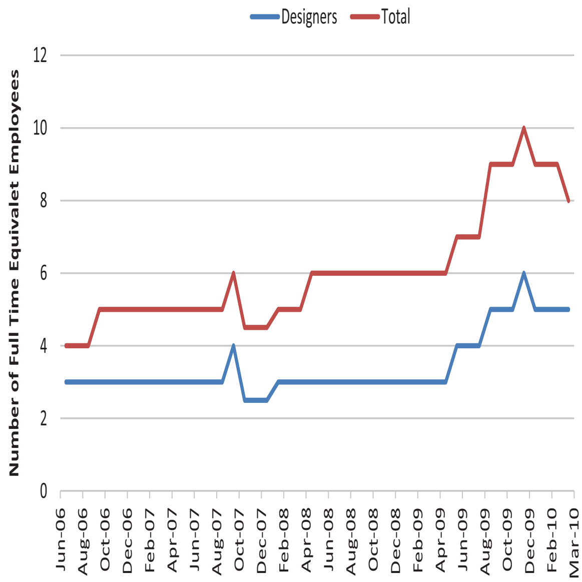



*Figure 4: Plot of the number of employees employed by the business over time*

In 1972 Larry E. Greiner developed a model of business growth based on his observations of five distinct stages of a business's growth (Mind Tools Ltd, 2009). Since then the model has frequently been used by companies to assess their businesses position and to understand how best to develop their management style to maintain growth (ten Have et al., 2003).

In its early stages from June 2006 onwards, Pro-Laser represented a classic Phase 1 company, focused on the creativity around the products and intent on opening up new markets and being driven by entrepreneurship. This phase is characterised by informal working practices and communication and led by the founders, in this case the technical specialist.

From late 2007 with the addition of dedicated manufacturing capability and the establishment of full-time designers based in Sheffield, the complexity of the business increased dramatically. In Greiner's model, this places an increasing burden on the management and running of the business, causing a leadership crisis.

Over 2008 a slow evolution occurred, as predicted by Greiner, to meet the crisis. The specialist moved position to take a uniquely technical role, and increasingly more formal procedures and documentation were established. This culminated in the research and implementation of a Quality Management Procedure, requiring formal sign off at key sections in design and manufacture and generating an auditable process.

This phase is expected to continue, with adoption of more organised and dedicated functions, such as accounting, work standards, budgets and more formal communication. This will reach a natural peak following any venture external to Rolls-Royce plc when the sudden influx of resource and work will overwhelm the existing management, leading to Greiner's phase 3: delegation and a decentralised organisational structure. This evolution is highly relevant to the knowledge strategy developed. It is important that the knowledge strategy integrates with the existing structure of the business and should be geared to support the business growth.

## 2.3 Business Strategy

At the time of writing the business remains wholly owned by Rolls-Royce and functions within the Rolls-Royce group. The vision is to launch the project as a spin-out joint venture with an appropriate partner. Spin out will occur for two reasons:

1. Fixtures and tooling do not represent core business to Rolls-Royce plc
2. The potential to scale up the venture is greater due to:
    a. The wider available market external to the Rolls-Royce group
    b. The resource limitations (in particular an employee cap) within Rolls-Royce plc.

The business objectives are twofold: to develop current capability in order to meet Rolls-Royce core business requirements and to maximise growth, fully exploiting the external market with a nominal target of over £100m sales. The company mission has therefore been defined as:

> *"To design and supply fixtures and tooling to Rolls-Royce Business Units and the wider aerospace sector, utilising flat-bed laser cutting and CNC press-brake manufacture. The Pro-Laser product will enable order of magnitude improvements in quality, lead times and cost."*

The following section provides a brief introduction to the concepts of a business model. The rationale behind the decisions that led to the above objectives is detailed, together with a fuller explanation of the strategy, and its relation to the Knowledge Management activities.

### *2.3.1 The Business Model*

The term "Business Model" a buzz term, popularised in the mid-late 1990s Dot Com boom (Magretta, 2002), can be defined as "a representation of a firm's underlying core logic and strategic choices for creating and capturing value within a value network" (Shafer et al., 2005). It is distinct to 'Business Strategy' which represents a business's decisions relative to external factors and competitors, as the Business Model describes the pieces used to construct the business (Magretta, 2002, Alt and Zimmermann, 2001).

Throughout this work the term Business Model will be understood to represent the architecture and central decisions or core values of a business relevant to: customers, value generation and sustainable growth. These will be addressed next, while the wider business strategy is addressed in the second half of this section.

### 2.3.2 Customers and Products

The novel technology represents a unique approach to manufacturing which could offer potential benefits in many sectors and in different applications. These include for example innovative fasteners for the home improvement market or lightweight medical applications. However, the key differential for this venture is the existing knowledge base.

In the knowledge economy a venture is in the strongest strategic position when utilising its existing knowledge. Therefore the new business will focus primarily on the design and manufacture of fixtures, with particular emphasis on (although not limited to) the aerospace market, leveraging existing experiences and designs.

Two categories of customer exist, internal Rolls-Royce plc customers and external customers: strong links will be maintained with Rolls-Royce following the spin out and initially it is expected that the majority of work will fall into the internal category. Typical customers within Rolls-Royce plc are Operational Supply Chain Units, the most common of which is Combustion & Casings. These units benefit from the lead-time advantages provided by the technology both in development and production.

External customers will be considered from all sectors and from all supply chain positions. However, aerospace firms will be sought as a priority in order to exploit and develop the existing knowledge base and establish a market niche. As the company grows and becomes established, the wider market can be addressed, allowing further development and exploitation of the technology.

### 2.3.3 Value Generation

The technology represents a step-change improvement to traditional tooling. It facilitates the production of highly bespoke products, as well as allowing high-volume production – to the order of hundreds of fixtures. Furthermore the modern manufacturing methods used ensure benefits such as precision, repeatability and modular construction are inherent in the designs.

Value is generated through the delivery of products with benefits over other or traditional products, such that customers are willing to pay a premium over cost of manufacture to realise the benefits provided.

In order to understand and develop the business strategy, an analysis was completed comparing the current product lines (as of July, 2009) against metrics evaluating the different benefits provided by the solutions. A matrix of the results is shown in Table 1, which synthesises the views of two individuals (the author and senior manager).

| Attributes: | Assembly Fixtures | Weld Fixtures | Guide Fixtures | Heat Treatment | Bespoke Press Brake Tooling | Laser / Water Cutting Fixtures | Coating / Masking Fixtures | Early Concept Production | Fast Make Brackets & Clips | Gas Shields | Pipe Production | Bespoke Clamps | Composite Layup | Inspection Fixtures |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flexibility (Variation) | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| Repeatability | × | × | × | × | × | × | × | × | × | × | × | × | | |
| Lead Time | × | × | × | × | × | × | × | × | × | | | | × | × |
| Added Quality | × | × | × | × | × | | | | | × | × | × | | |
| Lightweight (Portable) | × | × | × | × | | × | × | | | × | | | × | |
| Low Cost | × | × | × | | | × | × | × | | | | | × | |
| Scalable (Size and | × | × | × | | | × | | × | | | | | | |
| Mobility | × | | | × | × | | | | | | | | | × |
| Precision | | | | | × | | | | × | | × | × | | × |
| Integrity | | | | | × | | | | | × | × | | | |
| Modular | | | | | | | × | | | | | | | |

*Table 1: Pro-Laser product matrix illustrating the key competitive attributes associated with different product lines (Derived July, 2009)*

Clearly there is a large variation of attributes across the different product lines. However, there are consistent benefits of flexibility (variation between products), repeatability and often lead time. This is crucial to understand as it highlights the need to develop products quickly and efficiently, but provide genuine quality improvements and be tailored to the customer needs.

The current cost structure is a Cost-Plus pricing model. That is, a margin is added to the variable cost of each project to cover fixed costs and potentially generate a revenue (Collier, 2006). This model is partially abstract with the current organisation between Pro-Laser and Rolls-Royce plc. While the venture exists as part of Rolls-Royce plc the price is represented as the hours charged to a project and thus no financial transactions actually occur. Finance is supplied in a separate transaction based on the hours utilised.

### 2.3.4 Business Model

Roy (2006) completed an initial market evaluation and study of the venture at the time of its inception. The remit was to evaluate the feasibility of the proposed venture and to devise an appropriate strategy with which to boost the value and growth of the business.

The study considered five potential Business Models. Each model was evaluated and its viability as a profitable model for the technology was assessed. These models were:

1. Design consultancy (Service)
2. Franchise
3. Premium-Value
4. Low-Cost
5. Services (Multiple Access)

There are many other 'standard' Business Models that exist – some authors would argue an infinite number – but those listed above represent the five most relevant to the design and manufacturing environment of Pro-Laser and those examined by Roy (2006).

In the study, Roy concluded that a hybrid franchise / consultancy model would maximise the business potential for scalability and revenue. The model recommends establishing a network of franchises supported by a web-based toolkit to generate 'standard' designs. The "mother company", the core Pro-Laser, would operate on a consultancy basis to meet more complex design requirements. This would allow a dual revenue model. The franchises maximise the potential revenue from previously designed solutions, (low cost, high volume) while the central consultancy employs experienced and high quality engineers working closely with customers to solve complex problems using innovative design. This further enhances the knowledge base which in turn supports the franchises.

To date the business continues to operate within Rolls-Royce and it is therefore not feasible to establish franchises prior to this launch. The company effectively operates a Premium-Value business model i.e. designs are generated on request to solve customer problems. This is a high-margin, low-volume model that markets high-end products for a premium. This differs to the consultancy as it is the products that are sold, rather than a service.

This model utilises a niche market and is highly knowledge intensive because products must offer either genuine improvement over alternative solutions or must solve an otherwise difficult problem. Both of these cases require a large degree of designer expertise and investment of time. This severely limits business growth to a rate determined by the availability of expert designers.

### *2.3.5 Sustainable Growth*

Roy (2006) completed Porter's Five Force analysis (Porter, 1998) on the fixturing and tooling industry as part of the venture study. Porter's analysis examines five fundamental competitive forces that determine the state of an industry, these are: new entrants, bargaining power of buyers, bargaining power of suppliers, substitute products or services and rivalry among existing competitors (ten Have et al., 2003). The resultant chart can be seen in Figure 5.

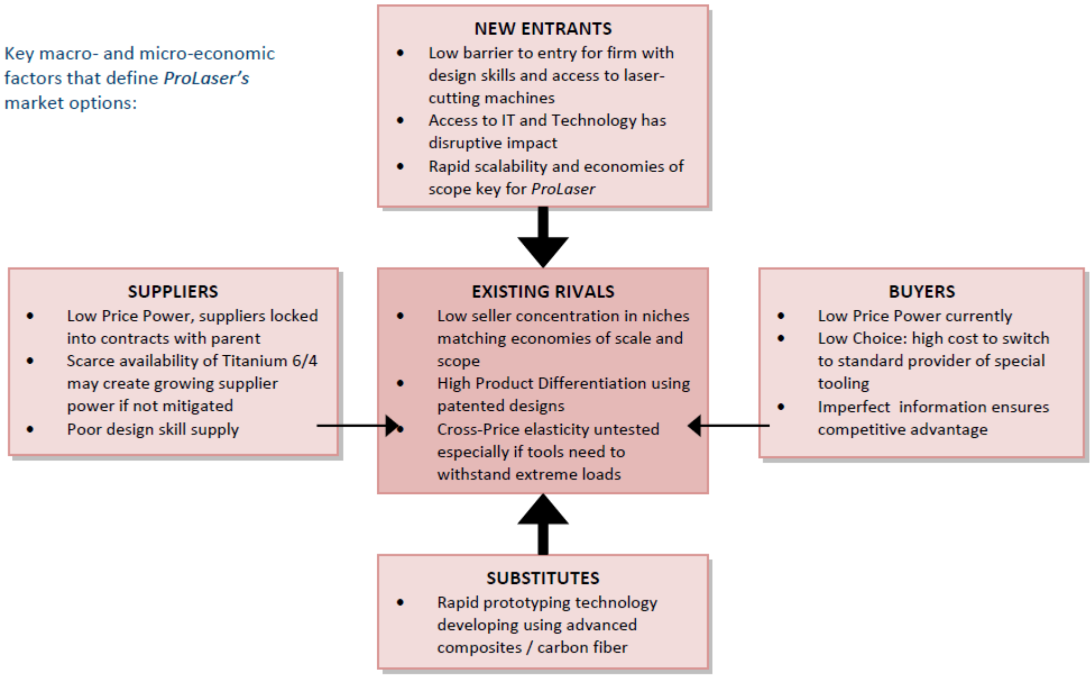



*Figure 5: A Porter's 5 force analysis completed by Roy (2006)*

These metrics indicate the capacity of a company to compete in the industry and must be acknowledged with appropriate strategy. To summarise each of the forces:

### Buyers and Supplies

In the tooling industry both buyer and supplier power is low: buyers have low price power – usually a result of the low-volume and bespoke nature of the products. But the same applies to suppliers as the raw materials are usually common and easily-sourced materials such as aluminium, titanium and gas. Neither party can therefore dictate prices, but neither can an existing business establish a barrier through price agreements.

### Substitute Products

Substitutes such as rapid prototyping could pose a threat, potentially offering a wider scope of products, but currently would be unable to compete on cost.

### New Entrants

The most significant concern arises from the low barrier to entry of competing manufacturers. A company would in theory only require a flat bed laser and press brake to compete.

**Existing Rivalry**

No known competition is thought to exist offering the unique fixturing produced by the technology.

The key conclusion from the study is that once launched, there exist very few natural barriers to entry if any. There is therefore a need to create a barrier to entry for potential competitors. Given the naturally low barrier, Pro-Laser must establish itself as *the* supplier of low cost fixturing, through rapid scalability and a leveraged knowledge base.

### 2.3.6 Business Success Measures

Three key success factors were proposed by Roy (2006) to assess the success of the venture:

1. Financial performance
2. Ability to identify and serve customers, both internal and external
3. Ability to create, manage and re-use intellectual capital effectively
    a. without the proliferation of designs and tools
    b. without the constraint of design time or availability of skilled engineers
    c. minimising reliance on tacit knowledge from in-house experts
    d. maximising knowledge use during operational processes

The critical nature of knowledge to the business is highlighted by the third metric, a response to the knowledge dependent Business Models proposed above. Without the leverage of knowledge, business growth will be constricted and an inadequate barrier to entry generated, leaving the business vulnerable to competition. The business has the benefit of being the first mover in the market and it is vital that this position is defended.

### Summary

This section has introduced and described the proposed Business Model and strategy to support sustained and long term growth of the venture. The nature of the tooling and the market environment is such that no natural barriers to entry exist. Only by pursuing aggressive growth utilising the primary differentiator – experience and past knowledge – can the business defend itself against possible competitors.

Roy (2006) concluded that to support the knowledge function of the business, a proactive programme of work was required to actively manage the business knowledge. It is this requirement that forms the foundation of the remaining work in this thesis.

## 2.4 Literature Review on Technology

This section is intended as supplementary to the reader wishing to understand more about the industrial application of the research. The two main manufacturing processes used, laser cutting and press brake forming, are described, followed by a brief introduction to the role of traditional fixtures and tooling.

### *2.4.1 Laser Cutting*

Laser cutting was first developed in the late 1970s. Initially a fixed laser was used and the workpiece was moved to facilitate the cutting. The typical power used was around 500W. By the mid 1990s lasers had an operating power of around 3kW. Flying optic systems had been developed and 125 m/min positioning speeds were achievable, and in 2006, the first 6kW laser was installed in the UK (Allcock, 2007).

Laser cutting is a thermal process, the coherent monochromatic beam is focused on the surface of the workpiece with a power density of the order of $10^6$ W/cm$^2$, vaporising the metal. Waste metal is blown through the cut by pressurised 'assist' gas, illustrated in Figure 6.

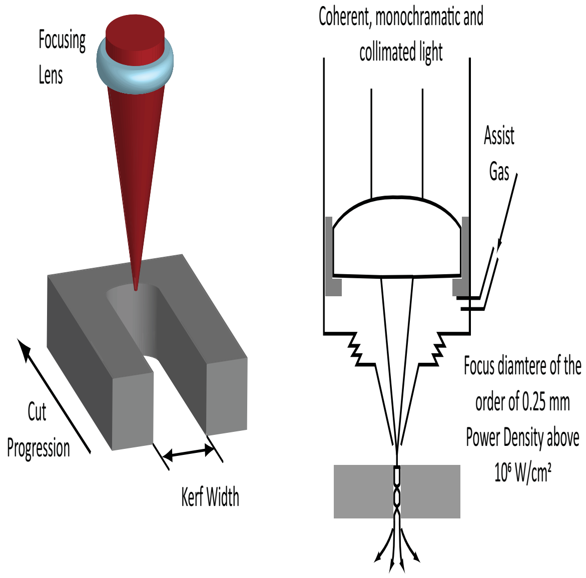



*Figure 6: Illustration of the laser cutting process (Caristan, 2003).*

There are seven parameters that control the cut of the laser: beam quality, power, travel speed, type of assist gas, nozzles, focusing lens and focal point position. A more detailed description of these can be found in Semiatin (2006). The exact parameters used are determined by the material cut, differences in thermal conductivity, reflectivity, melting point and density, which will require different cutting parameters (Webb and Jones, 2004).

Laser cutting offers many advantages over traditional methods of cutting such as punch presses or cutting, including increased accuracy, better edge finishes and smaller kerf widths (typically 0.1 – 1.0mm) (Webb and Jones, 2004). Laser cutting can also cut much more complex shapes compared to traditional tooling without long or specialised set-ups and from thin or flexible materials.

Abrasive water jet cutting is a viable alternative to laser cutting, capable of cutting to a similar accuracy but up to material thicknesses of 152mm and with no heat affected zone. The disadvantage is a much increased complexity of operation, requiring the disposal of abrasive material and high-pressure plumbing (Webb and Jones, 2004, Semiatin, 2006).

Laser cutting is ideal for producing specialised short run or prototype parts, especially those with complex or intricate geometries. As the process is non contact, there is limited load placed on the workpiece (although a marginal load is generated from the assist gas) and it is often used for sheet metal work in the aerospace industry, permitting profiles to be produced in light or malleable workpieces.

The projects designed at Rolls-Royce Sheffield are primarily produced on site, using a Mazak 2.5kW laser. The laser is capable of cutting mild steel up to a maximum thickness of 22mm and with a cutting feed rate of 4 m / min. The system is driven using Mazak's bespoke "Smart System" software and can read most standard 2D CAD drawings.

### 2.4.2 Press Brake Forming

Press brake forming is a process whereby the workpiece is placed in an open die and pressed into the die via a ram. It is typically used to form long narrow bends that are unsuitable for pressings, or for low volume production pieces. Press brake forming is not only capable of producing complex bends, but also other operations such as blanking, piercing, flattening and flanging (ASM, 1988).

There are four types or styles of press brakes, classified depending on their mode of load generation: leaf, mechanical, hydra mechanical and hydraulic. These range from the simple leaf press brake, manually operated bars limited to light gauge materials to modern fully hydraulic CNC operated press brakes (Benson, 1997).

Considering a hydraulic press brake here for simplicity, the tooling consists of two parts: the bottom die and the upper punch (sometimes termed the blade). The die is held in the bed of the press, while the punch is driven down by the ram (Benson, 1997). Unlike traditional press forming, the shape is not necessarily formed by the shape of the die, but rather by the combination of the distance into the die the punch enters and the span width of the die, creating a three point bend illustrated in Figure 7 (Lascoe, 1988).

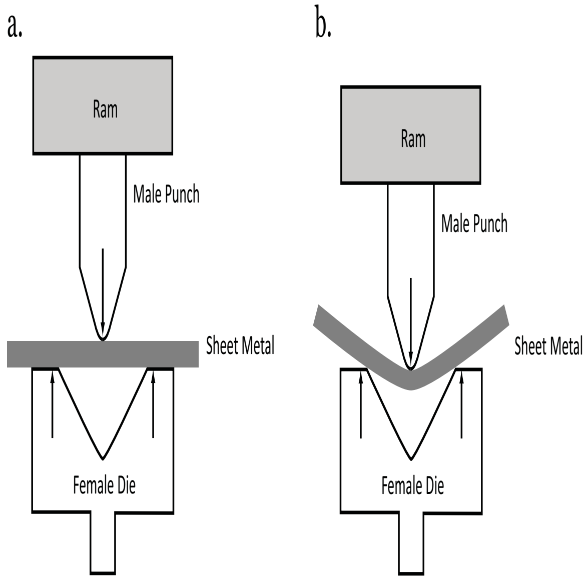



*Figure 7: Illustration of the press brake tooling, showing (A) the three points of bending on the sheet and (B) the sheet being pressed beyond its elastic limit (Lascoe, 1988).*

The illustration in Figure 7 demonstrates the most common use of the press brake, air forming. There are two other types of bending: Coining and Bottom Bending. Coining utilises a very high load to cause the material to flow, generating the required shape. It is often avoided, however, due to the excessive loads required. Bottom Bending uses a much reduced load, but one that is still large compared to air forming. It is similar to Coining in that the radius is still stamped into the material; however, spring back is controlled using the tool radius rather than stamping the entire tool. Today, air forming is much preferred, allowing non-specific tooling and greatly reduced loads to be used (Benson, 1997).

Rolls-Royce Sheffield utilises the fully hydraulic press brake, OptiFlex manufactured by Ursviken, which can deliver a load of 100 tonnes. The fixtures and tooling produced by Rolls-Royce Sheffield often utilise the capability of the press brake, primarily though air-bending but other techniques such as blanking or forming have been used with much success.

### 2.4.3 Jigs and Fixtures

The function of a jig or fixture is to rapidly or easily locate and position a workpiece in order to perform a manufacturing operation on it, typically cutting operations such as drilling or machining. They are production devices that maintain the relationship between the tool and the workpiece facilitating the manufacture of duplicate parts (Hoffman, 2003, Haslehurst, 1981). Typically fixtures consist of a locator, support points and clamps, to secure the part correctly (Cecil, 2001).

The terms jig and fixture are often used interchangeably within the context of manufacturing. Both Haslehurst (1981) and Hoffman (2003) define the difference as two-fold:

- Jigs are devices that support or are placed on a workpiece, which not only hold the workpiece but guide the cutting tool (usually via hardened steel bushes). A fixture, however, holds the workpiece securely and includes setting gauges or references to define the location of the fixture and workpiece in relation to the cutter.
- Jigs are typically handheld (unless very large) and not fastened to the machine table, while fixtures, as the name suggests, are fixed to the machine table.

In the work presented here, following the above definition, the majority of designs addressed will be fixtures as opposed to jigs. However, for simplicity the difference will not be stressed explicitly.

When developing a fixture, the basic principle is to limit the workpiece's degrees of freedom in such a way that the position is maintained during loading. The design of a fixture requires a different approach to a component. Henriksen (1973) defines five design stages, addressing the following functions: locating, clamping, supporting, applying guides and finally defining the fixture outline or structure.

Traditional fixtures and tooling can be substantial investments in both time and resource depending on their application, manufacturing methods and material. In the aerospace industry a typical machined fixture could take 12-16 weeks and cost in the order of £25,000 (Halliday, 2006).

The industrial work supported by this research uses unique design and manufacturing methods to develop bespoke tooling in much shorter lead times than the traditional tooling illustrated.

### 2.4.4 Tooling

The term 'tooling' has a myriad of connotations depending on the context used. It is defined by the Oxford English Dictionary as "the process of designing and supplying the machine tools needed to produce a product" (OED, 2001) or more generally by Merriam-Webster as "to shape, form or finish with a tool" (Merriam-Webster, 2007).

For the purposes here, tooling will be considered different to fixtures and jigs in that it is the tool itself which manipulates or modifies the shape of the workpiece as opposed to a fixture which only locates the workpiece during an operation.

The most common 'product tooling' are those of dies and moulds, but tooling can range from inexpensive hand tools to substantial and complex machines (Walker, 1996, Gates, 1949).

In general, tooling is required to have two key attributes (Boyes and Sedlik, 1985, Haslehurst, 1981):

1. The tooling must be accurate – the accuracy of the final product is directly dependant on the accuracy of the tool.
2. The tooling must be cost effective; the cost associated with the tooling needs to be carefully weighed against the benefit provided by the tooling.

The tooling supplied by the industrial group utilises novel design to provide accurate and cost effective tooling.

## 2.5 Example Products and Solutions

In order to supplement the reader's understanding of the technology developed, several examples of the products developed (specifically those referred to later) will be given here.

### 2.5.1 Assembly Fixture

The example presented here is a typical solution that exemplifies the benefits offered by the technology over traditional tooling.

The requirement was to produce a fixture that would position a titanium skin (for an engine splitter) and a series of additional details so that the parts may be riveted together. The fixture must not only accurately position and clamp all the parts, but must also facilitate access for the operator to rivet the components. The skin is a complex formed surface, roughly horseshoe shaped.

This fixture could have been designed and manufactured using traditional machined or fabricated methods. However, the complex form of the skin would have entailed extensive machining or fabrication. The previous solution was fabricated and can be seen in Figure 8(a). Here the value of the fixture would have been embedded during the manufacturing process. Any change in the final design of the parts would incur a large cost to remanufacture the fixture. Furthermore the use of heat during construction increases the possibility of material deformation reducing the accuracy of the fixture and the final component.

The solution developed by the team in Sheffield, (shown in Figure 8(b) embeds the value of the product in the design stage and manufacture is significantly less expensive than traditional and much faster to produce.

*Figure 8: A traditional fixture (a) and the fixture developed by the team in Sheffield (b) for construction and assembly of an engine splitter*

The fixture was constructed from 2mm and 3mm stainless steel and bespoke clamps were developed to retain the component. Material cost was approximately £250.00 and it took around 180 hours to design and manufacture, representing a six fold reduction compared to traditional tooling. Novel assembly features avoid any use of heat treatment, increasing accuracy and the novel clamping mechanism increases repeatability.

### 2.5.2 Welding Shields

Argon shields represent one of the most unique solutions developed by the technical specialist. In order to create high integrity welds, the weld torch must operate in an oxygen depleted atmosphere (to around 50 parts per million). This is achieved by displacing the air around the weld line using inert Argon gas.

A problem arises in trying to create this environment. Simply propelling Argon into the vicinity of the welding torch creates eddies that draw in oxygenated air exacerbating the problem. A ‘fog’ of Argon is actually required which slowly immerses the weld line in Argon, depleting the oxygen. Typically devices were constructed ad hoc by individual welders which pumped Argon through cotton wool shown in Figure 9(a). These were time consuming to produce and use, and did not necessarily guarantee repeatable welds.

The requirement was to produce a set of shields, which would provide high quality and repeatable welds across a series of Outlet Guide Vanes and potentially scaling across different engines.

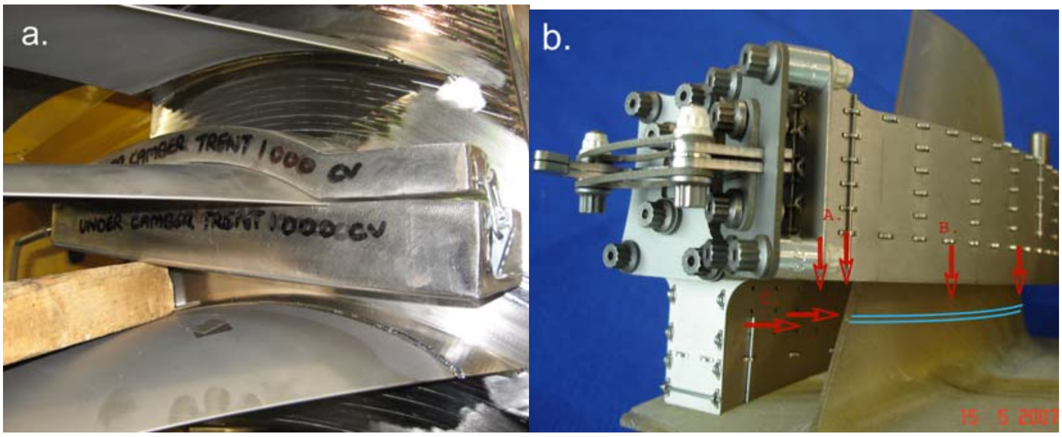



*Figure 9:Photographs comparing traditional 'ad-hoc' solutions (a) and the Pro-Laser developed argon shield (b) to weld an Outlet Guide Vane.*

The fixture developed, shown in Figure 9(b), consists of two parts that hook together either side of the blade. Inside are a set of carefully designed and positioned baffles though which the Argon gas is diffused. Two parallel sheets interface with the curve of the hub and provide the axial position of the fixture. The blade interfaces provide the horizontal position. The welder then works from one side of the blade using a sheet to guide the torch.

### 2.5.3 Consulting Solution

Tooling alignment in press brakes is critical to achieving accurate bends. A solution was required that would remove any horizontal misalignment between the top and bottom tools of a press brake.

The technical specialist developed a solution over several iterations. A new clamping technique was developed that would lock material in place which would otherwise slide freely. The specialist then developed a mechanism which used the upper tool to move and align the lower tool. Once aligned, the locking mechanism is activated retaining the lower tool in the correct position. The entire assembly can be seen in Figure 10.

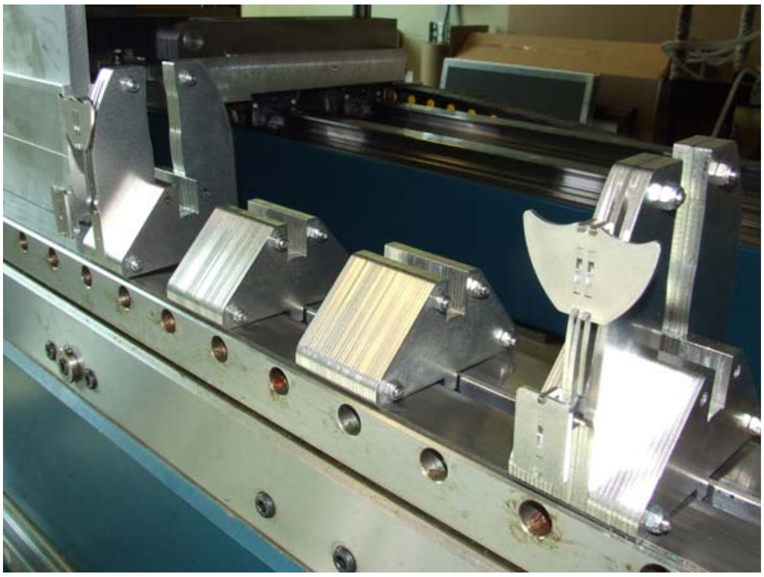


*Figure 10: Press Brake alignment tool in operation*

This solution is believed to be unique and while non-trivial to develop, provides a reliable and repeatable method that can be adopted across future products. This represents an example of a consultancy solution, which required significant research and investment but which could be adapted and rolled out as future high-volume solutions by franchises.

## Chapter Summary

The preceding chapter has introduced and described the industrial context and motivation by which this thesis is driven. Beginning with a historical perspective of Rolls-Royce and the research strategy pursued, the venture was introduced, together with the devised model for business growth and the wider market strategy. Finally the manufacturing processes used and products developed were described.

Moving forward the reader should have a clear understanding of the need for a proactive strategy to protect against knowledge loss from the specialist and to maximise the company's existing knowledge base. This knowledge must be utilised in order to support the business growth and create a competitive advantage over other manufactures wishing to compete. The following section provides a wide literature review, introducing the theoretical foundations behind Knowledge Management, before describing the different methods and approaches that can be used to meet the objectives above.

# Chapter 3 Literature Review of Knowledge Management

*"...and for the labour of two days you asked for 200 guineas?*

*"No, it was for the knowledge gained through a lifetime"*

*James Whistler (1878) from [Whistler vs. Ruskin], 1878*

This quote highlights the potential value of knowledge and succinctly encompasses the fundamental rationale behind Knowledge Management. The following chapter presents a review of the existing literature and research of knowledge and Knowledge Management.

The aim of the chapter is to introduce the core concepts, developments and applications of the field of Knowledge Management, providing the reader with a sufficient understanding of the research environment in which this thesis sits, in order to explain the decisions made and the approach taken later in this research.

The chapter is separated into seven sections and begins by establishing some required definitions before a formal introduction to Knowledge Management is given. The key ideas and a discussion on them are presented on the nature of knowledge and its role in business. The subsequent four sections introduce the implementation of Knowledge Management, initially examining the strategies used, common systems, its role in engineering and finally Knowledge Management strategies adopted in Rolls-Royce. The final section discusses the issues of evaluating Knowledge Management approaches.

## 3.1 Definitions of Data, Information and Knowledge

In the new and developing field of Knowledge Management, there has been much discussion and debate on the nature and definition of knowledge, its relation to information and data and if it can indeed be assessed and managed as a commodity (Machlup, 1962, Grant, 1996c, Sveiby, 2001, Alavi and Leidner, 2001). As a precursor to understanding the concepts of KM it is important to define what is meant by the terms, Data, Information and Knowledge and in particular their relation to each other. Here the common arguments are given and a description of their meaning as used within the following research.

### 3.1.1 Data

The word data comes from Latin, meaning “what is given”. It is what we can perceive, experience or measure (Brazhnik, 2007). In the field of KM, Peter Drucker’s (1993) definition of data as a “a set of discrete facts” is often cited as a clear and unambiguous definition which highlights the separation of data from its context. There are few strongly contradictory definitions or opinions to this; therefore Drucker’s definition will be accepted here.

### 3.1.2 Information

Etymologically, information originates from the Latin, “*in forma”* meaning to give form or put into shape an idea (Oxford English Dictionary, 2001). The word has since undergone various developments before appearing in English, and today is defined as that “with the capacity to inform”. Checkland (1981) describes information as a “combination of fact with context, meaning and relationships” which is supported by Drucker’s (1993) similar definition of “data with attributes of relevance and purpose”.

Like data there is little debate or discussion on what constitutes information, most probably as it is a familiar concept and easily distinguished from pure data. In this research, information will be considered according to the definitions above, that is, as a body of data with context and presented in order to inform the audience.

### 3.1.3 Knowledge

A basic definition of knowledge “is the sum of what is known: the body of truth, information, and principles acquired by mankind”(Merriam-Webster, 2009). It is the additional contextual understanding of facts that provide the foundation for our decisions (Brazhnik, 2007). This ability to make decisions is crucial in all aspects of life, and as the facilitator, knowledge is a valued commodity.

Following the definitions of data and information given above, Little and Ray (2005) state that information becomes knowledge when it is interpreted by individuals and given a context. This creates the implicit definition that knowledge can only exist within an individual – without an individual to understand it, it is simply information.

Little and Ray introduce a host of complex issues with their statement: if knowledge is required to make a decision and knowledge can never exist without an individual to interpret, how can a system ever make a decision? Central to this debate is the concept of 'knowing'. A system can be created to respond to a set of inputs according to a set of rules, but the system does not truly 'know' anything. It is accepted that there is something additional that substantiates knowledge.

The philosophical discussion on the definition of knowing will not be explored in depth here. However, it will be assumed throughout that knowledge is implemented by individuals. But knowledge can by definition be transferred by a system if it can be entered and subsequently read by a different individual in such a way that it empowers that individual with the capacity to make decisions, which by common sense we know can occur.

For the purposes of this research, Joia's definition (1999) will be taken as the clearest explanation of the relationship between knowledge, information and data:

$$\text{INFORMATION} = \text{DATA} + \Sigma\,(\text{attributes, relevance, context})$$

$$\text{KNOWLEDGE} = \text{INFORMATION} + \Sigma\,(\text{experience, values, patterns, implicit rules})$$

As an explanation of this, an analogy could be the price of shares. If a decision was required whether to purchase a particular stock, the decision could not be made simply on the price of the share. Nor even if its entire history of values were known. This data would clearly need to be put into the context of the entire market, creating information on whether the company has performed well or poorly. Even if the shares have not gained in value, they could still be considered to have performed well if a systemic fall in the market had occurred. The decision to invest in the shares however requires the addition of knowledge such as how to respond to the information available for that particular share given its past performance. This is illustrated schematically by Pierce (Figure 11).

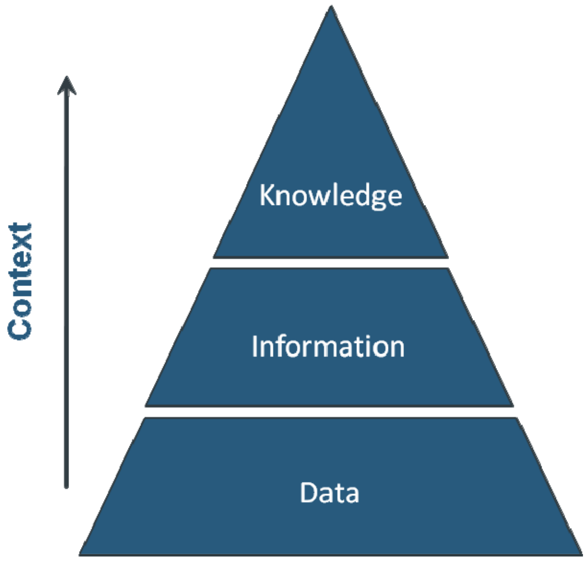



*Figure 11: Illustration of the relationship between Data, Information and Knowledge from Pierce 2001 (Pierce, 2001b)*

This illustrates the difficulty in managing knowledge, as opposed to data or information. Knowledge management is not, and cannot simply be a passive storage of data. There must be additional contextual understanding in order to support a user in acquiring knowledge.

### *3.1.4 Experience and Understanding*

These terms are often used in conjunction with knowledge and in particular knowledge reuse activities. The terms can generate significant confusion as in common language they are usually used synonymously with knowledge. The Oxford English Dictionary (2001) defines experience as “Knowledge resulting actual observation or from what one has undergone”. Building on the previous definitions of knowledge, it is argued by the author that experience describes the *activities* that lead to knowledge generation over time, through repeated applications of existing knowledge.

Knowledge generation is discussed in further detail in section 3.3.5, but traditionally a person will have generated knowledge through experience over time. For example a mechanic may have knowledge of how to change a spark plug having changed many before. In theory the perfect knowledge transfer activity would remove the need to repeat tasks to generate knowledge. Although many would argue here that the 'new' inexperienced mechanic would not be able to cope with unexpected problems as well as the experienced one. This ability is simply a result of more knowledge. If all knowledge was transferred, the novice mechanic would be equivalent to the experienced mechanic.

Some research has tried to quantify experience and demonstrate its reuse (Delaitre and Moisan, 2000). The paper discusses reuse of equivalent situations, but their concept of experience reuse does not differ from the idea of knowledge reuse, except that there is no opportunity to use knowledge generated through other means such as simulated experiments, yet the benefit of knowledge reuse is to avoid needing previous experience.

Here, experience will only be considered as a process of obtaining knowledge. The one caveat to this statement is the acknowledgement that there is a degree of learning required to be able to reuse knowledge.

Understanding too, is often cited alongside knowledge and experience. The Oxford English Dictionary (2001) defines it as "intellect, capable of judging with knowledge". Clearly there is an overlap here between the person's intelligence and their ability to interpret knowledge. The distinction made here will be of a person's ability to appreciate 'why'. That is to say a person may have the knowledge to make a decision, but may not understand why the decision should be made.

## Summary

This section set out to clarify the meanings of several of the key terms within KM, namely those of data, information, knowledge, experience, and understanding and in particular their relationship to each other.

There are many dangers associated with specifying precise definitions of terms, especially with terms that have implications in common language and those that remain a point of discussion and study within academic fields. In particular the concept of what constitutes knowledge remains a strong point of debate for both philosophers and managers.

Here a basic dictionary definition and the key ideas behind each term were presented and some of the issues of debate introduced. Finally the position taken in the following research was clarified, accepting that it is only a position assumed for the benefit of the study presented.

## 3.2 Introduction to Knowledge Management

Despite its relative youth as a discipline, KM has already grown and evolved rapidly producing a significant body of literature, noticeable not least in the breadth of its subject matter and the extensive debates and studies it has already generated (Bontis and Serenko, 2009).

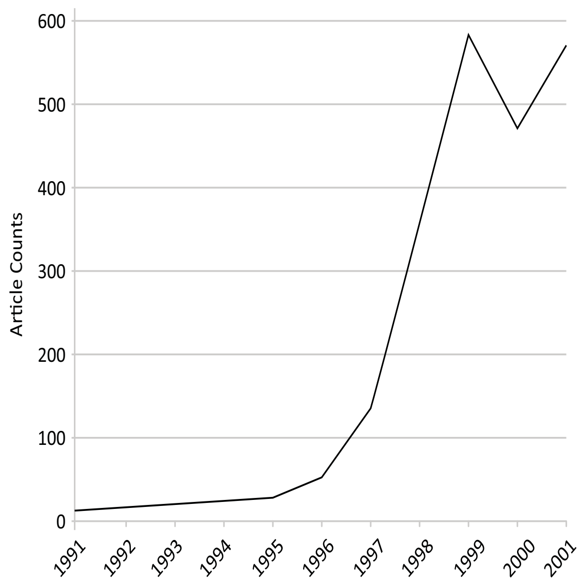



*Figure 12: Plot of the number of articles published between 1991 and 2001 relating to KM (Ponzi and Koenig, 2002)*

A demonstration of the increasing popularity of Knowledge Management research can be illustrated by Figure 12 showing the increasing number of published articles relating to Knowledge Management over the ten year period from 1991 (discussed below), or by the rising number of dedicated journals:

| Journal | Rank | Origin |
|---|---|---|
| Journal of Knowledge Management | 1 | 1997 |
| Journal of Intellectual Capital | 2 | 2000 |
| Knowledge Management Research & Practice | 3 | 2003 |
| International Journal of Knowledge Management | 4 | 2005 |
| The Learning Organisation | 5 | 1994 |
| Knowledge and Process Management | 6 | ~1994 |
| Journal of Knowledge Management Practice | 8 | 1998 |
| Electronic Journal of Knowledge Management | 10 | 2003 |
| VINE The Journal of Information and Knowledge Management Systems | 14 | 1971 |
| Knowledge & Innovation: J. Of the KMCI | 15 | 2000 |
| Knowledge Management for Development Journal | 17 | 2005 |
| J. of Universal Knowledge Management | 19 | 2005 |

*Table 2: A selection from the top 20 Knowledge Management journals as ranked by Bontis and Serenko (2009). Dates of first issue sourced by author, March 2009. Journals not listed were not accessible by the author.*

The following section will introduce the origins and concepts of this complex and rapidly growing subject. An initial high level view of KM will be presented beginning with a historical view of the subject, the key theories and their criticisms and the relevance and role to companies in the modern world will be discussed. Towards the end of the chapter more detailed explanations of the common activities and approaches will be presented and discussed.

### 3.2.1 Defining Knowledge Management

What really is Knowledge Management? What are its aims? What are the associated activities and consequently what are its successes and failures? These relatively simple questions have generated numerous responses, a consequence of:

1. The many different perspectives that exist on Knowledge Management
2. The broad array of activities associated with it.

In order to approach this question, it is necessary to examine the historical origins of the subject. The conceptual origins of KM may date back several decades – as described earlier, Bell predicted knowledge as a rising economic distinguisher as far back as 1974. But it was Karl Wiig who first coined the term ‘Knowledge Management’ at a Swiss conference sponsored by the United Nations International Labour Organisation in 1986 (Beckman, 1999). Wiig defined KM as managing the deliberate and systematic process of building, renewing and applying knowledge to maximise an enterprises knowledge-related effectiveness or to realise the best of its knowledge assets and to provide a competitive advantage (Wiig, 1997b).

It was realised that if knowledge was a company’s competitive advantage, then it needed to be approached in as strategic and proactive manner as previous distinguishers had been in the past. Knowledge Management is therefore used to describe the strategy by which a company strives to use its knowledge.

It should be clear from this description why defining the boundaries of the field is so difficult. In short, the aim is to support strategic business development by managing a typically intangible and human-orientated resource often using (although not limited by) information technology systems. Thus by its very nature, KM encompasses a wide range of issues and subjects. Bibliometric and other literature studies highlight the contributions from the fields of economics, innovative research, organisation theory, information systems, marketing, management strategy and entrepreneurship (Subramani et al., 2003), while elements from other fields can also be discerned, such as psychology and sociology, human interaction and issues of learning and epistemology. Subramani et al. (2003) illustrates the different facets of KM in Figure 13. The implication of attempting to manage human nature to the benefit of the wider business ensures that it remains a challenging subject of research.

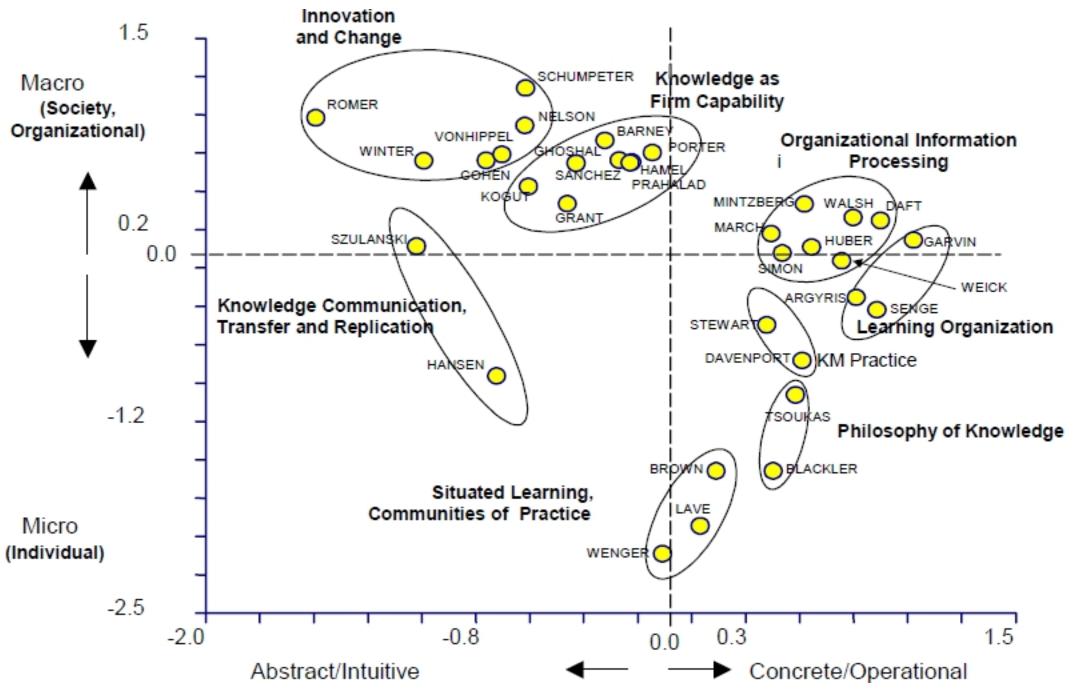



*Figure 13: Plot illustrating the different approaches in Knowledge Management against a basic metric analysis (Subramani et al., 2003)*

There is nothing new about the concept of encapsulating and transferring knowledge - routines and training manuals have existed for many years and as Hansen (1999) points out, it is the equivalent principle behind master craftsmen taking on apprentices. Businesses passed on through generations of the same family safeguard the ideas and accumulated wisdom safeguarded, supporting the future survival of the business. However, Alavi and Leidner (1999) argue that it is technology that has allowed a more systematised approach, facilitating extensive codification in databases and firm-wide Knowledge Management. Beckman (1999), too, argues that it is only by the IT capabilities that Knowledge Management exists as a deployable strategy. Consequently KM is now invariably described alongside the IT systems that support it, yet it must be remembered that these tools are only facilitators.

Joseph Firestone in his paper “On doing Knowledge Management” (Firestone, 2008) argues strongly on the damaging nature this lack of agreement brings to the field, in particular when evaluating its successes, which given the potential for misnaming KM; “...makes it likely that any overall evaluation of KM from whatever source, is inaccurate”.

The difference between traditional training manuals and apprenticeships, however, lies not with the means of implementation but in the strategic approach to its management. Thus the goal is not just to promote learning, but for learning to provide competitive advantage. Thus the key differentiator of KM represents its strategic role within the business. It is against this that its success should be measured: after all if an activity provides no discernible benefit what is the reason for its implementation?

### *3.2.2 The Knowledge Based View of the Firm*

The so called “knowledge-based view of the firm” [KBV] is arguably one of the major cornerstones to the underlying theory behind KM. In this section the origins of this perspective, dating back prior to the advent of knowledge theory will be presented. The intention is to demonstrate the changing and rising appreciation of knowledge in the academic view of the firm and underpin the rationale for KM. In the following section the practical implications will then be discussed demonstrating the application of this knowledge theory to the firm.

In 1959 Edith Penrose (1914 –1996) published her book “The Theory of the Growth of the Firm” (Penrose, 1959). She espoused her belief that a firm’s growth was dynamically constrained by the availability of human resource, founding the concept of the resource-based view of the firm [RBV] (although this term would not be applied until 1984).

The Penrosian view of the firm was of an administrative body with control over firm specific or unique resources, described as “a collection of individuals who have experience working together” (Penrose, 1959). While studying oil companies in Iraq, Penrose had observed that in trying to grow, firms were limited by the availability of these unique resources – those employees ‘tied’ to the firm through experience. Recruitment of new employees was possible but they would not become effective resources instantly, thereby creating a natural limit to the rate of the firm’s growth.

Penrose then extended this theory of growth to suggest a relationship between a firm's resources and its competitive advantage (Kor and Mahoney, 2004). She argued that it was the aim of managers at all times to generate growth[3] by maintaining competitive advantage through the *efficient* use of these resources and not necessarily the employment of more resource. This perspective challenged the established view of a firm's resource as labour, capital, and land.

In 1984 Wernerfelt published his now critically acclaimed paper entitled "The resource-based view of the firm" in which he furthered Penrose's arguments (Wernerfelt, 1984). Wernerfelt argued for a need to view the strategic capability of firms, not from the perspective of their products, but from their resources, or as Connor (1991) phases it "costly to copy attributes". An effective growth strategy he argued consisted of a balance between development of new resources and the exploitation of existing resources. While this may seem unimpressive and less than ground-breaking at first, it is a markedly different approach to traditional strategies.

Of relevance to the research here is the continued evolvement of what constitutes a firm. Wernerfelt furthers Penrose's view of a firm as a set of unique resources but lists a much wider set of resources: "brand names, in-house knowledge of technology, employment of skilled personnel, trade contacts, machinery, efficient procedures, capital etc." (Wernerfelt, 1984). This view in turn provides the foundation for the rising appreciation of knowledge.

In the early 1990s several papers raised the issue of distinct resources, not as tangible assets, but intangible assets. Described by Connor (1991) as follows:

> *"...inputs that cannot be purchased, such as learning-by-doing and organizational culture are, on average, likely to be more specific to the firm than purchasable inputs and hence have the potential to be the more specific rent-generators."*

[3] Penrose assumes equivalence between growth and profits, a view discussed in depth in Jacobsen JACOBSEN, L. (2008) Another 'Final Word' on Penrose". *The History of Economics Society's Annual Meeting.* Toronto, Canada.

Pralahad and Hamel (1990) published their article on Core Competencies – approaching the subject from the perspective of organisational capability (this is discussed and applied in section 5.2). Finally in 1996, Grant (1996c) advocated the idea of a firm as an "institution for integrating knowledge" arguing for a new "knowledge-based view of the firm" [KBV].

The RBV of the firm had acknowledged the role of knowledge in the company as a resource but only as a generic one. Advocates of the KBV argued that Knowledge is *the* strategic differentiator embedded throughout the organisations, culture and identity, routines, policies, systems, and documents, as well as individual employees (Grant, 1996c, Grant, 1996a).Following from the traditional RBV of the firm as one intent upon efficiently managing resources, the KBV describes the primary role of the firm as the "integration of knowledge" (Grant, 1996a). Importantly therefore it is not the knowledge that a company possesses, but the ability to effectively apply its knowledge (to create competitive advantage) and to generate new knowledge from its existing knowledge assets (Alavi and Leidner, 2001). This new theory of the firm therefore calls for the need to manage not a company's physical assets, but rather a company's knowledge. The wider backdrop to this theory is the so called 'social evolution' – as Drucker (2007a) terms it – of the working class. The rapid decline of the blue collar worker has given rise to the so called knowledge worker, established in the new post-industrial 'knowledge-based economy' (Brint, 2001, Bell, 1974). However, which came first – the knowledge worker or the knowledge economy – resembles the classic chicken and egg paradox.

The above introduction and discussion has been noticeably orientated towards academic study and debate. Today it is widely accepted that we reside within a knowledge-orientated society and that this new economy requires new approaches and strategies for businesses to operate effectively. It is less clear, however, what strategies businesses should take in this new economy. The practical implications of this evolving environment will therefore be discussed in the following section.

### *3.2.3 The Motivation for Knowledge Management*

A critic would argue that despite the evolution of different views of the firm and the advocacy of knowledge as a competitive advantage, the nature of business has changed little. Drucker (2007a) argues that a business comprises just two activities, marketing and innovation – described as understanding customers' needs and innovating a means to profit from this need. The 'new' knowledge theories do not appear to change this. What then is the motivation for KM – why should businesses care?

It is the means by which they generate profit that has changed. Two different arguments can be given. Fundamentally they are the same, but with differing perspectives. The first is the practical, ground level view, the second a higher macroeconomic perspective of a business.

First the ground level view. Grant (1997) approaches the question in his 1997 paper "The knowledge-based view of the firm: implications for management practice". Grant argued that, while executives have acknowledged the role of capabilities to generating competitive advantage, the KBV provides the "microstructure". True, businesses generally still exist to achieve the same aims – market and innovate in order to profit. They provide a product or service and charge an appropriate price dependent on the value added by the business. The key question is how to add value.

Tapscott et al. (2000) stated that increasing wealth can be achieved by "adding knowledge value to a product or service through innovation, enhancement, cost reduction or customisation", while Edvinsson and Sullivan (1996) listed sources of value from knowledge as: "Innovation, complementary business assets, processing, distribution, finance, sales and purchasing" and suggested conversion mechanisms such as sales or integration with the existing business.

There are many complex means of leveraging knowledge to gain these benefits. On a practical level they can be summarised in some basic examples:

1. Reuse of prior knowledge to a similar application removing costs of rework or reinvention.
2. Use of existing knowledge to exploit a new opportunity.
3. Use of experiences or lessons learnt to avoid repeat errors.
4. Use of captured knowledge to improve services and processes.

It should be stressed, however, that a true knowledge-orientated company is geared very differently to that of a traditional organisation. The culture and approaches taken will be very different and this goes beyond the tangible examples given. It also important to highlight the increasing returns offered by knowledge-based products and services. Once innovated that value is never lost when shared or used – if anything it is enhanced, as argued by Nonaka and Takeuchi (1995).

To add value, the question must be asked – what is the customer purchasing? It is never 'a product' but what the product can do for them (Drucker, 2007b). Stewart (1997) suggested that the true importance of knowledge can be shown by 'following the money' trail which inevitably leads to knowledge, citing examples such as the steel plant which completely computerised its processes allowing low volume production of unique alloys. The steel produced has become highly knowledge-orientated. It is not the raw materials that represent the primary cost but the cost of knowing how to manufacture the unusual alloys. The company is successful because it leverages this knowledge quickly and efficiently without lots of experienced workers.

From the customer's perspective it too is not just buying material. Common steel alloys are manufactured in bulk and could be purchased at lower costs. But here the value to the customer is in obtaining the specific alloy they need, reliably and at a lower cost than those made using traditional 'hands on' methods.

Viewing the argument from the other, wider economic, side of the coin, it is argued that knowledge as a business's most important asset is reflected in stock market evaluations. Increasingly, companies are valued significantly higher than sum of their tangible assets (Truch, 2001). The effects of this are exemplified by the "dot com" bubble. This additional value is termed the company's intellectual capital and is increasingly being valued and accounted for by companies, as illustrated in Figure 14.

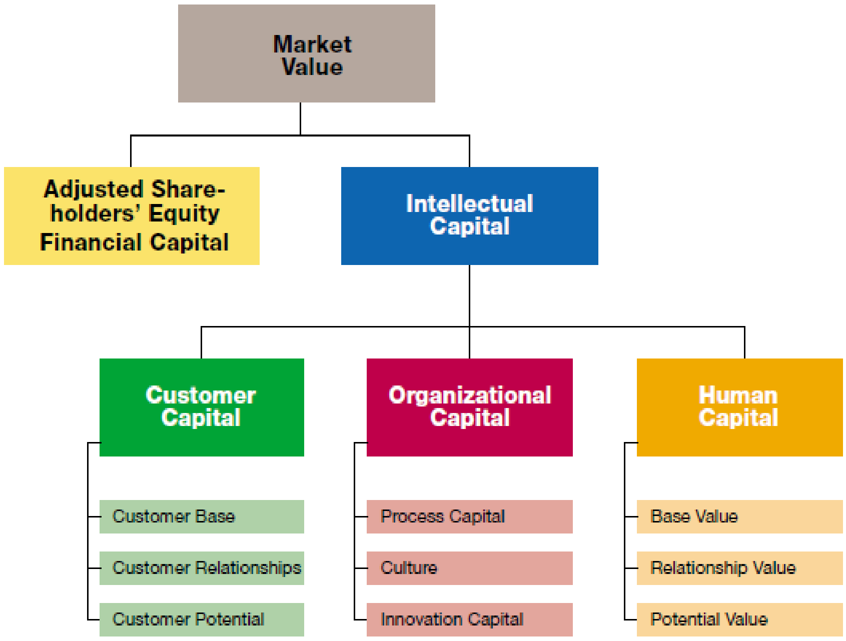



*Figure 14: Financial and intellectual capital (Pierce, 2001a, Skandia, 1994)*

This is also highlighted by the rise in research trying to measure the intellectual capital in business, typically pursued by Scandinavian companies, notably Skandia (Edvinsson and Sullivan, 1996). Skandia defines intellectual capital as "the possession of knowledge, applied experience, organizational technology, customer relationships and professional skills" (Edvinsson, 1997). The argument is that a large proportion of resource is invested in improving company knowledge, but this investment is not reflected on the balance sheets. Skandia therefore devised the Skandia Navigator to assess both the financial and non-financial measures of the business – this will be discussed in more detail in section 3.7.4.

As a simple example, if a new company was established and populated with equivalent equipment, employees and finance to Microsoft, could this new company produce a product to compete with Windows? The answer would be no. Microsoft as an organisation has additional knowledge associated with it, generated and learnt over time which it can utilise to generate a better product.

Ironically, at the time of writing, Google has recently announced its entry into the Operating System [OS] market (Pichai, 2009). In the author's opinion this will be a fascinating demonstration of the application of knowledge. Windows XP performed most of the tasks needed by its users. The subsequent Windows release (Vista) was slow to impact the market – particularly with upgrades (Janco Associates Inc, 2009) . The author would argue there was not sufficiently new functionality offered or needed for customers to want to upgrade.

It is also unlikely that Google will develop a significantly different product to Windows as it isn't required. Furthermore, anything produced would need to maintain compatibility with other products. Google must therefore believe it can sufficiently leverage its knowledge and experience in producing other applications (notably its browser Chrome which the system will be heavily based upon) to produce a product capable of competing with Windows, by being a better product. If this occurs, it will have demonstrated a failure on Microsoft's part to have strategically managed its knowledge base to maintain an advantage over its competition.

In some respects, Microsoft has been trying to address this very threat with Windows 7. Microsoft notably released versions to key development companies early in the development cycle, engaged in a very proactive customer feedback programme and spent a large amount of time implementing a more responsive and leaner system. Writing in the autumn of 2009 it remains to be seen if these steps have been successful.

### 3.2.4 The potential impact of mismanagement

The cost to a company of failing to manage their knowledge can be significant, impacting the company in three ways:

- The increased cost and time of searching for information required.
- The cost of intellectual rework and the opportunity loss to the enterprise.
- The damage and impact caused from decisions based on erroneous or incorrect information (Feldman and Sherman, 2001).

This demonstrates the need for a robust integrated KM strategy – a strategy integrated with the company's existing workflow and culture. This is particularly important in engineering, where innovation is key to a company's growth, and the impact of erroneous or incorrect information can be catastrophic.

Companies are also being driven to manage knowledge more proactively, not through strategic desires to generate greater competitive advantage, but simply to maintain and safeguard their existing intellectual property and knowledge base. This has been driven by the aging workforce and compounded by greater mobility in the job market. Employers no longer employ staff for life and conversely many employees are just as ruthless when assessing prospective employers (Truch, 2001). Over the period 1996-2001, the percentage of employees in the same job as 12 months ago fell from 90% to 87% (Macaulay, 2003). The result is a need for companies to capture, insure and manage their existing tacit knowledge – Knowledge Management.

An often quoted example of information mismanagement is the Tacoma bridge disaster. During the early 19$^{th}$ century, many new bridge designs were conceived such as the Maidenhead Railway Bridge, and early suspension bridges such as the Clifton Suspension Bridge. After several collapses of suspension bridges, extensive work was undertaken to better understand the effects of wind on structures. This culminated in Melais' 1888 Deflection theory and was improved in the 1930s by Moisseiff, Bleich and others.

Despite these theories the Tacoma Bridge was built without any of the recommendations in the work, resulting in the catastrophic collapse of 1940. Clearly the knowledge and understanding that could have avoided this collapse was not used. Primarily this was because it was felt that the work did not apply (Horton and Lewis, 1991) because the bridge was significantly larger than anything built previously and no effort was made to enquire or consult if this scaling would have an effect.

This demonstrates the importance of not just storing knowledge but ensuring its deployment and use in the correct situation. If knowledge is not correctly targeted, it will not be used and the knowledge must be reusable to be of any value.

The case also highlights the importance of human consultation during problem solving. In this case, the designers could easily have consulted experts within the field such as Moisseiff et al but did not. Despite the current advances in data storage, media and computational power, utilising experts is still vital and must form a component of a knowledge strategy (Hahn and Subramani, 2000).

### Summary

This section presented a brief overview of the origins and evolution of KM, highlighting its rapid growth during the 1990s. In particular, emphasis was placed on the evolving perspective of the firm with respect to knowledge and its importance to a firm.

In any field there are many different strands of research and KM arguably encompasses more than the average. Here the underlying theory behind this research has been presented. Having established a theoretical base, the following sections will build on the different strands relevant to the research.

## 3.3 The Nature of Knowledge

Epistemology – "the study or a theory of the nature and grounds of knowledge" – has existed for thousands of years, originating in ancient

Greece (Merriam-Webster, 2009). This study has spawned countless philosophical debates on what is knowledge and what it means to 'know'. Key theories and their advocates range from Plato's dialogue "Theaetetus" distinguishing between true belief and knowledge (Plato, 2008) to Popper's Evolutionary Epistemology, applying the laws of evolution to knowledge and scientific theory (Popper, 1979).

Leaving aside the philosophical debate as the interest here is in implementation, it is important to attempt to define and characterise what knowledge is. This section will present a brief view of some proposed descriptions and classifications of knowledge, examining in detail three of the commonly used distinguishers. The final section will also discuss the concept of knowledge generation and the summary will highlight the position taken in this research on the different forms of knowledge.

### *3.3.1 Classification of Knowledge Types*

In traditional epistemology, knowledge is born from the perception by humans of external objects (Nonaka and Takeuchi, 1995), the theory identified three forms of knowledge(Musgrave, 1993):

- Knowledge of things and objects.
- Knowledge of how to do things.
- Knowledge of statements or propositions.

More modern classifications have attempted to define knowledge differently, in terms of its context or role. Blumentritt and Johnston (1999) present several ideas, such as Lundvall (1996):

| | |
|---|---|
| Know-what | Knowledge about facts that can be broken down and easily codified |
| Know-why | Knowledge about principles and laws |
| Know-how | Skills, the capability to undertake a given task successfully |
| Know-who | Information about who knows what and who knows how to do what. |

This particular method of classification provides an easy working approach to describing the knowledge captured. It does not describe the nature of the knowledge however. Fleck (1997) classifies the knowledge types according to their physical embodiment or existence (the method of storage or codification) resulting in the breakdown as follows:

| | |
|---|---|
| Formal knowledge | embodied in codified theories and formulae |
| Instrumentalities | embodied in tools and instruments, learnt through practice |
| Informal knowledge | embodied in verbal interaction, rules of thumb, tricks of the trade |
| Contingent knowledge | embodied in the specific context; distributed / trivial information |
| Tacit knowledge | embodied in people, rooted in practise and experience |
| Meta-knowledge | embodied in the organisation, general culture such as values |

While these definitions can be a useful method of categorisation to study the forms of knowledge, it does not lead towards a natural strategy for managing the knowledge. In the author's opinion none of the above categorisations are either satisfactory or all-encompassing in their own right. This is to be expected given that knowledge can be classed according to its subject, its use, its location, its form and its creation. There are of course differences between knowledge of what something is and how to do a task, but when we are considering its management, the primary questions should be what is it, where is it, can we share it and how can we create more?

There are three distinguishing categories that are important. The first is Tacit vs. Explicit distinction introduced by Polanyi (1966) – the extent to which we can transmit the knowledge. The second is Formal vs. Informal – a distinction formed from the level of structure embodied by the knowledge. The third is the distinction between Personal vs. Corporate knowledge – where the knowledge resides. There are many more different classifications, such as Process vs. Objective knowledge, but the three above represent the most important measures for those wishing to manage the knowledge. These three classifications will be detailed in the subsections below, followed by an introduction to the theory behind knowledge generation.

### 3.3.2 Tacit vs. Explicit Knowledge

The distinction between tacit and explicit knowledge is one of the most important and useful distinctions when considering Knowledge Management.

Explicit is the more easily defined category, usually described as knowledge that can be taught, articulated, codified, stored and readily transmitted. Tacit knowledge is ironically more difficult to describe, but its concept is clear. It is the additional personal or context driven 'knowing' that cannot be easily articulated (Nonaka and Takeuchi, 1995). McAdam, Mason and McCrory (2007) produced an insightful study of the perceived interpretations of the term "tacit knowledge", where they conclude that it is typically "individualistic", "organisationally based" and directly related to skill and learning.

The seminal work on tacit knowledge was by Michael Polanyi writing in *Personal Knowledge* (Polanyi, 1958) and *The Tacit Dimension* (Polanyi, 1967). Polanyi's starting principle was that "we can know more than we can tell" citing our ability to recognise faces better than we can describe someone's appearance. Since then there have been vast discussions on the ideas forwarded by Polanyi and the synonymous ideas of Simon on bounded rationality (Miller, 2008).

In KM, the traditional focus was primarily on explicit codified knowledge (McAdam et al., 2007). Systems were constructed primarily to capture codified knowledge (either in automated systems or databases) and redistribute this knowledge.

Tacit knowledge is now being viewed increasingly as the more important resource Grant (1996b). Howell (1996) stated:

> *"Just as technological innovation up until the 1960s was treated as an unexplained variance in economic growth and performance, so tacit knowledge as an element within technological innovation has, until recently, been seen in a similar way".*

This has led to different approaches, utilising information technology systems not to store and house knowledge, but to facilitate communication and its access to experts, an approach often called Personalisation (as opposed to Codification) (McMahon et al., 2004).

Both forms of knowledge (tacit and explicit) are now recognised as being crucial to a company and both must be accurately managed as part of the knowledge strategy. However, by its very definition management of tacit knowledge represents one of the most challenging tasks of knowledge management.

### 3.3.3 Formal vs. Informal

Following closely to the personalisation and codification classification is the view presented by Hicks et al. (2002) that argued information and knowledge can be classed as “formal” or “informal”. Formal is described as knowledge (or information) with specific structure or context, such as text “logically constructed to convey the context or subject” or verbal explanations (Hicks et al., 2002). Informal is described as unstructured text or conversational verbal dialogue. As an example a database would represent a formal method of record, while a memo or e-mail would be more informal. Having no predefined structure, a user would need to read an e-mail all the way through to understand.

This classification ties in closely with personalisation and codification. The instinct is to describe codified knowledge as formal, but this would be incorrect. Not all explicit knowledge is structured. For example, engineers’ logbooks contain large amounts of explicit knowledge, with little or no structure and therefore remain informal (McAlpine et al., 2009).

When using common terms to describe precise definitions, there also exists literature with a different interpretation of the terms, such as Kaye (1995). Kaye describes formal and informal sources along the traditional definition of the terms, as ‘impersonal’ or ‘personal’. During this research, however, the above definition will be taken.

There has been research into managing both formal and informal knowledge. Naturally from an IT perspective, formal is the easier to manage, but it is argued that informal documentation is underrepresented, often containing rich knowledge which is rarely accessed (McAlpine et al., 2006).

### 3.3.4 Personal vs. Corporate Knowledge

This final classification addresses the location of the knowledge, and also subtly the embodiment of the knowledge. The concept of a person's knowledge is common and familiar to most people. As described above, in traditional epistemology knowledge was inherently perceived as distinct to a person. Yet since the very origins of Knowledge Management theory, practitioners discussed and approached the concept of organisational or corporate knowledge (Davenport and Prusak, 1998). That is, as Wiig defines it "The knowledge and understanding embedded in an organization's people, processes and products or services, along with its traditions and values." (Wiig, 2006). This knowledge differs to individual knowledge, as it cannot be replicated outside of the company.

As an abstract example, imagine four companies all manufacturing similar products, with each company consisting of four engineers A to D. All the engineers have similar jobs ($A_1$=$A_2$, $B_1$=$B_3$ etc). If we were to take the best engineer for each job (one from each company for example) and produce a new company, consisting of say, $A_3$, $B_2$, $C_1$, $D_4$, it would be expected that this company could produce products better than any of the previous companies could, but in reality this is highly unlikely because of a lack of organisational knowledge. The four engineers would need to learn to work together and develop a set of new processes for the business. While they each have experiences from their previous businesses, they may not be relevant or may not be applicable in their new role as the context, processes and colleagues have changed. This has a direct influence on the growth of SMEs, in which much organisational knowledge is lacking at the start. While clearly not the only factor, this effect contributes to a natural limit on the growth of small businesses.

It is important to highlight, as Nonaka and Takeuchi (1995) point out, that the company still relies on the individuals to create and generate (see below) the organisation's knowledge, but their view is of a transformation from personal knowledge to organisational knowledge through its application and use.

Management of corporate knowledge has been approached from a variety of perspectives, including those concerned with measuring intellectual capital, generating knowledge or utilising an individual's knowledge for the benefit of the business (Wiig, 1997a). However, Tumoi (2002) points out the majority of research into organisational cognition concluded that it is not possible to objectively codify and store organisational knowledge. What is important however is that organisational knowledge is managed from a global level – for example ensuring that short term efficiency gains from redundancy do not cause a long term reduction in effectiveness from a loss of organisational knowledge. It is also important that individuals are strategically managed to ensure a progressive organisational knowledge base.

### *3.3.5 Knowledge Generation*

Knowledge generation occurs through two different actions, internal generation or external acquisition. The first is the more typical and 'default' approach, as companies generally accrue knowledge through their activities. Occasionally it is necessary or beneficial to acquire it from other, external sources as with any other commodity. Innovation is about time; if it will take too long to generate internal knowledge and competencies then it becomes necessary to acquire this competency externally. These two approaches are described below.

#### Internal Knowledge Generation

The definitive work on knowledge generation is the universally acclaimed (Google lists 17,000 citations) book "The Knowledge Creating Company" by Nonaka and Takeuchi (1995). This book was arguably the first book to highlight the importance of managing the generation (as opposed to the storage of) knowledge. Specifically the authors argued that generation within an organisation relied on the interaction with its tacit and explicit knowledge, its manipulation (from tacit to explicit termed as externalisation) and its application to new problems.

Nonaka and Takeuchi (1995) describe this process as a continuous spiral through which the "old self" is transformed into a "new self" by acquiring new context, illustrated in Figure 15.

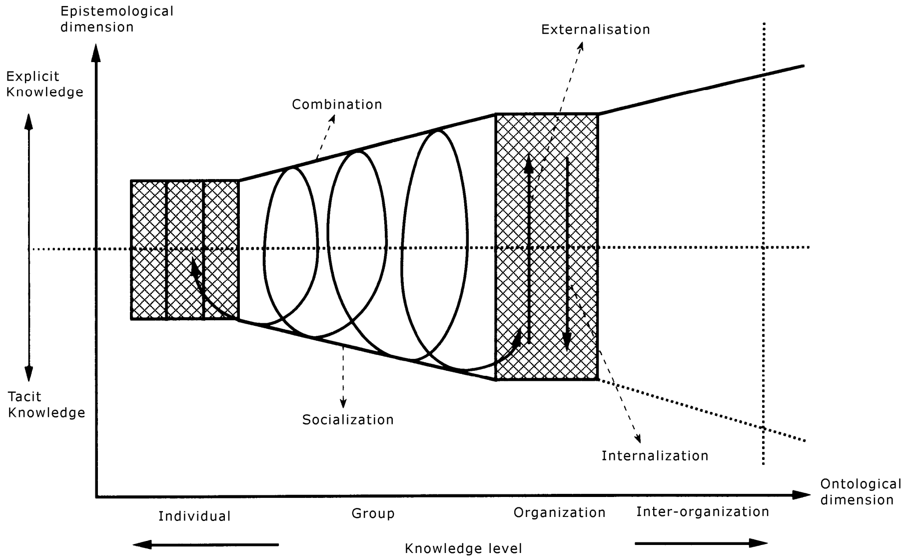



*Figure 15: Nonaka and Takeuchi's illustration of organisational knowledge creation (1995)*

Sena and Shani (1999) further discuss the ideas of knowledge generation. However, they question whether knowledge generation can actually be managed explicitly. Knowledge generation cannot be 'caused'; however, a healthy environment to support knowledge use (and as Nonaka and Takeuchi suggest, knowledge generation) and its sharing can be created through proactive management.

For this project, the objective is to support knowledge reuse, and knowledge generation will be seen as a consequence of that. The alternative to internal generation, knowledge acquisition, is described below.

**External Knowledge Acquisition**

Some companies now realise that the originality of knowledge or ideas matters less than its usefulness. Indeed British Petroleum offered a "Thief of the Year Award" specifically awarded to the employee who has "stolen" the best ideas in application development (Davenport and Prusak, 1998). A study by Cohen and Levinthal (Cohen and Levinthal, 1990) described a company's ability to use external ideas as its "absorptive capacity". Interestingly the study found that the main activity of research departments was as a result of using knowledge external to the department, rather than as a result of the researchers conducting their own experiments.

Many companies acquire knowledge tactically by purchasing it directly. The most effective is to hire experts, bringing their expertise into the company. The alternative is to purchase it via acquisition. In 1995 IBM purchased Lotus for $3.5 billion, fourteen times its book valuation. This decision was not driven by the potential revenue from its sales but from an appraisal of Lotus' unique knowledge of software applications – in short the company's expertise (Davenport and Prusak, 1998).

This was also the driver for EL Products purchase of Grimes, both manufacturers of lamps. EL Products wished to improve its product line by employing the advanced expertise and knowledge of Grimes to design and produce a better lamp. An improved lamp was introduced, but the process was a failure. EL Products had failed to realise that the key knowledge needed to produce the lamp was held by the Grimes' employees, who were not transferred with the purchase; thus the knowledge to produce the lamps was not transferred and production failed (Davenport and Prusak, 1998).

The precise mechanisms and support for knowledge generation are beyond the scope of this thesis. Knowledge generation has and will continue without needing support from the researcher. The key point here is that generation within a company pivots off prior and existing knowledge. It is therefore vital that companies not only maintain their existing knowledge, but actively use and reuse their knowledge in order to generate value.

### Summary

This section has introduced some of the key descriptors and classifications of knowledge that will be used throughout the remaining research. The relevant background theories and research on the descriptors have been briefly mentioned and the position taken here towards these forms of knowledge have been highlighted.

This section has introduced some of the key descriptors and classifications of knowledge that will be used throughout the remaining research. The relevant background theories and research on the descriptors have been briefly mentioned and the position taken here towards these forms of knowledge have been highlighted.

The final subsection addressed the theory of knowledge generation. Knowledge generation could be discussed in an entire chapter but it is not necessary here however. Therefore the two mechanisms have simply been presented including a description of Nonaka and Takeuchi's knowledge spiral theory. This section represents a conclusion of the more theoretical discussions of Knowledge Management. The subsequent sections of this chapter will therefore address the implementation and activities of Knowledge Management.

## 3.4 Activities of Knowledge Management

This section will introduce and detail the primary activities of Knowledge Management, beginning with an overview of the primary strategies before rapidly selecting and describing in detail the approach most relevant to the research presented here. The section concludes with a discussion on developing a strategy for a business.

To clarify the terminology used in this section, a Knowledge Management *strategy* will be considered as the company's tactical use of one or more different *methods* to manage knowledge. A method will be considered as a subclass of a strategy, each supporting different *activities* such as knowledge generation, or reuse.

### 3.4.1 Global Differences in Knowledge Management

Many different approaches can be taken in Knowledge Management to achieve a variety of different aims and objectives. Takeuchi (2001, reviewed in Lloria, 2008) identifies divergent approaches taken by different countries (or more accurately cultures). European countries have typically focused on the measurement of knowledge as intellectual capital and a corporate asset. For example the development of the Skandia Navigator (Edvinsson and Sullivan, 1996, Edvinsson, 1997) was designed to manage and report on the company's intellectual capital in its annual report.

The exception to the European approach is the UK, which tends to pursue the more proactive management of knowledge taken by the USA. Takeuchi argues that the USA, more so than other countries, has led the adoption of information systems to effectively manage and in particular codify a company's knowledge base.

The Japanese emphasis differs again, more often focusing on the repeated generation and adoption of knowledge within a company as exemplified by Toyota's Knowledge Management practice (Sanchez, 2004). Whereas the western Anglo-American approach focuses on technology as the basis (or facilitator) for change, the eastern approach emphasises the people and culture as the primary mode of change. Ironically, a project needs elements of both approaches for successful adoption and benefit. As Davenport and Prusak (1998) point out "The mere presence of technology won't create a learning organisation" and it will also need elements of measurement to ensure continued success and improvement.

In the research presented here, the requirement is unambiguously to manage the business knowledge base, and to minimise potential knowledge loss from a leaving expert. Therefore, the Anglo-American approach will be used here, accepting the caveat that no single method should be taken in isolation.

### *3.4.2 Knowledge Management Strategies*

It is often useful to break down and segment the activities of Knowledge Management into a consistent framework, either to support a general methodology or simply to present the different approaches in a consistent and structured manner.

Heisig (2009) describes frameworks as either prescriptive, implementation-orientated frameworks – effectively a methodology to support adoption as described in Lovett et al. (2000) – or descriptive, more theoretical frameworks characterising the different attributes of Knowledge Management, such as the work by Holsapple and Joshi (1998). Here the term framework will be taken as the definition given by Weber et al. (2002) as “a holistic and concise description of the major elements, concepts and principles of a domain”, thereby representing the descriptive framework described by Heisig.

Many organisations and much research have attempted to create ‘the’ framework prescribing the essential elements of Knowledge Management (Holsapple and Joshi, 1998, Hahn and Subramani, 2000, Griffiths and Remenyi, 2008). However, given the wide domain and range of requirements for Knowledge Management, no single framework is likely to satisfactorily encompass all activities and issues.

Here, two frameworks will be presented in brief: Nonaka and Takeuchi’s classic model and Hahn and Subramani’s developed model.

The first, Nonaka and Takeuchi’s classic model, shown Figure 16, is possibly one of the most widely quoted of frameworks. Developed in the early 1990’s at the outset of Knowledge Management, the model tries to define a structure for managing tacit and explicit knowledge using different methods of knowledge transfer such as codification (termed externalisation here). The eastern emphasis on knowledge generation and individual learning is clearly apparent in the different methods described.

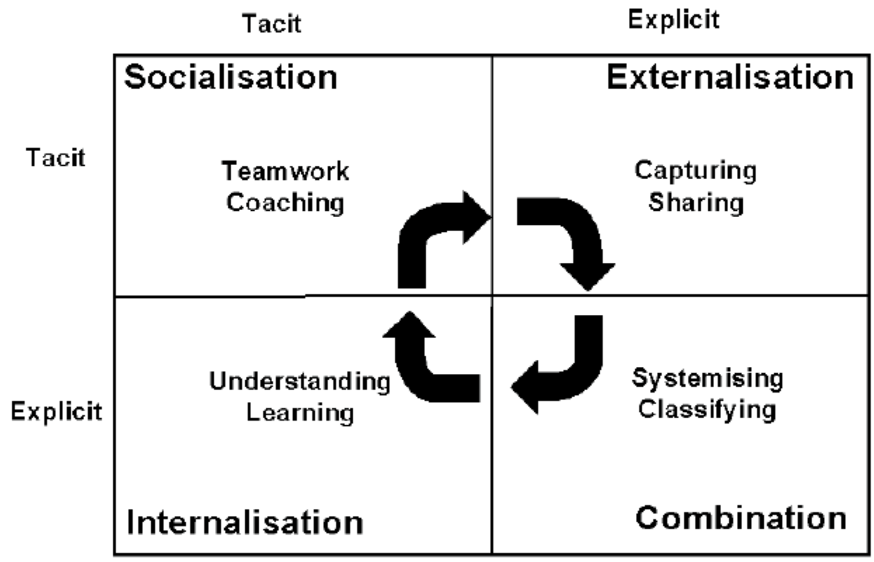



*Figure 16: The Nonaka & Tekeuchi framework of knowledge transfer (Nonaka and Takeuchi, 1995)*

Nonaka and Tekeuchi illustrate the different methods used to convert between tacit and explicit knowledge, and the assumed reuse of knowledge. These are:

- Socialisation: The process of converting new tacit knowledge through shared experiences such as apprenticeships.
- Externalisation: The process of articulating tacit knowledge into explicit knowledge.
- Combination: The process of converting explicit knowledge into more complex and systematic sets of data.
- Internalisation: The process of embodying explicit knowledge into tacit knowledge.

Although the model provides a useful framework for a knowledge sharing strategy, Nonaka and Takeuchi's theory is now heavily criticised as being over simplistic (Suresh, 2007). No distinction is made on the nature of the knowledge, how it is to be deployed and whether it is even possible to modify or convert between tacit and explicit.

The reality is that there are many facets to knowledge and, as illustrated before, many ways to classify and define knowledge. This has generated a variety of avenues that envisage to utilise this capability ranging between extremes of codification and personalisation (McMahon et al., 2004).

The second framework (shown in Figure 17) proposed by Hahn and Subramani (2000) furthers the approach by Nonaka and Takeuchi but defines more rigidly different methods and tools that can be used. It can still be subjected to similar criticisms and remains an extremely simplistic representation of knowledge. However, the framework accounts not just for the location of knowledge (described as Artefact or Individual) but also the level of structure – formal or informal. This therefore corresponds to the classifications of knowledge described in section 3.3.The framework therefore represents a more relevant tool when considering what knowledge is available and how to convert and use it.

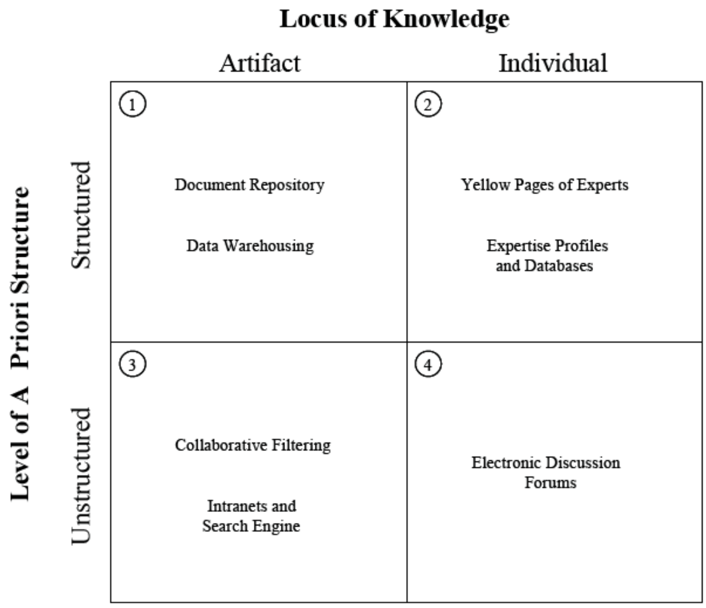



*Figure 17: Knowledge Management model developed by Hahn (Hahn and Subramani, 2000)*

Here there are four types of systems and methods described:

- Cell 1, document repository and data archiving. This is a non-human approach intended to store and index documents and data in a structured form. This primarily drives objectives 1, 2, and 4 (from the SECI model). The utopia is the creation of a single robust storage system allowing easy access and searching as well as providing a means for quantifying and managing the data. This method is limited, however, to documents and data that can be coded and stored. It is also debatable as to whether it is knowledge or simply data that is being stored.

- Cell 2, often termed as hard wiring individuals (Hahn and Subramani, 2000) accepts that certain knowledge resides in individuals but that the individuals themselves may be structured. If a metaphor for Case 1 is a library then Case 2 may be represented as the Yellow Pages (Davenport et al., 1997).
- Cell 3, Intranets and Search engines. The web best exemplifies this method of storing data. Here intelligence is invoked during the *request* for information. Documents are stored unstructured, but intelligent search engines are still able to deliver targeted knowledge.
- Cell 4, Electronic Discussion Forums, one of the most epitomised uses of today's communication infrastructure. These facilitate interpersonal tacit-tacit discussions, but by using the forum a record is kept. Combined with a search engine, this can create a powerful tool.

Clearly neither of these two strategies encompasses all aspects involved within KM. Noticeably, neither framework addresses the level of automation involved in the codification strategies described. For example, in Cell 1 of Hahn and Subramani's framework, structured and codified knowledge can be stored as a knowledge database but knowledge can be structured and codified into an automated expert system which would still fall within Cell 1 yet is a markedly different approach.

Reflecting on this framework it can be argued that within the Anglo-American perspective the primary activity of Knowledge Management is to identify, transmit and reuse knowledge. These activities can be seen in all cells of the frameworks presented. Specifically however, the activities of Cells 1, 3 and 4 are not just to transmit or share knowledge, but to capture, structure or add intelligence to the knowledge so that it may be accessed and reused by many users and more accurately. Rouse et al. (1986) summarises this, stating that for [knowledge] systems to be useful, they must "record, organise, reuse and curate knowledge".

Earlier, a discussion was presented which argued that KM could occur without the use of information systems, but that for KM to be adopted as a deployable and valuable activity it must leverage the capability and benefits of modern computation technologies. It should be clear that to address successfully the activities described, different technologies and systems can be developed. These technologies and systems will be described in section 3.5.

### 3.4.3 Developing a Strategy

If Knowledge Management is to have an impact in the company, it must be successfully integrated to support the most critical aspects of the business. It is important therefore that the KM strategy is aligned to that of the business objectives. This presents a difficulty, given a company's business strategy may involve its current or future "game".  A company has two options: either to use its current business strategy to define what knowledge is needed (and how it should be managed) to make it successful or to define a strategy so as to best leverage its current knowledge base (Davenport, 1999).

Attempts have been made to create a formal process for a developing strategy, such as mapping the knowledge landscape, identifying gaps and addressing gaps. The majority of these appear to be involved with mapping relatively explicit knowledge, such as academic papers or patents using mathematical algorithms to create evolving schematics and maps (Boyack, 2004, Hellstrom and Husted, 2004).

To develop a strategy aligned to the business requires key choices such as (Davenport, 1999):

- Is tacit or explicit knowledge more important to manage?
- Which knowledge domain is most important to the firm – customer knowledge, competitor knowledge or product knowledge?
- Where does the knowledge environment most need improving – knowledge creation or knowledge reuse?
- Should the firm make or buy its knowledge in specific areas of the business?

- Which aspects of the firm's knowledge environment should be measured?
- How will the firm make money on its knowledge?

For example, Hansen et al. (1999) compare the two strategies of personalisation and codification adopted by different consulting firms. Randall Love is a firm specialising in the implementation of information systems, while McKinsey and Bain offer strategic advice and highly customised solutions.

Randall Love's codification approach provides value to the customer by supporting faster and cheaper repeat implementation, the reuse of knowledge saving work and allowing faster growth as the knowledge base expands. McKinsey and Bain's personalisation approach still uses some form of codification, but the primary source of knowledge is from colleagues. The personalisation strategy relies on channelling the correct expertise and in one-to-one sharing of knowledge. Value is generated by creating an environment of highly-trained experts able to solve complex problems.

Davenport et al. (1997) review a series of Knowledge Management projects and identify four broad types of objectives that appear repeatedly in projects. These are:

1. Creating knowledge repositories
2. Improving knowledge access
3. Enhancing cultural support for knowledge reuse
4. Managing knowledge as an asset

Although the paper does not discuss the objectives in detail, it does provide a succinct summary of common objectives observed in Knowledge Management projects. A knowledge strategy for a business will encompass one or more of these key objectives. The exact strategy is, however, dependent on the aims and objectives of the wider business.

### Summary

This section has provided the reader with a finer, more precise explanation of the actual activities of Knowledge Management. The difficulty throughout has been to describe the wide and extensive field of Knowledge Management in sufficient detail, concisely and without over-generalising. A broad global perspective of Knowledge Management was therefore provided in the first section highlighting the three main themes developed across the world.

In the second section the theme relevant to the work here was discussed in detail, with two frameworks presented to illustrate the various strategies and approaches that can be taken in Knowledge Management. Finally the last section discussed in general terms the difficulty of selecting a strategy and presented some of the key questions facing knowledge practitioners before summarising the common objectives for Knowledge Management activities.

## 3.5 Knowledge Based Systems

Knowledge-based systems [KBS] are a class of information technology systems used for managing a company's knowledge - to support the activities described above "record, organise, reuse and curate knowledge".

There exists a broad range of KBS which vary in scope and intelligence, from knowledge repositories, files and information often structured in a semi-intelligent manner, to expert systems, automated systems intended to replicate and/or replace human capabilities (Beckman, 1999). This section will introduce the common tools associated with KM and their typical applications or usage.

### 3.5.1 Introduction

The terms Knowledge Management and knowledge-based systems are often synonymous with each other. However, it should be clear that here KBS refers only to the system. Historically KM and knowledge systems have developed apart. Knowledge systems have developed with improving technical capabilities, such as the development of intelligent algorithms and increased computational power (Sandberg, 2003, Edwards, 1991). KM, however, has developed in response to the changing economy.

Expert systems originated in the mid 1960s as a branch of artificial intelligence systems intended to encapsulate human capability (Liao, 2005). These then developed into a range of different systems, one of which is described as KBS. Within this domain (computer science) a KBS is defined quite specifically and differently to a conventional software program. Traditional software encapsulates domain knowledge within the software program. In a knowledge-based system knowledge is separate. In the simplest KBS there are two modules, a “knowledge base” and an “inference engine”. The consequence of this is that the knowledge may be added or modified easily, in some instances by the inference engine itself (Hopgood, 2001).

Today the terms have become significantly blurred. Commonly the term KBS is seen as a catch all term for software systems directly addressing or storing knowledge, of which expert systems are now seen as a subset. This open terminology will be that adopted here, thereby including communities of practice and knowledge directories as a type of knowledge-based system. This allows for a more direct link between the knowledge strategy and the knowledge-based systems developed to support this strategy.

In the subsequent subsections, the following will be described: expert systems, and in particular the subcategories of ontologies and data mining, knowledge repositories, knowledge mapping or topographies, communities of practice and product lifecycle management systems. An illustration of some of these can be seen in Figure 18. Here CSCW is an abbreviation of computer supported collaborative work.

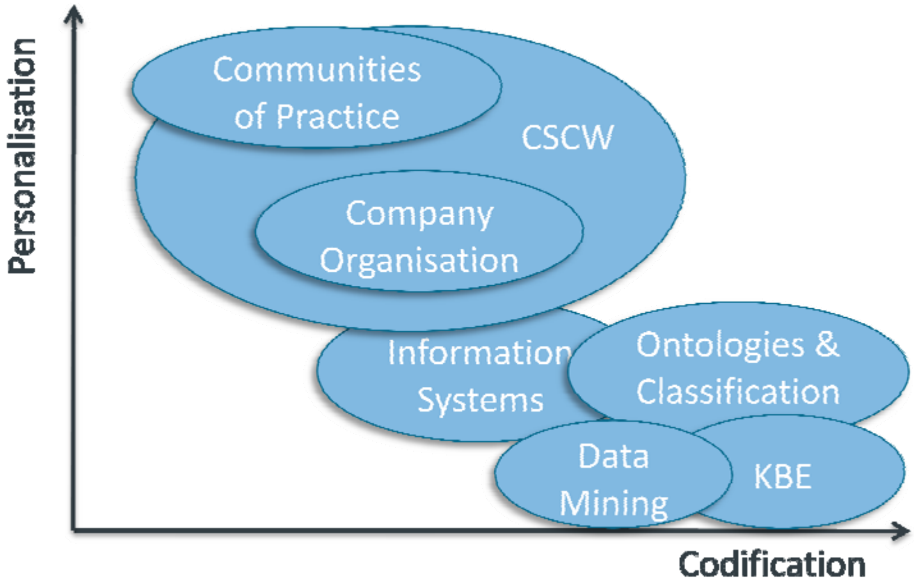



*Figure 18: Plot of different systems against the level of personalisation and codification involved, adapted from McMahon et al. (2004)*

### 3.5.2 Expert Systems

The traditional knowledge systems are described as expert systems. These are programs which "embody expertise in a particular specialised domain"(Hopgood, 2001) or "encapsulate human ability in a skilled activity, and [are] capable of applying this to support or replace human actions"(DTI, 1990). These can be targeted at design optimisation or problem solving environments.

During the early experiments with artificial intelligence (AI) dating back to the 1950s, from the mid 1960s to the mid 1970s – often referred to as the romantic period of AI – truly autonomous expert systems were widely thought to be feasible within a only few years (Jackson, 1999). History clearly shows the gulf between the perceived possibilities and the reality.

Early systems were doomed by their own goals, as they were developed as general-purpose problem solvers. They were found to be too weak, needed constantly updating and required a considerable amount of knowledge input. These developed into more specific problem solvers and have achieved greater success. One of the earliest systems was created by General Electric

(GE) in 1983 to reason the cause of fault in locomotives and was successfully adopted across all their repair centres (Turban, 1988).

Today, expert systems can be separated into a series of different types of systems. While Liao (2005) lists 11 types of expert systems, they can be summarised for brevity into three methods:

- Those that focus on knowledge representation, using ontologies to create reusable domain knowledge.
- Those that focus on intelligent mining of existing data, either using nearness searches such as case-based reasoning or more intelligent data mining methods.
- Those that focus on the elicitation and reasoning from knowledge, such as rule-based systems or fuzzy logic systems.

Rule-based and fuzzy systems are both decision making systems. Rule-based stores its knowledge as a set of rules: given input data, the system applies these rules to reach a conclusion. Fuzzy systems are similar, although they utilise fuzzy logic allowing for uncertainty in decision making more akin to the reasoning of humans. In engineering, rule-based systems have been adopted to support geometry generation. This will be discussed in further detail below.

### 3.5.3 Ontologies

Ontologies are a branch of expert systems which address very specifically the means for representing knowledge in an actionable format by creating a vocabulary to represent the knowledge. The term ontology is of Greek origin describing the study of being or of existence (Oxford English Dictionary, 2001). Once a knowledge base has been described in a language that can be interpreted, a reusable domain model can be created to utilise and communicate this knowledge (Liao, 2005).

A large quantity of research has been carried out in the field of ontologies, resulting in numerous studies and applications. One of the most common is the OWL language, which defines ontologies using classes, properties and instances and allows users to automatically handle web integration (Bandini et al., 2008).

The research and development of ontologies is closely linked to the development of the Semantic Web, the envisioned future of the World Wide Web, championed by Tim Berners-Lee et al. (2001). The core idea is that if knowledge can be represented in a form capable of being understood by software, it is possible to build intelligent systems to solve queries and problems themselves. For example if a user needed to know what time a store's opening hours were, in the Semantic Web this knowledge would be sufficiently codified for a software program to retrieve the times, because it would 'know' what 'opening times' represented.

Despite many successes, ontologies are hampered by the expertise required in establishing them. HTML (the language behind web 1.0) was sufficiently easy to interpret that a large number of people were capable of establishing basic web pages but ontologies are significantly more complex and may not offer the return on investment promised (Brewster and O'Hara, 2007). There is also the lack of requirement. The Semantic Web and its ontological foundations are capable of solving complex and multivariable problems. For the average web user however, this simply isn't required – at least not yet. Finally, despite the use of common languages such as OWL, which allows inter-ontology linking, there must still be common practices and definitions. These must be adopted and managed, not an easy task as the present web's explosive expansion has demonstrated (Shadbolt et al., 2006).

The result to date is that ontologies are and have been successfully implemented in a number of systems. However, these are typically well bounded domains and ontologies developed specifically for the domain. These problems also tend to be characterised by clear variables and repeating objectives such as exemplified in Bandini et al. (2008).

### 3.5.4 Data Mining

Data mining is an approach specific to eliciting strategic knowledge from large databases, often involving terabytes worth of data (Corperation, 2005). The term data mining applies to a range of tools that determine patterns and relationships within the data.

Data mining applies exclusively to numerical or boolean data, but a more recent development called text mining uses similar principles to determine patterns and structure within text blocks. Text mining has seen limited use within industry, but has been used in the field of literature to study book structures and test plagiarism claims.

Applications of data mining are naturally in codified and high volume environments, such as biomedical research (Hahn et al., 2002), where large scale DNA sequencing and systematic measurements of molecular interactions have created a vast influx of data that needs to be stored and analysed. Other applications include telecommunications, often extracting billing and usage information, or climate data, determining patterns to create more sophisticated models (Han et al., 2002).

Data mining offers very powerful methods of understanding often hidden contextual information, but referring to our definitions on knowledge it is a moot point as to whether knowledge is truly managed here or if it is simply analysing and outputting new information.

Data mining is in wide use across Rolls-Royce, but for the purpose of this project it is not relevant, the emphasis in this project being on low volume, tacit knowledge.

### 3.5.5 Case Based Reasoning

Case-based reasoning [CBR] differs to data mining, although both methods use intelligence to elicit knowledge from a database. In CBR, the emphasis is on retrieving the knowledge most relevant to a problem rather than generating new knowledge from across the knowledge base. This knowledge can then be utilised to minimise the re-work or even to guide development of a new solution.

Whereas data mining drew knowledge from across the database, arguably generating new knowledge, CBR simply retrieves knowledge. From one perspective therefore, CBR is again not a knowledge system but a structured search algorithm. Given the definition earlier though, it is a system designed to support the storage, retrieval and reuse of knowledge and therefore should be considered as a KBS.

### 3.5.6 Knowledge Repositories

Knowledge repositories are probably the most common type of system implemented to manage knowledge. They typically contain broad but structured explicit knowledge in document or data form. These have evolved from the earliest database computer systems to vast arrays of documents on company intranets. Documents are defined here as objects (electronic or otherwise) containing written prose providing information on a subject, but which importantly do not have any predefined structure associated with them such as reports or memos.

Care should be taken to differentiate here between knowledge repositories and document management. Document management is a similar concept to knowledge repositories, if not exactly the same. It is, however, not typically considered a Knowledge Management tool. The primary difference is the lack of knowledge generation in document management. Although documents may be organised, the aim is not to generate or elicit additional knowledge, but rather passively to store existing documents in a practical sense. They are not designed to support the retrieval or reuse of knowledge and will not be considered as a KBS.

Knowledge repositories represent an attempt to codify knowledge into a single point source for all of the domain knowledge 'known' by a company. Probably one of the key distinguishers of a repository is the level of structure and depth of knowledge held. Databases represent highly structured data.

Document repositories represent poorly structured information (often collections of reports). Knowledge repositories are intended to store knowledge with enough structure and context that knowledge can be readily found, but also understood without a large degree of time or prior knowledge required.

### 3.5.7 Knowledge Topographies and Directories

Topography means to describe the relative place or position of objects or features (Oxford English Dictionary, 2001). In KM, the term is used to describe the mapping or listing of key knowledge resources. A larger section is devoted to the discussion of knowledge mapping in section 5.2. Here, however, it will be described from the perspective of Knowledge Based Systems.

Described above in Davenport's Knowledge Management strategy as the Yellow Pages of experts, topographies or directories identify people with particular skills and knowledge. The systems do not contain any knowledge – they are simply pointers to resources.

The simplest system is a database of experts and their corresponding field of expertise. A user simply needs to search for the appropriate field of expertise and will be presented with a list of experts. The greater the depth of information in the database, the more powerful it is, for example including a person's depth of knowledge on a subject as illustrated in Figure 19.

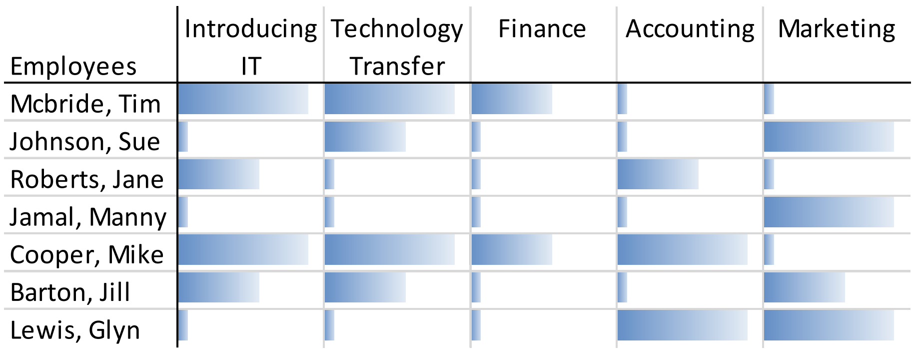



*Figure 19: A knowledge topography, adapted from Probst et al.*

In 1995 Microsoft launched a project called SPUD "Skills Planning "und" Development", to build a people-orientated map. It used a knowledge structure to evaluate employees in four key areas such as IT, each with their own sub categories. Each competency is completed to one of four skill levels, with clearly defined benchmarks for assessing. Thus a user can search for example, the top five personnel that have the competencies for a particular project in say the Washington area (Davenport and Prusak, 1998).

Rolls-Royce has, over the past three years, deployed a similar principle assigning employees skill levels between 1 and 4 in key areas. This occurs at department level as skill leaders identify the criteria of the different levels and department heads assign the levels accordingly. This allows the company to manage its skill levels in key areas, but it is not intended for inter-employee communication.

British Petroleum's virtual teamwork uses knowledge repositories together with novel technologies such as video conferencing to support distributed teams across the globe. The example cited by Davenport and Prusak (1998) is of a hardware failure on a drilling rig in the North Sea (1995). An expert in Aberdeen was contacted and the faulty equipment was placed in front of a video camera on a satellite uplink, allowing the expert to see the problem and talk the engineers through the solution.

Knowledge directories/topographies manage the use of tacit indirectly and do not capture knowledge or redistribute it. They facilitate access to the expertise and knowledge required and it ensures a connection between "islands of knowledge" potentially across geographical, corporate or team boundaries (Probst et al., 2000).

These are primarily suited for large and/or widely distributed companies and offer little benefit to small localised companies. They represent the extreme personalisation approach, with no codification of knowledge.

### *3.5.8 Communities of Practice*

Communities of practice (COPs) are traditionally self-organised groups of employees who shared common interests, aims or work practices (Davenport and Prusak, 1998). Communication between users is generally through technology driven means such as e-mail, or dedicated community programs such as Lotus notes. Users are able to share experiences with the group or request advice or solutions on problems.

Studies of the people in the workplace and their exchange of information have shown a large proportion of knowledge transfer occurs informally, in tea rooms and around water coolers. These inter-team discussions offer an opportunity for members of different teams to learn about the others' projects and are a valuable means of sharing knowledge.

The emphasis of COPs is on informal communication, building and improving relationships while sharing knowledge and solving problems. Over time the aim is for the community to develop a single identity unique to that COP and rich in knowledge (Enkel et al., 2000). In short they attempt to support geographically distributed users in communicating and sharing knowledge as richly and informally as at the water cooler.

The value of COPs has now been realised in many companies and often plays a key role in a knowledge strategies. Dedicated programs such as Lotus notes or web-based technologies allow past discussions to be stored and indexed, allowing new users to find previously discussed solutions or experiences, albeit on a 'pull' basis.

Like all personalisation approaches, COPs are limited by the people involved. Clearly it requires a large knowledgeable community to exist and one which is sufficiently trusting for individuals to feel they can share knowledge openly. It also requires individuals to use it. In fact, it is actually detrimental in the long term for users to bypass the community and speak directly to each other as no knowledge base will be established.

### *3.5.9 Knowledge Based Engineering*

In engineering, knowledge and knowledge-based engineering (KBE) is seen as a vital technology for the next generation of design. It is stated that KBE will have the same importance for companies in 2010 that CAE/CAD/CAM (Computer Aided Engineering, Design & Manufacture) had in the 1990s (Howard, 1998) and that dependence has shifted from "… a lot of material held together by a little bit of knowledge" to "…a lot of intellectual content in a physical slipcase" (Stewart, 1997).

Knowledge-based engineering systems were akin to the original expert systems described in section 3.5.2. The primary difference between the two is simply that in KBE systems are designed to develop and output geometry.

In the early days of AI and expert systems, programmers and engineers believed that intelligent systems held the key to engineering in the future. The concept was to create systems capable of solving design problems and tasks, but the results were disappointing (Sandberg, 2003). It was found that to solve anything particularly complex required an excessive amount of time programming in parameters and relationships; in short it was quicker to solve using humans (Sandberg, 2003). These projects suffered a problem with scope, as did the early expert systems.

The solution lay in dividing the types of problems into creative and routine work – using a computer's capacity for repetitive calculations to solve high volume numerical tasks and a human's creative and lateral thinking to develop new and original ideas (Sandberg, 2003). This is widely thought to support the accepted runner-repeater-stranger classification (Esain and Rich, 2006):

- Runners: products which exhibit a feature of consistent demand or volume which need to be produced to satisfy customer demand.
- Repeaters: products that are not consistent in their demand but display a pattern.
- Strangers: products that are rarely and unpredictably demanded by customers.

Thus the level of automation used would be inversely proportional to the level of unique expertise required.

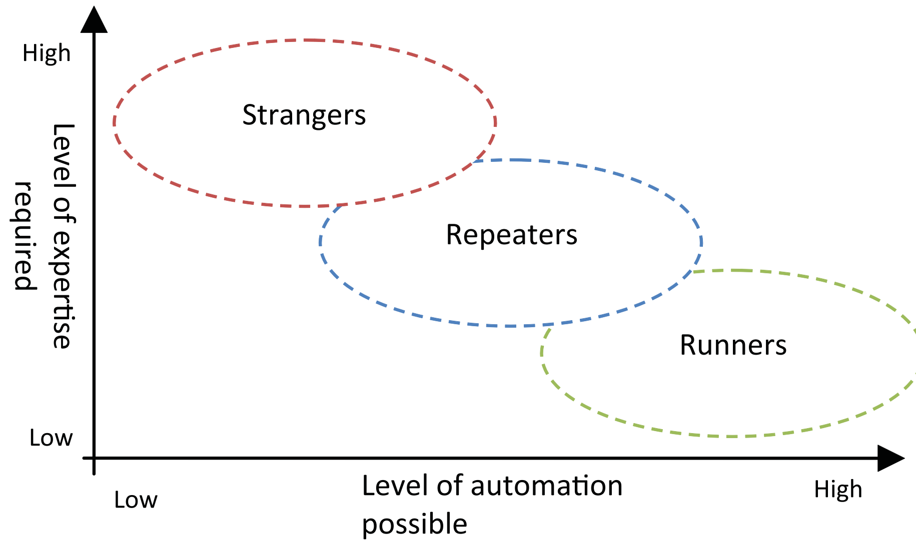



*Figure 20: Schematic illustrating the different product classes with respect to the degree of automation possible*

Because of this distinction there are a number of different approaches that have arisen. For example:

### Parameterisation

Parameterisation is the action of characterising a geometric design as a set of variables or parameters, where a parameter is a value which is seen as fixed for a particular case, but varying between cases (Oxford English Dictionary, 2001). Hence a system is pre-programmed with a series of designs easily modified by key parameters to produce bespoke designs for different criteria, with each product modified from a template design. An example could be mobile phone cases as the principle and layout of the designs can be the same, but the sizes may vary between different phones.

Parameterisation represents a relatively high level of automation – there is no conceptual design involved. This is appropriate for 'runner' type designs and could be operated by individuals without out any required understanding of the design.

### Optimisation

Geometry optimisation techniques have been developing for many years, initially born from the work of Newton and Leibniz in calculus. In the general sense, optimisation can be defined as "the search for a set of inputs (not necessarily numerical) that minimise (or maximise) the outputs of a function" subject to various constraints (Keane and Nair, 2005).

In engineering, optimisation systems search for and derive an optimum design given a criteria and set of rules. More recently these systems develop and analyse geometry directly through finite element analysis, with the results from these analyses directly influencing the geometry for the next analysis.

These systems are suited for medium or high value and volume products, typically 'repeater' type products. For example Rolls-Royce conducts large scale optimisation of engine blades. However, their operation requires much more expertise than parameterisation, but still little conceptual design.

Clearly these two example approaches are subtly different to the 'intelligent' knowledge systems previously described. Knowledge engineering has now come to be a specialised subset of knowledge-based systems and generally incorporates geometry and configuration in CAD software packages together with traditional Knowledge Management systems (Lovett et al., 2000).

### 3.5.10 Product Lifecycle Management

A different approach within Knowledge Management in engineering is that of product lifecycle management [PLM] systems. These systems are a strategic approach to organise and manage all of the information generated and associated with a product throughout its life and, importantly, for all different users from management to production.

PLM systems evolved in the late 1990s from product data management [PDM] systems. PDM systems themselves developed out of the sudden need to manage the large quantities of digital data created following the increasing widespread use of CAD systems. PDM systems had been around since the 1980s, but early systems were solely limited to the management of CAD files. Over time these came to encompass increasing amounts of data and activities beyond that of design activities, and grew into what are now termed PLM systems (Liu et al., 2009).

Several drivers can be identified for PLM systems, such as (Ming et al., 2005):

- Increasing product complexity
- Increased outsourcing and collaboration
- Geographically distributed design teams
- Shorter product lifecycles
- Mass customisation demands

To tackle these challenges, PLM systems are seen as a 'digital backbone' (Abramovici and Sieg, 2002) from which to manage a portfolio of products, processes and activities from initial concept through to end of life and disposal (Sudarsan et al., 2005). This allows central product-centric management and co-ordination of activities across the supply chain (Ming et al., 2005). In short the aim of PLM systems is to increase business revenue by managing not individual processes, but all activities associated with the product's life.

Popular PLM systems on the market include (The PLM Technology Guide, 2008):

- Teamcenter Engineering by UniGraphics Siemens (UGS)
- Enovia MatrixOne by Dassault Systemes.
- SAP PLM by SAP

Rolls-Royce uses Teamcenter across its primary sites. According to Liu et al. (2009) Teamcenter is marked by a strong collaborative platform, PDM workflow management and CAD/CAM integration, but has poor manufacturing process management and architecture.

At the outset of this project (2006), use of Teamcenter in Rolls-Royce was relatively limited, although common parts and CAD storage functions were in use. During 2007, Rolls-Royce announced large scale deployment and significantly increased its role in product development and manufacturing (Fulcher, 2007).

Traditionally PLM systems have not necessarily been considered Knowledge Management tools and, as described, existed primarily as logging and storage of CAD models, albeit with reports and other documents. Knowledge associated with these files is usually limited to meta-data and some CAD parameterisation (Brooks, 2009). The vision is, however, to integrate seamlessly the information flow throughout the product's life, allowing access to upstream and downstream information. For example, allowing designers to modify designs to suit easier manufacturing or utilise common or standard parts early in the design process.

However, as with the document management systems above, storing reports does not imply Knowledge Management. Users must still record rationale and other design knowledge, in order to embed it within the PLM system. One solution has been to incorporate tools such as the Design Rationale editor (described later) into Teamcenter (Ahmed et al., 2005). But here the PLM is a launch platform and not a KM tool in its own right.

Its primary role therefore remains that of a process management tool. A crude indication of this is the relative emphasis of PLM to processes compared to knowledge indicated through basic Google searches, shown in Table 3:

| Search Term | No. Of Results |
|---|---|
| "Product Lifecycle Management" | 1,460,000 |
| "Product Lifecycle Management" +Process | 946,000 |
| "Product Lifecycle Management" +Knowledge | 562,000 |

*Table 3: Table showing the number of search responses to different search terms (Sourced by author, November 2009)*

Clearly the number of documents citing knowledge is significantly lower than both the total number of results for PLM and the results pertaining to PLM and processes.

Writing in 2002, Abramovichi and Sieg present a survey describing the status of development of PLM systems into businesses. Key findings include observed adoption by large companies (54% with PLM systems, 2/3 of companies with plans to implement), but slower uptake by SMEs (14% of small companies showing implementation activity). Implementation was primarily observed to support the design activities and support across the entire product was still significantly lacking. This situation will undoubtedly have improved, driven specifically in companies such as Rolls-Royce offering 'Totalcare", but no wide ranging and equivalent survey has been completed.

Recent research such as Ming et al. (2005), Lee et al. (2008) and Liu et al. (2009) argues that PLM systems have had a clear benefit to businesses often through its very implementation, but still do not provide a complete, integrated process. In particular the gap between design and manufacture has still not been closed. Ming et al. (2005) goes further and lists seven 'gaps' in PLM, including improved design-manufacturing interaction, maintenance functions and increased knowledge capture.

Like many of the tools previously discussed, the implementation demands of PLM are significant and while the technical capability may exist, this does not immediately imply successful adoption. Despite this, PLM systems are likely to become more popular and commonplace in engineering. Two reasons should be highlighted; first as companies become more responsible for the end product safety, audit trails of manufacture and design rationale become ever more important. Second, as cloud computing develops and collaborative working becomes more commonplace, PLM systems represent a convenient way to combine the two. Centrally based software and files will allow designers to access and modify geometry on remote systems, with modifications automatically logged and stored, all as part of the PLM system.

The issue of knowledge capture within PLM still remains unsolved and whether these systems will evolve into a true knowledge base or remain a passive facilitator for file storage and logging is still an open question.

Based in Sheffield, the business associated with this research has never had access to the Rolls-Royce Teamcenter. The infrastructure required to build a secure link to existing Rolls-Royce sites was deemed too expensive and unnecessary, given the distinct role of the business. That said, the lessons learnt through the early use of PLM systems were incorporated into the research and development of the Design System.

### Summary

The preceding section has introduced and described some of the key information technology systems used in Knowledge Management, collected under the term knowledge-based systems.

In particular, detail has been presented on the systems used and developed in the field of engineering. While not an exhaustive list, the intention has been to provide the reader with some of the key differentiating themes, such as the level of automation, codification and intelligence embedded in the systems. Different approaches and systems are in continued development, but most if not all embody different degrees of these parameters.

These ideas will be returned to when discussing and detailing the rationale behind the system developed in Chapter 4.

## 3.6 Knowledge Management in Rolls-Royce

Rolls-Royce is a knowledge intensive organisation, as exemplified by ex-chairman Euan Baird's statement "To create new products and services we need two inputs: clients and knowledge"(Rolls-Royce plc, 2006a).

In 2001, a series of three reports were produced assessing the current knowledge assets in Rolls-Royce, the business requirements and finally a strategy for closing the gap between the two. The reports highlighted the lack of a unified knowledge vision and strategy, and a lack of dedicated, skilled staff for managing knowledge. In particular, the company was perceived to be weak at knowledge generation and capture. But the reports did identify numerous tools that were being used, such as the intranet that could be rationalised and improved (Cadas, 2001, King et al., 2001).

Today, Rolls-Royce has established a team of dedicated staff within the Research and Technology group to lead the company's KM strategy. Additionally, many individual business units have Knowledge Management staff within the units and these meet with the central KM team regularly (Cadas, 2008). The intention therefore is the establishment of a global strategy managed from Research and Technology and implemented at the business unit level.

The following section details and reviews the Rolls-Royce Knowledge Management strategy and its organisation of methods and tools.

### 3.6.1 Rolls-Royce Knowledge Management Strategy

Rolls-Royce Knowledge Management is primarily focused around people, the key source of knowledge within the company, and has developed several tools and processes to capture or redistribute this knowledge.

Rolls-Royce identifies roughly three different interactions with people: "Formal Review and Sharing Knowledge", "Sharing Knowledge less formally" and "Creating and Capturing Critical Knowledge". These can be shown schematically in Figure 21. Each interaction has a number of tools or processes associated with it and these are detailed below.

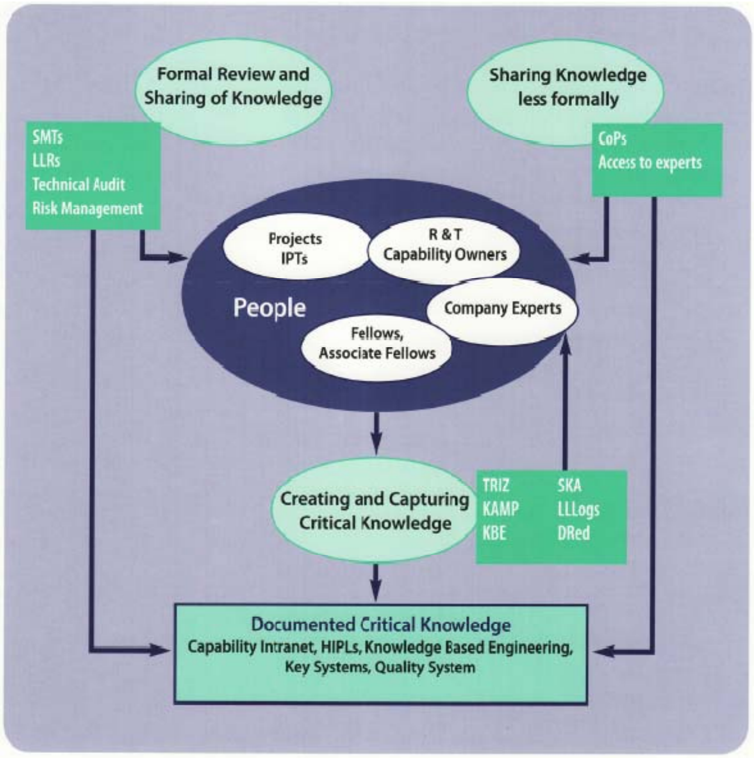



*Figure 21: Summary of the main aspects of Rolls-Royce's knowledge system (Rolls-Royce plc, 2006a).*

**Company Experts**

The following methods and programmes are targeted at developing experts and ensuring their knowledge is available within the company. The programmes in operation are:

- Company Fellows: Rolls-Royce fellows and associate fellows are recognised by the company as experts within their fields. There are approximately 20 fellows in subjects such as materials, design and propulsion systems. The technical specialist is an associate fellow in fixturing.
- Company Skill Owners: 21 Key skills have been identified across the company and leading professionals assigned as skill owners. These individuals lead skill groups, ensuring continued development of engineers within the skill field and maintaining adequate people capability within the company.
- Research and Technology Capability Owners: Similar to skill owners, capability owners are responsible for technology development. These owners are required to maintain an extensive and current

understanding of their technology, recognising opportunities for the business and to define research strategies.

- People Pages: Sited on the intranet, people pages are the Rolls-Royce "yellow pages" detailing an individual's area of expertise, contact details, current role and projects.

**Formal review and sharing of knowledge**

These methods represent more formal records and programmes within the company.

- Technical Review: Three audit teams exist to conduct formal gate reviews covering all product programmes. Every product has gated technical reviews at specific stages within development and production. The teams are highly experienced, with a wide product knowledge providing high level solutions to problems. The intention here is to utilise small, experienced teams across many products, who can advise on common problems and share their knowledge.
- Risk Management: The process of identifying key risks present within a project and defining strategies to mitigate them. These can be documented and the actions recorded based on lessons learnt. These can be used to anticipate future risks and to treat them better.
- Lessons Learned Reviews: These are facilitated sessions, lasting between two hours and a day, held with team members at key phases of a project. They are used to document lessons learnt and share them with future projects ensuring mistakes are not repeated.
- Peer Assist: New to Rolls-Royce, this has been widely used within BP and Shell. Similar to the lessons learnt, Peer Assist is a facilitated meeting between new and experienced teams at the start of a new project. The intention is to give new teams the benefit of a previous team's experience but it can also provide past teams with new perspectives on problems.

In the majority of these cases, the resulting documents are then stored online on the Rolls-Royce intranet, but may in some cases be kept on locally shared drives.

**Sharing knowledge less formally**

Referring back to section 3.4.2 and Nonaka and Tekeuchi's model, these tools correspond largely to the socialisation cell (tacit to tacit knowledge sharing).

- Communities of Practice: Discussed in section 3.5.8, the Rolls-Royce COP is like most other communities. Located on the company intranet, each COP has a skilled facilitator managing the community and controlling membership.
- Storytelling: Based on the old proverb "When an old man in Africa dies, a library disappears". Storytelling is used within communities of practice as an ice breaking and team building exercise. In this project we have tried to adapt this to more formal methods of knowledge capture.

**Creating and capturing critical knowledge**

These are some of the tools used in Rolls-Royce to aid knowledge creation and to record it during creation.

- TRIZ (Theory of Inventive Problem Solving): A methodology and collection of tools used to structure and aid problem solving (Altshuller, 1973).
- Knowledge Acquisition and Modelling Process (KAMP): A method targeted at capturing and publishing knowledge specifically for non knowledge experts. It is invoked from a business need, such as a retiring expert. A recent starter is then tasked with a set of documents based on interviews with the expert and guided by a knowledge expert.
- Knowledge-based engineering: As described in Section 3.5.9, this is the use of advanced software techniques to capture and reuse knowledge.
- Design Rationale Editor (DRed): This is discussed in detail and trialled later in Section 4.5. DRed supports decision making, recording the decisions made and their rationale during the design process. It has been applied successfully in several projects across Rolls-Royce.

**Documented critical knowledge**

Key knowledge is documented across parts of the Rolls-Royce intranet. This is in several forms:

- Capability Intranet: The intranet encourages the sharing of key processes and technologies. The pages are generally owned by process owners and skill owners, sharing their own expertise.
- Lesson Learned Logs (LLLogs): There are around 50 logs within the company which are accessed via the capability intranet. The log allows anyone wishing to share knowledge to contribute their experiences.
- Hazard Identification Prompt Lists (HIPLS): These are created based on previous work and are intended to provide new project teams with "things to think about", highlighting typical high risk factors.

**X-Media**

Additional to the above techniques, Rolls-Royce has recently supported a programme of work with Sheffield University producing a set of tools called X-Media (Ciravegna and Staab, 2006). These tools encompass a variety of research subjects examining the means for a distributed knowledge environment. Relevant to the research here is the aim to improve knowledge retrieval, in particular the mining of large scale textual data using K-search (Lanfranchi et al., 2007).

In Rolls-Royce this is being trialled in engine repair and overhaul reports. These reports are completed by engineers after examining and testing engines. Although a word template is used, the engineers often complete the form very differently, using different phrases, terminology and levels of detail. The X-search intelligently indexes the reports and can deliver back the relevant reports. For example, if a particular part was showing signs of wear the search inputs could be "part no. xxxx is wearing on one side". X-search assigns the attribute of wear to the part and finds similar cases, even if the product is described differently e.g. "replaced worn coil". This naturally requires the system to have an updated ontology linking the part name "coil" and its part number and linking worn and wearing.

Collaboration or utilisation of the work was suggested. However, the emphasis of the project here has always been on capture and utilisation, rather than search and retrieval.

### 3.6.2 Review of Methods

Clearly a variety of tools and methods have been developed within Rolls-Royce. Reviewing these there are clearly some lessons to be learnt and some methods or tools that could be utilised.

The favoured delivery mechanism across these methods is unmistakably the intranet. It facilitates access to a variety of different forms of media and documentation across the entire Rolls-Royce site. What is also apparent is that it is complex, difficult to navigate and find specific knowledge and does not support knowledge capture in itself – web pages can only be updated by site owners, not users. A solution would be to utilise the intranet mechanics and behaviour, but allowing users to input and store knowledge directly and in a consistent structure.

The techniques become easier to analyse if they are grouped into loosely passive and proactive methods. Here passive is seen as those methods designed to evolve passively over time, such as the development of company fellows, while the active methods are those that can be launched given a business or project requirement to capture or utilise knowledge:

| Passive | Active |
|---|---|
| Company Skill Owners | Technical Review |
| Company Fellows | Risk Management |
| R & T Capability Owners | Lessons Learnt Reviews |
| People Pages | Peer Assist |
| Communities of Practice | Storytelling |
| Capability Intranet | KAMP |
| TRIZ | KBE |
| | DReD |
| | Lesson Learned Logs |
| | Hazard Identification Prompt Lists |

*Table 4: Classification of Rolls-Royce KM methods into passive and active types*

The passive methods listed in Table 4 are not a viable approach for the research and business presented here. Although long term, these approaches could be utilised, for example the development of individual experts for different fields. In the short term, they do not support the transfer of knowledge from a retiring expert.

The Rolls-Royce strategy encompasses both personalisation and codification approaches, splitting the remaining active approaches into these two classes results in the following table:

| Personalisation | Codification |
|---|---|
| Technical Review | Risk Management |
| Lessons Learnt Reviews | Storytelling |
| Peer Assist | KAMP |
| | KBE |
| | DReD |
| | Lesson Learned Logs |
| | Hazard Identification Prompt Lists |

*Table 5: Classification of Rolls-Royce KM methods into personalisation and codification strategies*

The personalisation methods here are all geared towards team interactions. However, even allowing for a single expert to act as the review panel or assisting peer, they still utilise a locally sited expert to review and advise new engineers and do not support long term capture and reuse of knowledge from a retiring expert.

The remaining codification approaches can be summarised into three methods, knowledge-based engineering (discussed earlier), project knowledge capture and review (such as DReD, lessons learnt logs) and proactive knowledge capture (such as KAMP and storytelling).

The primary problem with many of these methods is the need to drive the methods. Often formal gate reviews are mandated, but active documentation of lessons learnt will need to be driven by senior staff.

### Summary

It is clear from the above discussion that Rolls-Royce has invested in various KM techniques. Given the size and nature of the organisation many of the methods developed are geared towards team interaction, formalised documentation and reviews and long term development of skill owners.

These offer limited benefits to a small, high growth business. Despite this, some of the methods could be adapted and certain approaches, such as the deployment of knowledge across an intranet could be adopted and developed to provide a platform for knowledge capture.

Further research and experimentation on specific tools (such as DReD) were completed and these are discussed later in section 4.5.

## 3.7 Evaluation of Knowledge Management

Despite the widespread adoption of Knowledge Management and the proliferation of knowledge-based systems, it has yet to be agreed whether the approaches taken are successful or even what defines success (Firestone, 2008). Specifically there has been little conclusive evidence on whether companies implementing KM strategies actually gain a performance advantage (Darroch, 2005).

The need to evaluate KM strategies is necessary however. Bose (2004) argues that if the systems cannot demonstrate their value through measurable success, "support for KM is unlikely to continue".

Primary to all businesses is the need to generate value and the use of KM is perceived as a means to improve value generation. It should seem clear that an analysis of the investment required and benefit gained would be sufficient to establish the business case for KM. In reality the evaluation of KM strategies encompasses an extremely complex set of issues, generated by the multi-dimensional nature of KM activities.

Fundamentally there is the problem of universal evaluation – what to measure and how to measure it. KM activities are unique to their environment; activities in different companies have different aims and objectives. As discussed, companies are motivated to implement KM for a variety of reasons – not necessarily to improve the immediate business returns. For example a company may try to safeguard competitive edge or mitigate against the loss of employees but evaluating Return on Investment

(ROI) would clearly not be appropriate. It is therefore difficult if not impossible to establish a universal metric with which to evaluate success.

The second issue is what to measure. By its very definition KM deals with the intangible. There exists no realistic quantification of knowledge, so to establish any form of value on the knowledge managed is extremely difficult. Furthermore, the role of nearly all KM activities is to support or interact with individuals, requiring changes in behaviours and attitudes. None of this is easily quantifiable or measurable.

Finally, from a research perspective the bespoke nature of KM activities and lack of universal measures severely restrict the evaluative research methods, such as comparative studies between companies, which can be conducted.

Despite these issues, research into frameworks and approaches for evaluating strategies – both qualitative and quantitative – is becoming an increasing focus for researchers. Having introduced some of the fundamental issues, the following sections will discuss the measures that have been developed and trialled to address these issues.

### 3.7.1 Different Strategies for Evaluation

A review of the literature encompassing evaluative approaches for KM activities demonstrates a fragmented body of studies. As with KM itself, an array of different approaches exist arising from the different perspectives of the researchers. This causes difficulty in summarising and categorising the different approaches taken. Some examples of the different approaches are: internal measures of intellectual capital, business wide key performance indicators and multi-company surveying with correlation analysis.

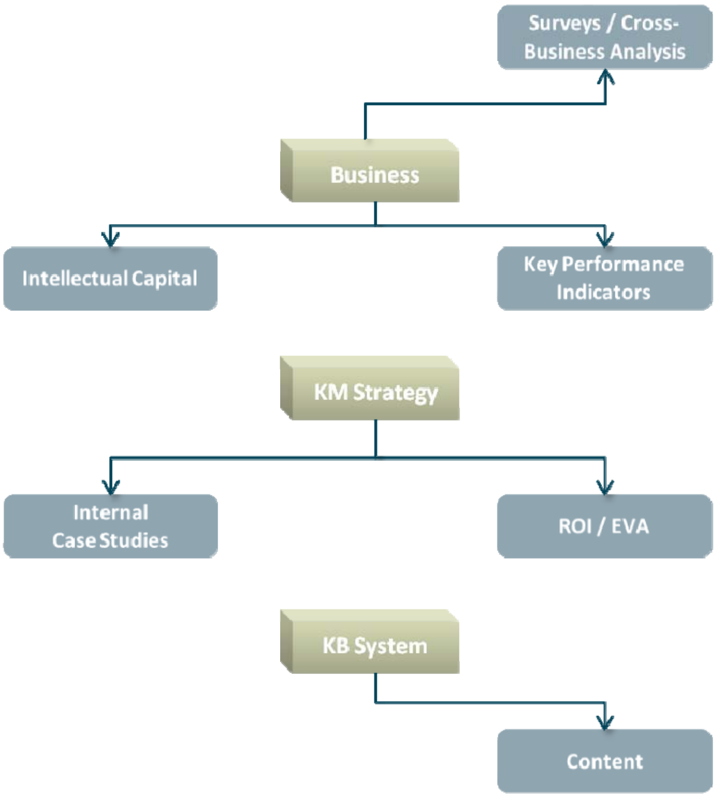



*Figure 22: Schematic illustration of the different levels of evaluation*

The primary distinguishing variable is the hierarchical level which the strategies evaluate. Figure 22 illustrates schematically the relationship between approaches and the level measured, moving from business wide measures down to individual measures of system content.

Each of the approaches listed has some merit and some drawbacks. The higher the level, the greater the appreciation of business wide changes and influence. The lower the level, the more detailed the measures can be. For example, measures of system content are relatively quantitative and detailed but ignore the wider implications of systems use. Davenport et al. (1997) argued that successful uptake or implementation *is* itself an indication of success and is a relevant measure.

A mid-level analysis of the KM strategy can be achieved to some degree through case studies and some quantitative measures such as return on investment. The latter can be achieved by an estimation of the resources saved by the KM strategy compared to the resources invested. Yet as already discussed, this does not encompass the wider business strategy.

At a higher level, the changing performance and behaviour of the company is the one true measure of success for nearly all KM activities. However, at this level external market influences and other business changes become significant. Furthermore, value may only be realised over a long period of time and short term measures will not reflect long term strategic improvements. As a consequence, two different approaches have evolved to overcome these drawbacks: the measurement of intellectual capital as an independent quantity using the popular 'Skandia Navigator' [SN] (Edvinsson, 1997) or the use of Key Performance Indicators [KPI] to measure multiple business indicators commonly within Kaplan and Norton's 'Balanced Scorecard' [BSC] framework (Kaplan and Norton, 1992). While highly popular, both have been criticised, for example Del-Rey-Chamorro et al. (2003) argues that there remains a gap between the strategic level and the operational level.

Finally, to reduce the effects of market and internal business changes and elicit links between business performance and KM activities, analyses of cross business surveys have been performed. The study by Darroch (2005) found no conclusive correlation between KM and performance. Furthermore, the level of analysis does not appreciate the differing aims and objectives of KM activities.

The following sections will detail some of the measures introduced here, divided into sections describing the different methods using KPIs and frameworks, High Level Measures and Correlation, Measures of Intellectual Capital, Project Specific Measures, and the Success Case Method.

### *3.7.2 Metrics, Key Performance Indicators and Frameworks*

The most common approach to measuring Knowledge Management and its effects has been using Metrics or Key Performance Indicators built into an encompassing framework. At its simplest, this approach dispenses with the problem of what to measure by using an array of different measures to create an overall 'picture' or impression of a particular facet of the business.

Here metrics are quantitative indices assigned to project attributes, such as complexity, cost or ratios (Bashir and Thomson, 1999). The term will be used fairly interchangeably with Key Performance Indicators, the latter usually referring to metrics or indicators already defined within a performance framework.

The theory is not new or unique to KM. For years managers have tried to measure and represent the performance of the business so as to inform the strategic decisions and direction of the business. Traditionally finance measures such as profitability, gearing ratios and earnings per share were used as the performance indicators. Yet in the highly competitive and globalised market, financial measures provide insufficient information and depth to decision makers (Kloot and Martin, 2000). Fundamentally competitive advantage, such as improving customer service, will not be reflected in financial measures (Eccles, 1991). Performance Management [PM] systems were therefore developed to 'diversify' measurement with the aim of identifying best strategies and align management processes with strategic objectives (Ittner et al., 2003).

Indicators are structured and output within a framework, which when viewed demonstrates the changing patterns of the business. Of these frameworks by far the most popular and widely used is the balanced scorecard, as a consequence of its flexible and customisable nature. The balanced scorecard first originated in the late 1980s and was developed and published by Kaplan and Norton in the early 1990s. It is described as being akin to "the dials in an airplane cockpit: giving managers complex information at a glance" (Kaplan and Norton, 1992).

The balanced scorecard divides the performance measures into different aspects, answering four questions (Kaplan and Norton, 1992):

- How do customers see us? (Customer perspective)

- What must we excel at? (Internal perspective)
- Can we continue to improve and create value? (Innovation and learning perspective)
- How do we look to shareholders? (Financial perspective)

It is intended to provide managers with information from four perspectives of the company in a single glance, illustrated in Figure 23.

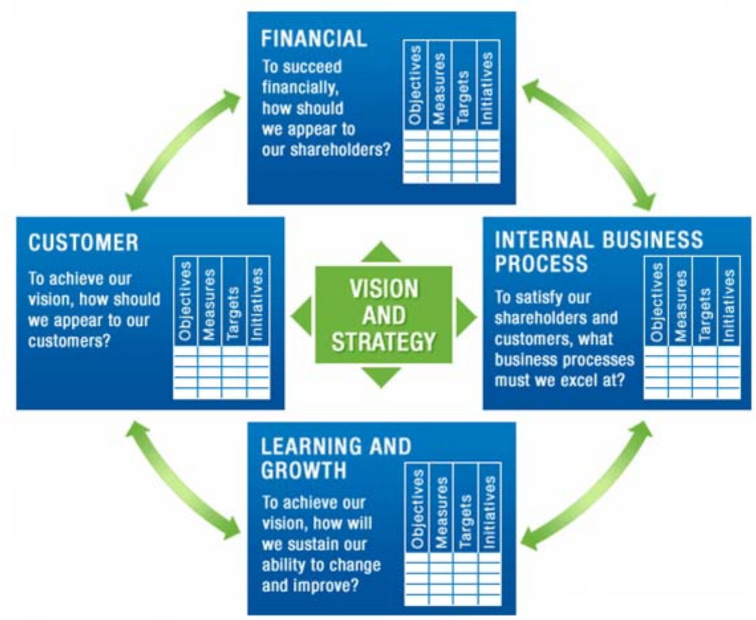



*Figure 23: Illustration of the balanced scorecard (Learn.com, 2008)*

Balanced scorecards are developed specific to each company, based on the nature of the company and their strategic direction (ten Have et al., 2003).

The principles of the BSC approach can be applied to Knowledge Management activities by adjusting the metrics and creating a KM index. This was the approach taken by Gooijer (2000) in developing a bespoke 'performance framework'. Typical metrics can be estimates of the volume of codified tacit knowledge, usage of the codified repository and level of collaborations across the company. The BSC approach offers an established structure by which a company and its activities can be measured. Its flexibility allows for a variety of measures to be utilised, both KM related and not.

The BSC does have disadvantages. For example, it does not address the issue of measuring intangible aspects of KM activities such as knowledge volume or system adoption. It is typically limited to between 16-25 measures, and often constructed from lagging indicators – the primary criticism of financial measures (although choices can be made to include some lead indicators). Importantly, however, it has also been criticised for a failing to 'decompose high level strategic measures' (del-Rey-Chamorro et al., 2003). This criticism can be applied to most, if not all frameworks. Their principle is to simplify the complex and changing business. Consequently subtle changes will naturally be obscured and causality difficult to discern.

Alternative frameworks have been proposed, such as Gooijer (2000) or Teruya (2004), but neither address the fundamental issues above. Furthermore the basis of any KM performance framework must be a balanced business wide perspective. Given the widespread adoption of the BSC developed to meet flexibly this precise function, it is difficult to understand the rationale for an alternative framework.

### 3.7.3 Correlative and High Level Methods

To address the issues faced with medium and low level evaluative approaches, a series of studies have attempted to correlate internal KM behaviour (as perceived by the employees) with business performance.

The method, exemplified by Darroch (2005), utilises business surveys to establish the extent of KM activities across multiple companies. In the case of Darroch, 443 companies were surveyed. Their responses are codified, weighted and in some cases input into some form of model such as Lee et al. (2005). The business performance is then correlated with the responses to establish whether firms responding positively to KM show any statistical improvement over firms responding negatively.

Conceptually this approach demonstrates the most potential for a conclusive view on the value and benefit of KM activities for a business considering investing in KM. Yet care must be taken when assessing these results. Of the studies reviewed, there appears limited evidence that the effects of KM can be determined using this approach (Joia, 2000, Chang Lee et al., 2005, Darroch, 2005, Uhlaner et al., 2007, Chen et al., 2009). Darroch (the largest study) concluded that there was insufficient evidence to prove a link between business value and KM.

Fundamentally the studies rely on subjective responses, usually to surveys. Chen et al. (2001) tries to avoid the use of surveys by using a panel of experts, but the experts remained external to the company and therefore have a limited perceptive. Critically most of the survey studies have limited responses and, critically, have limited responses per company. Chang Lee et al. (2005) use just one source (a senior executive) per firm and acknowledge the limitation, but argue that the most informed executive was chosen. This prompts the question – how is the executive informed? It does not address the fundamental question of how to evaluate the internal impact. This leads to the continuing question of causality. When correlating firm performance and Knowledge Management, is knowledge the cause of increased performance or are the firms that have adopted knowledge strategies simply more strategically aware and more competitive?

There are some conclusions that can be drawn from these approaches, notably internal correlation between measures. While these remain theoretical, taking ‘activities’ as the input, rather than evaluations of performance benefit, the conclusions are believed to be more reliable. Darroch’s (2005) study in particular concluded that greater capture and dissemination of knowledge improved knowledge responsiveness. The more knowledge is shared, the more likely it is to be utilised. This is important as, for many companies, greater knowledge use is a success measure regardless of the lack of a proven link between knowledge use and performance.

The statistical and correlating approaches do have a role. Long term, the methodology offers potential for conclusive evidence of the effect on performance of KM. But this conclusion will be dependent on a well founded, large scale survey over multiple companies and importantly sampling within the companies.

### *3.7.4 Intellectual Capital*

Intellectual Capital [IC] is defined by Stewart (1997) as 'formalized, captured and leveraged knowledge'. It was popularised in the early 1990s by authors such as Stewart (1991), Reich (1991) and Drucker (1993).

The concept of accounting for IC followed soon after, partially as an aside to KM activities and strategies but with similar aims to the PM frameworks described above. The aim was to try and account for the intangible business assets together with the financial. A full review of IC accounting is given in Roslender and Fincham (2004).

The rationale was that if a firm's value is dependent on its intangible assets, (its intellectual capital) increasingly seen as the disparity between the 'book value' and 'market value', some measure was required to quantify its value. Furthermore, in theory improving IC would improve the business performance, thus an accurate measure allows for accurate investment. Although as Joia (2000) highlights, IC must still be linked to the firm's business strategy to generate value.

The increasing awareness of IC measurement and management led to the Skandia Navigator [SN], developed by Leif Edvinsson on behalf of Skandia (Edvinsson, 1997). The aim in Skandia was to generate an accelerated learning curve that would "rapidly integrate corporate knowledge into tangible assets" (Edvinsson, 1997). The value of its IC was the extent to which financial benefit could be gained from these assets. The Navigator was developed to provide a dynamic and holistic measure of the company's underlying value (Edvinsson and Malone, 1997).

The Navigator was developed using a reductionist approach from the high level market value, down to value-generating 'building blocks' from which the value of intangible assets can be asserted, previously illustrated in Figure 14.

The Navigator then uses 91 IC metrics and 73 traditional measures arranged into five focus areas to construct a model that represents this value (Bontis, 2001). An example of the Navigator applied is shown in Figure 24.

| | 1997 | 1996 | 1995 | 1994* |
|---|---|---|---|---|
| **FINANCIAL FOCUS** | | | | |
| Direct yield (%) | 5.96 | 5.93 | 6.16 | 6.60 |
| Net operating income (MSEK) | 1,130 | 1,215 | 1,258 | 1,399 |
| Market value (MSEK) | 19,206 | 20,092 | 20,702 | 21,504 |
| Total yield (%) | 7.73 | -0.62 | 5.06 | 4.44 |
| **CUSTOMER FOCUS** | | | | |
| Customer satisfaction index (max. value = 100) | 69 | 58 | 56 | n.a. |
| Average lease (years) | n.a. | 8.6 | 8.5 | n.a. |
| Average rent (SEK/sq.m.) | 951 | 960 | 970 | 1,041 |
| Telephone accessibility (%) | 60 | 71 | 60 | n.a. |
| **HUMAN FOCUS** | | | | |
| Human capital index (max. value = 1,000) | n.a. | 615 | 617 | n.a. |
| Employee turnover (%) | 10.0 | 10.1 | 7.9 | 7.7 |
| Average years of service with company | 12.0 | 10.0 | 10.1 | 10.2 |
| College graduates/ total number of office staff (%) | 36 | 32 | 31 | 31 |
| **PROCESS FOCUS** | | | | |
| Occupancy rate measured by area (%) | 93.7 | 91.8 | 89.7 | 89.3 |
| Financial occupancy rate (%) | 96.2 | 94.9 | 93.0 | 91.2 |
| Net operating income per sq. m. (SEK) | 553 | 569 | 590 | 657 |
| Costs per sq. m., Sweden (SEK) | 304 | 274 | 276 | 272 |
| **RENEWAL & DEVELOPMENT FOCUS** | | | | |
| Property turnover: purchases (%) | 0.2 | 3.1 | 3.2 | 0.8 |
| Property turnover: sales (%) | 8.1 | 1.1 | 6.1 | 0.4 |
| Change and development of existing holdings (MSEK) | 235 | 311 | 333 | 313 |
| Training expense/ administrative expense (%) | 0.8 | 1.0 | 1.5 | 1.0 |

*Figure 24: The Skandia Navigator applied to "Skandia Real Estate", taken from the 1998 Annual Report supplement entitled "Human Capital in Transformation" (Skandia, 1998)*

A brief examination of the report highlights some of its benefits and shortcomings, for example:

- This division of Skandia is clearly facing a changing market. The financial indicators show a reduced yield, lower income and a reduced market value, possibly as a result of the decreasing average rent.
- Internal measures show positive changes, such as customer satisfaction and occupancy rate increasing, demonstrating improving processes.

- Areas for concern exist, in particular increasing employee turnover and increasing years of service, which may suggest that early and mid career employees are leaving and may account for the drop in the Human Capital index.
- Skandia may have addressed staff turnover by increasing the proportion of new graduates, investing in training to ensure long term continuity.

This short discussion is intended to demonstrate the richness of a cross business view, but also the difficulty in inferring causality, in this case the reason why years of service and graduate intake are both increasing.

The SN's strength is in providing a broad, high-level coverage of organisational and process business factors. Thus internal changes and policies can be altered to change the strategic direction of the business. Furthermore, use of the full array of metrics and measures identified by Edvinsson can be selectively used to examine different aspects of the business. For a full example, see Skandia (1994).

The Navigator's weakness, like the BSC, is the difficulty of extracting causality. For example, is the increased rate of occupancy above caused by a more efficient sales process or by increased market demand for property? Roos et al. (1998) cited in Bontis (2001), found that alternative interpretations of three key metrics could be put forward to explain the changes. Thus businesses would be required to understand in detail what each metric actually implies for the company.

Since the Navigator developed, other frameworks have been developed and a review is provided in Bontis (2001). These include the 'Technology Broker' approach developed by Annie Brooking in 1996, which uses a series of survey questions to form an IC benchmark, or Sveiby's 'Intangible Asset Monitor', which assesses the external structure, internal structure and competence of people. This last facet probably offers the most scope for quantification of company capability, but is still reliant on individual metrics of people, rather than the actual intellectual capital.

Recently however, there is evidence that IC accounting is not viewed as critically as it once was. A survey of 10,000 annual reports by Bontis (2003) found that only five firms actively referred to IC. This does not necessarily mean that it has been abandoned. Reviewing literature and reports suggest that it may have simply developed past IC measurement to holistic, people development programs, rather than trying to measure and quantify value, simply to improve and measure the behaviour and development of all staff. This is actually illustrated when examining Skandia's own annual reports. The annual reports from 1998 and 1999 both contained dedicated sections focused on the Navigator. The annual reports from 2000 - 2003 include sections on Human Capital, but with decreasing references to the Navigator and significantly, IC. In 2004, Skandia reshaped the business to 'strengthen coordination' across the group, implementing their 'Phoenix' program as part of improved Human Resource Planning. From then onwards, no mention is given to the Navigator or IC, although emphasis is given to employee development and knowledge sharing with the groups (Skandia, 1998-2006).

### 3.7.5 Project Level Quantitative Methods

Section 3.7.2 introduced the concept of Key Performance Measures and Metrics as a means for evaluation over the business as a whole. The primary criticism with this approach is the lack of detail, causality and project specific evaluation that can be elicited from the high level metrics. To address this, specific low-level measures and calculations can be used to evaluate a particular project, and while the KPI frameworks evaluate changes over the business, these measures evaluate at project level.

The most commonly used measure of projects is 'Return on Investment' [ROI], the rate of return achieved on the capital employed. A simple value can be calculated by dividing the value of benefits by the cost of investment, often written (Collier, 2003):

$$ROI = \frac{\text{Net Profit after Tax}}{\text{Shareholder Funds}}$$

There remain questions over which is more valuable: a low investment with a high ROI, or a high investment with a low ROI? The second will generate more profit, but requires greater capital. When applied to KM activities, the common problem of what and how to measure benefits is encountered yet again.

Millen et al .(2002) argued that ROI measurements are important for activities (specifically in their paper COPs) for two reasons: justification to senior managers of investment and identification across companies of successful and unsuccessful COPs. Millen et al. (2002) proposed two approaches to evaluation: user estimates of time benefits and storyboard comparison of known project durations. Both proposals are viable options, but both incorporate assumptions. The first is that an accurate perception of savings can be gained from users, the second that two projects are sufficiently similar that a direct comparison can be made.

Kim (2006) argued against using simple financial or numerical measures, arguing that the emphasis of KM is on improving cross business processes. However, as argued by Davenport et al. (1997) project level measures are needed and have a vital role in evaluating KM. Four internal measures are suggested to indicate the success of KM, listed as:

- Growth in the resources associated with the activity

- Growth in content and its usage of activity (targeted at codified repositories)
- Survivability of a project following loss of a key leader
- Financial return or benefit

On reflection, some measure of individual project success is useful and often required. Although these measures may only indicate the *perceived* value of the activity by the users, this still produces an important indication of success.
For example Fedor et al. (2003) used user surveys to correlate the internal factors affecting user perceptions on project success tuned to reflect KM activities. Fedor et al. (2003) found that when organisational support is low, KM was seen to positively affect the perception of project success. However, it could therefore be argued that the respondent's perception of value may have been distorted by the low organisational support, thus no additional value is actually gained and ROI is zero. Regardless of the absolute value, in this situation, KM was viewed as a positive support for the team members and this has its own consequence and value.

The reality is that knowledge activities are a change in culture and working practices which are not easily valued and financial evaluations in particular are not always relevant. While low level measures will never reflect the wider impact of the system, they do provide a necessary report on its low level adoption and impact.

### 3.7.6 Success Case Method

The final method that will be discussed utilises project-based case studies. Section 3.7.5 introduced the idea of using comparative case studies to evaluate benefits. But it is often difficult in SMEs or low volume manufacturing to generate like for like projects. The method here was developed as a semi-structured means for generating anecdotal evidence of success or failures.

Termed the 'success case method', the approach was not developed with Knowledge Management in mind, but rather as an evaluation method for training or other employee-focused initiatives (Brinkerhoff, 2005). The approach compares the top and bottom adopters of a learning activity in order to obtain a qualitative study of the activity's success (Brown, 2008). Specifically, a two stage process is used. Potential cases (or people) that have benefited from the activity are surveyed. Interviews are then conducted with the cases that form the upper and lower margins – those that demonstrate successful adoption and those that have failed. Via the interviews and reports, evidence is gathered to demonstrate the benefits and issues with the activity under evaluation (Brinkerhoff, 2005).

Kim (2006) supports the success case method, arguing that through analysis of the 'best' and 'worst' case scenarios, the governing factors can be elicited. The author is inclined to agree, however ideally new cases should be analysed regularly to build up a portfolio over time, providing a timeline for change and better understanding of the issues. Unless rigorously adopted over a long period of time with many projects, the method is still unlikely to determine wide scale business change. This, however, presents a question of resource and the effort required to obtain the required evidence.

### *Summary*

This section has reviewed the different approaches that have been taken to evaluate the effects and impact of KM activities. The key findings from this review are the limited extent to which formal evaluation has taken place and that many studies were unable to demonstrate conclusive evidence of success (Darroch, 2005).

Throughout this section, the difficulty of linking low level KM (often intangible) activities to business wide and financial performance has been highlighted. North (1999) cited from Forstenlechner et al. (2008), argues that the only two methods that achieve this are Skandia Navigator (Edvinsson, 1997) and the Balance Scorecard (Kaplan and Norton, 1992). While these methods offer the most potential for business wide analysis, other methods are still required to establish the effects on a lower level. Notably, both the Navigator and BSC do not adequately address causality i.e. to determine if KM is actually generating value or if the introduction of tools and studies simply cause changes themselves as famously highlighted by the Hawthorn study (Mayo, 1949).

It is argued here that none of the measures described above independently and adequately evaluate and characterise the effects of the introduction of a new knowledge strategy. Large scale and multiple company surveys with correlative analysis demonstrate significant potential for eliciting general themes of success and failure of KM. Yet conclusive evaluation of the internal effect of a knowledge strategy can only be achieved through the use of multiple methods, in particular using both high level and low level metrics and widespread use of qualitative feedback, case-based analysis and user perceptions.

## Chapter Summary

The preceding chapter has endeavoured to provide the reader with a thorough understanding of the field of Knowledge Management from basic principles and definitions to the current boundaries of research and the limitations to the field. Particular emphasis has been given to the role of KM in business and specifically engineering, discussing the reality of implementing and adopting KM and the limited experimental validation that has been performed.

Knowledge Management is not without its critics. Wilson (2002) described it as an ideal, promulgated by consultancy companies. He argued that it is based on two foundations, the fad of marketing information systems and a utopian idea of organisational culture which is impossible to implement. Yet Ponzi and Koenig (2002) argued that 'fads' typically peak in five years and decay shortly after. KM has not decayed, however. Furthermore Ponzi and Koenig observed a contraction and recovery in 2000 and 2001 and argued that the field is morphing into a clearer and more established concept. This is an argument supported in part by the increased subject breadth demonstrated in 2001 and the views of Heisig (2009).

In design and manufacturing environments, the use of design knowledge and information is now accepted as a crucial factor in product development (Court et al., 1997). This chapter has demonstrated the wide range of approaches and systems developed to encourage and improve design knowledge reuse, such as product lifecycle systems (Sudarsan et al., 2005), process-based support (Baxter et al., 2007, Blessing, 1994), cased-based reasoning (Leake and Wilson, 2001) and optimisation methods (Keane and Nair, 2005) . Yet there remains no consensus on how best to support a designer's knowledge activities and significant challenges to establishing regular design reuse remain (Busby, 1999, Ball et al., 2001).

KM has become a necessary and unavoidable activity for all businesses in order to maximise business value and maintain their competitive edge. Yet research is required to determine how best to implement knowledge activities and importantly, establish the effects of different activities. The remainder of this thesis addresses this deficit.

# Chapter 4

## Development of The Design System

*"In post-capitalism, power comes from transmitting information to make it productive, not from hiding it"*

*Peter Drucker (1995)*

As emphasised in the literature review, the principle aim of KM is to leverage the existing knowledge of a company to generate value. The following chapter describes the rationale, development and basic evaluation of a KM strategy designed to support these aims in Pro-Laser.

### 4.1 Design System Framework and Rationale

The fundamental aim of Pro-Laser is to establish itself as a market leading supplier of fixtures and tooling. As the first mover with a paradigm shift in technology, the strategy was that of being "furstest with the mostest"*(sic)* (Drucker, 2007b). Market analysis indicated that for the venture to establish itself successfully ahead of potential competitors, it must establish and leverage a knowledge base to create a competitive advantage in terms of quality, cost and lead time.

The recommendation of the report by Roy (2006) was to exploit two different characteristics of the technology in a hybrid premium value-consultancy business model. A proactive knowledge strategy was proposed in order to proactively manage the business's knowledge base. This was to serve a multifunctional role – to protect against knowledge loss from the retiring expert and to create a barrier to entry for potential competitors.

The proposal was for a codified knowledge base. Tacit 'personalisation' approaches had been immediately ruled out for two reasons. Firstly the key knowledge holder would be leaving, thus removing him as a viable source.

Second, tacit-orientated systems such as communities of practice could never feasibly be adopted because of the small size of the business.

It was not clear what form this codified system should take. Therefore, in order to develop a suitable system framework a series of steps were taken to identify the key parameters relevant to the system. These were:

- Establishing the requirements of the business
- Deriving the products and the means for supporting their design
- Assessing the existing knowledge currently utilised in the business
- Examining the proposed growth and development of the business
- Determining the end users

The following chapter describes the derivation of each of these parameters before detailing the chronological development of the system. As the primary aim of the system was to integrate with the business, development used an iterative trial and error approach. Existing best practice tools and approaches both from Rolls-Royce's own Knowledge Management department and the wider literature were selected, implemented and trialled within the business. Not all approaches were found to support the ultimate aims of the system but have been included for completeness. Furthermore, several system aspects were originally developed in isolation, but were increasingly incorporated into a single system. To illustrate the remaining chapter sections, the sections are shown schematically against their chronological implementation in Figure 25.

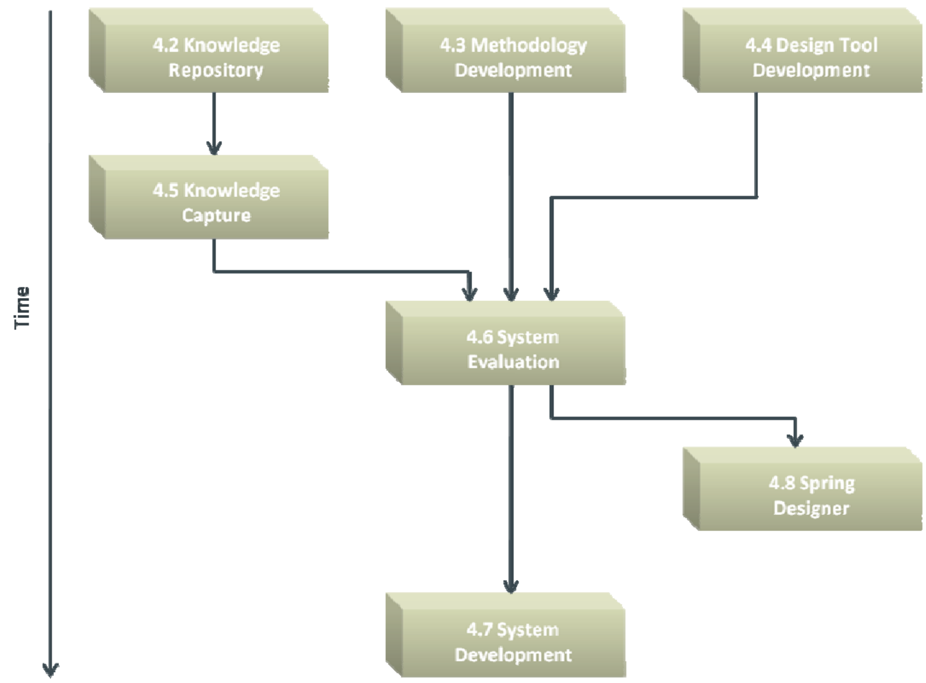



*Figure 25: Schematic illustration of the chapter sections against the chronology of their implementation*

### *4.1.1 The Business Requirements*

The business's key differential is the use of the innovative technology to provide consultancy-based solutions to complex customer problems and to supply premium-value products rapidly and at volume. The emphasis throughout is efficient delivery of complex, quality products.

The system must therefore provide valuable support via knowledge at key stages of the design process in order to ensure better quality, reduced lead time and minimal cost. Additional but associated requirements were identified as:

- Support for faster response to an enquiry
- Better costing and time estimates for problems
- Immediate indication that customer enquiry is in scope
- Guidance for novice end users
- Support for training and development
- Recording of design rationale and reasons for selection of solutions
- Support for 'simple' mechanical analysis
- Support for new concept generation

Initial ideas were to create automated routines based on codified rules. Component geometry could be imported and the system would generate a structure around this geometry, utilising design rules and routines derived from the expert's approach. This would represent the traditional knowledge-based engineering approach described in section 3.5.2.

Following a study of the products it became apparent that the complexity and variety of the products currently developed would create a substantial challenge for any automated system to meet. The majority of products were bespoke in one aspect or another. An entirely automated rule-based system was therefore discounted in favour of a user-driven system to support the designer's activities. However, it was suggested that key automated tools could be developed, embedding some knowledge into geometric rules.

### 4.1.2 Product Types

An analysis of the technology demonstrated that the majority of products produced in the business were classed as strangers, with some repeaters present and no runners, with only a few exceptions. The strangers correspond to the more consultant-based arm of the business, while the runners and repeaters represent premium value products. A different knowledge strategy was therefore required for different product types.

For common or 'standard' tooling requirements, for which traditional solutions would be adequate, the business must be able to design and produce products faster than traditional tooling companies. The knowledge strategy must be geared towards providing prior and existing knowledge to support faster design and efficient throughput, from job acceptance to job delivery and feedback. The obvious knowledge to utilise here is past design knowledge to minimise rework and reduce bottlenecks. However, there must also be efficient capture and redeployment of knowledge associated with manufacture, CAD programs, costing and job quoting. In short all the functions associated with the production and delivery of products to customers must be supported to remove time and cost.

For strangers or bespoke solutions, the business competes via innovative solutions, that is to say the value adding function is the solution to a complex problem and not necessarily the finished artefact. The knowledge strategy must therefore support more analytical design and knowledge associated with material behaviour such as bending calculations and spring design.

The solution to this dual strategy (standard tooling and bespoke solutions) was to provide an array of different support functions for different scenarios and products.

### 4.1.3 End Users

The system had to be designed with the end user in mind. The primary users would be design engineers. These after all represent the primary value adding resource in the business. Three levels of designer were defined corresponding to their experience:

| | |
|---|---|
| **Novice designer** | Less than one year of design experience |
| **Experienced designer** | Several years of experience |
| **Expert designer** | Extensive experience and understanding |

Each of these user classes can be separated into two groups, those who have experience of the technology and those who don't. This directly affects the knowledge the user seeks. For example an expert may join the project without prior experience of the technology and would therefore need product knowledge, but minimal process knowledge.

Additional users were also identified:

| | |
|---|---|
| **Workshop Engineer** | Manufacturing Engineer |
| **Salesperson** | Customer facing salesperson |
| **Business Administrator** | Supporting payroll and administration |

These users have their own requirements:

- The workshop engineer is likely to need manufacturing knowledge and laser cutting files from previous projects.
- The salesperson will need a means to show the technology capability and product range as well as providing a quote for a new project, potentially while based off site.
- The administrator would benefit from accessing details of the costing of projects, material required and hours taken.

The system would need to be built to provide support for all user classes, but different classes may require different interaction with the system. For example, external customers could never have been able to access the full knowledge base or technical capabilities of the system, but could be given access to a limited or lightweight version of the system, shown in Figure 26.

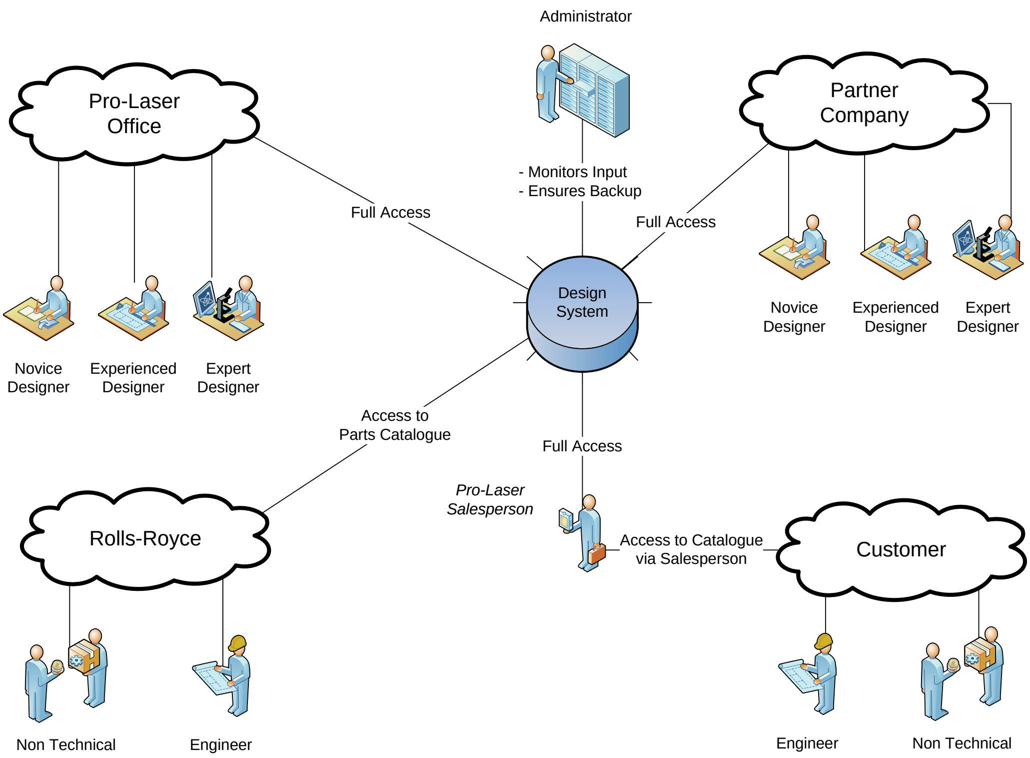



*Figure 26: Schematic of the typical user interactions with the Design System*

### 4.1.4 Business Growth

The intention was to rapidly grow the business, potentially forming a joint venture with an external company in order to gain resource and share IP.

While the main office would likely remain based in Sheffield, long term growth would create the need for additional offices, potentially located in several sites both domestic and international.

While this growth is projected, the knowledge system must be built not only to support the potential topological expansion, but also to support incoming resource as well as other business functions such as customer interaction and links to Rolls-Royce plc.

At all times it was expected that expert knowledge would be a limited resource. In particular, if the project was to merge with another tooling company it is likely that there would be a large gain in resource requiring expert knowledge. These engineers would most likely be capable and experienced design engineers who would be unfamiliar with the specific technology. The system would be crucial to maximising this resource.

### 4.1.5 Observations of Existing Knowledge Use

Early into the research period, time was spent observing the designers' existing interaction with the expert to understand what knowledge was sought from the expert and where difficulties in the design process were occuring.

Three aspects of support were identified, loosely supporting Lundvall's (1996) classification of the forms of knowledge transfer: know-what, know-why and know-how. Designers sought knowledge of existing designs and the rationale behind them, they sought advice on how to proceed with the design process and they sought support and advice on how to implement the design – notably the embodiment of their ideas into CAD and calculations of geometry.

Rouse et al. (1986) cited from (Keane and Nair, 2005) stated that to be useful in supporting innovation, systems must be able to "record, organise, reuse and curate knowledge". Thus the system would be required to provide a structure by which knowledge can be systematically stored and to deploy knowledge currently sought from the expert by other designers, although it must be remembered the knowledge sought from the expert does not represent the only knowledge present in the business.

### *4.1.6 The Proposed Framework*

A system framework was therefore designed to address the core knowledge accessed from the expert, together with knowledge and capability to support the designer at key points. Three different components were suggested to support each of the observed existing types of knowledge:

**A Knowledge Repository**, the pivotal component of the system, a store of all the available knowledge on past designs including:

- Knowledge on how they were designed, the rationale, their requirements, who designed it and when.
- Rich media to increase understanding of functionality such as how the designs work, including photographs, CAD renders and videos.
- Documentation associated with the project including quotes, reports, CAD files and laser cutting files.

This repository was also required to support the capture of new knowledge associated with projects with minimum effort and overhead.

**A Methodology**, developed from observations of current design practices and best practice methods to guide users through the design process.

- Inclusion of access to training documentation
- Effectively communicating the captured knowledge through the system at appropriate points in the design process to assist engineers (intelligent design advice) and provide searchable data

**Design Tools**, a set of bespoke, semi-intelligent embedded tools to aid the designer during the design phase, in particular supporting the construction of geometry in the CAD software. The proposed structure of the system is illustrated in Figure 27.

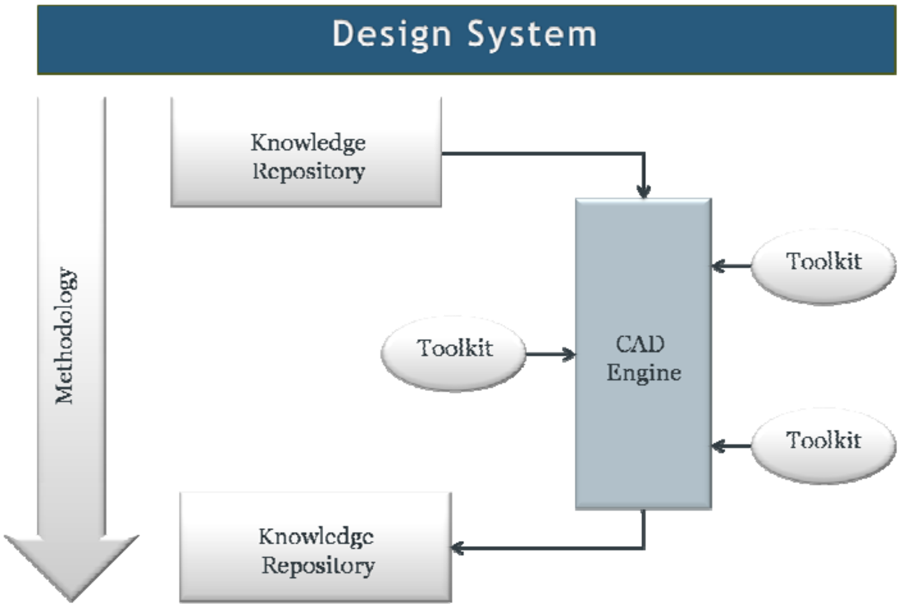



*Figure 27: Diagram illustrating the relationship of the Knowledge Repository, Methodology and Design Tools*

The intention was for the designer to access knowledge prior to designing a new product, utilise various tools during the geometry generation by using the CAD system and then to enter the newly generated knowledge back into the system (knowledge capture potentially being achieved through existing Rolls-Royce methods). Overarching this is the accessible methodology to guide novice engineers through the design process.

As indicated above, the different products and user classes have different requirements. To account for this it is expected that different users will use different parts of the system. For example an expert designing a stranger will primarily use the CAD embedded tools, while novice designers will primarily access the system through a web interface. The three 'cores' of the system were originally developed in relative isolation; however the final iteration of the system combined these components to provide continuous support for designers.

### 4.1.7 The 'Vision'

The primary activity behind this strategy was to create an explicit knowledge base by codifying tacit design rationale and storing this in an interactive system which could be accessed by designers.

The system was designed as an iterative system. Over time the knowledge base would continue to grow, creating a substantial knowledge base containing all previous experience, lessons learnt and projects. It is in this knowledge base that the competitive advantage required by the business to succeed would exist.

To illustrate the long term vision for the system, a set of scenarios were created highlighting the potential benefits of the system:

- An existing product is damaged and a replacement required:
  - Workshop engineer searches and locates project on the system
  - Engineer downloads the laser files and recuts fixture
- A client requires a modified version of an existing key design
  - Design engineer accesses parameterised model of the design, makes the required parameter changes and produces the updated design
- A repeat fixture is required:
  - Engineer searches the system for a similar fixture, a match is found
  - Engineer downloads the CAD files, reads the design rationale and the lessons learnt, understands the benefits and limitations of the design and modifies the CAD geometry to meet the requirements
- A stranger is required
  - Experienced or expert designer searches the system for similar projects, none are found
  - Design engineer produces new design, utilising calculations and numerical analysis tools embedded in the system
- A salesperson is asked to quote for a fixture
  - Salesperson searches system and retrieves similar project
  - Salesperson is able to provide client with a summary of the existing fixture to demonstrate capability
  - Costing details from existing project is used to estimate costs of new fixture

## 4.2 The Knowledge Repository

The knowledge repository was designed as the first point of contact for users faced with a new design. Studies indicate that experienced designers rely heavily on past designs (Ahmed et al., 2003) and the repository was intended to provide the knowledge that will allow new designers to do so as well.

In this section research has been primarily focused on developing and structuring the repository. The aim was to provide designers with the maximum relevant information while requiring the minimum input information.

### 4.2.1 Version 1:

Initially, a lightweight catalogue of parts was created as a means for tracking the parts or fixtures produced. This was developed using Visual Basic code in Excel, to provide a series of input forms and elementary searching and output forms. Although originally conceived only to store basic data, the catalogue quickly evolved into a more encompassing database. Version 0.2 of the catalogue shown in Figure 28 included pages or tabs of fields covering the following parts: function, design detail, manufacturing detail and costing.

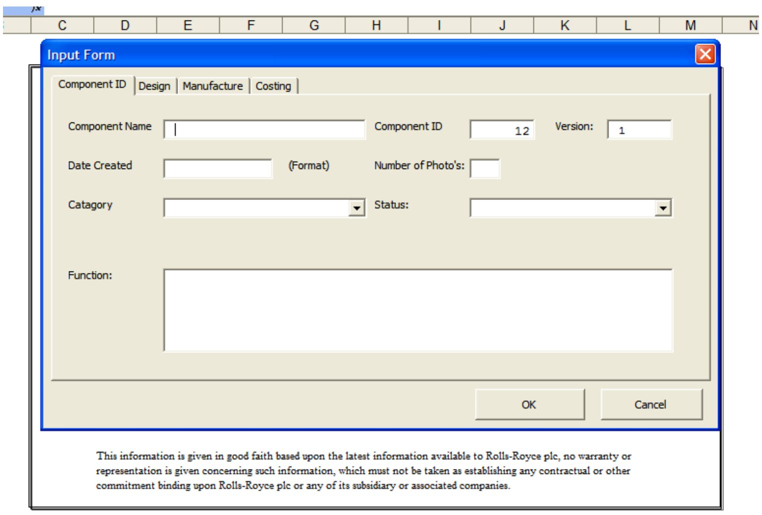



*Figure 28: A screenshot of an early developed input form within Excel. (All screenshots are shown to illustrate the nature and layout of the interface rather than to illustrate specific text and data)*

This was quickly updated to be more user friendly and to store additional data about the parts catalogued. It also now accepted and displayed photographs of the parts.

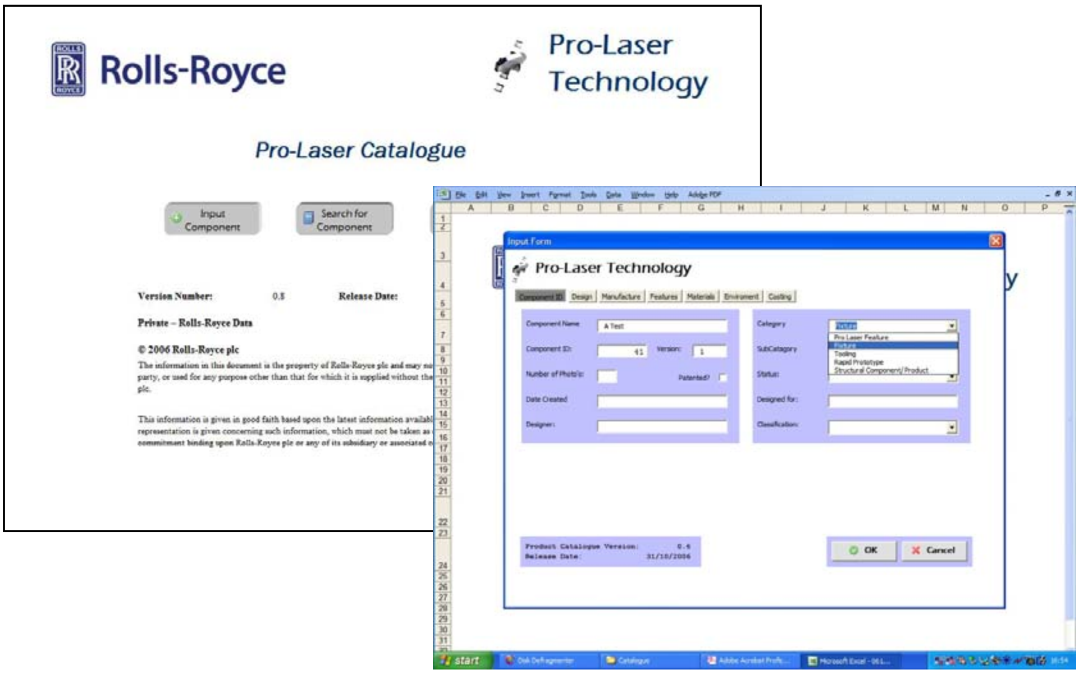



*Figure 29: Two screenshots of the sixth iteration of the catalogue.*

This catalogue was used successfully for a period of time; its critical drawback however was its reliance on Excel and its inability to operate over a distributed domain, using macros for input restricted multiple users accessing and using information concurrently. The long term business plan relies heavily on the ability to scale up this knowledge transfer and its integration into working practices, which would not have been successfully supported using Excel.

### 4.2.2 Version 2:

At the beginning of 2007, an update was led by the author and a software engineer commissioned to produce an online equivalent of the Design System. The system was built using the latest .NET 3 technologies and a rich SQL database. This provides the freedom and capacity to build in any additional capabilities that may be required at a later date, in particular potentially integrating the system with the CAD software.

This system incorporated the first work completed on the Toolkit, namely the parameterisation of a potential runner product. This was completed by a colleague and will be detailed further in section 4.4.1. This version was used primarily to test the feasibility of embedding parameterised models and to demonstrate the capability of a distributed system.

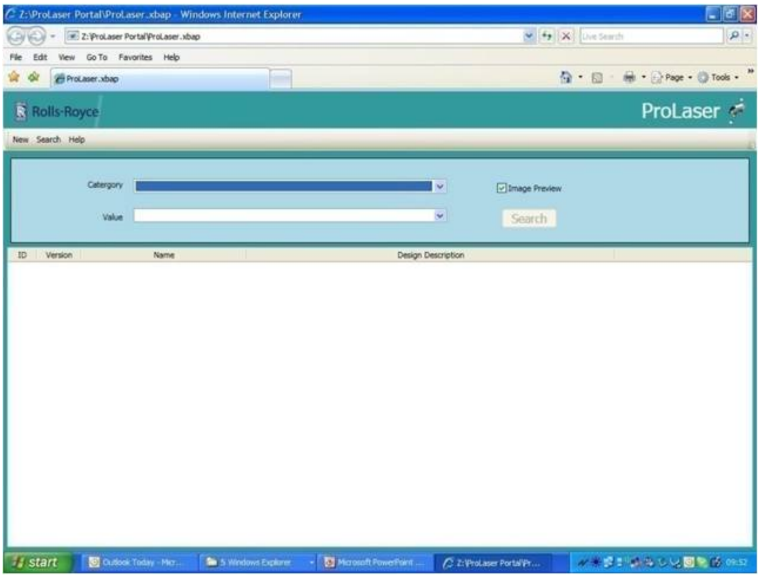



*Figure 30: Version 2, the online catalogue, illustrating the basic search field*

Although an improvement in terms of distribution and access, the system was not aligned entirely with the Excel version. In particular there was no input function and many of the data fields were not displayed due to time constraints.

Extensive discussions were held with the design engineers. Their requirements were determined and analysed against the current shortfalls of the system. A list of key changes required was produced and in March 2007 the system was improved to include an additional “Google” type search function and more data fields were displayed, including the addition of case study documents.

As described by many authors such as Davenport et al. (1997) and Swan et al. (1999), the single biggest source of inertia to building a successful knowledge management is from individuals. Knowledge has always been a source of influence and power and thus individuals are naturally predisposed to harbouring their specialist knowledge. To create a successful knowledge management project requires a change in this belief. At this stage the system was still being driven primarily by the author, with little input from the designers or the technical specialist. Two problems were observed, the first was the difficulty of inputting data, which still had to be entered via Excel, and the second the lack of time cited by the engineers.

The first problem was tackled by requesting additional work on the system to provide an input page and a means to upload files and photographs. This was completed in July 2007.

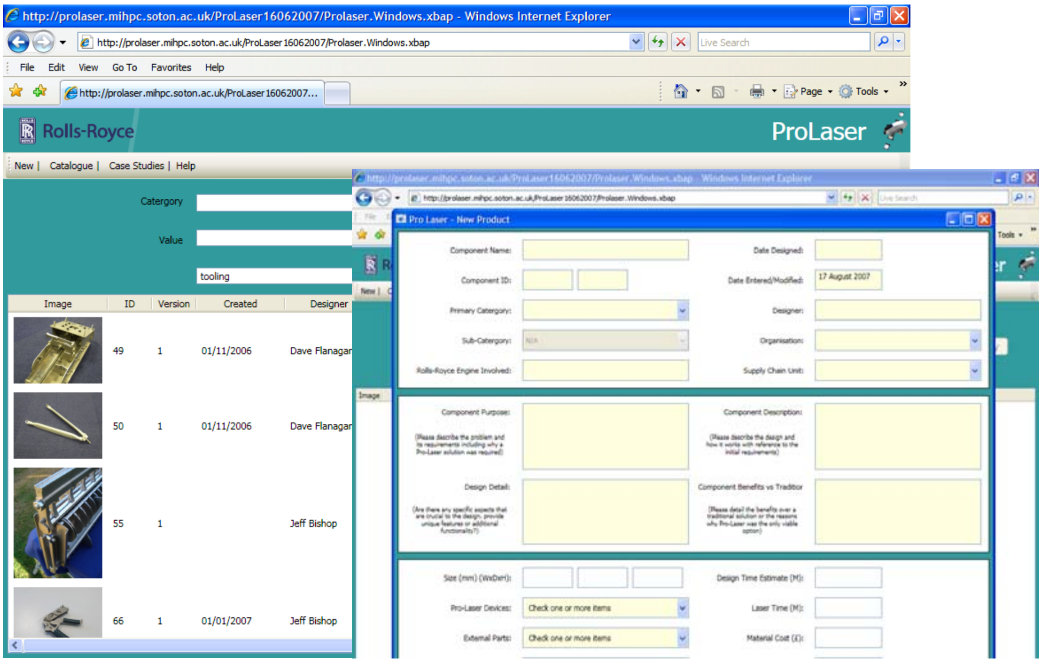



*Figure 31: Screenshot showing the next version of the catalogue and inset, the input page, shown to illustrate interface.*

The second, more difficult problem is likely to remain throughout the project. Specialist engineers are always in demand within the company, but it is vital, however, that they put time aside for the benefit of the system in order for it to be of any value. To encourage input, the author led a structured plan whereby the designers set aside half an hour following the completion of any design to input the details in the system. A job list was created on a white board and weekly team meetings initiated to support a more team-focused approach. The intention was to try and understand the pressures put on them and to share with them the approaches we were taking with the system.

This was not successful; the designers spent too little time in the office to support the regular meetings and did not maintain the job list on the white board. By the end of 2007, only a few details had been input on the system by the designers, and most of these were achieved through the intervention of the author.

It was at this stage that the meeting of ideas from the methodology, discussed below in section 4.3, merged with those of the system and knowledge capture. That is to say it was realised that moving forward knowledge must be captured concurrently with design process rather than as an independent process.

## 4.3 Methodology Development

Systemised and validated product development processes are increasingly being adopted across industries to reduce lead times and cost and to improve repeatability and product quality (Tate and Nordlund, 1996). Indeed Cooper and Kleinschmidt (2007) argue that the existence of a high quality product process is the strongest driver of profitability for a business engaging in new products. These formalised processes are also becoming necessary due to rising product complexity and the increased collaboration necessary to develop these products.

In order to best support the designers with knowledge, the system had to be designed around a structured process, itself a function of support.

As Blessing (1994) argued, 'design' relates to both the product and process. Designers must therefore have both process knowledge and product knowledge. A design methodology was therefore required that reflected the current procedures undertaken by the designers.

The following research provides the reader with an understanding of the role methodologies take in the design process, the relevance to KBS and presents the derived methodology for Pro-Laser.

### 4.3.1 Design Process Theory

A "Design Process" describes the set of activities by which designers develop new solutions (Tate and Nordlund, 1996). They are typically prescriptive in nature, presenting the process akin to a recipe which the designers should follow. It is often more accurate to describe the development process as a "Methodology" – defined as a body of rules or set of procedures – the principles of which the designers must utilise (Merriam-Webster, 2009). However, the terms are commonly used interchangeably and only if the difference is significant will it be highlighted here.

A history of the development of 'prescriptive' design methodologies can be found in Blessing (1994). Key developments will be briefly highlighted here in order to contextualise the later work presented in this thesis.

Prior to the Second World War, design was seen as a largely unstructured activity undertaken by highly motivated and creative individuals with little thought for formalised routines. Erkens (1928) did initiate the development of systematic design by proposing a step by step approach involving testing and evaluation during the 1920s. However, it was during and immediately following the war that a sound foundation of theoretical design was laid by key authors such as Kesslring, Niemann, Matousek and Leyer. These authors produced work on various aspects of design, for example describing overlying principles for deriving shapes and emphasising the need to express critically the design requirements prior to conceptual design. Hansen among others developed the ideas of systematic design culminating in a generic but systematised design methodology separating out key phases of the design process and shown below (Pahl and Beitz, 1988).

| | |
|---|---|
| **1)** | Determine the crux of your task, because it is common to all solutions. |
| **2)** | Combine the possible elements purposefully, for all solutions develop from such combinations. |
| **3)** | Determine the shortcomings of every solution and try to reduce them or their effects. |
| **4)** | Select the solution with the fewest shortcomings. |
| **5)** | Provide documentation to permit practical evaluation. |

This methodology was a significant development because it separated out sections of the design process and specifically identified a separation between the identification of requirements and the generation of ideas (or as Hansen puts it "combine the possible elements purposefully").

Blessing lists several more methodologies developed in the 1950s and 1960s, such as Wallace in 1952 and Alger & Hayes in 1964. During the 1970s these models evolved and expanded, increasing the emphasis on the stages prior to conceptual design (Blessing, 1994). The development of novel design processes appears to peter out towards the end of the 1970s and by the middle of the 1980s models such as Pahl and Beitz's (1977) design process became widely accepted.

While no one theory is taken as the definitive process approach, modern theory now accepts that there is a need to systematise the design process, given the increasing complexity of designs and collaboration between designers (Cross, 2000).

In the 1990s, rather than developing new ideas about the process of design, developments in design theory focused more on the development of design methods and the interaction of the designer with IT based support tools (Lehtonen, 2006). These were developed to formalise many of the existing 'intuitive' approaches. Methods developed include approaches such as objective tree mapping and quality functional deployment [QFD] or the Russian theory of inventive problem solving [TRIZ], designed to support and rationalise the creative approach (Cross, 2000). Some of these methods will be examined in more detail later.

The question of how best to support a designer's activities with IT is an open question and likely to remain so for the foreseeable future. Furthermore, it is also accepted that no one design process will ever be sufficient to describe all design activities. However, a clear and common design process should be the natural basis for any system intended to integrate with a designer's process.

It is therefore important not only to understand and describe the current design methodology, but to understand if it is appropriate to incorporate existing tools within the system to support prescriptive and formalised design.

### 4.3.2 Approach Taken

It was recognised early in the research that the design process used by the experts and the designers associated with the project may not be a typical prescribed approach to design. It was also believed however that essential stages would still exist, such as:

- Identification and clarification of requirements
- Idea generation
- Design embodiment
- Manufacturing

The approach taken to identify and develop a suitable methodology relied heavily on the observations and work produced during the knowledge capture activities (detailed in section 4.4), the most relevant methods of which were "Storytelling" and "Case Study Analysis" – asking the expert to describe the development of individual products and the activities involved in their development. These provided an initial understanding and two proactive activities were also run to support this, the first as part of a trial to evaluate the design rationale editor [DReD], the second a design exercise completed by a design consultant who supported this section of the work.

Time was also spent with the other design engineers discussing their approaches taken to problems, their use of CAD within the process and any differences they have observed between the expert's methodology and their own.

A final source utilised was the technical specialist's own documentation describing the principles which he has developed to describe his approach, featuring in his book, *The Influence of EVE (Bishop, 2004)*. He was not comfortable with the concept of a prescriptive design process. But he did believe in a set of theoretical guidelines or principles which new designers should follow.

### 4.3.3 Derived Methodology

Several key distinguishing features were identified in the specialist's approach to design notably:

- Fast down selection of ideas to an encompassing concept. In fact no parallel consideration of ideas was visible, although it cannot be assumed that this does not occur.
- A 'zooming' stage, whereby the expert focuses on one key area of the design, before "zooming out" and integrating this within the entire design.
- Rapid prototyping, in particular by the expert. Small trials and manufacturing experiments are used often through the design. This results in a fast design iteration process.

These ideas were analysed and combined into a methodology illustrated by the flowchart in Figure 32. Although this captured methodology primarily represents the design expert's approach, it must be converted to a process which will be suitable for new designers to follow.

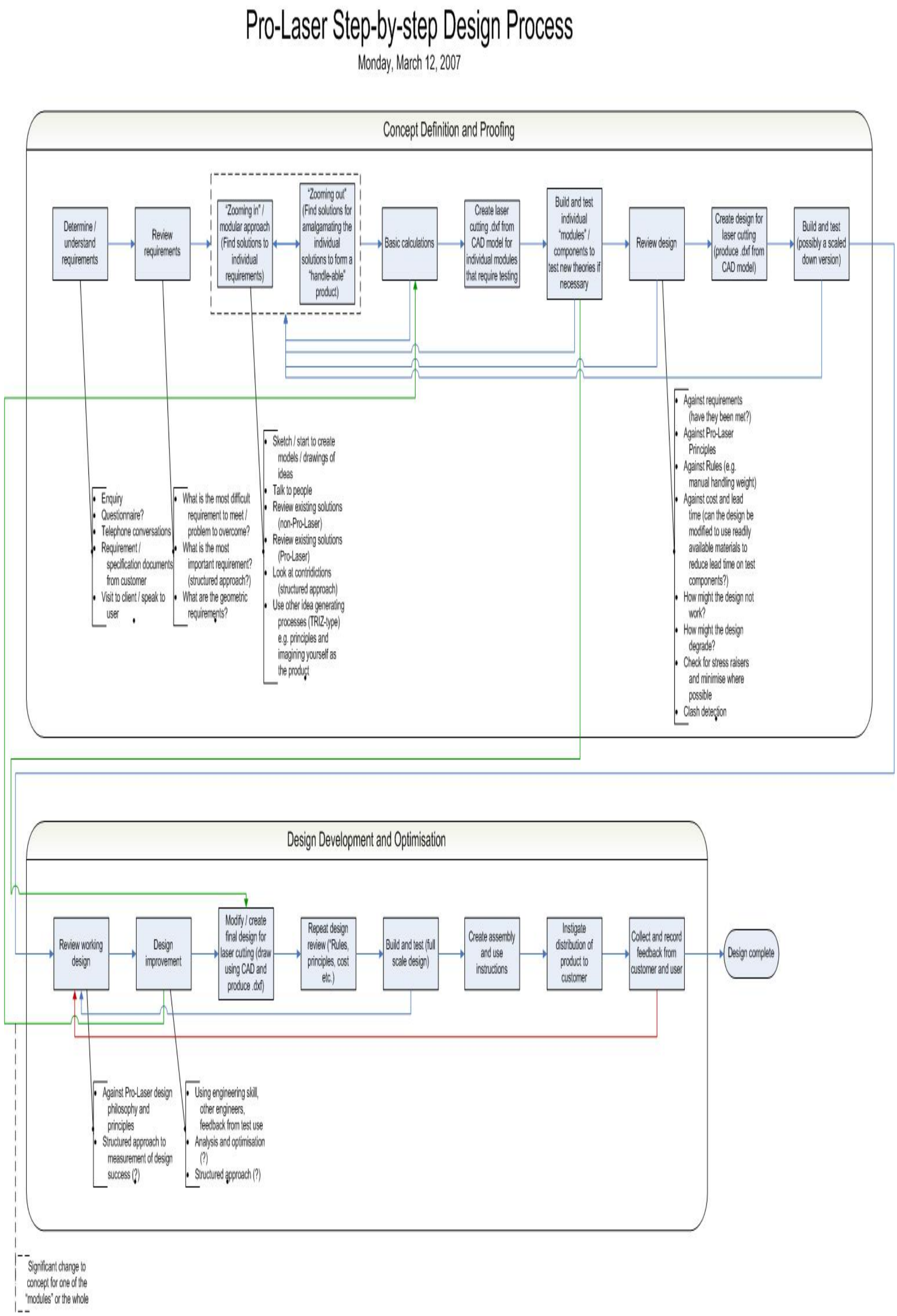



*Figure 32: First iteration of the identified Pro-Laser methodology*

Together with the flowchart, the expert's principles of design were adapted, separated and harmonised into a more succinct form by a design consultant developing three different essences of the technology, termed “philosophies”, “considerations” and “principles”. These names refer to different types of support provided.

The intention here is that while following a descriptive design process, a novice engineer could also refer to these essences as a ‘prompt’, thus ensuring that the designer has considered the core principles of the technology. It is for this reason that the developed approach is a methodology rather than simply a prescriptive design process.

### *4.3.4 Methodology Feedback*

To improve and iterate the methodology it needed to be tested. This was therefore integrated within the Design System test week (section 4.5). A design consultant produced a two day training course which taught the basics of the technology, the three essences and the technology methodology. Feedback was obtained largely through observation and comments recorded by the designers themselves. The designers were also asked to rate the methodology according to three questions and an open comments box.

The full study is detailed later, but here the results relevant to the methodology will be discussed. The full feedback forms can be seen typed up in Appendix A. However, the results of the ratings (on a scale of 1 to 5) are shown in Table 6:

| | Design A | Designer B | Designer C |
|---|---|---|---|
| Degree of uniqueness: | 2 | 3 | 1 |
| How well defined do you feel it is: | 2 | 3 | 2 |
| How easy it was to follow: | 2 | 3 | 3 |

*Table 6: Ratings given by designers to the methodology*

Together with the feedback from the designers, two points were apparent. Firstly the methodology was not perceived to be unique or significantly different to the design process encouraged by most design companies. Secondly the methodology did not support the user in interacting with the Design System. It was not clear how one should support the other.

Designer A tended to be against the idea of a design process, arguing the principles should be printed off and used but that the methodology…

> *"…should never develop to more than this as every problem and customer is unique".*

He also felt strongly that the methodology was not unique, yet despite this his approach was the least conforming of the three designers to the methodology. He felt that the templates/forms provided to record the requirements were too restrictive for designers. However, he did produce several concept sketches providing a record of his ideas and development.

Designer B was extremely methodical in approaching the problem and used the templates extremely well. It is felt that the process appealed to the designer's own method of designing and as a more experienced designer, he may have been happier following a stated process. The degree of personal feelings and experiences should not be underestimated when designing a process for people to follow.

In his feedback, designer B suggested the need for peer review to be included within the design process. Although the system is intended to minimise the level of interaction with an expert designer, it must be realised that this will still exist and will be necessary in some designs.

The test also reaffirmed the value of the concept sketches. Even basic and poorly annotated sketches together with the final solution can indicate the thought process and reasoning behind the final design. In future the system will account for this and sketches will be scanned in on crucial designs.

### *4.3.5 Methodology Development*

The issues raised during the test week can be summarised as follows:

- Lack of novelty of design process
- Lack of integration with the Design System
- Need to support concept selection
- Need to ensure minimum 'paperwork' and overhead

The first point should not be viewed negatively. However, its acknowledgement allows for a shift in focus. Rather than trying to observe and identify the process currently in use, an acknowledged process can be incorporated. This should then be adopted to support key points of integration with the system. Additionally a means for supporting concept selection was also required, but the entire process must place minimum demand on the engineers – one of the key benefits of the technology developed at Rolls-Royce Sheffield is the short lead times offered.

The proposed solution was to split the methodology into lightweight and heavyweight versions. Thus for small, repeat products the lightweight route is used minimising overhead, but recording less knowledge and providing less support. For complex and auditable products the heavyweight route is adopted.

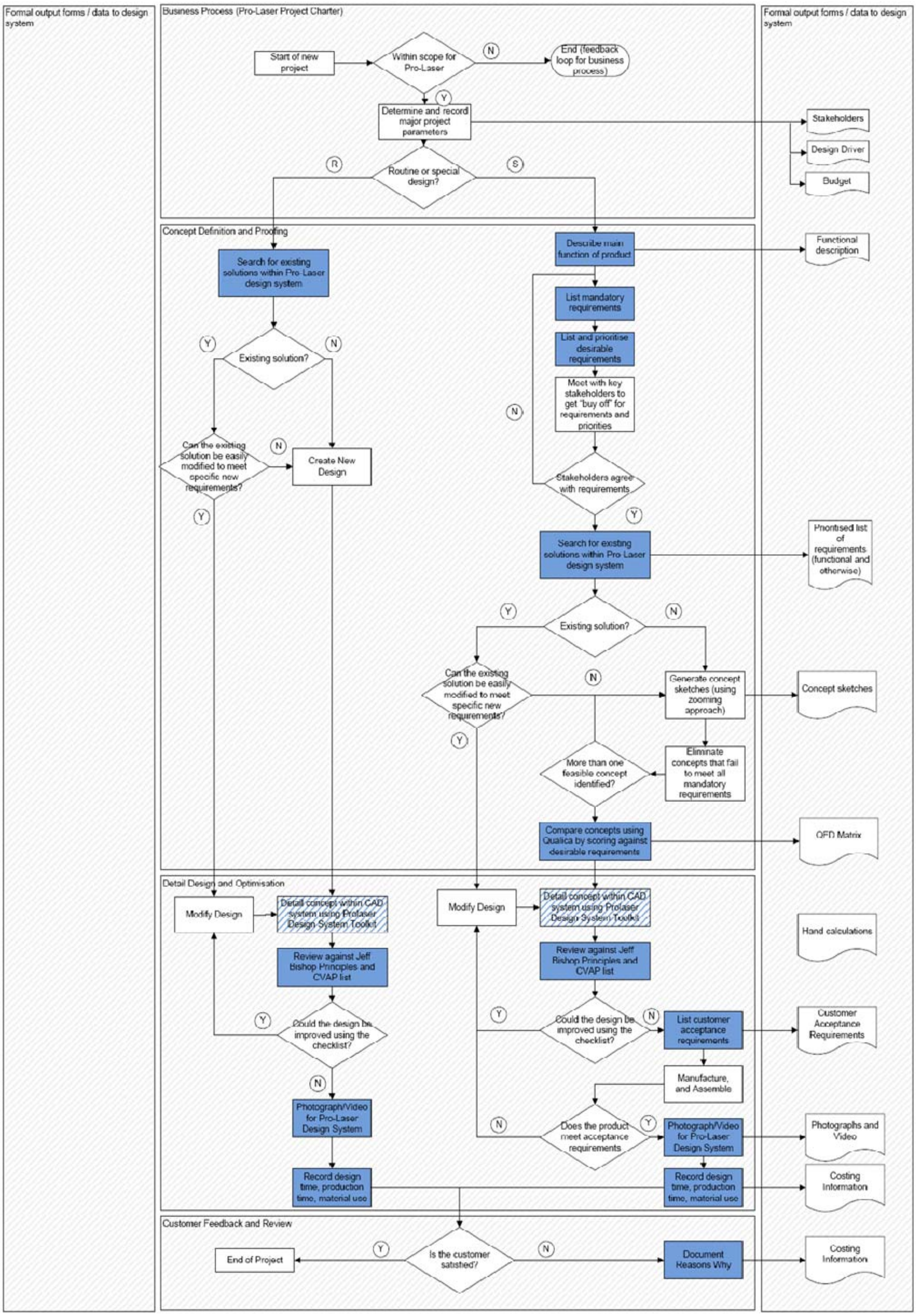



*Figure 33: Updated Methodology, blue boxes signify interaction with the Design System*

In addition to this it was suggested to use Qualica QFD, a software package to implement Quality Functional Deployment (QFD). The package has been recently introduced to Rolls-Royce and offers a selection of forms for managing project design. Qualica offers a formal and independent means for creating and understanding relationships between customer requirements and deliverables. It emphasises the need to identify, document and weight the design requirements, from which optimum trade offs can be developed.

### Qualica Trial

To trial its use in the methodology, a series of forms were created specific to the developed methodology. These were then completed from the perspective of a new designer. Screenshots of the package in use can be seen in Figure 34.

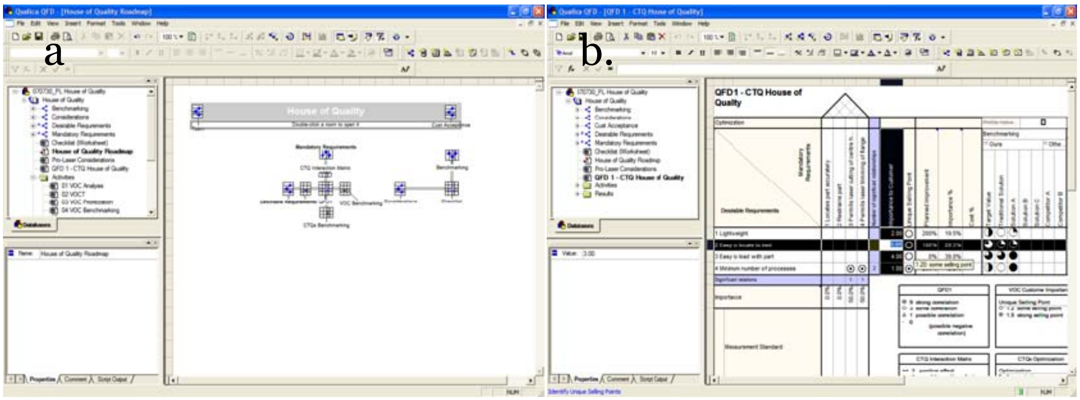



*Figure 34: Screenshots of Qualica showing the overall roadmap (a) and inputting correlations between requirement, desirables and customer weightings (b).*

Following the mock use, the results were presented and reviewed by the team. While the benefits of formal identification of requirements were appreciated, the need to weight requirements and work through forms during design was felt contrary to the core principles of the technology. The Design System was viewed as a system to support creative design, which would not necessarily be enhanced by Qualica. It was also felt that the flexibility of the technology was such that direct tradeoffs between parameters were rarely required. More often in situations where design conflict occurred, it was possible to 'design out' the issue and this was preferred even at the expense of more development work.

### 4.3.6 Methodology Validation

To further validate the methodology a second design task was developed, comparing the approaches of a novice designer to the technical specialist. The designers were presented with a series of day-to-day problems requiring development of a solution and instructed to follow the developed methodology.

The test started well and the requirements successfully elicited by both designers for the first problem (a mobile phone holder). Discussions arose with the specialist, however, when he was asked to produce three different concepts – he did not agree nor understand why this was needed. This highlighted the observation made earlier that the expert down selects ideas early in the design process. The test did not proceed, although the novice later proceeded to use the methodology to complete a design successfully.

This highlighted several implications:

- The technical specialist cannot always be used to test the system or aspects of it. As an experienced designer his approach is naturally well established and it is perhaps expected to be different.
- The test (and discussion) demonstrated how resistant designers are to changing their approaches to problems. It also demonstrates the potential issues involved in trying to enforce a different methodology.

It must also be remembered that as the business develops it will be required to develop auditable processes, for example to meet customer expectations and demonstrate that the optimum product has been developed. A structured process requiring documentation will be implemented at some level. It is not unreasonable therefore to ask designers to record requirements, sketches and notes as the design evolves.

### Summary

This section has introduced the concepts and basic literature behind standardised design methodologies, in particular those involving prescriptive design processes. Through observation, active testing and feedback a methodology incorporating the ethics of the designers has been developed. The methodology allows for both detailed and fast development processes and identifies key interactions with the Design System.

During the development of the methodology, the different approaches adopted by individuals (in particular the expert) became increasingly apparent as well as the difficulty in trying to enforce a common approach. The designers down select ideas early in the process and do not formally record other options, preferring a fast iterative development involving the manufacture of sub assemblies or parts. It is important however that records are kept of designer's rationale, that support is provided for new designers unfamiliar with the design process and that interaction with the system is encouraged at strategic stages.

It is clear that there exist common stages through which all the designers move. These range from collating and understanding the requirements, through the concept stage, design, production and finally delivery to the customer. Although enforcing a strict process may indeed limit the designer's creativity, it was proposed that by using the Design System aligned to the methodology it would be possible to capture the rationale as intended. The knowledge repository was therefore restructured to support these interactions.

While the methodology itself was left largely unaltered, its adaptation to the repository required significant simplification. Further testing of the methodology incorporated into the Design System will occur as part of the final evaluation section.

## 4.4 Design Tool Development

The 'design tools' are intended as a collection of different semi-intelligent tools embodying the knowledge-based engineering principles of codified rules and automated routines described in section 3.5.9. In particular, whereas the knowledge repository and methodology are designed to support designer's workflow and decision making, neither directly support geometry generation.

It was recognised that in supporting the scenarios described in section 4.1.7, different approaches were needed to support geometry generation. For new and bespoke products, geometry would need to be generated from scratch. Tools could be created to support calculations. For highly repeatable products geometry could be encoded to allow rapid modification by more novice engineers. This dichotomy is illustrated in Figure 35.

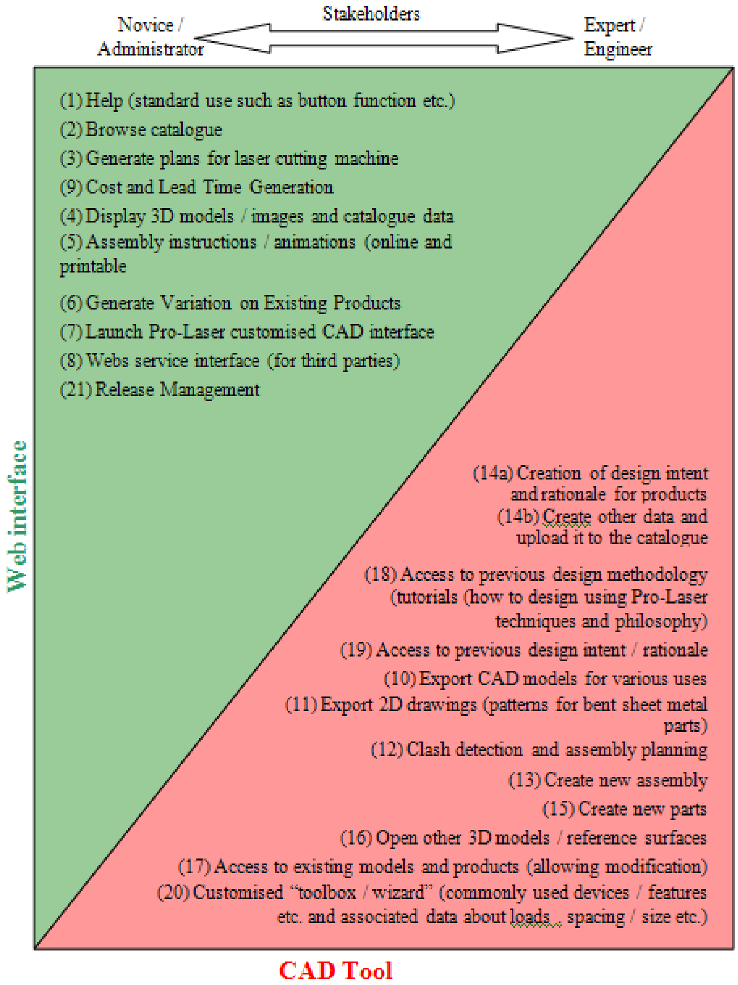



*Figure 35: Design system requirements illustrated against the stakeholders and interface*

The diagram illustrates the functions that the system needs to perform against the interface used and the intended users. The top left functions would be accessed through the knowledge repository and web-based interface while those in the bottom right would be directly related to the CAD tool.

Geometry generation accessed through the knowledge repository would utilise parameterisation, while the toolkit for CAD work would use either CAD tools or independent calculators, such as Excel based macros. These different approaches were trialled and are described in the following sections.

### 4.4.1 Full Product Parameterisation

In its most fundamental form, geometric parameterisation is the representation of geometries by mathematical variables. Typically, however, relations are introduced between different variables so that a limited set of driving variables are used to determine the entire shape and form of the product. In optimisation and design, these variables are then used to aid the optimisation process by creating a more powerful representation of the geometry, which can then be manipulated or systematically varied to produce an optimum design against a set of criteria.

One of the most commonly cited examples of parameterisation is the NACA series of aerofoils, which describes any member of the series with just four parameters (Keane and Nair, 2005). Modern CAD software packages offer the capability to define parameters explicitly and allow them to be driven, either from within the CAD package or, increasingly, by external software.

Product parameterisation allows for faster reuse and ease of modification and provides greater flexibility in quickly varying and adapting designs. The disadvantage can be an increased complexity for engineers not familiar with the product. Often they need to spend time ‘unpicking’ the design to understand the parameters in full prior to modification. It has also been argued that limiting a design to set parameters dissuades designers from creating novel step changes to the design.

**Test Design – Interactive Press Brake Tooling**

The product – interactive tooling for a press brake – was designed by the expert to create 180° bends in materials with high spring-back. The tooling is a unique design, using titanium springs which respond to the downwards motion of the press to create side loads forming the bend. Its design is specific to the material and bend radius required but by varying the shape of the titanium springs, the design can easily be adapted for different bends. It therefore represented an ideal product which could be produced on demand for a variety of different applications.

The technical specialist created a set of design rules relating 5 key input parameters to the most important variables in the design. Using these design rules the tooling was drawn and parameterised in Solidworks™. However, the intention was for novice engineers to access easily and produce this tooling without needing to learn and 'unpick' all the details associated with the product (thereby shortening the rework time). An interface was therefore created to drive the parameterised model through the knowledge repository and automatically output the required geometry files, as shown in Figure 36. The knowledge repository itself contained associated knowledge to understand the input parameters, and if required the full product.

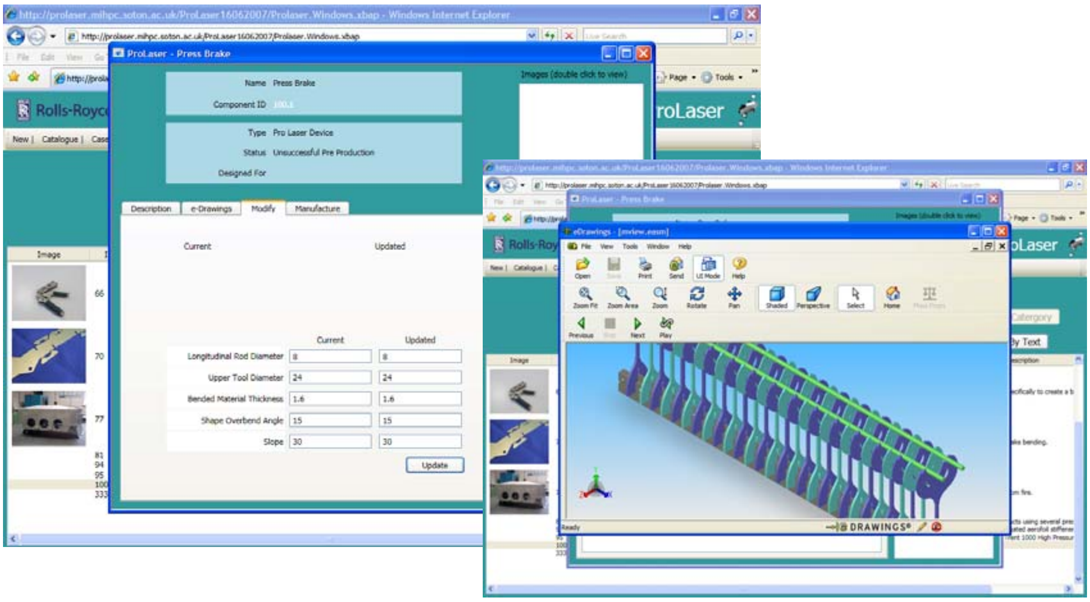


*Figure 36: Screenshot of the web-based user interface driven by Solidworks and the output geometry (inset)*

The developed system was a successful proof of concept; it was exceptionally easy to modify and to generate new 3D geometry. Yet it also highlighted the high level of coding and effort required to create the parameterised model and the interface. In particular it required different skill sets; product expertise had to be captured from the expert (in this case by another engineer) and encoded into CAD, which subsequently required a software developer to create the interface with the knowledge repository.

The web interface was designed to support rapid manufacture by novice engineers, yet as the business developed this requirement did not materialise. Mass production of repeat fixtures has not been needed. The high level of initial effort required to parameterise the product will only create a return if a large number of similar products are required. Therefore, full product parameterisation was not pursued.

### 4.4.2 Common Features

'Common features' are devices used regularly within the fixtures and tooling developed at Rolls-Royce Sheffield. They include novel joining techniques, locating aids and manufacturing aids. As more fixtures are designed, new features are continually devised.

These were identified early as being crucial to support both novice and experienced engineers when designing products from scratch. Having a set of features which are regularly used that can be easily imported ("drag and dropped") into the CAD environment reduces the need to redraw geometry and also ensures the use of tested and reliable geometry.

These common features were parameterised into UniGraphics, scaling with a single driving variable (the material thickness) and are regularly used by the engineers. However, they are not, as initially intended, integrated with the Design System. The intention was that different features would be stored within the knowledge repository and could be directly opened into the CAD system. Designers would always have access to standard features and be given access to new features as existing ones are developed. The reality is that designers keep the files on their local file system and as they modify the 'common' features themselves do not upload the new versions. This significantly weakens the benefits of a searchable knowledge repository and a common knowledge base of optimised geometry.

### 4.4.3 Automated Common Features

Although distinct to the Design System, the parameterised common features were successful – they were often used and provided a rapid means for generating geometry. Their main limitation, however, was the 'drag and drop' behaviour. This behaviour limits each import to a single feature. Thus a designer placing ten features would need to perform ten operations.

In August 2009, an engineer from RRIOPL was attached to the business. Over the following six months the engineer further developed the original common features into an automated tool built within the CAD system. The tool allows designers to specify the parameters required, such as material thickness, spacing and the number of features required and will then scale and place the features as required. The tool has provided significant benefits to the designers, vastly improving their ability to generate large scale fixtures and tooling efficiently.

This tool is again distinct from the Design System. Yet the tool demonstrates precisely the approach theorised during the early research and development of the Design System, that is experienced designers can be supported using semi-intelligent geometry generation tools. It also demonstrates that while full product parameterisation may not be feasible, the embedding of design rules into commonly used features can be successful. At the time of writing the engineer remains attached to the business working off-shore and is currently developing additional tools to support flat-patterning of geometry.

### 4.4.4 Independent Calculators

The designers are regularly required to make decisions during design and manufacture, such as the spacing of joining features along an interface, the shape of springs to provide certain loads or the tooling choices to create specific bends. The technical specialist has the experience and past knowledge to judge these 'by eye'. Novice engineers do not. Therefore a set of tools and tables were suggested which would contain data and formulae to support the novice engineers in making these judgements.

The tools would again be accessible through the Design System, but were conceived for use by engineers from their desktop. In the early development version of the system these tools consisted simply of bend tables created by the technical specialist. These would allow designers to look up a required bend angle against the material type and determine which tooling set and which settings were required for the press brake to create the bend.

### *Summary*

The toolkit was conceived as a means for supporting the more geometric tasks of the designers. Through the experiences of the early development system and the early testing period described later in section 4.5 it became apparent that the vision of a fully integrated knowledge and CAD system was unlikely to be within the scope of the project.

Development of a CAD interface is heavily dependent on software development expertise and on the choice of CAD software. Over long term growth, neither of these can be assumed.

As the business develops and grows there also appears to be less demand for mass production of repeat fixtures than originally expected. This significantly reduces the need for a fully integrated system. Trials have also shown that many geometric features can be easily dragged and dropped between parts or from libraries in the CAD package and full parameterisation can also be implemented within the CAD package without the need for an interface.

Despite this, numerical tools such as the bend data and geometry such as common features provide significant benefits to designers and further tools, both internal and external to CAD will be developed.

## 4.5 Knowledge Capture

Following the initial development of the knowledge repository, one of the primary aims was to capture the expert knowledge and populate the repository with a critical mass of knowledge. According to Hahn and

Subramani (2000) this is a crucial requirement to ensure the adoption of any knowledge-based system.

Although the Design System is populated concurrently with the design process, in order for the system to be usable and of value to other engineers it had to have an initial body of knowledge prior to launch. Furthermore, as one of the primary aims of the project was to mitigate loss of knowledge from the design expert, a research activity was needed to capture this knowledge.

The initial aims were to capture existing designs and experiences from the specialist. A number of methods were trialled and used. The approach taken to evaluating these methods is illustrated in Figure 37. The methods trialled were a combination of those relevant from the existing Rolls-Royce knowledge methods, together with those from literature introduced in Chapter 3. The primary methods and tools selected were:

| Methods Used: | Tools Used: |
|---|---|
| **Storytelling** | **DreD** |
| **Shadowing** | **Video recording** |
| **Structured Interviews** | |

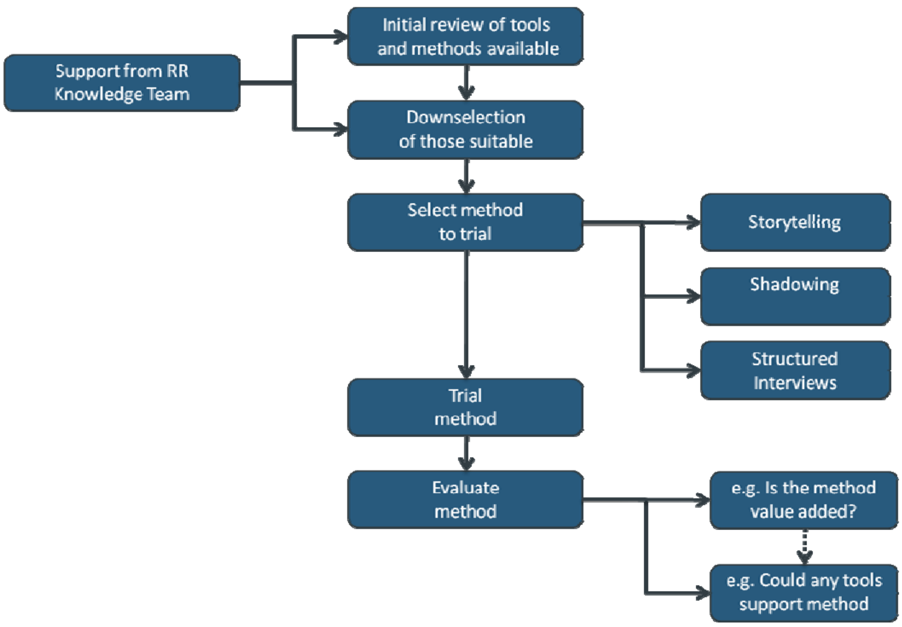



*Figure 37: Flow diagram of the approach taken to evaluating knowledge capture methods and tools*

The majority of these methods have been used to try and codify otherwise tacit knowledge. The design expert has photographed the majority of the fixtures and archived the drawings, but to understand how the expert designed and more importantly why, requires additional knowledge of the background requirements, design drivers and rationale.

### *4.5.1 Storytelling*

This is adopted from the approach described in section 3.6.2. The technical specialist was asked to describe the design process for key products as a story and key stages of development were noted down. These developed into formal documents called case studies. The benefit of storytelling was to generate a chronological perspective of the methodology that the expert uses during design. The disadvantage was a poorly structured output. Many of the early cases studies were very different to each other and were time consuming, with many of the sessions taking several hours each.

To aid this process a program called DRed – Design Rationale Editor was trialled. This was created by Dr Rob Bracewell from Cambridge University and funded through the University Technology Partnership for Design (UTP) by Rolls-Royce and BAE Systems (Bracewell et al., 2004). The tool is widely used throughout Rolls-Royce (Cambridge, 2005).

The tool supports decision making – either to aid problem diagnosis or in creating a solution (Rolls-Royce plc, 2006a). The intention is to capture the steps taken throughout design and record the rationale for these decisions.

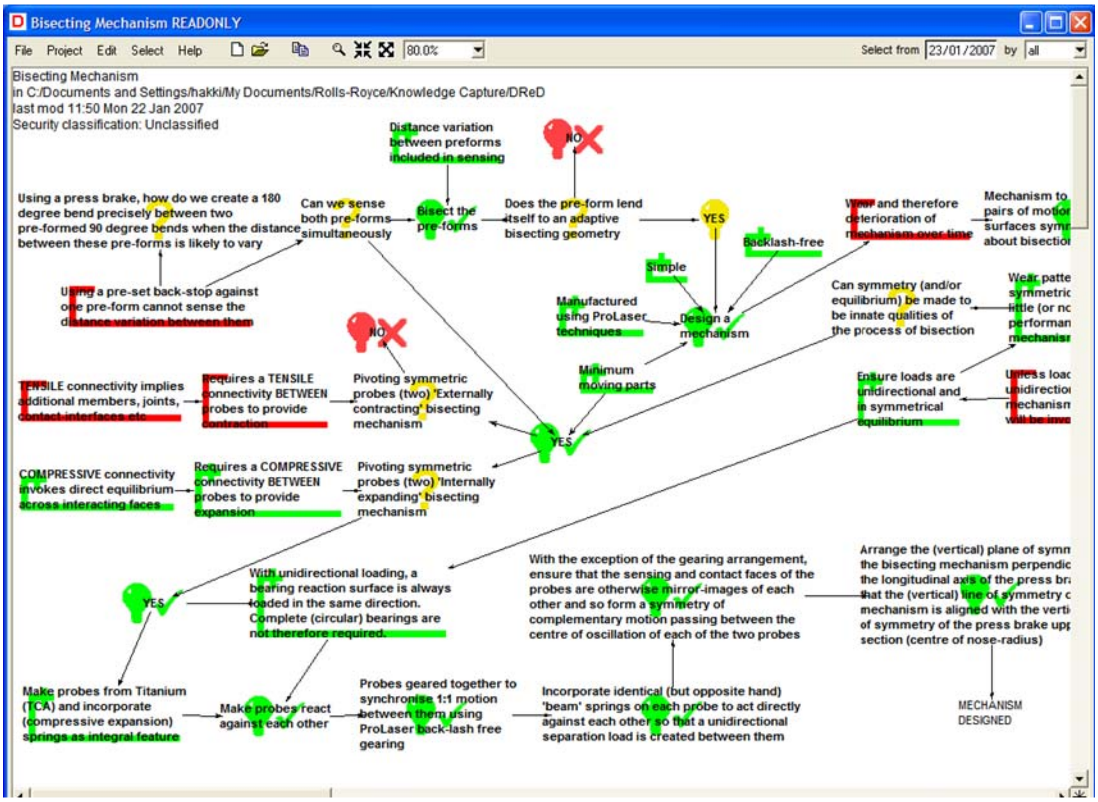



*Figure 38: Screenshot showing a typical use of DReD. Screenshot shown to illustrate interface.*

It was found that while DReD offers a visual representation of the steps taken through the design process it was extremely difficult to use the tool retrospectively. It forces the designer to think of several concepts and select the most appropriate, but in returning to the problem, many of these have been forgotten and generated little valued knowledge.

It was also felt that the tool was targeted at a team of designers working on highly optimized, high cost products. To operate DReD during the design process requires a user consciously recording the process. In a team, one member can be tasked with this but for single designers who need to focus primarily on the design in hand, recording rationale while designing is extremely disruptive. It was not pursued therefore as an applicable tool at this stage of development.

### 4.5.2 Shadowing

To further understand the design process undertaken by the expert, a period of time was spent shadowing. By observing the designers at key stages of their design an understanding was obtained of the unique approach and methodology employed. This again proved very time consuming but several studies were completed. This provided the grounds for the methodology introduced earlier. While successful at providing greater understanding of the process, it was too time consuming and intrusive to be continued for a large number of projects and regular knowledge capture.

### 4.5.3 Structured Interviews

To gain more codified and structured knowledge the case studies evolved into structured interviews. These were developed to capture all the knowledge associated with a particular design. Unlike the storytelling, this is not intended to capture the entire design process but to provide a complete understanding of what the design is for, how it works and the origins of the design.

A set of questions were developed, based largely on the experiences of storytelling and on the knowledge repository. These questions form the structure of the interview through which the specialist was taken. All the interviews were videoed – providing a supplementary source of knowledge.

The resulting case studies contained all the required knowledge to enter a part into the repository, but also contained additional detail required to redesign a similar part or where appropriate to model and parameterise the part. The interviews worked well. The increased structure created a much more focused question and answer session with the expert. While they still involved a large investment of time, the resulting documents and videos were significantly more cost effective and valuable than storytelling.

### 4.5.4 Other Captured Knowledge

Additional notes were also taken while discussing general points. The expert had many snippets or 'gems' of wisdom – supportive comments, ideas and theories that the expert uses – that were captured but were not project specific. These were collated into a document and embedded within the system.

## Summary

Managed knowledge capture activities were concluded at the end of 2007. By this time the prototype knowledge repository had been established and located on site in Sheffield, allowing designers to access the knowledge captured but also to input knowledge and files.

A package summarising all of the captured knowledge was delivered to Rolls-Royce Sheffield. This consisted of:

- 54 Case studies
- 46 Hints and tips
- 10 Product specific documents on 'how-to' design types of products
- A two day introduction training pack to the technology
- Frequently Asked Questions
- Categorised captured principles such as
    - Questions to ask customers
    - Designing interfaces for specific machines
    - Advice on the design process

Captured product knowledge is illustrated in Figure 39, which lists the most important products and features and the level of detail captured.

**Knowledge Matrix**

| | Example (Associated fixture / tool) | Catalogue entry (as it stands at the moment) | Case study (detailed understanding of how it was designed) | Description (how to use a technique or device or how to design a fixture) | Scaleable drawing | Scaleable model feature in NX (drag and drop) | Parameterised model feature | Understanding of detailed physics | Set of rules derived from detailed physics | Rules embedded into model feature or into design system/NX |
|---|---|---|---|---|---|---|---|---|---|---|
| Springs and clamps | y | | | | | | | | n | n |
| Threaded shafts | y | | y | | | | n | n | n | n |
| Backlash free gears | y | y | y | | | | n | n | n | n |
| Twist Lock | y | y | y | | y | n | n | | | |
| Twist Lock Spanner | y | y | y | | y | n | n | | | |
| Slot Rivet | y | y | y | | y | n | n | | n | n |
| Slot Lock | y | y | y | | y | n | n | | n | n |
| Bumtag | y | y | y | n | y | n | n | | | |
| Pip-Less Hole | y | y | y | n | y | n | n | | | |
| Chamfer-less Hole | | y | y | | y | n | n | n | n | n |
| Press Brake Bend Aid | y | y | y | n | y | n | n | | | |
| Nut Stud Plate | y | y | y | | | n | n | | | |
| Interlock Plate | y | y | y | | | | | | | |
| Thumbpad | y | y | y | | | | | | | |
| Jigsaw Sheet Locking | y | y | | | | | | | | |
| Omega Grid | y | y | y | | | | | n | n | n |
| Labyrinth | y | y | y | | | | | n | n | n |
| Rules and guidelines (from FAQs) | | | | | | | | | | |
| Flush Mounted Bolt | y | y | n | | n | n | n | | n | n |
| Locking Hairclip | y | y | n | n | | | | | | |
| Sprung Hole Locater | y | y | n | n | | | | | | |
| Magnetic Sheet Metal Clamps | y | y | n | n | | | | | | |
| Assembly Fixture | | y | y | | | | | | | |
| Loaded Machining Fixture | | y | y | | | | | | | |
| Laser Machining Fixture | | y | y | | | | | | | |
| Surface Treatment Fixture | | y | y | | | | | | | |
| Part Marking Fixture | | y | y | | | | | | | |
| Curing / Heat Treatment Fixture | | y | y | | | | | | | |
| Welding Fixture | | y | y | | | | | | | |
| Curing / Heat Treatment Tool | | y | y | | | | | | | |
| Direct Forming Tool | | y | | | | | | | | |
| Rapid Prototype | | y | y | | | | | | | |
| Rolls Royce on Engine Part | | y | | | | | | | | |
| "Repeater" | | y | y | | | | n | n | | |

**Key**

| | | | |
|---|---|---|---|
| (green) | Captured from Jeff | y | Captured |
| (orange) | Not sure whether we need to capture it from Jeff | ? | Not sure whether we need yet |
| (red) | Needs to be captured from Jeff | n | Need to get |
| (grey) | Not to be captured from Jeff | | Not needed |

**Notes**

Any other "repeaters" need to be established by Rolls Royce and added if required

Ongoing development of the catalogue will tend to merge the catalogue entry and case study column such that the catalogue contains more information about how products work and how they were designed through integration of a design process flowchart

*Figure 39: A summary of some of the specific knowledge captured. Matrix is shown to illustrate the structured approach to capture.*

Following the launch of the Design System, knowledge was expected to be captured more regularly and effectively from both the expert and other designers. However, further knowledge capture was limited and an early indication of inertia from designers against knowledge sharing was observed. Designers appeared not to view the activity as a worthwhile and necessary activity against the pressure to deliver tooling and fixtures.

It is vital that designers use the system as a concurrent throughput of knowledge by inputting knowledge and searching for it. Only through its use can the system be of value to the business. It was therefore realised that the system would need to be improved and optimised for ease of use and to encourage designers to use it.

## 4.6 System Evaluation

To conclude for or against the project hypothesis required an evaluation of the system to determine what the impact and effect of the Design System was. The wider impact and effect of the Design System to the business and the designers could only be evaluated once the fully developed system had been established (Chapter 6). However, to gain feedback from the prototype and iterate the development, an early test was conducted with the aim of:

*"assessing the effectiveness of the current Design System, training and associated knowledge in the full development and production of a fixture design".*

A preliminary test was devised and run, accepting that the system was only a trial version, but with the aim to better understand the limitations of the system in order to improve the system.

### 4.6.1 Strategy for Evaluation

Because of the limited uptake seen by the Design System and relatively short period in which the test was required to be done, a proactive rather than passive observation was suggested. The test would evaluate the effect of obtaining and reusing the knowledge from the system on designers faced with the design of a new or 'stranger' fixture.

Many empirical studies of designers and their activities have been completed, such as Blessing (1994). Often these can be direct comparative studies, examining the activities of multiple designers or teams faced with an equivalent task. These studies, however, can be of limited use invoking little comparability or validity (Bender, 2003). This is particularly true when assessing Knowledge Management activities, where the lack of measured environmental variables and little appreciation of the working context often invalidate any study claiming to evaluate the effects of Knowledge Management. However, in this early stage of testing the intention was only to evaluate the use and direct effect of the system. In this situation, only the Design System is under evaluation and a comparative study is adequate. The key stages of planning and implementing the evaluation are illustrated in Figure 40.

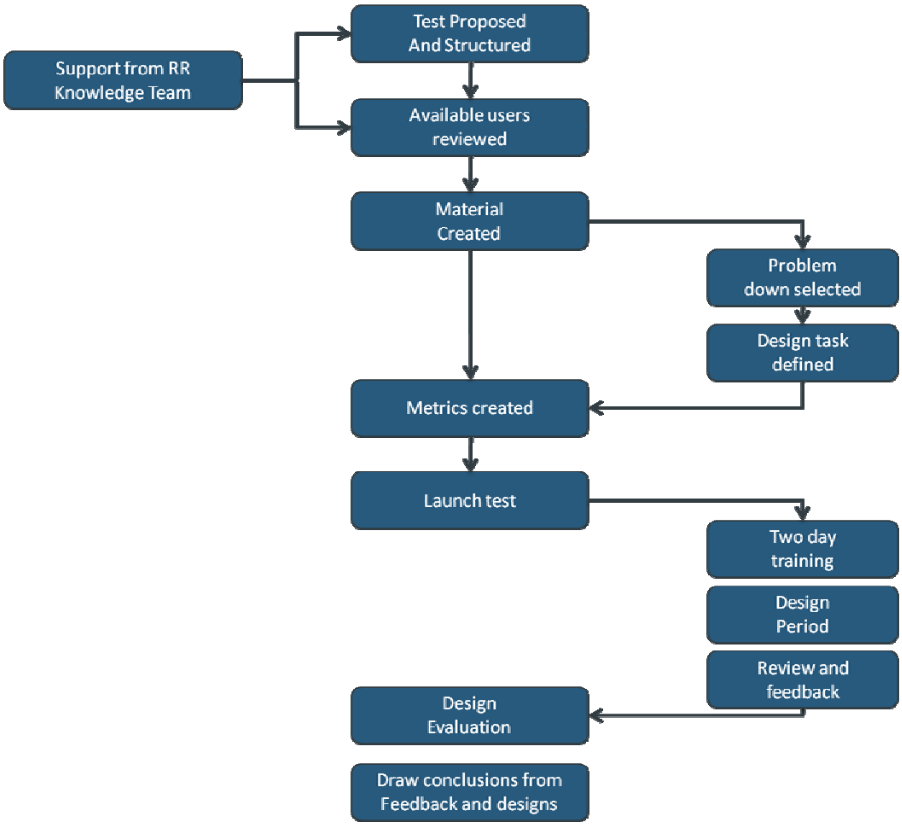



*Figure 40: Key stages of the design and implementation of the system evaluation*

The proposed study was designed to compare the solutions of two similar groups of designers to a set problem. One group would be given access to the knowledge base and the other would not. The resulting designs would be assessed and compared to determine if significant or observable benefits were provided through the use of the system. It was acknowledged, however, that differences between designs could be attributed to individual's experiences as much as or more so than the knowledge supplied through the system. Therefore a large sample population would be required to observe a statistically significant result. Due to the limited number of available engineers this was not feasible.

With a small population of users, there is limited benefit in comparing within the group. Clearly the maximum understanding of the system would be gained by providing all users with access and gaining feedback from them all. A comparative study was therefore proposed that compared novice engineers' solutions to the technical specialist's and an existing design.

As well as comparing the designs it was also necessary to understand the process by which the designers worked in order to understand any influences the knowledge provided. Therefore extensive use of observation and feedback would be used to support the comparative results.

Five engineers were available to support the evaluation – the Technical Specialist [TS], an existing Manufacturing Engineer [ME], and three novice engineers unfamiliar with the technology (designated A, B and C). The three designers had varying design experience but it would have been too complex and not necessarily feasible to try and evaluate this experience and normalise any results. All had over five years of design experience but had no design experience with the Pro-Laser technology.

### 4.6.2 The Evaluation Strategy

The test period was a week. It was accepted that a new designer would need some initial training in order to create a design using the technology at all. Therefore the initial day and half was dedicated to training, introducing the design principles of the technology and describing the methodology. The design challenge was presented on the second day. Days three and four were set aside for designing and on day five each person presented and discussed their design to the group, as illustrated in Table 7.

| | Morning | Afternoon |
|---|---|---|
| Monday | Introduction and explanation of the week's aims<br><br>Day 1: Training<br>Design & manufacture principles | Day 1: Training<br>Design & manufacture principles |
| Tuesday | Day 2: Training<br>Pro-Laser Design Process<br><br>Shop floor visit (review press-brake & laser equipment) | Design Task<br>Introduction and "pack" handout<br>Shop floor visit (review task with operations staff)<br><br>Review and feedback on training |
| Wednesday | Training on use of prototype Design System<br><br>--Design period-- | --Design period-- |
| Thursday | --Design period-- | --Design period-- |
| Friday | --Completion of design-- | Open discussion on various designs<br>Review and feedback on completed week |

*Table 7: Test week timetable*

The explanation of the design task on the Tuesday would be the designer's first exposure to the problem (including the technical specialist).

### 4.6.3 The Design Problem

The selection of an appropriate design problem was not trivial. The problem needed to be simple enough to be completed during the test week, while significantly challenging in order to invoke innovation and a need to use the knowledge base. Additionally, as the technical specialist was being used as a control, he was required to have no previous experience of a similar problem. Three potential problems were found (listed in Table 8), all of which represented real designs required by clients.

| Design Problem: | Positives | Negatives |
|---|---|---|
| *T700 Accumulator* | - Novel problem<br>- Specialist is not an expert | - 5-Axis fixture - may required detailed explanation<br>- ME has previously designed a version |
| *Tube Assembly* | None | - Fixture is relatively standard<br>- ME's experienced<br>- Limited scope for innovation |
| *Casing Part Marking* | - Problem is easily explained | - Large part and required fixture<br>- Limited scope for innovation |

*Table 8: Comparison of potential design problems*

Following the comparison of positives/negatives in Table 8, it was agreed to use the Trent 700 accumulator fixture. This required the production of a fixture to position and secure part of an accumulator while a 5-Axis Laser trimmed and cut the part to size.

### 4.6.4 The Design Task

An accumulator is a pressurised storage vessel, usually used to contain a non-compressible hydraulic fluid under pressure as a reservoir or energy storage medium. The accumulator is used within a hydraulic system to provide a reserve of pressure, which compensates for leakage and the effects of fluid expansion and contraction from temperature variations. This design task focuses upon the generation of fixturing to produce the shell/casing structure for a diaphragm accumulator.

The accumulator for the Trent 700 is created from two pressings, shown in Figure 41.

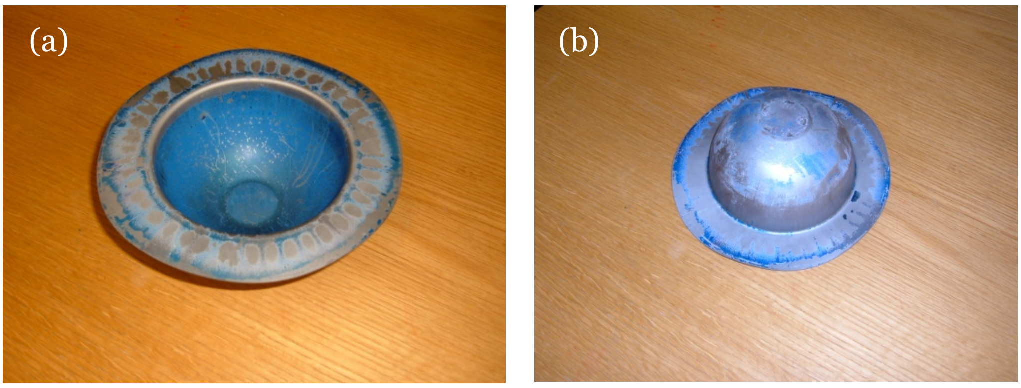



*Figure 41: Photographs of a pressing for one half of the T700 accumulator*

The pressing shown in Figure 41 is processed using a 5-axis $CO_2$ laser, which removes the flange and cuts a centre hole in the base, as shown in Figure 42.

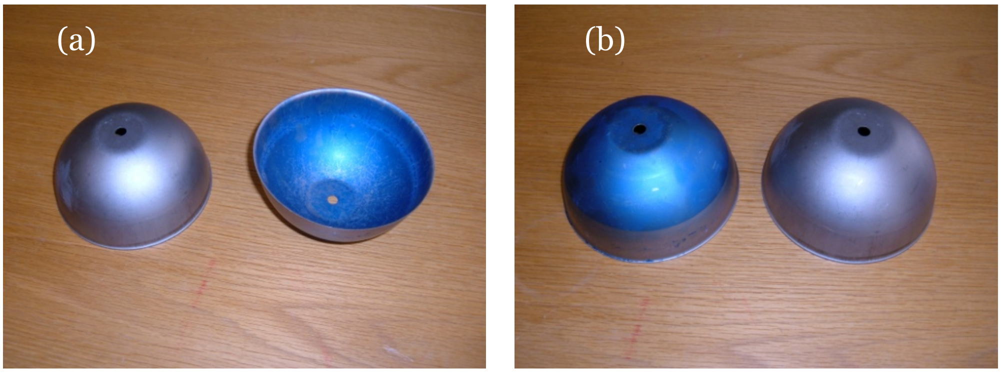



*Figure 42: Photographs of both halves of an accumulator following the laser machining process.*

The two halves are assembled and welded together, as shown in Figure 43.

*Figure 43: Dry fit assembly of two halves, creating the accumulator*

The task is to design and produce a fixture to hold and secure a pressing in place, so that a 5-axis laser program can trim the flange to size and cut the centre hole. The laser program can be assumed to be flexible and providing there is adequate room for the laser head to manoeuvre, the pressing can be mounted in any way desired.

The task represents a significant design challenge. The laser head stand-off is approximately 1.5mm and the head is a tapered cone ~150mm tall, mounted on a ~120mm square arm. The part must be cut perpendicular to the surface in order to weld the accumulator together. Thus due to the size of the laser head, the cut direction for the flange must be from the open side. Yet the flange is trimmed to a 2mm lip. As a consequence there is little or no means to secure the part using the flanges without creating a design that would be damaged by the laser cutting.

Due to the complexity of the problem the designers were shown around the manufacturing environment and able to ask questions from the operators. Additionally they were given a document detailing the key aspects to consider when designing for the 5-axis laser.

The ME attached to the project had already designed a solution, utilising magnets to hold the part in place, shown in Figure 44.

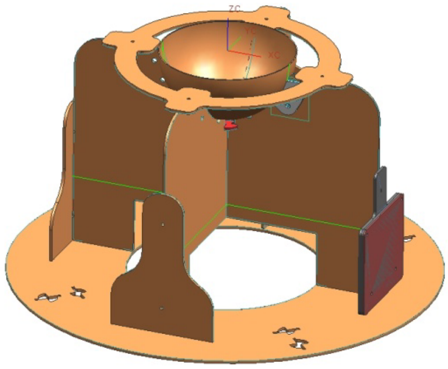


*Figure 44: CAD render of the Manufacturing Engineer's solution*

The design was unsuccessful, however, as the magnets were not sufficient to retain the 'bowl' and prevent swash. This solution would be kept from the novice designers but used to compare the results. As a result the Manufacturing Engineer would not design during the week.

### 4.6.5 Design Solutions

All the designers successfully completed designs and all were significantly varied both in their solution to the problem but also the method employed in solving the task. In order to understand the conclusions drawn below, each of the designer's solutions will be described.

**Designer A:**

Designer A choose to use a four spoke method of supporting the accumulator bowl in a single position (bowl down) for both operations i.e. cutting the centre hole and trimming the flange. Figure 45 (a) shows the completed fixture, (the uncut accumulator is shown in blue).

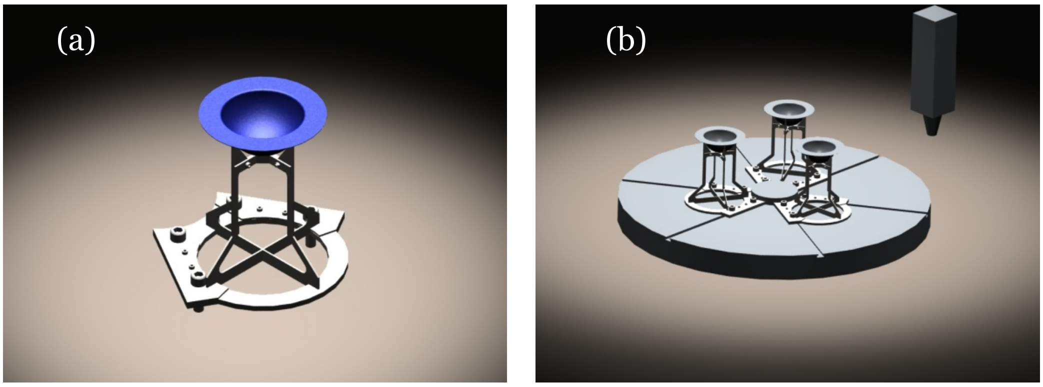



*Figure 45: CAD renders of Designer A's fixture*

The accumulator is secured using thin posts to support the bowl by the flange radius. Using a thin support (less than the 2mm cut distance) the supports will not be damaged by the laser. The large pegs align with the T-Slots on the base of the 5-Axis Laser and although they are not bolted, the angle of the T-Slots ensures it will be fixed in all dimensions. Multiple fixtures may be used in one batch Figure 45 (b).

The bowl is further supported by the flattened base. Adjustability is achieved via lockable bolts in the support arms. Unlocking the bolts permits the arms to slide, adjusting to the size of the bow (the variation in horizontal position would be achieved entirely by the flex of the arms).

In order to test some of the assumptions made by the designer, the fixture was cut and manufactured by the author (shown in Figure 46).

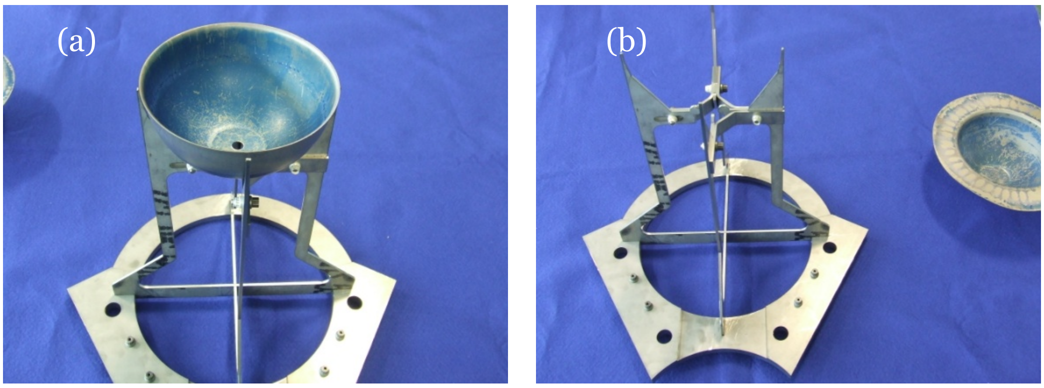



*Figure 46: Photograph of the constructed fixture, with (a) and without (b) the part*

The construction demonstrated a weakness with the design interfacing with the rim of the part. The locking method of the arms was not sufficient to account for manufacturing tolerance in the diameter. Additionally, as shown in Figure 46 (a), the arms are not slim enough to avoid the beam of the laser.

The designer did not reuse any geometry directly, primarily because he was using a different CAD system (Solidworks) to the commonly used system (UniGraphics). However, the designer did access the Design System to support his development of the interface of the 5-Axis Laser base.

**Designer B:**

Designer B chose to use a two stage process, the centre hole to be cut in one position and moved to a second position to trim the flange. Thus the bowl could be located securely (bowl down) between four vertical supports while the centre hole was cut. In a second operation the bowl is then located on a separate threaded spike, a nut anchoring the bowl down using the centre hole, to allow trimming of the flange.

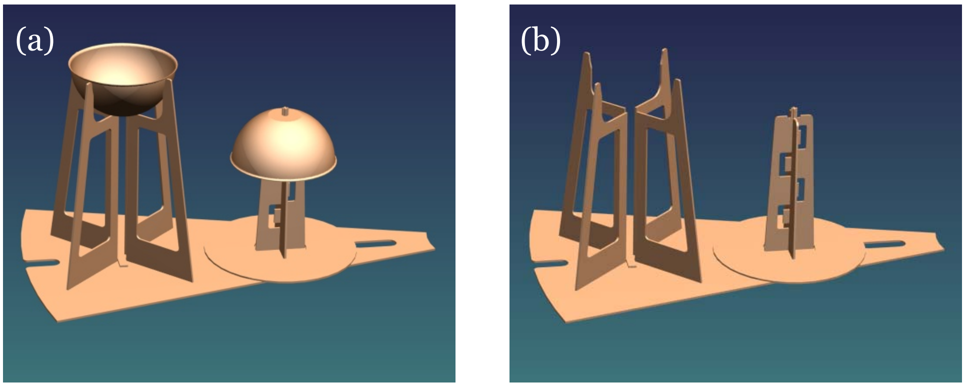



*Figure 47: Designer B's fixture shown with (a) and without (b) the part located*

Designer B did reuse geometry, specifically the threaded edges of the plates to create the threaded spike (shown on the right in Figure 47). While this geometry could have easily been recreated, time was saved by searching and importing the geometry and it ensured a tried and tested geometry was used.

**Designer C:**

Designer C also chose to use a two stage process and designed two corresponding fixtures for the two stages. The design utilises gravity loaded springs to secure the part and cut the centre hole, then a separate fixture with a dowel to locate the part on its hole.

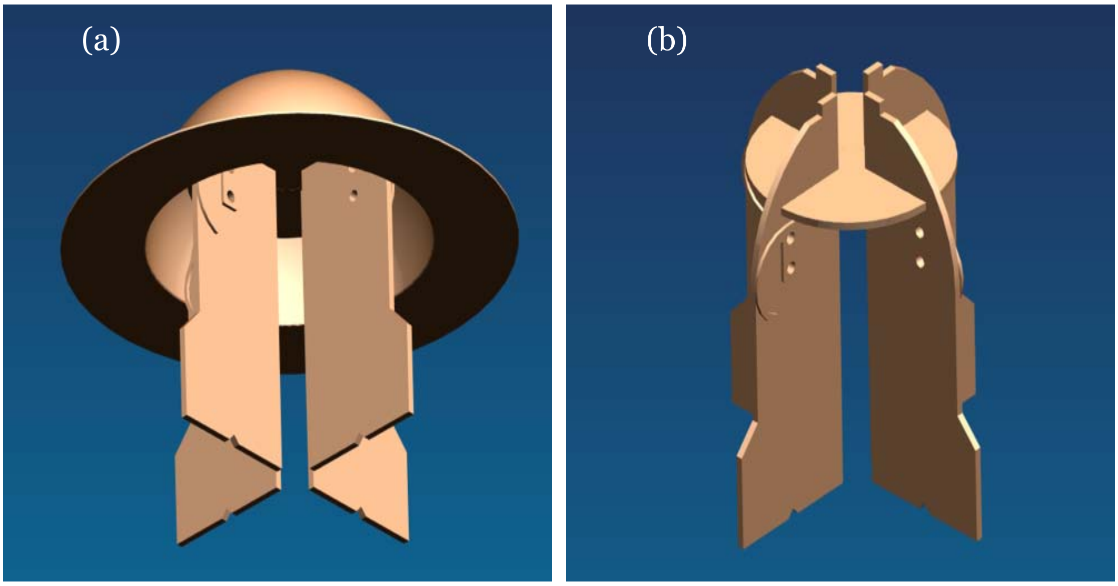



*Figure 48: Shows the first stage fixture, with (a) and without (b) the part located (the part sits over the springs).*

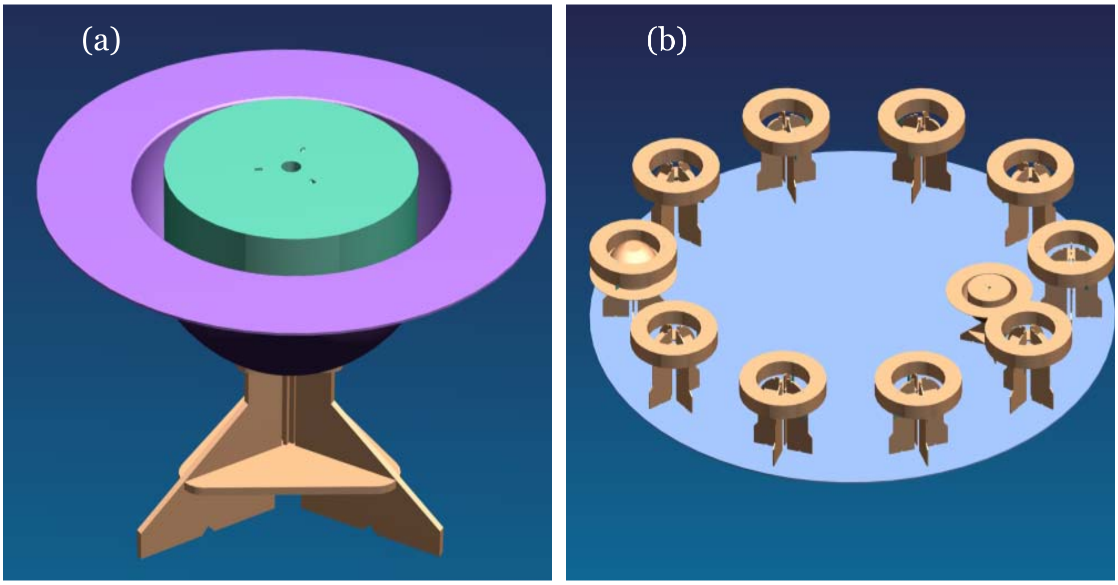



*Figure 49: CAD renders showing the second stage fixture (a) and a suggested array of fixtures for large scale production (b)*

The designer realised the primary problem with using gravity to locate the part was the part’s own lack of mass. He therefore developed laminate rings to sit over the part and provide additional mass. The internal springs are still required to centre the part and it is assumed there is a natural trade between the strength of the springs and the mass used.

This designer did utilise the Design System to some extent when trying to design the springs. Direct geometry re-use did not occur, but knowledge transfer was apparent in the design of the spring.

**The Technical Specialist:**

The technical specialist's solution was markedly different in approach to the others. The specialist realised in that order to secure the part accurately, it had to be supported using the radius of the flange (like Designer A) to maintain sufficient stability while cutting (as opposed to referencing off the flattened base). The specialist also assumed that if the fixture was accurately secured, it would be possible to trim the flange in two separate operations.

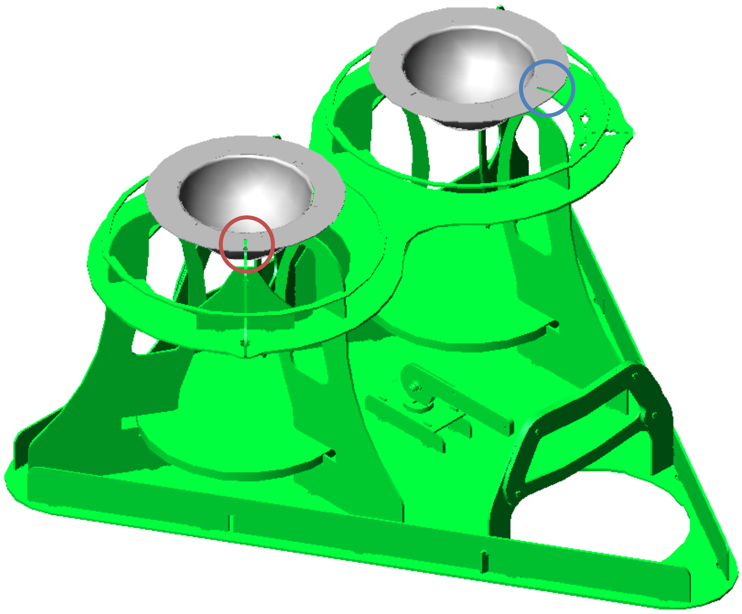


*Figure 50: CAD render of the expert's solution, the 'notch' cut is ringed in blue, and the alignment 'post' in red.*

The specialist therefore developed a two stage fixture, as shown in Figure 50. The part is first loaded in the right hand side, positioned using three sprung supports. The laser is then programmed to cut the centre hole, 3 equi-spaced cuts, (each an arc of 60 degrees) and an alignment 'notch' in the flange. The part is then removed and sited on the left hand side of the fixture, aligned radially using the notch and 'post', and a new part loaded on the right. The laser can then cut the remaining three segments around the flange. Using the two stage process the laser will never need to cut across the supports. Additionally, the specialist choose not to use a flat base and incur the additional problems of using flush fastenings, but rather to support the fixture off the bed and use a sprung cam in the centre to locate on a T-Slot, which when rotated, pulls the fixture flat to the bed.

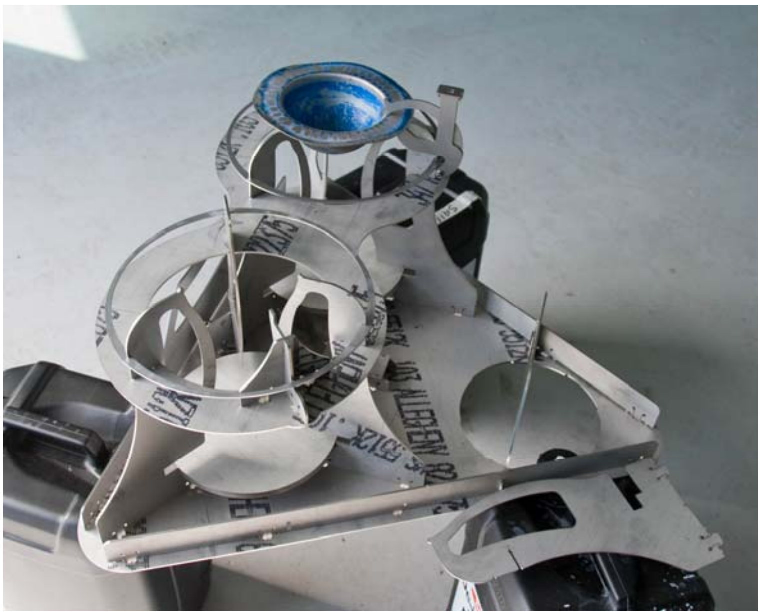


*Figure 51: Photograph of the final version designed and manufactured by the expert*

The fixture was constructed in order to test the design. Improvements were required as the construction did not hold the part correctly. The sprung support arms were too stiff and the part did not sit correctly within the supports. Following the test week the expert continued the design to include over centre clamps to hold the part securely and the final solution shown in Figure 51 was deemed successful.

As expected, the specialist did not use the Design System, but geometry reuse did occur from the specialist's own archive. The specialist's solution is significant in its radically different approach and construction to the other designers. Not only are fundamental assumptions made by the others challenged (the idea of having to the cut the flange in a single cut), but novel solutions were invented to facilitate the ideas (the notch and post idea). The solution demonstrates the challenge faced in trying to mitigate the impact of the specialist's retirement and the limitations of a knowledge base created from existing solutions. However the need for the expert to test and modify the design also highlights the limitations of any designer designing without trials.

### 4.6.6 Results, Observations and Feedback

In order to evaluate the effect of the Design System, two approaches were chosen – qualitative measurement of the designs using metrics and more informal written and verbal feedback.

**Design Analysis**

Prior to the test week a set of metrics were derived to try and provide a quantitative measure of the different designs. These metrics were based on the requirements specification given to the designers (although the requirements were not listed in the same manner as the metrics). These metrics are shown in Table 9.

| *Performance Criteria:* | Designer A | Designer B | Designer C | TS | ME |
|---|---|---|---|---|---|
| *Mandatory* | | | | | |
| Locates part | No | Yes | - | Yes | No |
| Secures part | No | No | Yes | No | No |
| Facilitates laser trimming correctly | No | Yes | Yes | Yes | No |
| Facilitates laser cutting of hole correctly | Yes | Yes | Yes | Yes | No |
| Safe for user | Yes | Yes | Yes | Yes | Yes |
| Fits in laser environment | Yes | Yes | Yes | Yes | Yes |
| Lifetime > 100 | No | No | No | Yes | Yes |
| Must locate within tolerance | No | No | - | No | No |
| Mounts to laser bed | Yes | Yes | Yes | Yes | Yes |
| | | | | | |
| *Desirables* | | | | | |
| Easy to operate | Yes | Yes | No | Yes | Yes |
| Sacrificial Parts | No | Yes | No | Yes | Yes |
| Fast to operate | Yes | Yes | No | Yes | Yes |
| | | | | | |
| Success measure: | 50% | 75% | 60% | 83% | 58% |

*Table 9: Comparison of designs based on the requirements specification*

The mandatory requirements are the functions that the solution must meet to be considered successful. The "desirables", are those that are clearly beneficial to the solution but not essential. All the metrics were designed to be absolute, minimising subjectivity. Cost and parts count were not included as these were not requirements given to the designers.

The ‘success measure’ represents the percentage of successful requirements met. Due to cost limitations not all of the fixtures could be built, hence it is not known if Designer C’s design does correctly locate the part and within tolerance. These assessments are therefore partly theoretical. To maintain consistency, the assessment of the technical specialist’s fixture was of the product at the end of the design week, rather than the later, improved design.

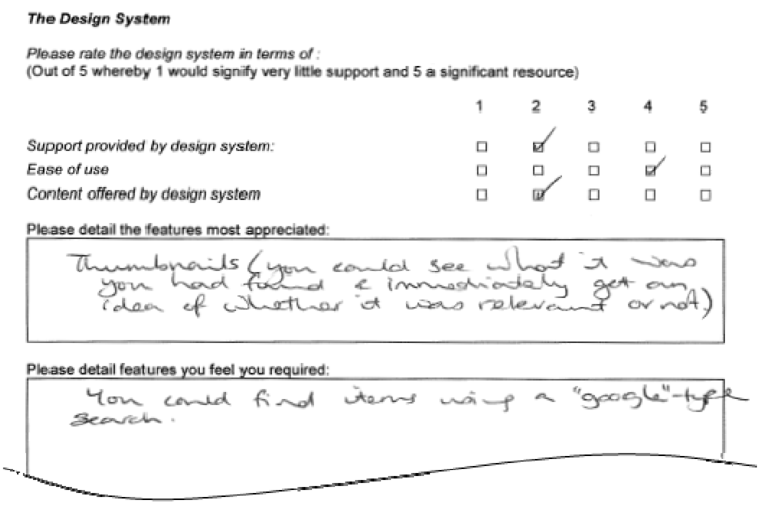
Based on these metrics, the expert’s design met the most requirements and was in theory the most successful. But what is interesting is the similarity between the Manufacturing Engineers ‘score’ and the other designers. While no single design is known to be truly successful, designers B and C’s are both thought to locate the part sufficiently to allow the laser cutting. As both B and C’s methods of mounting were influenced by the use of the Design System’s content, this demonstrates the potential benefit of the system to support novice designers in producing a design comparable or better than an existing Manufacturing Engineer utilising his own knowledge.

Clearly, however, the differences between the designs could also be attributed to the individual’s differing experiences and perhaps reference to similar problems, but this cannot be known.

**Feedback**

The novice designers were asked to complete a questionnaire focused on their experiences during the design task and of the Design System. Informal feedback was also gained through discussions and observations of the designers.

The feedback forms were split into three sections, focusing on Design System, the case studies and the design task respectively. Each section contained a both open questions and ‘scored’ questions, as shown in Figure 52.


**The Design System**

*Please rate the design system in terms of :*
(Out of 5 whereby 1 would signify very little support and 5 a significant resource)

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| *Support provided by design system:* | ☐ | ☑ | ☐ | ☐ | ☐ |
| *Ease of use* | ☐ | ☐ | ☐ | ☑ | ☐ |
| *Content offered by design system* | ☐ | ☑ | ☐ | ☐ | ☐ |

Please detail the features most appreciated:

Thumbnails (you could see what it was you had found & immediately get an idea of whether it was relevant or not)

Please detail features you feel you required:

You could find items using a "google"-type search.

*Figure 52: Section of a feedback sheet completed by Designer B*

The results of the scored questions are shown in Table 10. Each question was scored from 1 to 5, where 5 corresponds to a high level or resource.

| | Designer A | Designer B | Designer C |
|---|---|---|---|
| Design System | | | |
| *Support provided by Design System* | 2 | 2 | 2 |
| *Ease of use* | 3 | 3 | 2 |
| *Content offered by Design System* | 3 | 2 | 3 |
| Case Studies Supplied | | | |
| *The value of content supplied:* | 3 | 4 | 4 |
| *The support provided with respect to the design task* | 3 | 1 | 4 |
| Design Task | | | |
| *Difficulty of task presented* | 5 | 4 | 4 |
| *Interest* | 5 | 4 | 4 |
| *Degree of step change from previous experience in design* | 4 | 2 | 4 |

*Table 10: Survey results focusing on the Design System*

The results clearly indicate that the designers felt the task was a significant challenge, but all felt the support provided by the Design System was limited. Given that its use can be seen from the designs (through the reuse of geometry), this either suggests they felt it could be significantly better or that they did not realise the extent to which it did influence them. Examining some of the comments suggest that it is the former.

All three stated that the photographs provided the most useful information on the fixtures although more CAD models would also have been useful. Both designers A and C cited that it was difficult to search the system and did not always return relevant results. In particular a 'Google' like free text search was required. The speed of the system also caused a major problem with the usability. It was extremely slow to search and access photographs.

It was felt that one aspect in particular was lacking – the rationale and detail behind the projects. Designer B argued that while many relevant fixtures were well described, there was little explanation of why they were designed as they were.

The second section of the feedback focused on the detailed case studies provided through the system. The designers agreed that they provided a rich source of information but argued that they were not useful during design. They were too large and too broad, although they also provided a chronological description of how the product was created, which proved useful in understanding the methodology but not in aiding problem solving. Designer A in particular stated that they were interesting and useful as background reading, but they would have been best used during the training.

The primary challenge cited by all designers was not lack of knowledge, but the difficult faced when implementing geometry generation. Difficulty was met when attempting to use existing geometry such as joining features imported into UG and this clearly highlighted the benefit a bespoke toolkit built within the CAD package would provide. However, the designers also highlighted the problem of trying to gauge the correct geometry and thickness for springs and clamps as well as the general structure. While the expert has an intuitive 'feel' for the strength required, the novice designers do not and hence require support.

### 4.6.7 Discussion

While production of all the designs was never completed, both the metric analysis and the feedback from the designers proved to be extremely valuable in understanding the potential benefits of the system and also the key areas required to improve it.

All three novice designers used the catalogue during the design process to find existing 5-axis laser fixtures to determine the best method of bolting to the laser bed. Designers B and C also used it for clamping ideas and some joining techniques. Through their subsequent solutions it is possible to see the benefit of reusing even basic features within a new fixture.

Changes were clearly required to the system. In particular, improved usability and a new search interface was required. The toolkit was required to include a tool to support geometry generation of springs. Finally the content of the system needed to be built on and improved, supporting more content and containing all new projects. This represented a concern given the inertia already demonstrated by individuals against inputting knowledge. The new system needed to be designed to improve accessibility and encourage use and input of knowledge.

## 4.7 Design System Development – Phase 2

The proactive evaluation of the prototype system demonstrated the systems potential to provide valuable knowledge and support. Yet it was also found to be difficult to use and did not contain sufficient knowledge – in particular concerning the rationale behind designs.

In July 2008, Rolls-Royce commissioned an upgrade to the system including the supply of dedicated hardware for the Design System to run from. The following sections introduce the rationale behind the modifications before describing the approach and development of the system from the early prototype to a system with the capability to provide holistic support throughout a designer's workflow. The final section of this chapter details some of the other tools developed to reside within the Design System.

The users and use cases developed in section 4.1.3 had not changed significantly. However, due to the technical limitations, the deployment of the system had changed from a system integrated and accessed from within the CAD system to a largely standalone system. This has two consequences.

Firstly while novice and expert users may seek and access different knowledge, the system will now be accessed through a single interface. As such the interface must provide varying levels of detail, but with clear signposting to allow easy navigation for all users. The second important consequence is that by creating a distinct system separate to the working 'interface', there is an inherent barrier against access currently as the users must consciously open another program to input or obtain knowledge.

Together with the issues highlighted during the evaluation week, substantial modifications to the system were clearly required. These can be separated into four distinct aspects:

**System Interface:**
A redesigned and improved interface was needed aligned to the user's workflow and allowing easy navigation and access. It must also support greater knowledge capture, expanding the current fields and encourage greater input.

**System Operation:**
A primary criticism cited from the trial evaluation was the poor usability of the system and the slow loading of pages with multiple images.

**System Functions:**
The system 'functions' were also heavily criticised, in particular the limited file upload tool and the poor search capability.

**System Toolkit:**
As discussed, the trial week also highlighted the need for designers to have access to more numerical tools allowing them to calculate and derive key parameters when designing sprung components.

The following section details the modifications taken to address each of these aspects.

### *4.7.1 Interface and Input Restructuring*

It was proposed that the knowledge repository be expanded to store additional information. Additional fields were created (such as 'security classification' and 'customer feedback') and some existing fields renamed to encourage more detail to be added. For example the existing field "Design Purpose" was renamed "Design Principle" and a descriptor added. Thus, rather than simply writing a one line 'purpose', designers were encouraged to add detail behind the rationale and behaviour of the solution.

The interface was changed aesthetically to highlight the 'improved' system and also to bring the system in line with corporate colours.

The main modification to the interface was the introduction of a 'gated' or multiple stage input process. Rather than a single input page, data is now spread over several pages corresponding to existing stages of the design methodology. This is intended to improve usage for two reasons:

1. Less knowledge is required upfront, lowering the time taken to enter 'chunks' of knowledge and making the task easier.
2. Interaction is required at existing and natural stages of the design process. These stages should become synonymous with interaction with the system and hence become part of the design process.

The web pages (requiring input of and displaying different information) have been designed to correspond to three stages of the design methodology. These are:

- *Job Initiation (Specification)*: displaying the job description, the designer associated to the project, the requirements of the client and the specifications relevant to the job.
- *Post-Design (Solution)*: displaying information on the design solution, the rationale behind the design, calculations and tools used together with photographs, CAD drawings, video and other media.

- *Job Completion (Appraisal)*: displaying information received following the completion of the project, modifications that were required, and feedback from the clients and designer.

A reduced version of the methodology, highlighting the different pages of the Design System is shown in Figure 53.

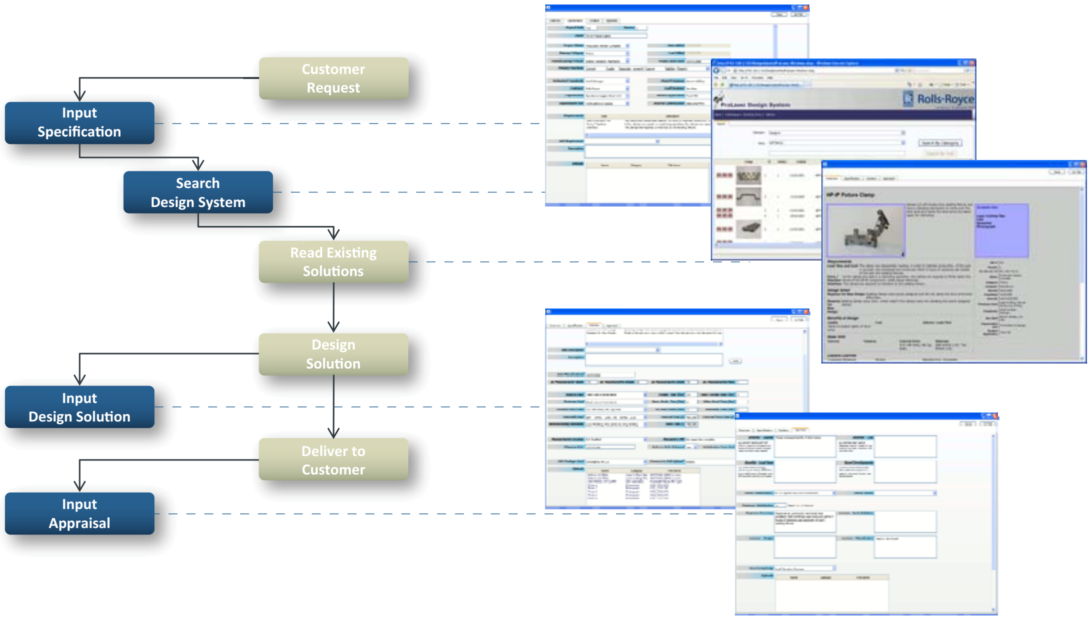



*Figure 53: Reduced methodology with screenshots of the system pages (shown to illustrate user interactions)*

In the previous version, to encourage designers to complete records in full, input fields were made mandatory. They would have to complete all fields before they could submit the information. Rather than completing the boxes in full, designers would often enter random and non-valid data in order to force the system into allowing access to subsequent forms. The updated system removes the mandatory fields but a graphical representation of the completed fields is used instead. Termed a traffic light system, three lights are shown, moving from red to amber to green as fields are completed (shown in Figure 54). Each light corresponds to a different input page and when the key fields on that page have been completed the light turns from red to amber. When all three pages are amber and the project has been marked as completed, they turn green.


*Figure 54: Illustration of the 'traffic light system', showing: a) partial complete status and b) fully complete status*

This gives an at-a-glance view of the completed stages and the level of knowledge held on a particular design (a crucial requirement identified by Marsh, 1997) to better visualise and signpost the knowledge available for designers. Furthermore, the intention was to simultaneously encourage small additions to the knowledge base and create a visual goal for designers to complete projects.

Several other changes were also made to the interface. To improve signposting and 'at a glance' product knowledge, a summary page was created, shown in Figure 55. Primarily designed for the 'Sales' and 'Management' users, the page has also been constructed to allow a pdf export which can be used in marketing work or business reporting.

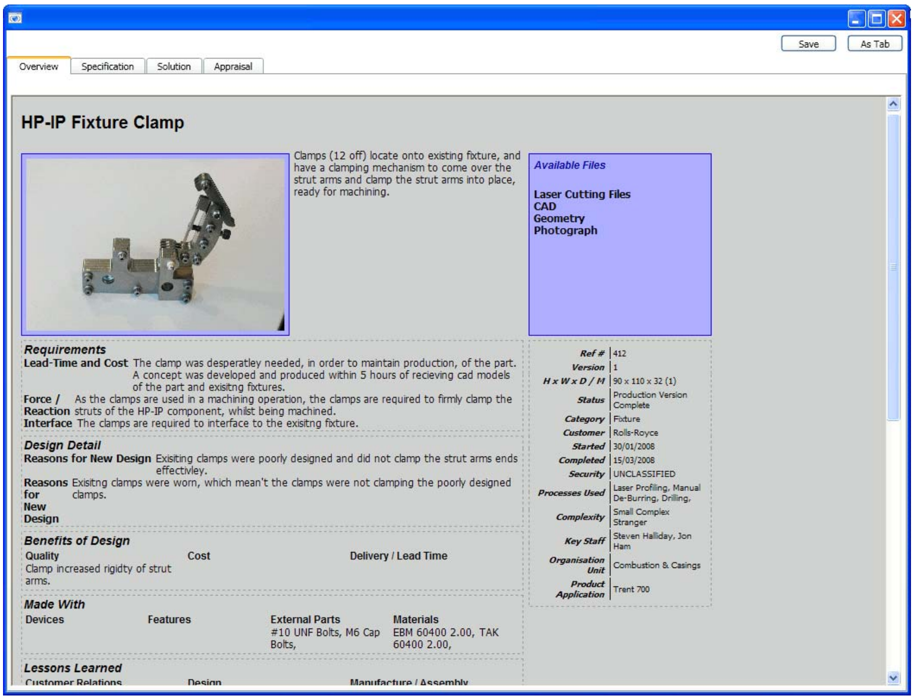



*Figure 55: Screenshot of a projects 'Summary' page*

Finally a 'duplicate' function was introduced to allow automatic creation of a new version of an existing project, either following a modification or as an adapted project. The function automatically populates the common knowledge elements such as customer and designer and allows detail to be given on why the modification was required. Again this is intended to minimise the quantity of knowledge required, while maximising the knowledge content by capturing redesigns and alterations.

### 4.7.2 Improvements to System Handling

Two modifications were made to the system's operation to improve the speed and handling of the program:

1. The reason for the slow loading of pages and the search results was due to the large image files being transferred. The system was modified to include a thumbnail generator. All images uploaded would have a duplicate scaled down image used when loading pages, while the full sized version was stored outside the database and could be downloaded on request.
2. To improve system load up, the coded link to Solidworks was explicitly removed. It had already been agreed not to link the program to CAD software, but by removing the 'check' for the software, load up time was drastically reduced.

### 4.7.3 Modifications to System Functionality

Changes were made to two system functions – the search function and the upload function.

In the prototype system, finding relevant projects was limited to a 'filter' based drop down menu. This allowed users to filter, for example, all projects designed by a particular designer. The disadvantage was that users could not search using key words, an approach many have become used to with the rise of internet search engines. Therefore, the new function included both a filter-based search and a 'free text' or 'Google' like search method, allowing users to search over all fields (but not uploaded files).

The ability to upload files and attach them to projects was one of the primary benefits of the prototype system, allowing users to provide rich media describing and showing project solutions. However, the function was limited to a fixed number of upload types and required each file to be added individually.

The new system was modified to allow multiple upload types and to allocate them to the three different input pages. Furthermore, block uploading was instigated, allowing users to select and upload several files quickly and simply.

To support greater future flexibility and system management an additional 'Administrator' page was created. Restricted via a password, this area provides the user with the option to modify and add to drop down lists, such as 'designer' or 'upload type'. A built in backup function was also created, allowing the administrator to backup the database to an external location. A screenshot of this page is shown in Figure 56.

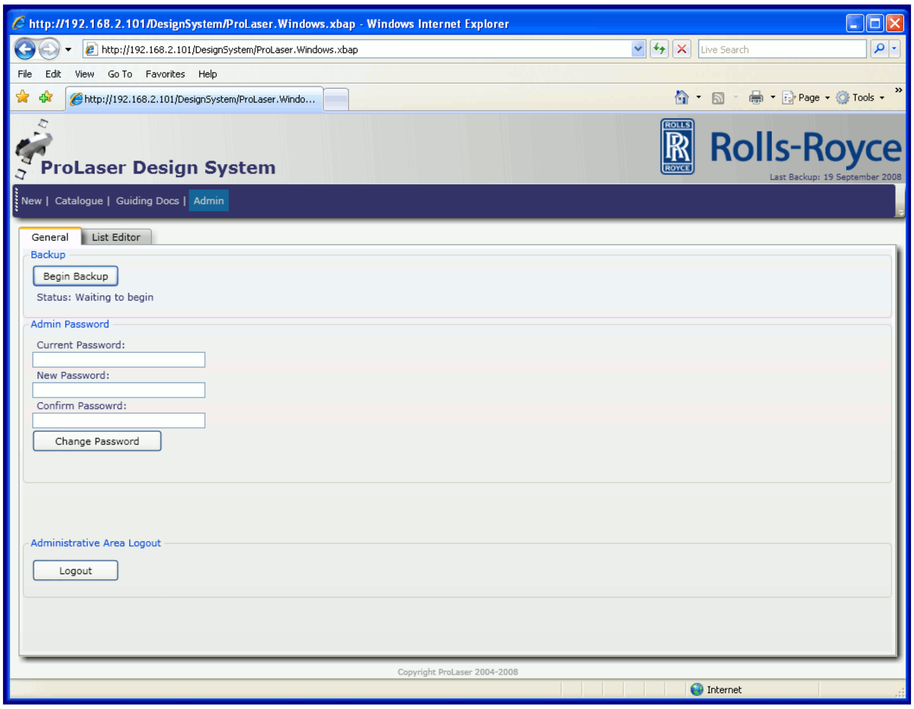



*Figure 56: Screenshot of the one of the Administrator pages*

The intention of these functions is to bring the system into much more regular use, changing the view of the system as an inert archive, to a flexible source and repository for key knowledge, documentation and files.

## 4.8 Spring Designer Development

The development of tools specifically designed to support designer's geometry generation activities has been introduced in section 4.4. The evaluation week also demonstrated that novice engineers need support in producing geometry, in particular when developing sprung components.

A series of tools were therefore researched to try and develop an easy to operate, yet flexible and reliable means of generating sprung elements.

### 4.8.1 Spring Design Background

As discussed in section 2.4.3, jigs and fixtures utilise clamps to exhibit a load on a workpiece, securing the workpiece against any machining loads that may be applied. The clamp uses a sprung element to generate the load on the workpiece.

Sprung elements are profiles that, once a deforming force has been withdrawn, will seek to return to its original state (OED, 2001). Typically springs have been produced from hardened steel or through heat treatment. In Rolls-Royce Sheffield, utilisation of the flat bed laser allows precise elements of any 2d profile to be cut. Coupling this capability with the unique elastic properties of Titanium 6-4 (6% Aluminium, 4% Vanadium) means that profiles cut using the laser can provide highly accurate and powerful springs for use in fixtures of any shape.

The disadvantage of such an approach to design is the inherent flexibility creates such a large geometric domain to design within that novice designers find it difficult to construct an appropriate model. Spring design is therefore considered one of the most difficult tasks faced by the designers in Rolls-Royce Sheffield. While the technical specialist has extensive experience in 'judging' the optimum geometry, many of the other engineers use trial and error. This can be time consuming and costly.

## 4.8.2 Lightweight Spring Designer

In early 2008 Rolls-Royce commissioned an external contractor to study the use and design of the springs. The intention was to understand better their behaviour and to aid designers in their use while designing.

The contractor produced two documents, detailing the spring behaviour and guidelines on how to design a spring. A macro tool within Excel was also produced. This tool consists of mathematical representations of four commonly used springs, each built into a Macro allowing users to specify the required key dimensions and return the necessary geometry.

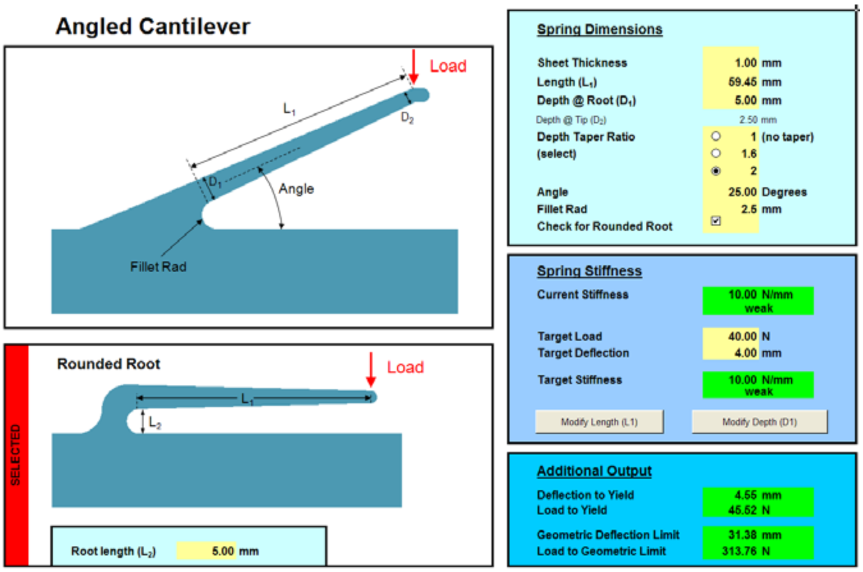



*Figure 57: Screenshot of the lightweight spring design support (Rowlson, 2008)*

This provided a simple, fast and easy to operate tool and successfully encoded a complex problem domain into a knowledge-based tool. Although it required some understanding of input loads, the interface was well suited for a novice design engineer. The tool did offer several benefits and was used typically for early design estimates. However the tool was limited by its small problem domain. Often the tool was simply not able to accommodate the complexities – notably the geometric boundaries required by the designers.

One of the primary benefits of the technology developed in Rolls-Royce Sheffield is the ability to develop rapidly bespoke and unique tooling. Yet the tool was limited to just four springs and thus did not adequately support geometry generation. It was therefore proposed that a tool be created that would widen the problem domain by incorporating other knowledge-based approaches – in particular optimisation – to support the rule-based system.

### 4.8.3 Evolutionary Approach

The bespoke clamps developed using the technology are usually designed for individual fixtures based on the load required, deflection expected and spatial envelope in which the design must fit. It was proposed that by modifying the principles behind Evolutionary Structural Optimisation, theoretically it should be possible to create a heuristic set of rules to generate geometry that will produce a given load for any given deflection within the spatial envelope required by the designers. This would represent a 'plug in' and go approach. Novice users could import geometry, select a required load and deformation and output the optimum geometry.

Evolutionary Structural Optimisation [ESO] is a heuristic optimisation approach beginning from an initially over-defined domain. Developed by Xie and Steven (1992) an iterative procedure is used where the domain is repeatedly analysed and the lowest stressed elements removed. A compliance function is computed and the solution with minimum compliance retained.

The approach proposes that an optimum structures may be achieved by gradually removing ineffective material (Tanskanen, 2002). Unlike other methods such as the commonly used SIMP method (Solid Isotropic Microstructure (or Material) with Penalization), ESO is a 'hard-kill' method, i.e. changes are made without accounting for sensitivities (Rozvany, 2007).

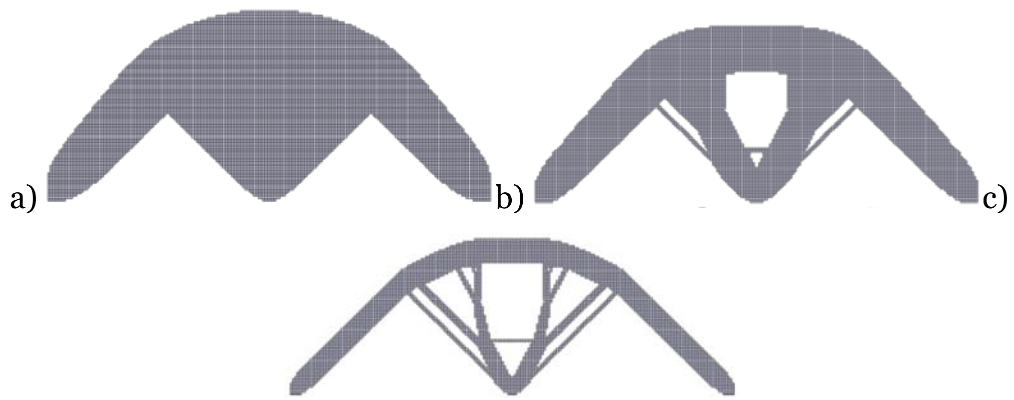



*Figure 58: Screenshots of three different steady states of ESO applied to a Michell arch: a) steady state 21 (b) steady state 28 (c) steady state 55*

Figure 58 illustrates a typical approach showing three stages of an optimising routine. The ESO process has been applied to compliant mechanisms in the past (Ansola et al., 2007). It was believed that it could be reasonably adopted to provide support for the designers and supplement the existing Design System.

A prototype system was developed utilising ANSYS and MATLAB, used due to the availability of the software and the author's past experience. MATLAB was used as the overall program but utilised the batch processing capability of ANSYS.

A prototype model was successfully created, emulating the results of previous studies, but only for non-compliant, static objects. Example screenshots of the model are shown in Figure 59.

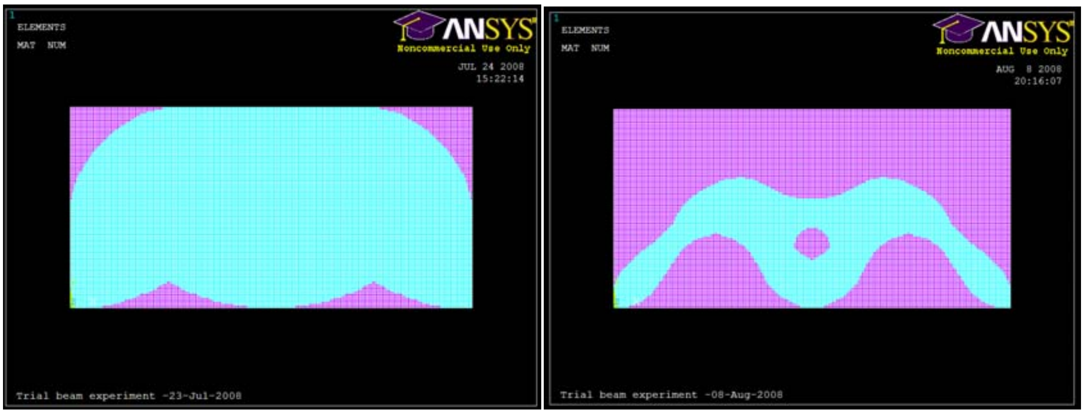



*Figure 59: Two screenshots, of the updated model a) screenshot after 199 iterations using the minimum stress, and b) 20 iterations using maximum stress*

However, many problems were encountered during the development – in particular the sensitivity of the method to different algorithms, especially the rejection rate. It was found that significantly altering the boundary conditions required varying the parameters in the algorithm simply to achieve a solution. This represented a significant concern – the intention of the tool was to support novice designers. Moving to a compliant mechanism would only create more variables and the need to control accurately the algorithm parameters.

Furthermore, the tool was naturally dependant on accurate mesh generation and modelling of the initial boundary conditions. Yet only one member of the Sheffield office has experience in Finite Element Analysis.

It was therefore apparent that the tool would not be fit for purpose. By introducing complexity to the design process and requiring an experienced designer to operate, the tool would not have provided support for novice designers – the ultimate aim. The lightweight designer was therefore maintained as the primary support mechanism for spring development.

While this aspect of the research was not pursued, it demonstrated several key lessons for future development of KBS. For example:

- The role of any system must have clearly targeted users. In the case here, developing a capable system which only one designer could operate demonstrated a failure to align the output to the users.
- Conversely, a system with a limited problem domain is not perceived to be valuable by designers who regularly need flexible and customisable solutions.

The research also demonstrates that when faced with large problem and solution domains, a tool will have to inherently limit the domains through assumptions or predefined solutions. Failure to do so, will, as the early AI systems found (Sandberg, 2003), result in a tool with weak capability or one which requires so many defined parameters that little automation is achieved.

This section demonstrates the need to support designer's conceptual and creative capabilities through tacit knowledge transfer and limit KBE to well-defined domains, which can best benefit from the high repetitive capability of computer systems.

## Chapter Summary

This chapter has described the development and refinement of a Knowledge Management strategy for the case study business.

The business requirements, end users and future 'vision' were used to provide the basis of the KM strategy. From this strategy a knowledge-based Design System has been constructed, evaluated and refined and an overview of the key development stages is shown in Figure 60.

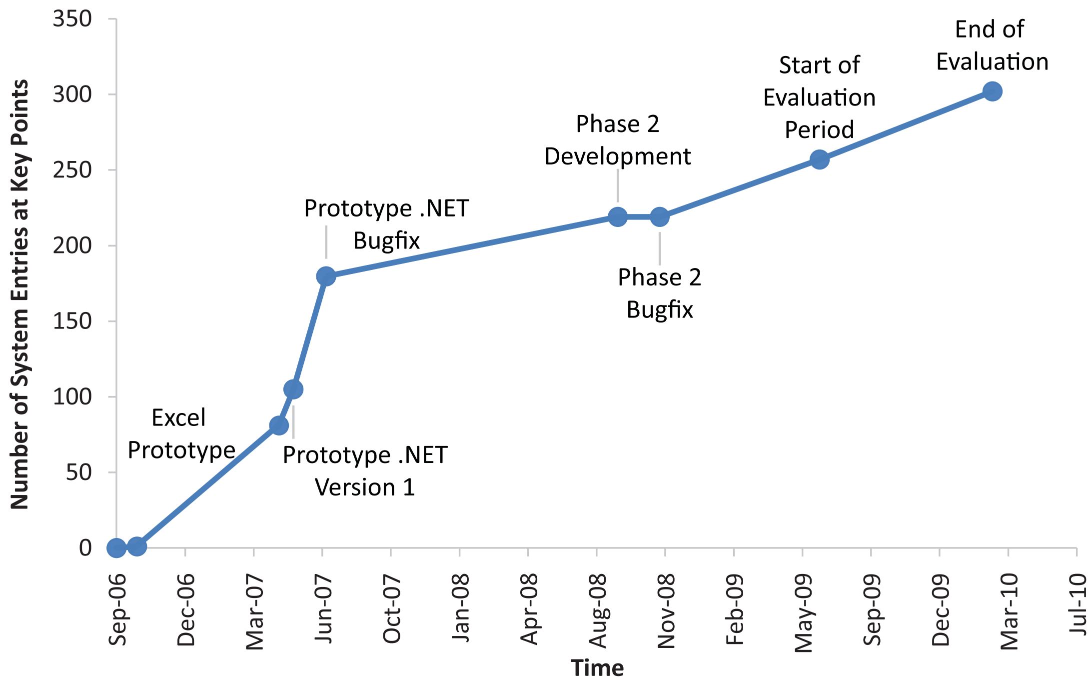



*Figure 60: Timeline of the key development stages of the Design System shown against the project population*

A design and manufacturing methodology was developed to support system integration and a series of knowledge capture techniques were utilised to create a critical mass of expert knowledge with which to launch the system. Finally a variety of KBE tools were researched to provide further support to the designers.

The knowledge strategy and Design System represent a bespoke 'best effort' solution to the problems facing the business case study. Chapter 5 will establish what effect this has on the business and if it meets the requirements set out in Chapter 1: mitigating against critical knowledge loss due to a leaving expert and supporting rapid growth of the business.

# Chapter 5

## EVALUATION

The aim of this research was to determine the effect and value a knowledge-based system can have on a small to medium enterprise faced with a potentially critical loss of tacit knowledge through a retiring technical specialist.

The research had to evaluate a 'live' business. The company couldn't be isolated from changing factors both external and internal to the business. There also exists no other company with sufficiently similar environmental variables with which to compare or contrast the change. Thus a multi-faceted approach was developed to evaluate the business over time and to establish if any of the changes can be attributed to the role of knowledge in the business.

The following sections discuss the rationale behind the approach taken, characterise the nature of this study and discuss some of the important environmental changes occurring over the period of study. The remaining sections of this chapter systematically present the different facets of the business evaluation. This includes the rationale behind the metrics used, results obtained and a discussion on the implication of the results.

### *5.1.1 Rationale behind the Evaluative Approach*

As discussed in section 3.7 there is no single accepted means to evaluate the success of a KM strategy. Different approaches can be used to evaluate different aspects of the knowledge activities. Yet the impact to the business (both positive and negative) is wide ranging and no single measure can be used to conclude business wide 'success'.

In this research, 'success' is defined as providing value to the business through the deployment and use of the knowledge-based Design System. Importantly, this is not necessarily limited to financial return. One motivation for the use of KM is to mitigate against knowledge loss. If business continuity is ensured, albeit at a net financial cost, the strategy may be deemed successful.

Business wide assessment can be achieved through use of a 'Balanced Scorecard' (Kaplan and Norton, 1992) or through the 'Skandia Navigator' (Edvinsson, 1997). In this research, due to the small size of business and the flexibility required, the balanced scorecard will be the chosen framework. However, the scorecard only represents a high level view and used alone is not sufficient to capture the detailed effects of the system. Furthermore, regardless of the metrics chosen, causality is difficult to infer through these high level frameworks. Therefore additional measures were also required.

Here the research adopts a multi-faceted approach to evaluation, based on an input/output analysis of the KBS. It was argued that the effects of the system can be determined by assessing the changing inputs, content and output of the system. In order to provide a rigorous assessment of the system, each of these factors must be assessed and understood. The approach will not try to combine all these measures into a single framework or output. Rather, conclusions will be drawn from each facet of the evaluation and a 'picture' built of the role and effect the system has had.

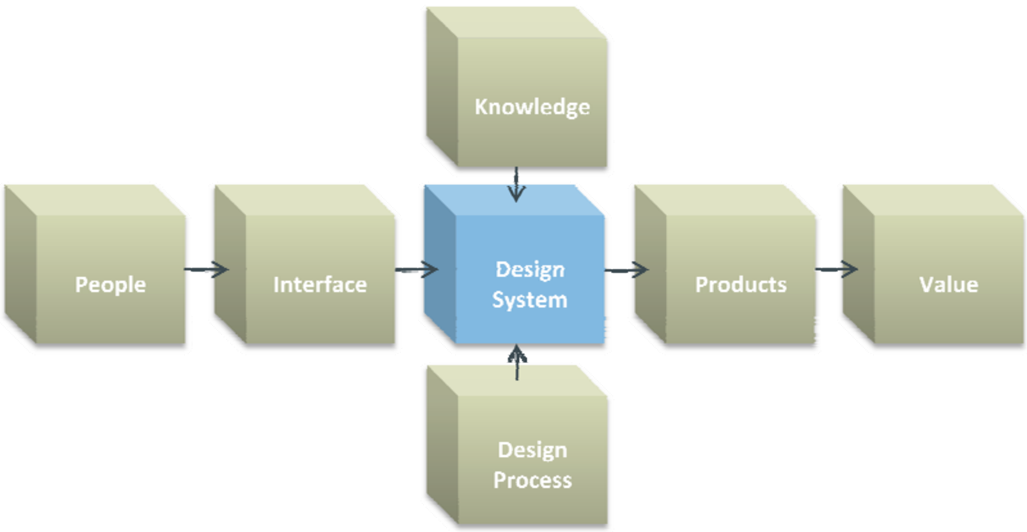



*Figure 61: Diagram illustrating the key input and output factors associated with the Design System*

Figure 61 is a schematic diagram illustrating the key inputs and outputs to the Design System. Moving from left to right, the system is used and accessed by the designers, and naturally through an interface, both of which require some form of characterisation. The system requires knowledge to be input, the quantity and completeness of which will directly affect the potential impact the system can have. The system's actual use during the design processes must be understood. Finally the system's role is to support the better development of products, through which value is generated in the business.

The evaluation therefore required each of these system inputs to be assessed and analysed over a period of time corresponding to the system's increased role within the business. The remainder of this chapter discusses and presents each of the measures used to evaluate change over these key inputs and outputs.

### 5.1.2 Characterising the Evaluative Approach

According to Blessing (1994) the nature of descriptive studies can be subdivided and described as follows:

- *Exploratory:*
  No working methods are introduced and the research is restricted to observation of how work takes place.
- *Comparative-exploratory:*
  Exploratory research in which the cases observed possess different characteristics.
- *Action research:*
  A design method (or tool) is introduced with the objective of studying its effect
- *Comparative-action research:*
  Action research where different methods are introduced.

The study presented here was therefore an "action research" based study, although its structure was that of continuous comparative study. The state of the business before and as the influence of the system was felt across the design team was compared. In this respect, the study was longitudinal, described by Bender (2003), to "determine changes of performance" within a predefined period of time.

The evaluative period ran for a period of eight months, from July 2009 to February 2010. During this time the researcher was actively based onsite and proactively encouraged adoption and use of the Design System initiated through training on the knowledge strategy.

Many of the variables measured can be presented as a continuous change over time. However, some more discrete variables cannot. In the majority of these cases, sampling was split to compare the state of the business in the initial four months (July to October) to the state of the business in the final four months (November to February).

Several important changes occurred to the business environment during the study period. Of particular significance was the departure of the technical specialist from the business in December 2009. In the period leading up to his departure, he slowly decreased his presence on site and his involvement in technical development. Prior to his departure additional (novice) resource was taken on. This represented a significant change to the business and also provided a test of business continuity. For a complete plot of employee numbers refer to Figure 4 in Chapter 2.

## 5.2 People: Mapping Individual's Knowledge

The 'people' represent the first key input to the Design System. Throughout, the system has been designed to support the designers' activities, not to replace them. As their own capabilities dictate their output, it therefore follows that any effect the system has will be a function of the designers understanding of the system and their ability to utilise the knowledge within the system.

For the purposes of the wider knowledge strategy, it was also necessary to determine the capabilities of the remaining engineers prior to the expert's departure.

To meet these requirements a twofold assessment of the designers' 'core capabilities' was conducted. The first assessment was made during the initial evaluation period (prior to the expert's departure) and the second at the end of the evaluation period.

### 5.2.1 Introduction to Knowledge Mapping

Knowledge mapping is a distinct but relevant form of knowledge codification. Unlike knowledge codification in its true form, knowledge mapping does not encode the knowledge itself, rather it encodes the knowledge of where, or how the knowledge in question may be found (Jetter et al., 2006). It is highly useful providing both a visual representation of potentially intangible knowledge, in identifying relationships between artefacts (Kang et al., 2003) and can support knowledge management processes by providing goals (Probst et al., 2000).

The knowledge map is typically used as part of a knowledge system, such as a list of experts or a map to artefacts of knowledge on an intranet. This role was discussed in more detail in section 3.5.7 under the section devoted to knowledge tools and methods. But knowledge mapping can also be used as part of the business strategy or better to understand business capability. For example, mapping the knowledge applications outlines the required knowledge through the value chain of the company, providing a view of areas requiring support and forming a structure to support the knowledge strategy across the business. It is this second application which is applied in this research.

Eppler (2001) lists five different forms of knowledge mapping with a company, listed as:

1. Sources
2. Assets

3. Structure
4. Applications
5. Development

Care must be taken when interpreting these headings, “Sources” for example is not a map of the knowledge sources *within* a business, but rather the sources of knowledge *accessible* or open to a business, such as external training, consultants or product manuals. Here discussion will centre on the method of asset mapping, a required analysis when considering the knowledge strategy of the business.

Asset mapping has existed under a different guise prior to the growth of the knowledge-based economy. It has been approached in different ways for many years in particular by Penrose (1959) and Wernerfelt (1984). In their considerations of the resource-based view of the firm, they analysed the relationship between a firm’s resources (or skills in Wernerfelt) and market opportunities. The conclusion was a firm’s optimal growth is achieved when a balance is met between exploitation of resources and development of new ones (Wernerfelt, 1984, Penrose, 1959).

The concept of a firm’s resources evolved to that of a firm’s “core competence”, a term defined in 1990 by Pralahad and Hamel (1990) and representing the “collective learning in the organisation”. In their paper they listed three measures, by which a core competence should be defined:

1. A core competence must contribute significantly to the perceived customer benefits of the end product or service.
2. A core competence should be competitively unique and as such must be difficult for competitors to imitate.
3. A core competence should facilitate potential access to a wide variety of markets

Pralahad and Hamel highlighted the difference between physical resources which deteriorated over time and competencies which were “enhanced as they are applied and shared”. Their research prompted reconsideration by many managers of where exactly resources (in the traditional sense) should be invested. If an activity did not support a company's core competence, why should it be invested in? This view can still be observed with many companies outsourcing often crucial activities such as transport and logistics, which do not represent their core competencies.

According to (Ljungquist, 2007) competencies or capabilities first appeared in the knowledge management domain in Grant (1996c). Grant does not explicitly discuss mapping capabilities, but his discussion on the knowledge-based view of the firm highlights the shift from resource-orientated companies, in which employees have certain competencies and are deployed accordingly, to companies *defined* by the collective competencies of the employees. This process illustrates an interesting example of the development of Knowledge Management where existing non knowledge-orientated techniques or beliefs have been adopted and synthesised with the concepts of knowledge.

Research into core competencies has continued separate and parallel to that of Knowledge Management (Wang et al., 2004, Ljungquist, 2007). However, the distinction between an employee's capability or competency and their knowledge is unclear, if it can be argued to exist at all. Returning to our earlier definition of knowledge as the basis of decision making, it can further be argued that this is therefore ultimately the enabler of ability. Following this assumption, it is argued here that the correlation between a person's ability and competence in a domain has a one to one parity with their knowledge in the same domain. Thus, a competency map will be topologically equivalent to a knowledge asset map, but rendered from a different perspective. The person most capable of a function will have the most knowledge of the function. This appears to be supported by Leonard-Barton's (1992) paper which describes a core capability as consisting of four dimensions of knowledge.

Lucia and Lepsinger (1999) argue against this theory, stating that capability encompasses a person's knowledge, skills, attitudes and behaviours. This suggests that competency is dependent not just on knowledge or experience but also on elements of the person's character – their attitude and behaviour. However, Eppler (2001) gives no consideration to the differences between knowledge and competencies, as exemplified by the following extract:

> *"... the following map provides an overview of a consulting team in terms of the competencies of its members. Large blocks represent expert knowledge...".*

Thus in Eppler's mind at least capability is directly related to knowledge.

Here, the principles behind competency analysis and mapping will be used synonymously with the principles behind knowledge mapping. That is to say gaps in the core competency map represent areas that require knowledge support. Thus we imply the basic assumption that mapping an individual's characteristics can aid future performance (Ley and Albert, 2003).

### *5.2.2 Implementing a Knowledge Asset Map*

The aim was to analyse the current state of knowledge or capability levied by the team in Rolls-Royce Sheffield. Rather than an attempt to facilitate the use of underused knowledge, mapping was intended to identify gaps in the knowledge base from the perspective of the business value chain. From this understanding a strategy can be constructed to support knowledge generation or transfer in weak subjects and by completing the analysis at two different stages, a rudimentary indication of the knowledge growth of the business can be estimated to provide a measure of the 'input' into the KBS.

Early in the programme of work, a map was constructed listing key products against the degree of captured codified knowledge relating to them. This was detailed in section 2.3.3. However, the initial mapping was limited to a set number of products. Following the implementation of the Design System and the slow uptake of the system, concern was raised as to the success of the knowledge transfer from the expert to the rest of the business. While product knowledge had been extensively documented, process knowledge was limited. In order to support the strategic transfer of all knowledge, an examination of the current shortfalls was therefore proposed.

Different strategies exist in determining relevant core competencies. Typically a top down approach is taken. This is described in detail in Ley and Albert (2003) but can essentially be broken down into three stages:

1. Examine future developments of the market and needs of the customer
2. Define required core competencies of the organisation unit and required individual competencies
3. Assess existing workforce against the desired competencies

This approach has its limitations; primarily that it relies on a large investment by the organisation to implement. It also assumes that the organisation knows its future market and needs of the customer.

Other approaches utilise analytical methods in order to determine those competencies of most value. Hafeez et al. (2002) demonstrated the Analytic Hierarchy Process to derive core competencies by determining the effects of competencies on a balanced scorecard system of the company. Thus by carefully constructing the scorecard using desired performance metrics, the core competencies required to improve the business (or at least the metrics on the scorecard) can be derived. Ley and Albert (2003) demonstrated a more mathematical profiling method utilising the theory of 'knowledge states'. These are formalised tasks of which a person may be capable or not. These states are interdependent, inferring that if a person is capable of one task they will also be capable of completing a task related to the first. This approach uses a proactive task-based method to determine individual capabilities, from which core competencies can then be developed.

In the study here, a largely top down approach was taken, with a slight exception. The primary aim here was not to drive strategic advantage but rather to limit the potential knowledge loss when the expert left. The approach taken can be separated into three stages:

1. What are the current business deliverables?
2. What processes are undertaken to produce deliverables?

3. What support functions are required to ensure business continuity?

To develop the gap analysis, several different sources were synthesised. Primary to this is the design-make process by the designers. Utilising the developed methodology and the business quality management procedure, at each stage of the design process the question was put, “what capability or knowledge is required to complete the stage of work” and the result produced the first basis of the core competencies. Support functions required in the office and workshop were also listed, including maintenance functions and health and safety training. Absent from this list are functions such as Human Resources and Payroll, which are currently not completed by the business. Finally an assessment of the primary product lines was completed. Each team member was then assessed on each competency against a 4 point scale shown in Table 11.

| Value | Corresponding Description |
| --- | --- |
| 0 | No experience |
| 1 | Some limited experience, but would need support from other designers or external support |
| 2 | Experienced across 1-2 applications, but still requires some supervision/support (internal or external) |
| 3 | Fully proficient across range of applications/projects |

*Table 11: Table detailing the rating system used for assessing competency*

### 5.2.3 Knowledge Mapping Results – October 2009

Each of the designers and the Manufacturing Engineer were given a self assessment form and instructed on the definitions of the four different levels of knowledge. The senior manager completed the report form for the technical specialist. The knowledge levels taken in October 2009 can be seen in Table 12.

| | | TS | Manager | Designer A | Designer B | Designer C | Designer D | Designer E | Mnfg. Engineer |
|---|---|---|---|---|---|---|---|---|---|
| Design Process | Understanding of business capacity | 2 | 3 | 2 | 2 | 1 | 0 | 1 | 1 |
| | Understanding of business aims | 2 | 3 | 3 | 2 | 2 | 1 | 2 | 1 |
| | Ability to scope lead-times | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 |
| | Understanding of product lines | 2 | 3 | 3 | 3 | 2 | 0 | 1 | 1 |
| | Understanding of Pro-Laser boundaries and limitations | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 2 |
| | Understanding of manufacturing processes | 3 | 2 | 2 | 3 | 2 | 2 | 2 | 2 |
| | Understanding of gas turbine and components | 3 | 2 | 1 | 3 | 2 | 2 | 3 | 2 |
| | Understanding of tolerances | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 |
| | Understanding of Pro-Laser costs and pricing | 1 | 3 | 2 | 2 | 1 | 0 | 1 | 1 |
| | Understanding of load bearing structures | 3 | 2 | 3 | 2 | 1 | 2 | 3 | 1 |
| | Understanding of numerical analysis | 0 | 2 | 2 | 0 | 0 | 1 | 2 | 1 |
| | Ability to generate load generating devices | 3 | 1 | 3 | 2 | 2 | 1 | 0 | 1 |
| | Understanding of load generating devices | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 1 |
| | Understanding of material properties & selection | 3 | 2 | 2 | 2 | 2 | 1 | 3 | 1 |
| | Use of CAD software | 3 | 1 | 2 | 3 | 2 | 3 | 3 | 1 |
| | Ability to flat pattern from 3D | 1 | 2 | 3 | 3 | 3 | 2 | 1 | 0 |
| | Understanding of EVE | 3 | 3 | 3 | 2 | 2 | 1 | 0 | 1 |
| | Use of Smart system | 2 | 2 | 2 | 3 | 1 | 1 | 0 | 2 |
| | Understanding of required manufacturing processes | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| | Capability to program parts for laser | 3 | 3 | 3 | 3 | 2 | 1 | 0 | 2 |
| | Capability to manufacture parts with laser | 3 | 3 | 3 | 3 | 2 | 1 | 0 | 3 |
| | Capability to manufacture parts with Press Brake | 3 | 1 | 2 | 1 | 0 | 0 | 0 | 1 |
| | Understanding of bend tables | 3 | 1 | 3 | 1 | 2 | 0 | 2 | 1 |
| | Capability with vibro bowl | 3 | 3 | 3 | 3 | 1 | 0 | 0 | 3 |
| | Capability with hand tools | 3 | 2 | 3 | 3 | 2 | 2 | 2 | 3 |
| | Capability of assembly | 3 | 2 | 3 | 3 | 2 | 2 | 1 | 3 |
| | Understanding of validation | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 2 |
| | Capability with validation tools | 2 | 2 | 2 | 3 | 1 | 1 | 1 | 2 |
| | Understanding of QMS procedure | 0 | 2 | 2 | 2 | 0 | 1 | 1 | 3 |
| | Ability to use Design System and archive procedure | 0 | 2 | 2 | 3 | 1 | 1 | 1 | 2 |
| | Understanding of knowledge strategy | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| Product Specific Knowledge | Fast-make component assembly fixtures | 3 | 1 | 2 | 2 | 2 | 0 | 1 | 1 |
| | Fast-make laser and water cutting fixtures | 3 | 2 | 1 | 2 | 3 | 0 | 1 | 0 |
| | Fast-make component welding fixtures | 3 | 1 | 1 | 2 | 2 | 1 | 0 | 1 |
| | Fast-make component fixtures for light and medium load machining | 1 | 1 | 2 | 2 | 0 | 0 | 0 | 0 |
| | Fast, lightweight fixtures for masking and coating procedures | 2 | 1 | 2 | 3 | 0 | 0 | 0 | 0 |
| | Precision pipe and duct production fixturing | 3 | 2 | 1 | 2 | 1 | 0 | 0 | 1 |
| | Unique and repeatable workpiece clamping solutions | 3 | 2 | 2 | 2 | 2 | 1 | 0 | 0 |
| | Product specific gas shields for high integrity welding applicat | 3 | 2 | 2 | 2 | 1 | 2 | 0 | 1 |
| | Fast make advanced press brake tooling | 3 | 2 | 2 | 1 | 1 | 0 | 1 | 1 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low cost manufacturing solutions to early concept components | 3 | 1 | 2 | 1 | 1 | 1 | 0 | 0 |
| | Low volume fast make clips and brackets | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 |
| Support Functions | Understanding of Press Brake maintenance | 1 | 1 | 2 | 1 | 0 | 0 | 0 | 0 |
| | Understanding of laser maintenance | 0 | 2 | 2 | 2 | 0 | 0 | 0 | 2 |
| | Understanding of gas monitoring & ordering | 1 | 3 | 3 | 3 | 0 | 0 | 0 | 3 |
| | Training on First Aid | 1 | 1 | 0 | 3 | 1 | 0 | 1 | 2 |
| | Level of fire training | 2 | 3 | 1 | 2 | 1 | 0 | 1 | 3 |
| | Understanding of COSH | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 3 |
| | Understanding of storage procedures | 1 | 2 | 2 | 2 | 1 | 0 | 1 | 1 |
| | Understanding of security policies | 1 | 3 | 2 | 2 | 1 | 1 | 1 | 1 |
| | Understanding of data policies | 1 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |

*Table 12: Results of the first individual knowledge assessment, taken in October 2009*

The results highlighted several areas of concern. In particular there is a lack of understanding of press brake manufacture by team members other than the technical specialist. This prompted a series of more direct knowledge transfer activities, including:

- Seminar conducted by expert on press brake tool design
- Written guidelines on press brake tool
- Additional support from the expert to the lead designer (A)
- Guideline handbook for design and manufacture

As of the evaluation in February the first three of these had been completed with much success. The final handbook was a work in progress, and would be completed over the coming months.

### 5.2.4 Knowledge Mapping Results – February 2010

The exercise was then completed again at the end of February by which time the expert had left the business. The respondents were encouraged not to try and recall their previous results and given the time between questionnaires this was unlikely. The differences between the recorded competencies given in October and February are shown in Table 13.

| | | Manager | Designer A | Designer B | Designer C | Designer D | Designer E | Mnfg. Engineer |
|---|---|---|---|---|---|---|---|---|
| Design Process | Understanding of business capacity | | | | 1 | | | 1 |
| | Understanding of business aims | | | | | | | 1 |
| | Ability to scope lead-times | 1 | | | | | | |
| | Understanding of product lines | | | | | 1 | 1 | |
| | Understanding of Pro-Laser boundaries and limitations | | | 1 | | | | -1 |
| | Understanding of manufacturing processes | | | | | -1 | | |
| | Understanding of gas turbine and components | | 1 | | | -1 | -1 | -1 |
| | Understanding of tolerances | | 1 | 1 | | -1 | | |
| | Understanding of Pro-Laser costs and pricing | | 1 | | 1 | | | |
| | Understanding of load bearing structures | -1 | | -1 | 1 | -1 | -1 | |
| | Understanding of  numerical analysis | | | | 1 | -1 | | |
| | Ability to generate load generating devices | | | -1 | 1 | | 2 | -1 |
| | Understanding of load generating devices | | | -1 | | | 1 | |
| | Understanding of material properties & selection | | 1 | | | | -1 | |
| | Use of CAD software | | | | | -1 | | |
| | Ability to flat pattern from 3D | -1 | | | | | 2 | |
| | Understanding  of EVE | | | | | -1 | | |
| | Use of Smart system | 1 | 1 | | 1 | | 2 | -1 |
| | Understanding of required manufacturing processes | 1 | | 1 | | | | -1 |
| | Capability to program parts for laser | | | | 1 | 1 | 2 | 1 |
| | Capability to manufacture parts with laser | | | | 1 | 1 | 2 | |
| | Capability to manufacture parts with Press Brake | -1 | 1 | 1 | 1 | | 1 | 1 |
| | Understanding of bend tables | | | | 1 | 1 | -1 | |
| | Capability with vibro bowl | | | | 2 | 2 | 3 | |
| | Capability with hand tools | 1 | | | 1 | | 1 | |
| | Capability of assembly | | | | 1 | | 2 | |
| | Understanding of validation | | 1 | -1 | 1 | -1 | | 1 |
| | Capability with validation tools | -1 | 1 | -1 | 1 | | 1 | 1 |
| | Understanding of QMS procedure | | 1 | | 1 | | | |
| | Ability to use Design System and archive procedure | 1 | 1 | | 2 | | 1 | |
| | Understanding of knowledge strategy | 1 | 1 | 1 | 1 | | 1 | |
| Product Specific Knowledge | Fast-make component assembly fixtures | 1 | 1 | | 1 | | 1 | |
| | Fast-make laser and water cutting fixtures | | | | | | 1 | 1 |
| | Fast-make component welding fixtures | 1 | | -1 | | -1 | 2 | |
| | Fast-make component fixtures for light and medium load machining | | | | | 1 | 1 | 1 |
| | Fast, lightweight fixtures for masking and coating procedures | 1 | | | | | 1 | 1 |
| | Precision pipe and duct production fixturing | | | | 1 | | 1 | |
| | Unique and repeatable workpiece clamping solutions | | | | 1 | 1 | 1 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Product specific gas shields for high integrity welding applicat | | | | | | 1 | |
| | Fast make advanced press brake tooling | | | 1 | | | 1 | |
| | Low cost manufacturing solutions to early concept components | 1 | | 1 | 1 | -1 | 1 | 1 |
| | Low volume fast make clips and brackets | | 1 | | | -1 | 1 | |
| Support Functions | Understanding of Press Brake maintenance | | | 1 | | | | 2 |
| | Understanding of laser maintenance | -1 | | 1 | 1 | | 1 | |
| | Understanding of gas monitoring & ordering | | | | | | 1 | |
| | Training on First Aid | 1 | | | | | -1 | |
| | Level of fire training | -1 | 1 | 1 | 1 | | -1 | |
| | Understanding of COSH | | | | 1 | -1 | 1 | |
| | Understanding of storage procedures | | 1 | | 1 | 1 | 1 | 2 |
| | Understanding of security policies | | 1 | | 1 | | 1 | 1 |
| | Understanding of data policies | | | | | | 1 | 1 |
| | ***Negative Changes:*** | 6 | 0 | 6 | 0 | 12 | 6 | 5 |
| | ***Positive Changes:*** | 11 | 16 | 10 | 27 | 8 | 31 | 15 |
| | ***Sum Change:*** | 5 | 16 | 4 | 29 | -3 | 34 | 12 |

*Table 13: The change in perceived competences between October and February*

Table 13 clearly shows a wide ranging positive increase in mapped competencies over the evaluation period. Overall the 'total' competency increased from 564 to 661, taken simply as the sum of all results (not including the expert in either value). The average increase was 0.27 per competency.

Overall the results were fairly consistent and expected but the values should be treated with some caution. Both sets of results were produced by the employees themselves and no audit was completed by the line manager. The value is gained from the employees' changing perception of themselves rather than absolute values. However, this is potentially compromised by recent experiences and moods (Shiffman et al., 1997). For example designer C's initial responses appear substantially lower than would have been expected. In the second assessment the responses are much more appropriate but this consequently infers a disproportionate increase.

Some important results are apparent. Five of the six engineers reported a higher competence level relating to Press Brake manufacture, indicating successful support gained from the knowledge activities listed above.

Designer E demonstrated the largest overall increase. As he had only recently joined the company, his learning curve would be expected to be the highest.

Importantly for the KBS evaluation, five respondents reported an increased understanding of the knowledge strategy and four reported an increased ability to use the Design System. Both results are significantly higher than the average capability increase. It is argued that this indicates a successful increase in awareness and capacity to utilise the KBS as a consequence of the presence and training given by the researcher.

All of these results may be caused simply by an increased awareness of the topic and a disproportionate increase in confidence by the engineers, causing them to cite higher capability. In theory the only true measure would only be determined through formal assessment. But observations indicate that Press Brake capability has improved dramatically over this period with all designers operating the tool regularly. Further the increased awareness is itself demonstration of successful knowledge transfer. It has changed the engineers understanding and highlighted the availability of knowledge, even if it has not all been ‘learnt’ by the engineers.

### *Summary*

This section’s assessment comprises a rudimentary method of analysing the employee’s core capabilities. The assessment is purely subjective and may be subject to some bias – little precise numerical analysis should therefore be drawn. However, the assessment does show several key developments:

- Increased training and knowledge activities correlate to improved capability responses.
- Knowledge strategy awareness and capability has improved over the assessment period.
- The new novice designer demonstrated the largest overall improvement, indicating a challenging and successful knowledge transfer process during boarding.

## 5.3 Knowledge: System Content

The system has been designed as a dynamic and holistic means to support design reuse, through the capture and redeployment of knowledge. The knowledge content is possibly the most influencing factor governing the system's use. The system's success is therefore dependent on the knowledge captured by the system. Section 5.5.3 assesses the extent to which the correct knowledge is captured. This section assesses how the system content has developed over time.

### *5.3.1 Review of System Media at Launch*

The final system was launched in November 2008 with 219 entries – a combination of the author's initial capture and input and some previously added projects. Due to the updated system, all links had been lost between uploaded files. Instead all additional media was given on two separate discs to allow input and upload.

Each project entry has 67 fields that can be completed and most but not all should be completed for a typical entry. For example, a simple but well documented project has 90% of the fields completed. The remaining seven fields were not applicable, such as 'Reasons for modification', which would only be relevant for a redesign.

The system content was analysed in February 2009, then monthly from June through to March. At the outset of the evaluation period, little of the media given on disc had been uploaded. The system contained just 345 uploaded files and 257 entries. Over the initial months of the evaluation as part of the author's support knowledge capture support these files were gradually added and by August almost 1400 files had been added, giving a total of 1693 uploads.

To simplify naming at the relaunch of the system, project numbering was set from 400 (all the projects started after November were numbered from 400). Thus when analysing the content it is relevant to separate the two periods of capture, denoted by 400- and 400+. Pre-400 projects (400-) are unlikely to change and will have a poorer completion percentage.

### 5.3.2 Analysis of System Content

To analyse the content of the system, each month (typically in the middle) the system content and list of uploads were exported together with the project folder directory. The project folder is considered a fair reflection of the active (and completed) projects as the designers need to create project folders when starting projects.

Figure 62 illustrates the number of projects entered into the Design System over the evaluation period. The plot shows the total number of projects added, the number of distinct active projects (removing multiple entries) and the number of completed or active projects missing from the system.

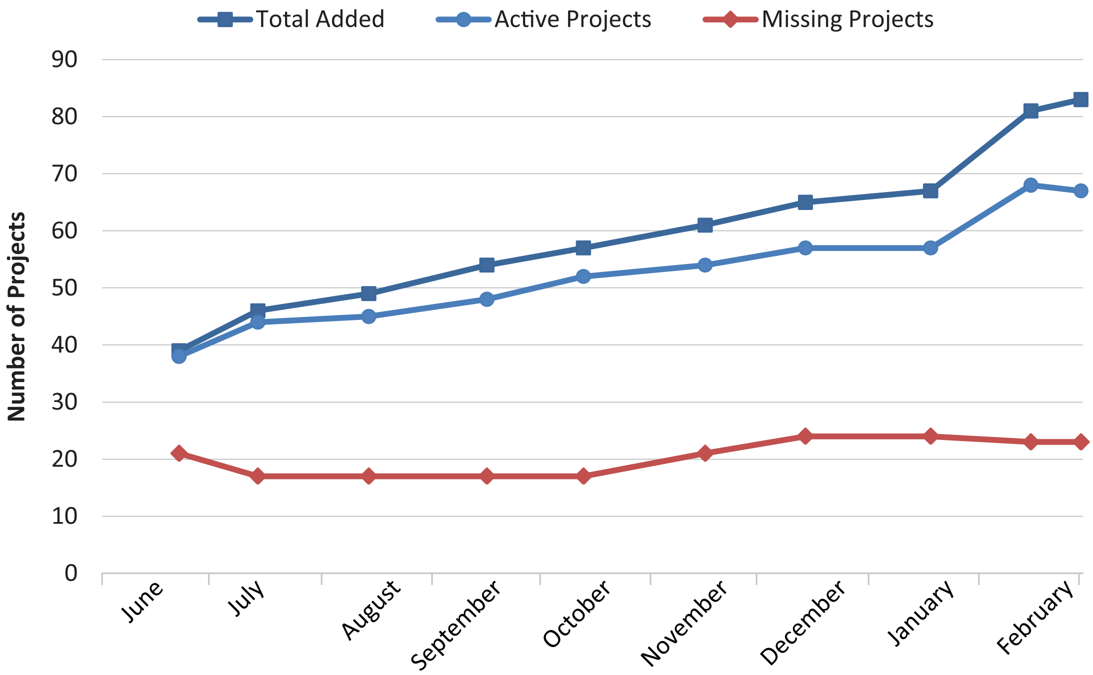



*Figure 62: Plot of the number of system entries (since handover)*

The plot reassuringly demonstrates continual input from designers. From July through to October new projects are systematically added to the system. A slight lag appears during November and December, but it levels out afterwards. The large jump in projects in January was due to an influx of requests, but all were input on the system.

Further analysis illustrates an increased reluctance to knowledge capture once a project has been completed. For example, in June a list of 21 projects that had yet to be entered into the system was produced. Personalised lists were circulated to the engineer, and all were requested to update the database with their projects. One designer did address the list and input his projects (4), but the majority did not. The list was reproduced in December and once again a request circulated to engineers.

In March a list was produced again and compared to the original from July, 23 projects were found to be missing but of these, 17 were on the original list from July. Just two new projects had not been added, out of 31 projects started. Thus concurrent capture of projects was excellent, but the same engineers that were actively updating the system did not return to past projects even when requested.

The observation demonstrates that once a project has been left for a period of time, it is significantly harder to encourage the designers to add it to the system. This proves the importance of concurrent knowledge capture hypothesised in section 4.7 and the need to adequately construct knowledge capture tools to support this. It also demonstrates that the engineers must be encouraged to keep up to date with knowledge capture and documentation.

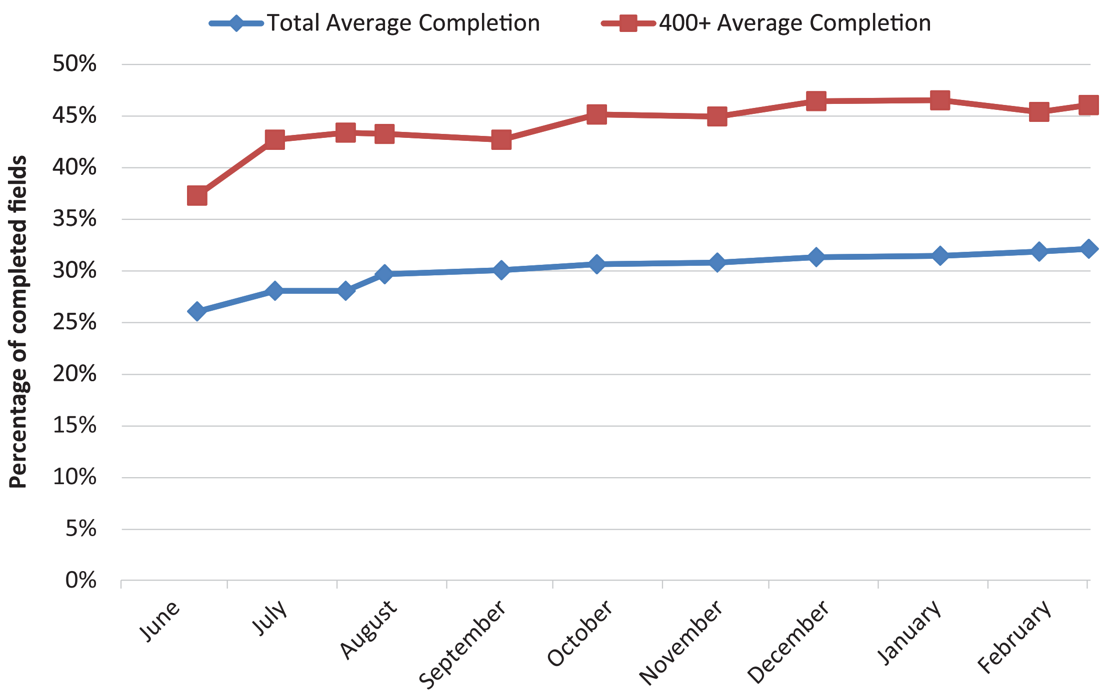



*Figure 63: Plot of the average completion of database fields over time*

Figure 63 shows a plot of the average project completion – the percentage of fields completed per project. Encouragingly, there is a sharp increase in the completion rate for the 400+ projects over June and July. This corresponds to the period of training and increased awareness of the system following the arrival of the author on site.

The completion rate remains fairly consistent but does move up slightly from an average of 43% to 46% between the first and second half of the evaluation period. Completing a frequency analysis of the 400+ entries into bands of 10 (shown in Figure 64) illustrates a roughly two peak weighting. The majority of projects fall either around 20-40% or 70-90%. Only one project is above 90%.

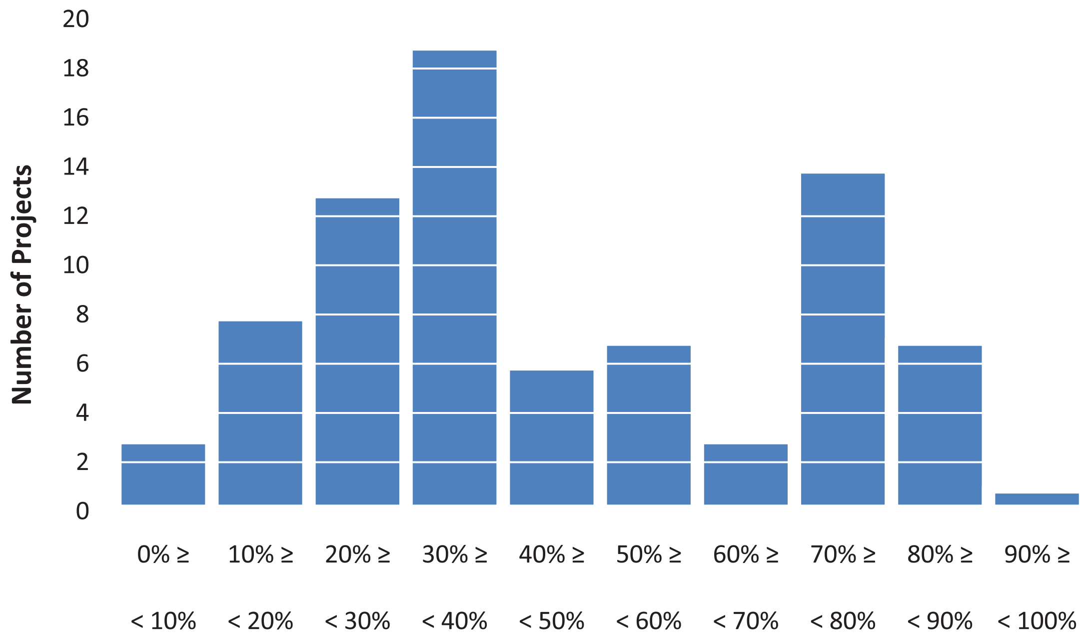



*Figure 64: Frequency analysis of completion rates*

The large number of projects falling between 30-40% indicate that more than just the first tab on the Design System – the basic specification knowledge (26% of fields) is being input. But analysing the traffic light system (shown in Figure 65) indicates mixed completeness. Few projects have adequate design and feedback knowledge to 'light' the second and third lights, indicating key elements are not being captured.

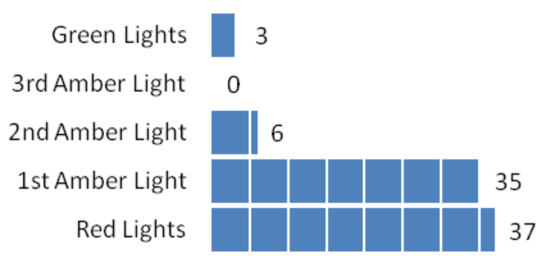



*Figure 65: Illustration of the 'traffic light' status of completed projects*

A further analysis was performed on the completed fields, this time to determine which fields were typically completed and if the pattern of input had changed over the eight month study. This is shown by the dot plot in Figure 66 (for simplicity, mandatory and automatic fields have been removed).

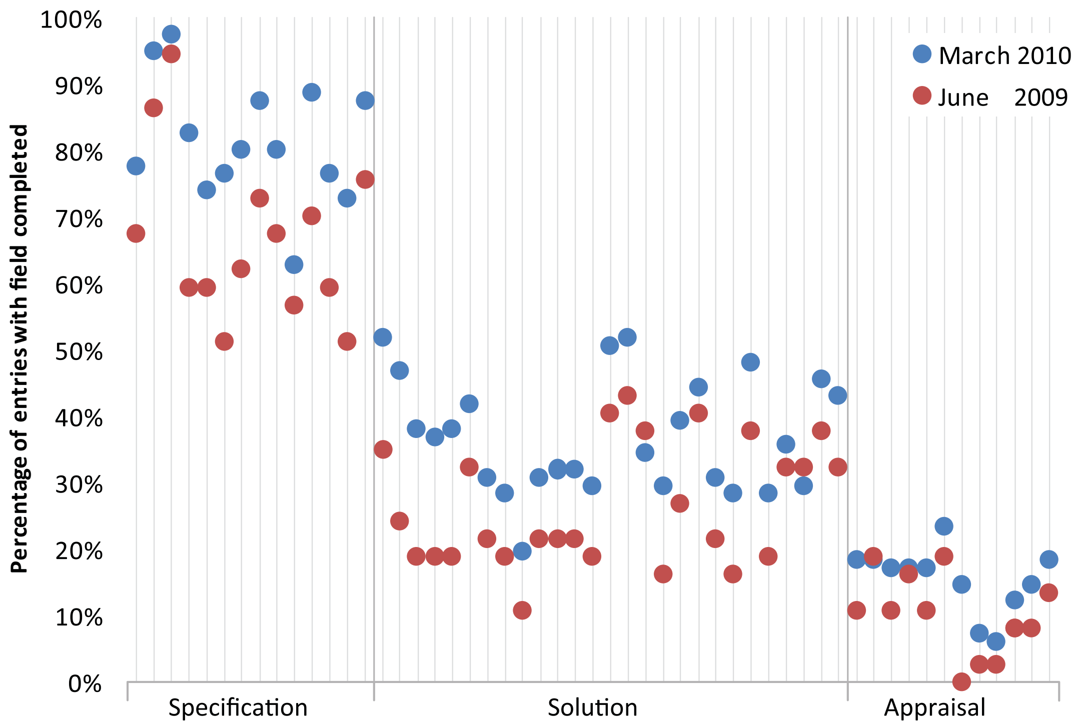



*Figure 66: Dot plot of the database fields, showing the percentage of project entries with entries for that field (fields are grouped by input tab)*

The plot clearly shows the improvement in completion since June and it also shows an emphasis towards the specification tab. Isolation of the descriptive fields requiring free text input is shown in Figure 66. As before, this illustrates a reasonably high completion of the requirements with some function and design description but poor appraisal, for both internal lessons learnt by the designer and feedback from the customer.

Isolation of the descriptive fields requiring free text input is shown in Figure 67. Surprisingly there appears to be no significant difference between completion rates for the descriptive and non descriptive fields.

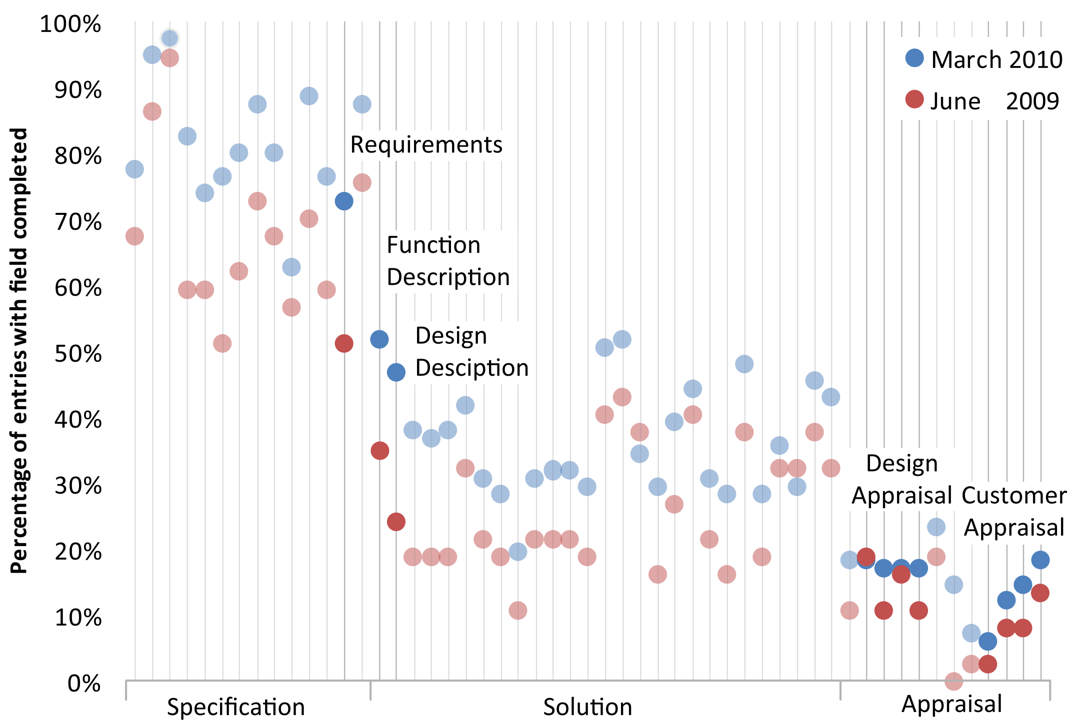



*Figure 67: Dot plot of the database fields highlighting the descriptive (free text fields)*

These plots therefore indicate that the reasons for not entering knowledge are likely to be process-based. This would then match on a micro level the macro level findings above – users are less likely to enter knowledge as time progresses.

### 5.3.3 Analysis of System Uploads

An analysis of the system uploads was also completed. It should be remembered that 'complete' projects should have several key files and documents attached. These are:

- Project quote
- Photographs*
- CAD files*
- Laser-cutting files
- Customer feedback*

Fields marked with a * are mandatory. The intention of the Design System is to act as a single point source for all project knowledge. Thus key communication, reports, client geometry and feedback should be all captured within the project entry as uploads. By March, a total of 1884 files had been uploaded to the system. Figure 68 shows the proportions of these files classified by type and location.

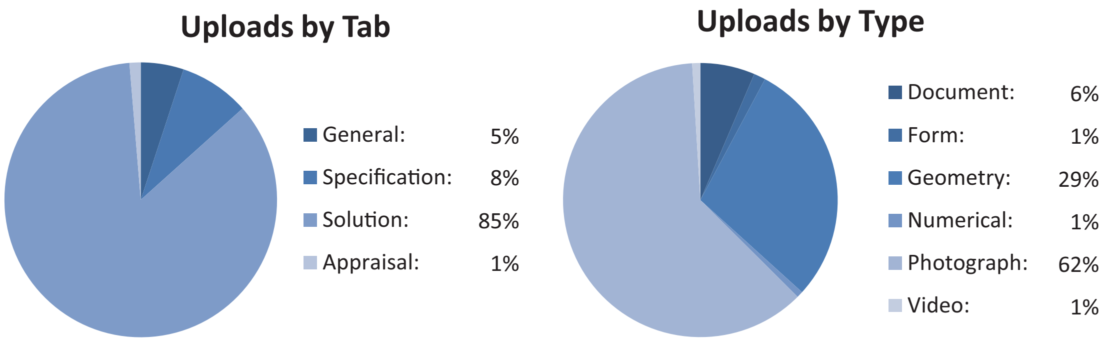



*Figure 68: Pie charts showing the proportions of different file types and locations*

A plot of the number of uploads (for the 400+ projects) illustrates a continued increase in the number of files uploaded over the evaluation period, shown in Figure 69.

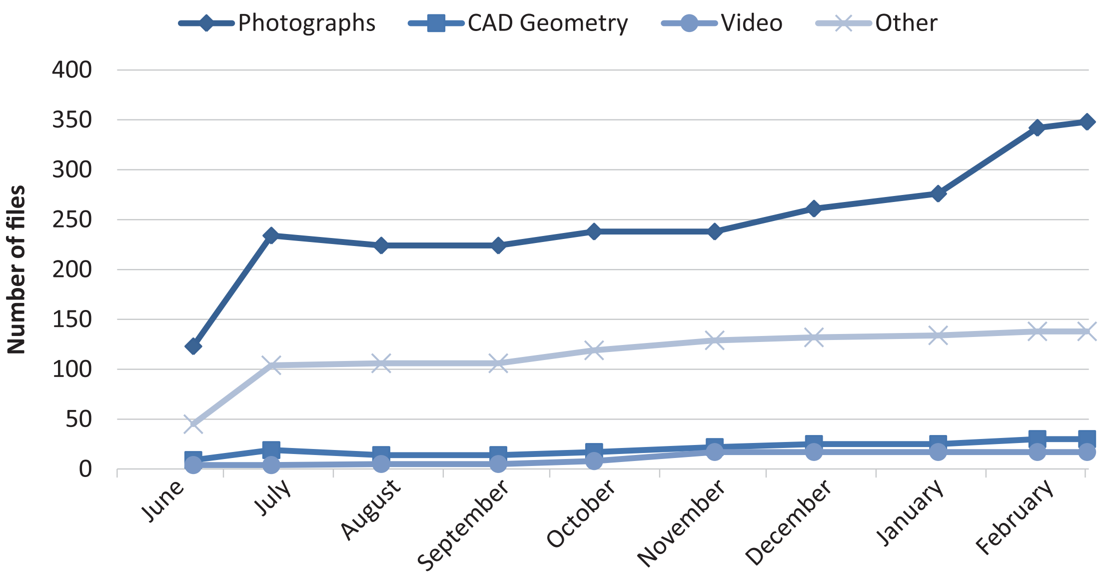



*Figure 69: Plot of the number of uploads for 400+ projects, shown by type*

Plotting by project (shown in Figure 70) illustrates that although around half of the projects added to the system have some files attached, there is cause for concern. In particular there are a large number of projects without photographs of the completed project and without the CAD geometry uploaded (arguably the two most valuable uploads).

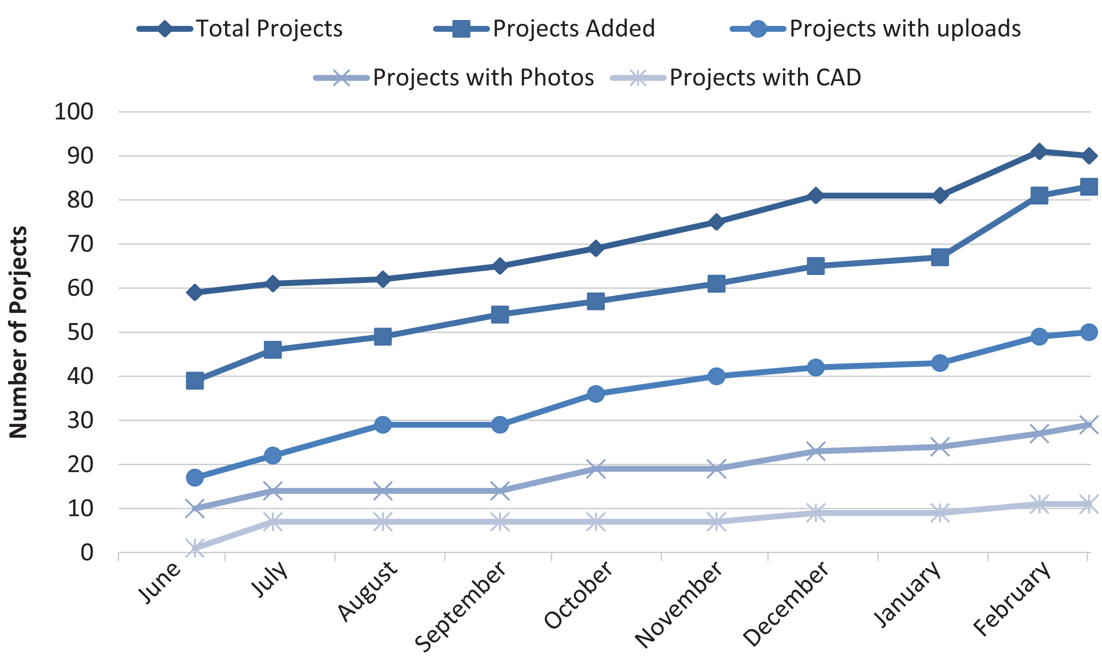



*Figure 70: Plots of the number of projects with uploads. Here those projects with photos and those with CAD (shown in light blue) are a subcategory of the number of projects with uploads and are not mutually exclusive*

Some lag between a project's initial entry and completion is expected, but this does not account for number of projects missing CAD files (72 by March). Total CAD uploads (over all projects) is shown in Figure 71 and as before shows a poor completion rate. The step increase in August is due to the reuploading of previous files by the author.

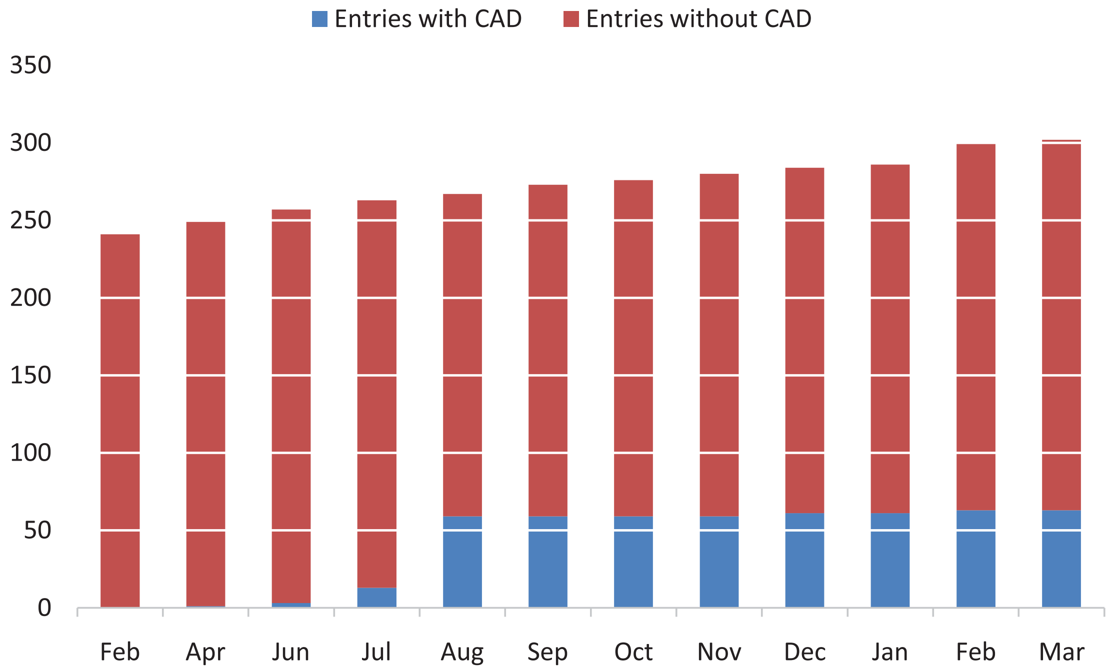



*Figure 71: Bar chart illustrating the proportion of all projects with CAD files*

This is of particular concern, given that a key user scenario of the Design System was to allow rapid modification and reuse of existing geometry. At the current completion rate, this is unlikely to occur. Further analysis was completed to understand which files were being uploaded and to understand if the same inertia issues as before were being encountered. Figure 72 shows the number of projects containing at least one uploaded file, plotted against the different upload types and grouped as before into the three different tabs. Photographs are listed twice as there are fields to support upload of specification photographs and to capture completed project images.

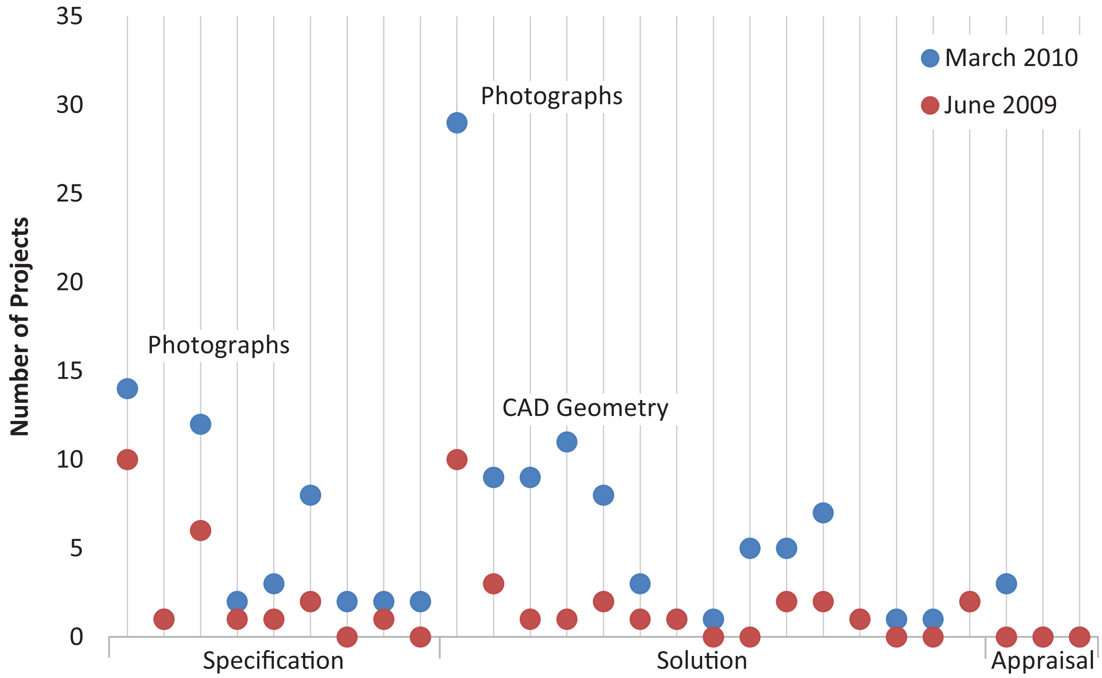



*Figure 72: Dot plot showing the number of 400+ projects with different uploads*

Figure 72 further supports the earlier plot, indicating that photographs were by far the most uploaded file type. The plot does not however demonstrate the equivalent correlation between upload proportion and the tabs. For example although appraisal uploads are clearly the least completed area, specification and solution appear to be utilised equally.

### *5.3.4 Analysis of Captured Knowledge*

As a final analysis of the system content, the content of the descriptive fields was analysed. These fields allow designers to provide as much detail as they feel necessary to describe the projects requirements, solution and to appraise their work. These fields are:

- Requirements
- Functional description
- Design description
- Design benefit - quality
- Design benefit - cost
- Design benefit - delivery
- Novel developments
- Customer satisfaction - overview
- Customer satisfaction - relations
- Customer satisfaction - design
- Customer satisfaction – manufacture and assembly

While some of the appraisal fields may not always be applicable, typically these should all be completed, providing as much knowledge and detail as possible. In order to gain a rudimentary assessment of 'information content', a frequency count was performed on the data in the descriptive fields for +400 projects from June and March. It was found that the average number of words increased from 35 per field in June to 50 words per field in March, while the percentage of fields completed increased from 55% to 57%. The completion rate could be further improved, but the increased knowledge content of the descriptive fields indicates that while the system has been steadily used, the detail added is increasing.

Two 'Word Clouds' were also generated (using the software 'Tag Crowd Beta', at http://tagcrowd.com/) based on the descriptive data from these fields and shown in Figure 73. The intention was to visually compare the descriptive data from June and March. The larger the word shown, the more frequently it appears.

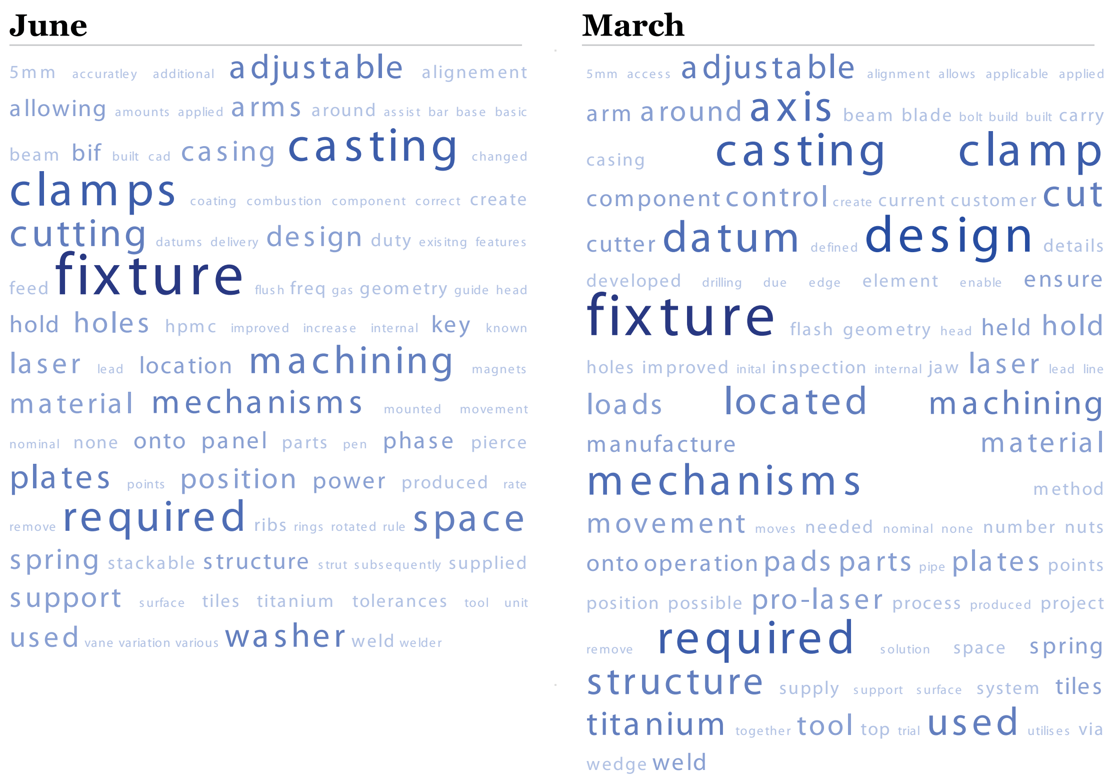



*Figure 73: Two 'word clouds' visualising the frequency of key words*

The clouds list the top 100 most frequent words, discounting commonly used words such as 'the'. The two clouds are relatively similar and do not suggest there has been a significant change in the content or subject matter captured. The most common words, as expected, relate to manufacturing (machining), fixturing (positioning) and geometry (holes, plates).

Noticeably missing from the clouds are words such as 'problem', 'change' and 'redesign', the words that would be expected in appraisal documents and reports. While this is by no means a rigorous analysis, it further suggests the lack of objective criticism and feedback from the designers advising others on how to improve the design in future.

## *Summary*

This section has presented an analysis of the system content over the evaluation period. Particular emphasis has been given to understanding the changes in content, the extent to which users have contributed knowledge to the system and the degree of completeness in the system. Several key conclusions can be drawn:

- Project knowledge has been continually captured throughout the evaluation period and system content has continually increased. Furthermore, since the start of the evaluation period the majority of new projects have been successfully added to the system
- Despite intervention by the author, the projects not logged prior to this period were not retrospectively added to the system.
- Project completeness increased marginally over the evaluation period – attributed to improved user understanding of the system
- Completion of the different stages of knowledge capture decreases with process. Specification knowledge is significantly better captured than appraisal and feedback knowledge, suggesting a process issue.
- There appears to be no significant difference between the completion rates of free text fields and multiple selection fields.
- System uploads were primarily photographs, typically under the solution tab.
- Project CAD files were poorly captured, representing a concern for users wishing to adapt and modify past geometry. But there does not appear a correlation between the input tab and file uploads, suggesting a non process-based issue influencing users.
- The quantity of knowledge in descriptive fields has on average increased from June to March but subject matter appears to be consistent. Visually representing descriptive content suggests that critical appraisal may be missing from these fields.

## 5.4 Design Process: Analysis of the Systems Use

Throughout the research so far usage of the system has been partially inferred. This section examines not just the extent to which the system was used, but also how and when the system was used.

Two methods of data capture were utilised to gain further understanding of the access and role of the Design System. These methods were 'daily diaries' kept by the designers over the evaluation period and logging embedded within the Design System. This section introduces the rationale for these methods, before presenting the results of the diaries, and then the data from the logging function.

### 5.4.1 Rationale behind Methodology

The intention was to understand the designers' knowledge activities and specifically their interaction with the Design System over the evaluation period. Reviewing the literature on time and motion studies, particularly in relation to design studies, results in several studies that have addressed the information 'behaviour' of engineers. The majority, however, were focused on the 'what' and 'where'. That means assessing the types of knowledge used and where the knowledge is sought. These studies include (Kuffner and Ullman, 1991, King et al., 1994, Baya, 1996, Marsh, 1997, Court et al., 1998, Hertzum and Pejtersen, 2000, Lowe et al., 2004, Yitzhaki and Hammershlag, 2004, Demian and Fruchter, 2006, Hicks et al., 2006, Wild et al., 2010, Allard et al., 2009, Robinson, 2010). The studies demonstrate a variety of methods, both direct and indirect, and are summarised in Table 14.

| Ethnographical Observation | Non-Ethnographical Observation | Self Reporting | Survey | Interview |
|---|---|---|---|---|
| Baya (1996) | Kuffner and Ullman (1991) | Robinson (2010) | Court et al., (1998) | Lowe et al. (2004) |
| Marsh (1997) | | Wild et al. (2010) | Hertzum and Pejtersen (2000) | Hicks et al. (2006) |
| Allard et al. (2009) | | | Yitzhaki and Hammershlag (2004) | |
| Demian and Fruchter (2006) | | | Ettlie and Kubarek (2008) | |

*Table 14: Summary of previous design studies*

The method used greatly influences the level of detail, accuracy and reliability of the data collected. However, these factors are typically offset by the primary limitation faced by many practitioners in this field of research, namely the limited access and support available from designers (Lowe et al., 2004). Obtaining behavioural data of a high granularity from engineers over a long period of time represents a significant challenge. For example, the study by Marsh (1997) represents a highly detailed and reliable study of designers, yet the high level of effort required limited the study to 17 days of observation. This was due to the time constraints of the observer and concern over the effect of continued observation. This limitation greatly diminishes the capacity of researchers to conduct detailed studies of knowledge use over extended periods of time and across multiple design projects. As a consequence, of the studies listed above only Marsh (1997), Court (1998) and Robinson (2010) examined the time of designers' activities and only Robinson (2010) and Wild et al. (2010) conducted contiguous studies.

Here the aim was to conduct both a longitudinal and contiguous study of the designers. The methods available for study are summarised below (ranging from the most intrusive to the least):

- Time and motion studies (observational)
- Personal activity logs (self-reporting)
- Work sampling (self-reporting)
- Surveys (retrospective)
- Application logs (automated)

A review of these measurement methods is given in Starren et al. (2000), but the key features of the methods are summarised in Table 15.

| Method | Description | Advantages | Disadvantages |
|---|---|---|---|
| **Time and motion** | Researcher follows and observes subject with a stopwatch, recording the duration of activities. | - Data collected is both accurate and reliable. | - High labour requirement.<br>- Can cause Actor-Observer or 'Hawthorne' effect. (Mayo, 1949) |
| **Diary studies** | Diary or activity logs are kept by subjects over the period of study, recording their daily activities. | - Chronological data is captured.<br><br>- Data *can* be highly accurate. | - Dependant on subject participation.<br><br>- Open to some subject bias or manipulation (Starren et al., 2000). |

| | | | |
|---|---|---|---|
| **Work sampling** | Discrete sampling of subject's activities is used to build a statistical model of proportions of time (Ampt et al., 2007). | - Highly detailed data can be captured<br><br>- Less intrusive than Time and Motion studies. | - Large sample population required for high confidence (Finkler et al., 1993)<br>- Cannot report on chronological changes. |
| **Surveys** | Subjects respond to pre-set questions. | - Little intrusion on subject's activities.<br><br>- Can capture rationale behind responses. | - Subjective responses affected by personality and memory<br>- Subjects often try and provide the 'right' answer |
| **Departmental logs** | Automated tracking or logging is embedded into systems allowing subsequent analysis. | - Highly accurate data is produced.<br><br>- Logging does not intrude on subjects activities. | - Requires interaction with a system to capture activity.<br><br>- Data is shallow, with little context |

*Table 15: Summary of the different assessment methods considered for the study*

The primary aim of the assessment in this research was to determine not just how long designers spent using knowledge but whether they used the KBS and at what stage during a project they typically sought knowledge.

The requirement to capture chronological data discounts the use of work sampling and to some extent the use of surveys (although this was used to supplement understanding in section 5.5). The longitudinal nature of the study would be too much of a drain on resource to implement a time and motion study. Finally use of automated logging, while potentially supplementary, would not capture interpersonal knowledge transfer. The agreed solution was to utilise a 'diary study' method in conjunction with system logging. The diaries would provide process-orientated data from the designers while the logging would provide data on the usage of the system.

The engineers were all asked to complete a pre-structured form at the end of each day termed interval-contingent recording (Wheeler and Reis, 1991), summarising the total time spent on any activity during the day and matching this against different projects. The engineers were asked to subdivide their time into 15 minute intervals but to sum up activities to ensure that for example three or five minute conversations would still be recorded.

The use of prose to capture greater depth behind events was considered. However, the endurance required from the longitudinal nature of the study necessitated a simple and highly structured means of capture. Wildermuth (2002) argued that the greater the burden, the less compliance. Therefore, the study was chosen to be purely quantitative, adopting the 'log' method described in Toms and Duff (2002).

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Activities were classified into 36 different activities and grouped into eight sections: communication, meetings, travel, management & administration, technical design, production, maintenance/upkeep, and design system. Part of a typical entry can be seen in Figure 74.

| Diary Record: | | Monday | | | | Tuesday | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 04/01/2010 | 04/01/2010 | 04/01/2010 | 04/01/2010 | 05/01/2010 | 05/01/2010 | 05/01/2010 | 05/01/2010 |
| | Job No: | Gen | 420 | 438 | 519 | Gen | 438 | | |
| *Communication* | | | | | | | | | |
| | Technical Specialist | | | | | | | | |
| | Manager | | | | | | | | |
| | Colleague | | | | | | | | |
| | Customer | | | | | | | | |
| | Administrators | | | | | | | | |
| | Suppliers | | | | | | | | |
| *Meeting* | | | | | | | | | |
| | Technical Specialist | | | | | | | | |
| | Manager | 0.5 | | | | 0.5 | | | |
| | Colleague | | | | | | | | |
| | Customer - On Location | | | | | | | | |
| | Customer - On Site | | | | | | | | |
| | Administrators | | | | | | | | |
| | Suppliers | | | | | | | | |
| *Travel* | | | | | | | | | |
| | Customer Related | | | | | | | | |
| | Other | | | | | | | | |
| *Management & Administration* | | | | | | | | | |
| | Management | | | 1 | 1 | | | | |
| | Administration | 3.1 | | | | | 1 | | |
| | Report / presentation writing | | | | | 4.1 | | | |
| | Conducting Analysis | | | | | | | | |
| | Training & Development | | | | | 2 | | | |
| | Marketing | | | | | | | | |
| *Technical Design* | | | | | | | | | |
| | Knowledge Access | | | | | | | | |
| | Preliminary Concept Definition | | | | | | | | |
| | Full Concept Definition | | | | | | | | |
| | Pure CAD Generation | | | | | | | | |
| | Finalising Design | | | | | | | | |
| | Outputting for Manufacture | | | | | | | | |
| *Production* | | | | | | | | | |
| | Experimentation / Prototyping | | | | | | | | |
| | Manufacture and Assembly | | | | | | | | |
| | Dress / Debur | | | | | | | | |
| | Validation / Measurement | | | | | | | | |
| | Service Support | | | | | | | | |
| *Maintenance/Upkeep* | | | | | | | | | |
| | Health & Safety | | | | | | | | |
| | Machine maintenance | | | | | | | | |
| *Design System* | | | | | | | | | |
| | Knowledge Input | | | | 2 | | | | |
| | Knowledge Access | | | | | | | | |

*Figure 74: Section of a typical diary entry showing the duration (in hours) of different activities during the day against different jobs*

The eight generic sections were primarily developed from the two previous time studies in Rolls-Royce by Marsh (1997) and Robinson (2010). These studies represent a useful benchmark with which to compare and contrast the results of the study. The detailed activity classification, particularly those relating to the technical design and production activities, were based on the design and manufacturing methodology developed in section 4.3 and combined with existing activities in the business (such as 'validation measurements'). A 'general' job was included for each day, as it was acknowledged that some activities are not project specific.

A one week pilot study was conducted using the lead designer. Appropriate changes were then made to the classification system, including clarification of activities with call out descriptors. Following this initial trial, the study was launched with all engineers. Training was given to each engineer and examples given of a typical entry.

### 5.4.2 Reported Knowledge Use

The diary study was conducted throughout the evaluation period of July 2009 to March 2010, over which period:

- 166 days were studied
- 719 working days were filled out by up to six engineers (although two joined midway through the study)
- 5532 working hours were recorded
- 44 different projects were captured (although not all were completed during the course of the study).

Once established as a regular part of each day, the diaries were generally filled out consistently by engineers, some opting to keep the diary open in the background to work on during the day. However, during periods of high workload they were occasionally left to the end of the week and completed using logbook notes. This provides some degree of concern in terms of their accuracy, but is unavoidable. As discussed above, the alternative would be to use retrospective surveying, which would be far more inaccurate. Reassuringly the engineers often asked for clarification on classification – often when recording a non-typical event, such as escorting visitors.

Using the top level classifications, an overall breakdown of the activities within the business was derived, shown in Figure 75. The Design System accounted for just less than 98 hours, while communication was recorded as 405 hours.

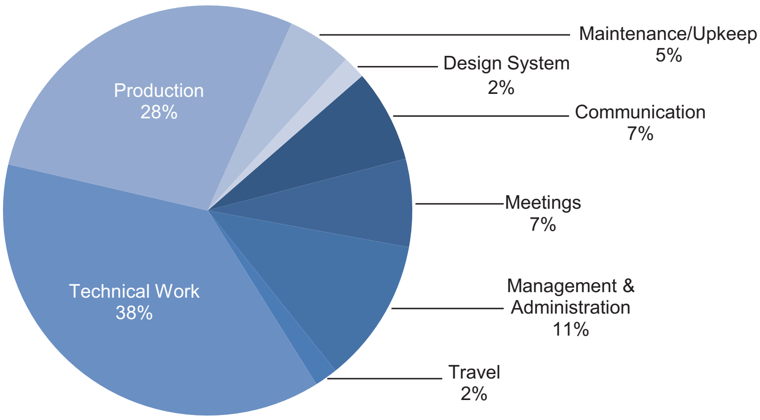



*Figure 75: Pie chart illustrating the overall breakdown of activities within the business*

In order to determine how much time was spent accessing or providing information, the detailed classifications were utilised and non-knowledge activities grouped together as shown in Figure 76.

For simplicity it will be assumed that all communication is the exchange of knowledge and information. While exceptions do exist, the majority of recorded activities within this classification were ‘discussions with colleagues’ that were typically project or problem focused. Meetings are shown separately but are not strictly knowledge transfer activities.

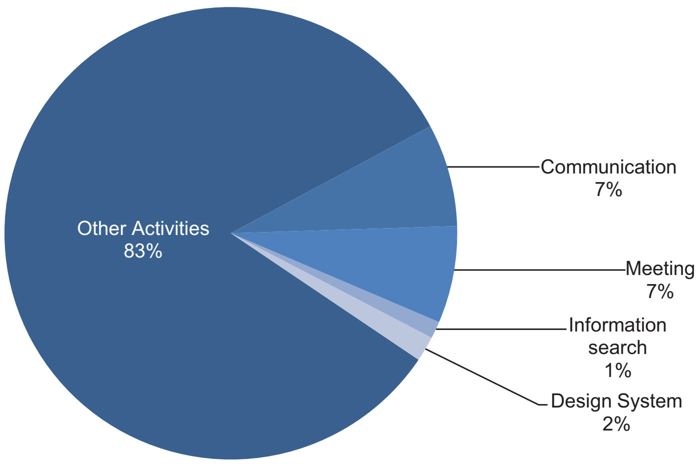



*Figure 76: Proportion of time spent on knowledge-related activities*

Here, ‘information search’ is distinct to the Design System and denotes the time spent by the designers acquiring the information that they need to complete their technical activities such as drawings from a customer.

According to these figures, the time invested in information and knowledge exchanges is significantly less than determined in the previous studies by Marsh (1997) and Robinson (2010). Specifically the time spent accessing or supplying knowledge and information was found to be 10% of a designer's total time, compared to 24% (Marsh) and 30%[4] (Robinson). This figure also appears low compared to other studies of activities, such as 18% in Court at al. (1998) and 40-66% cited in King at al. (1994).

Codified knowledge use (3%) does correspond strongly to the 3.73% determined by Robinson. This suggests that even using the diaries on a daily basis, the designers may have underreported the time spent discussing their work, either with clients or colleagues.

These figures also suggest that despite the emphasis on and provision of the Design System, a relatively small proportion of time is actually invested in codified knowledge, compared to verbal knowledge exchange (communication and meetings). As a further analysis, a breakdown of the communication class was elicited, shown in Figure 77.

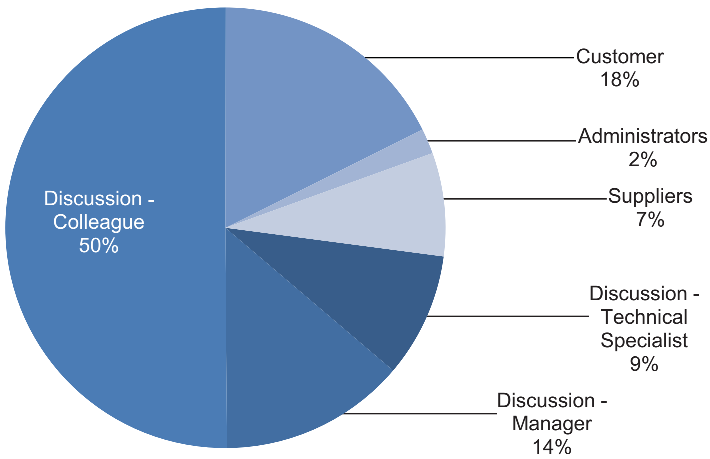



*Figure 77: Breakdown of the communication activities.*

Perhaps the surprising result from Figure 77 is the low proportion of time spent in discussion with the technical specialist compared to other colleagues. This could in part be explained by the expert's decreasing time on site and his departure, five months into the study. But even when corrected

[4] Taken as the sum of 'discussion' and 'solo technical information search'.

for, this value is low. A chronological plot of the interactions with the technical specialist is shown in Figure 78.

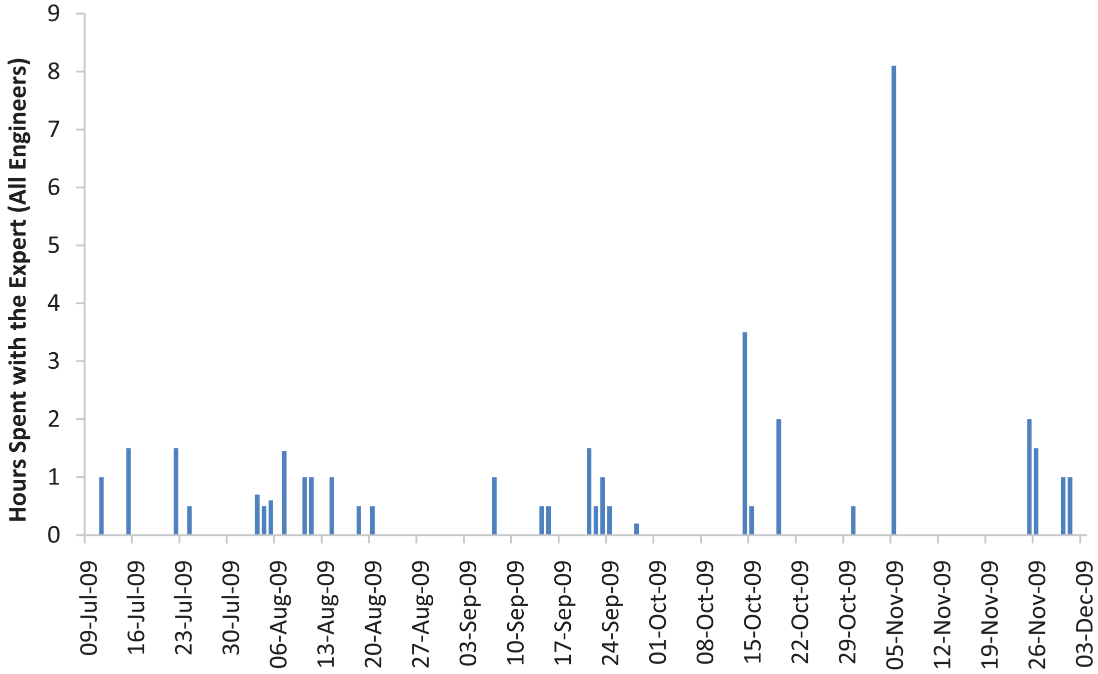



*Figure 78: Plot of the time spent with the expert per day from July to December*

The plot shows a sporadic but often clustered interaction with the expert. While this could be due to the expert's availability, it is more likely that this indicates problem-orientated interactions rather than planned meetings and reviews. This is supported by the author's own observations and is best illustrated by the high cluster in the week of the 17th and 24th September, where all interactions were from a single engineer requiring support for a single but complex problem. The occurrence of multiple interactions over several days also highlights the iterative and discussion-based support provided by the expert, rather than a single up front transfer of knowledge. Thus the expert is providing feedback on actions taken rather than just instructing the engineers what to do.

### 5.4.3 Reported Interactions with the System over Time

Utilising the diaries, the reported interactions with the system over time can also be elicited and are shown in Figure 79.

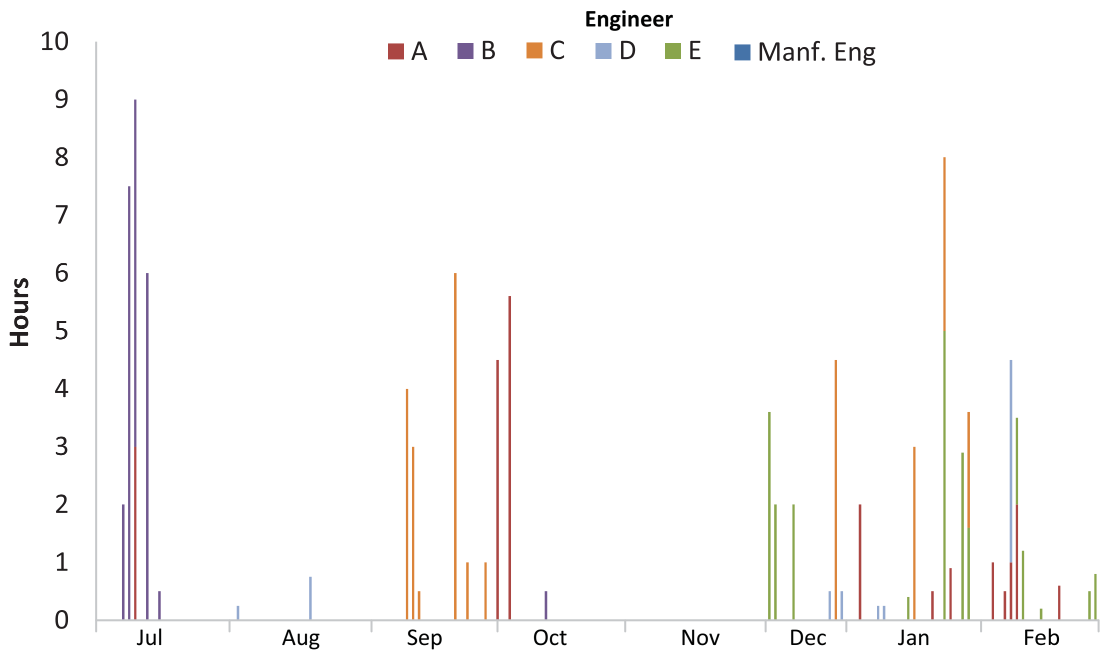



*Figure 79: Plot of the time spent using the Design System (for input and output)*

Again, clustering can be observed and there are periods when the system is little used. It is also apparent that the system is used more frequently by some engineers than others. For example, designer E (a novice engineer who joined the company at the end of November 2009) has made heavy use of the system, while designer B has used it much less frequently.

Examining the proportion of time spent accessing versus inputting knowledge from and to the Design System demonstrates that 82% of the time was spent inputting knowledge while just 18% of the time was spent accessing knowledge. Furthermore, only designers A, D and E reported using the system to access knowledge, while all designers used it to input knowledge. Therefore, based on the information given by the engineers, far more time is spent inputting knowledge than acquiring knowledge. Initially this would seem to be a major concern, as the intention of the system is to save time and allow business scale up. These figures suggest that the upfront investment far outweighs the utilisation. But this would be incorrect. Clearly a far higher proportion of time is spent recording knowledge, but time spent accessing knowledge is not a fair measure of its utilisation as it is far quicker to read a document than to write one.

It is likely that the method of reporting via the diaries is not sufficient to capture all the interactions with the system. The engineers were asked to complete the diaries to the 'nearest 15 minutes'. Despite this, examining the diaries suggests a general underreporting of short events such as telephone calls and conversations. It is hypothesised that due to the fast-paced environment and high number of short events, when reporting at the end of the day the engineers may not remember and hence may not record all activities.

It is probably fair to assume same-type events will have been recorded equally. Thus the proportions of time spent communicating in different ways is probably correct but the overall values are perhaps underrepresented. The exception is likely to be the Design System. Knowledge capture work requires a reasonable investment in time and is likely to have been captured by the diaries. Knowledge access is not likely to have taken such a long period of time and these events may be underrepresented. This is discussed further below.

The system's continued usage is clearly a positive result and the heavy reliance on it by the two novice engineers is also a measure of success. Perhaps the only disappointing result is the low knowledge utilisation by the more experienced designers, B and C. The system (and the knowledge contained within) was designed to support all users. This appears not to have been entirely successful. As discussed in the following section (5.5), it appears that it may be because some users view the system as a repository rather than a resource.

### 5.4.4 Recorded Interactions over Time

System logging was implemented to understand with greater precision the interactions with the system. Two functions were used: first the standard Windows Server – Internet Information Services [IIS] was enabled from the outset of the server's launch (Microsoft, 2007). Secondly, during the evaluation period a bespoke system was developed to capture more detailed interactions. This was implemented in January 2010 and corroborated the system-generated data and provided additional insights.

The IIS function records the requests made to the server from a client for data. It does not record the content of the request but does encode any files requested, for example image file names, the ip address of the requester and the time and date of the request. By analysing which images are requested, it is therefore possible to elicit the page requested, such as when a search is conducted, a project opened and files uploaded.

From the launch of the system to March 2010, over 5700 requests were made to the server. However, care must be taken in interpreting these requests. For example, the server requests do not record when data is saved, nor when a page is closed, so it is not therefore possible to calculate the length of time the system is actually used for or to determine automatically the frequency of access. Some estimates can be derived through further analysis of the logs, however.

The number of 'sessions' can be inferred from the data if a time constant is used. If two events are separated by a time $t$, greater than a constant $\tau$, the events can be considered as distinct sessions. Figure 80, Figure 81 and Figure 82, show the number of distinct sessions per month, for $\tau$ = 10, 30 and 60 minutes.

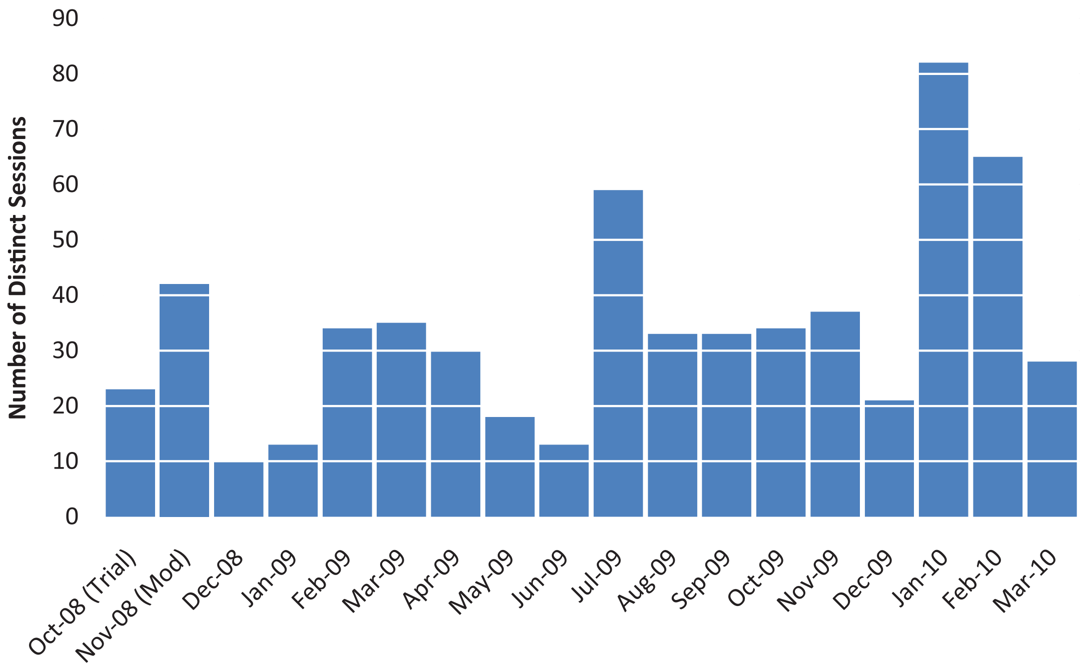



*Figure 80: Number of distinct session, τ = 10min*

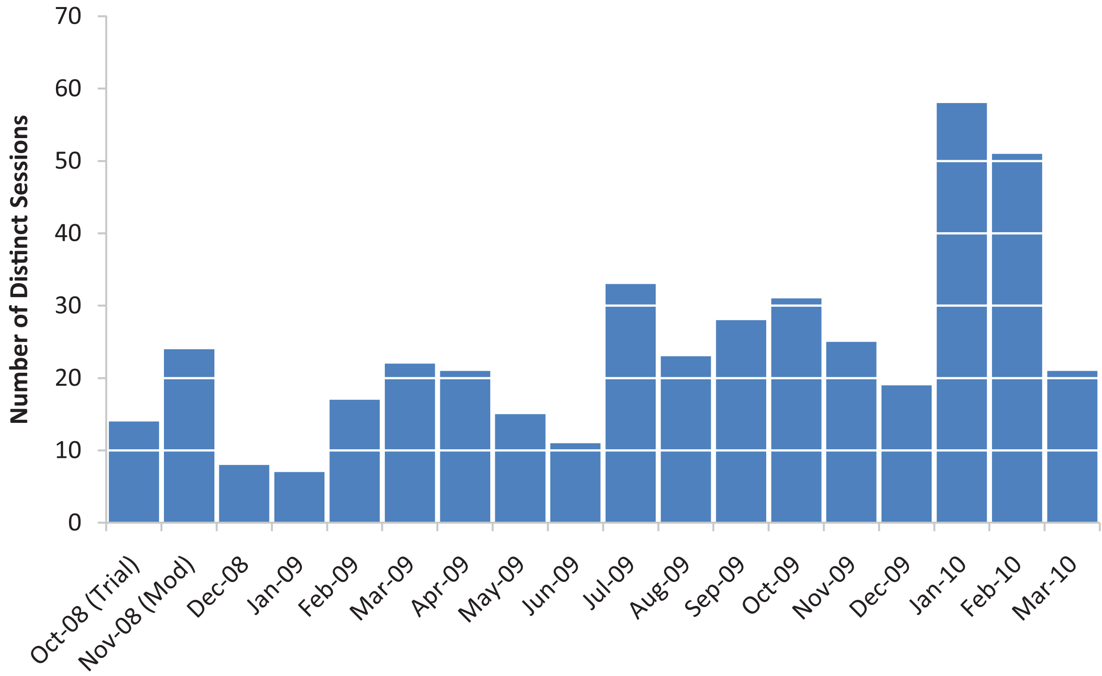



*Figure 81: Number of distinct sessions, τ = 30min*

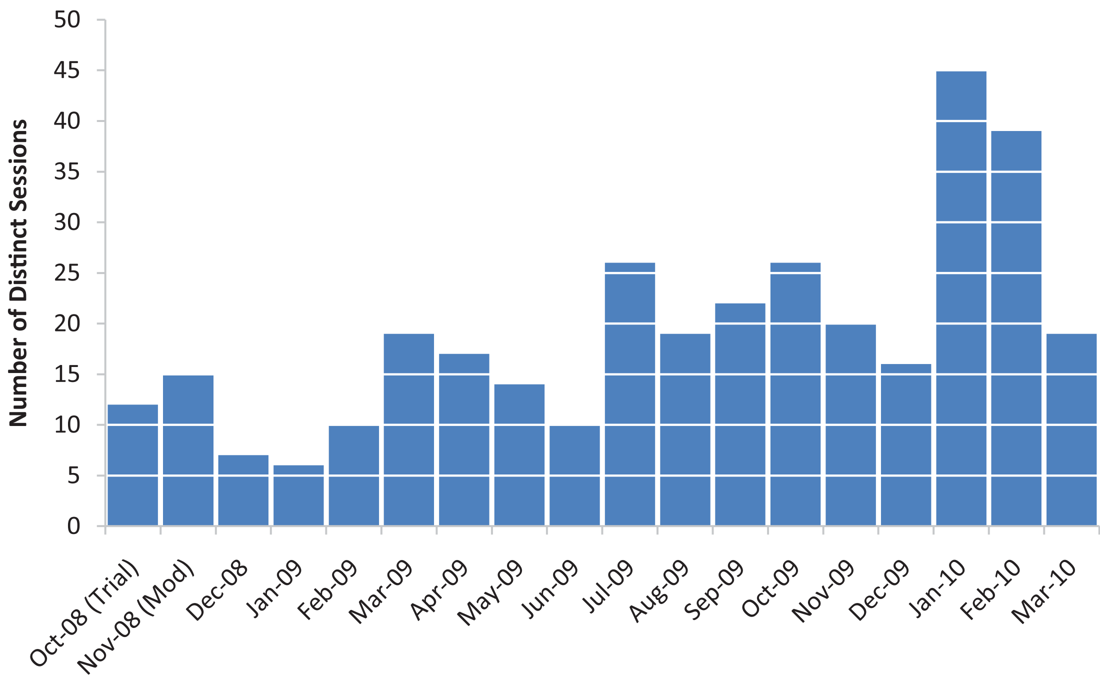



*Figure 82: Number of distinct sessions, τ = 60min*

These plots cannot show a 'typical' session length, but they are able to demonstrate the overall usage. That the plots are consistent with each other, albeit with reducing numbers of sessions for increasing τ as expected, indicates that usage patterns did not change. Users did not start using it for longer (or shorter) periods of time.

The analysis demonstrates a generally increasing usage of the system from a minimum when first launched to a peak in January 2010. The plot also shows much more consistent usage than that reported in the diaries.

A number of key points are noticeable. Three jumps in usage can be observed in March 09, July 09 and January 10. The first two correspond to the author's presence on site, the third simply increased use of the system by both novice engineers. This suggests that a visible presence on site does indeed have an influence on system usage. The low usage in Dec 09 is believed to be a consequence of extensive holiday taken during this month.

The plots show periods of declining use following peaks, for example following March 09, and to some extent January 10. This may correspond to decreasing motivation or simply different stages of product cycles. The large drop from February to March 2010 is of particular concern as it corresponds to the departure from site of the author and arguably the ‘loss’ of support from a ‘key’ individual. As Davenport et al. (1997) argues, the “likelihood that the project would survive without the support of a particular individual” is a measure of success. Based on this metric therefore, the drop may seem to suggest a failing activity. However, the figure from March simply shows usage at a rate comparable to the months prior to December/January. It does not show critical failure of the project, but rather that Davenport’s metric has been met and the system remains in use. Long term trends are yet to be seen, but to date the outlook remains positive.

### *5.4.5 Analysis of Usage*

As discussed, an additional logging program was developed to understand better exactly how the system was being used. This program was launched during January 2010 and ran until the end of March 2010. 52 working days were logged and 983 events recorded, shown in Table 16.

| Event Type | Number of Events |
|---|---|
| Close Project | 130 |
| File Upload | 139 |
| Open File | 127 |
| Open Project | 200 |
| Save Project | 130 |
| Search By Filter | 43 |
| Search By Text | 214 |

*Table 16: List of the different number of events recorded*

Again some care must be taken when interpreting these figures. An open project may be saved multiple times without reopening, while closing the Design System using internet explorer will not be recorded.

Thirty three ‘Resaves’ (with no reopening of a project) were counted. Combined with the figures above, this suggests that projects were opened for knowledge capture and knowledge access in almost equal amounts.

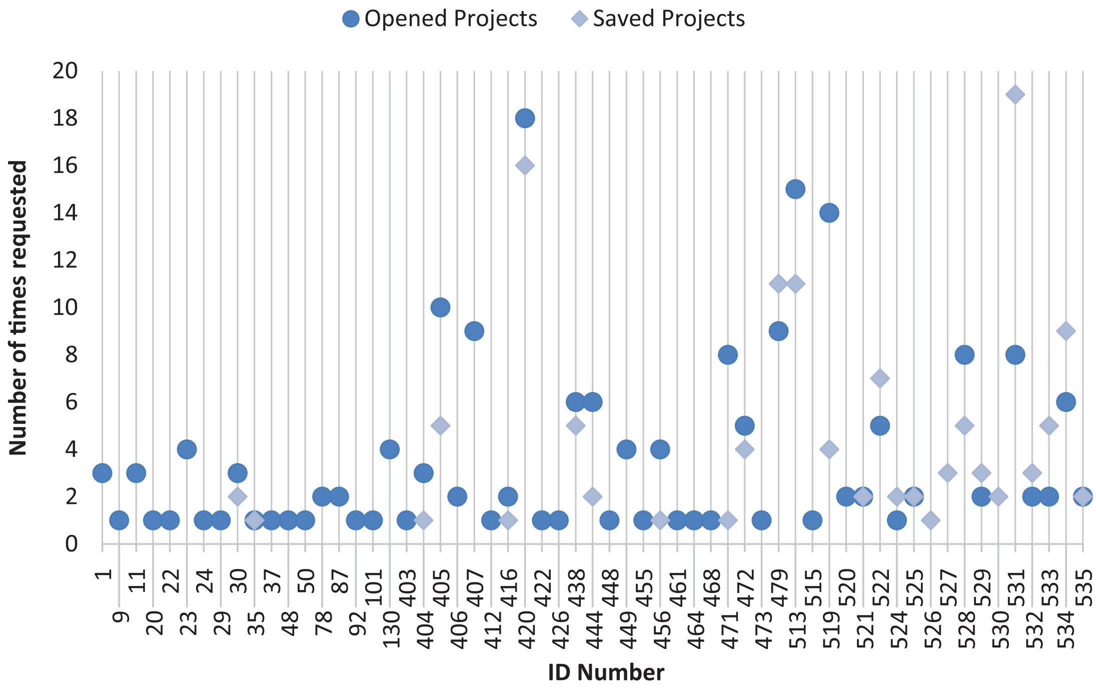



*Figure 83: Plot of the projects opened and the projects saved*

Figure 83 illustrates the number of times different projects were accessed (projects not accessed are not listed). The plot indicates a low usage of most products, in particular those added during the early development phase (1 – 200). The projects accessed the most are typically those which correspond to knowledge capture (saved projects), such as 405, 420, 479 and 513. There are a few exceptions such as 407, utilised in the case study in section 5.6.3 and 471. The suggestion is that majority of projects are scanned and utilised once or twice and not returned to.

The results from the list of events in Table 16 also indicate a strong preference for free text search rather than the filter-based search. An analysis of the search terms shows that a large proportion (80 searches, 37% of searches) are numerical project numbers and actually refer to just 24 unique projects. The designers are often seeking known projects.

An analysis of the different files accessed through the system is shown in Figure 84. Like section 5.3, file types are shown grouped by the Design System tab. The most commonly opened files are clearly solution photographs. This is followed strangely by the design handbook a generic design guidance document currently being produced by the team. It remains in progress which may account for the high access rate. Interestingly, CAD geometry and CAD renders are also frequently utilised, a result supported by findings in section 5.5.3. Surprisingly, videos were not heavily used, but this may be a result of the low number present on the system.

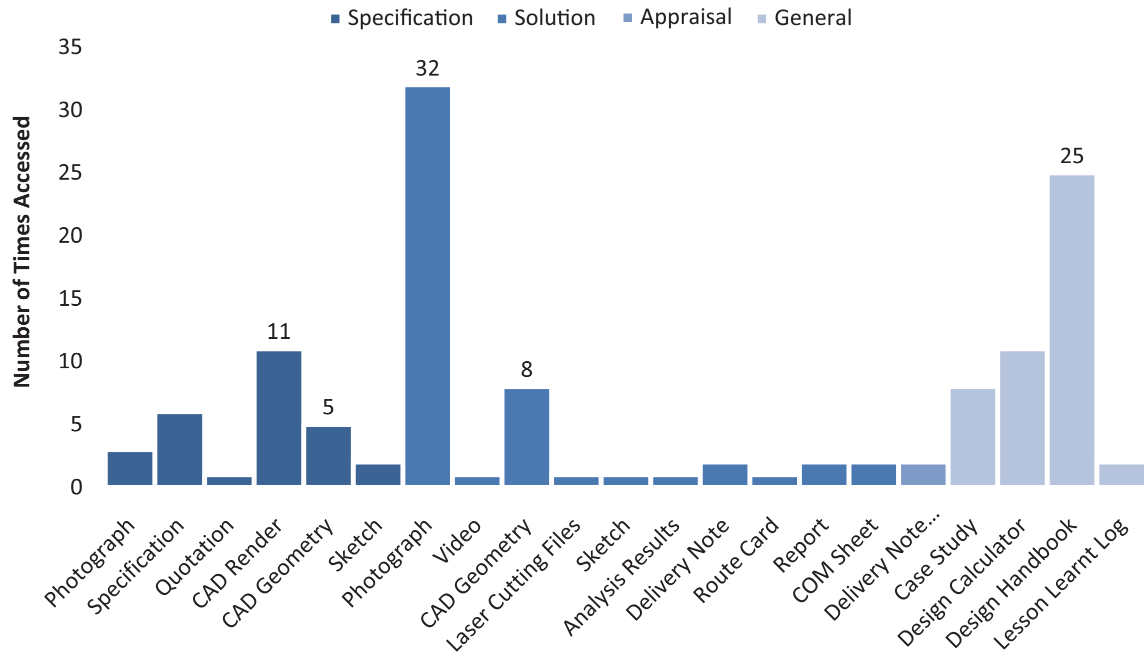



*Figure 84: Plot showing the frequency of access against file types*

The typical time spent reading or accessing the system cannot easily be determined as there is no means for eliciting the start of a new session or the end of an existing one. Plotting the time between the opening of a project and the next as a frequency plot (shown in Figure 85) illustrates, as expected, that most pages are accessed for a few minutes before a new command, either opening a new project, closing the existing one or uploading a file occurs. Yet the plot also indicates that often pages are often left open for up to 15 or 20 minutes and it is not until the time interval reaches 2 hours that occurrence drops off.

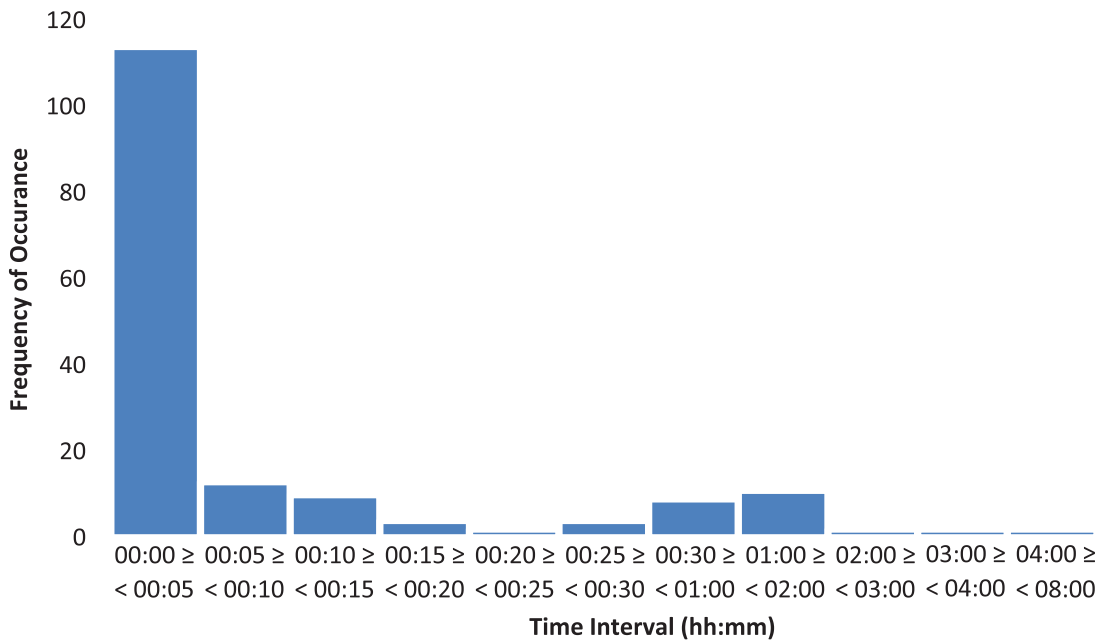



*Figure 85: Frequency plot of the time between the "Open" command and subsequent command*

The events occurring after 30 minutes would be assumed to correspond to new sessions, but this is not always the case. For example, an entry in the log (shown here) shows that a project was opened, left for 30+ minutes and then utilised further.

| | | | |
|---|---|---|---|
| 13/01/2010 | 15:27:37 | OpenProject | ID: 513 Version: 1 |
| 13/01/2010 | 15:59:00 | FileUpload | ID: 513 Type: 262 |

This is likely to be an exception to the rule. If it is assumed that the events beyond 30 minutes in the above plot indicate a new session, the session lengths can be determined by calculating the period between the start of a new session and the end, taken as the last operation before a set period of inactivity. This value was set as 45 minutes. The following frequency plot can therefore be determined:

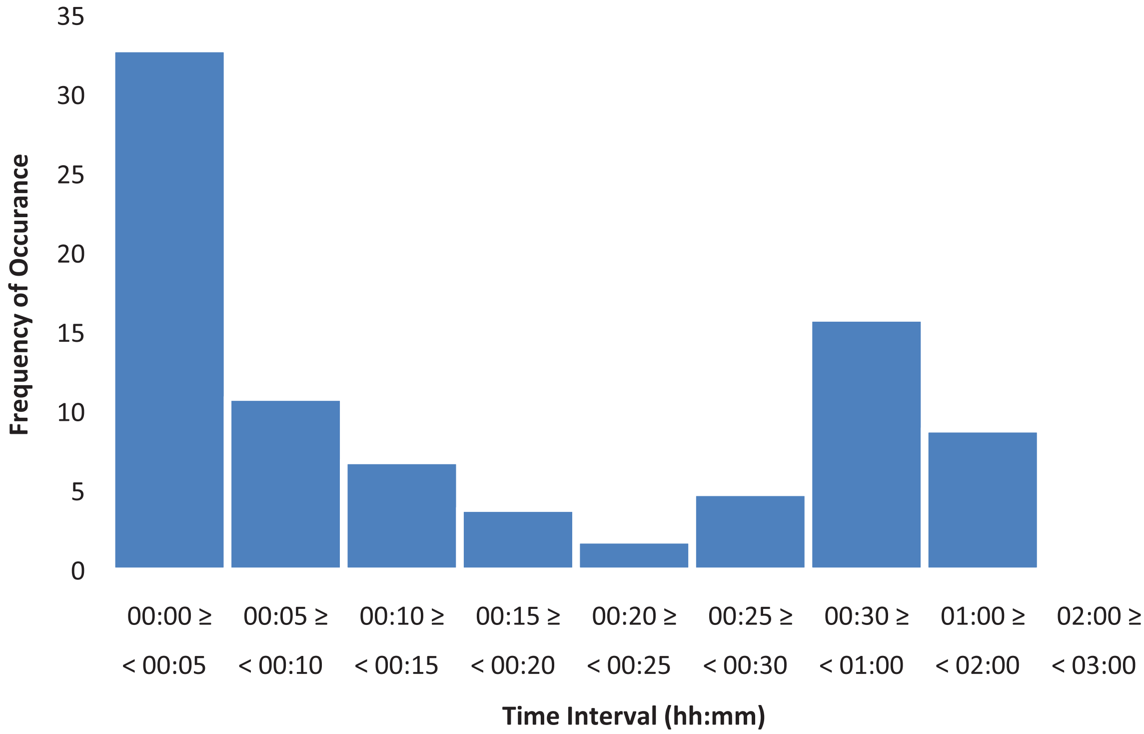



*Figure 86: Frequency plot of the session lengths assuming a maximum down time of 45 min*

The plot again indicates that the majority of sessions were less than 15 minutes, but that a significant number were over 30 minutes long. These may be sessions involving knowledge capture while the shorter sessions correspond to knowledge access. However, without further study this cannot be determined in any greater detail.

### 5.4.6 Knowledge Use during the Design Process

The analysis has so far examined the use of the Design System in isolation from the other design and manufacture activities. This section and the following present two analyses of the system's role as a component of the design process.

It is typically accepted that knowledge is commonly utilised the most during the initial stages of a design (Pahl and Beitz, 1988). Schneiderman (2000) in particular argued that creative work involves a four-phase model – collect (previous works), relate, create and donate. It is understandable why a designer would want to understand either a previous project or to deepen his existing knowledge of the project's domain prior to starting design. Yet designers frequently encounter problems during a design's development, often requiring knowledge-based support to overcome issues.

An analysis of the diaries was conducted on a subset of the diaries (six months), specifically to determine to what extent the designers access knowledge during the design process. Due to the difficulty in obtaining project data, a wider analysis was not possible. Over these six months 33 distinct knowledge interaction days were recorded and these can be seen plotted in Figure 87. To develop this plot, all of the days when knowledge interactions occurred were extracted from the diaries (which may involve multiple interactions), together with the associated job. The start and end dates of the jobs were then used to determine the point (as a percentage of project duration) that each of the interactions occurred. Those projects that are ongoing were plotted using predicted end dates and are coloured red. Clearly these may not be as accurate as the projects already completed.

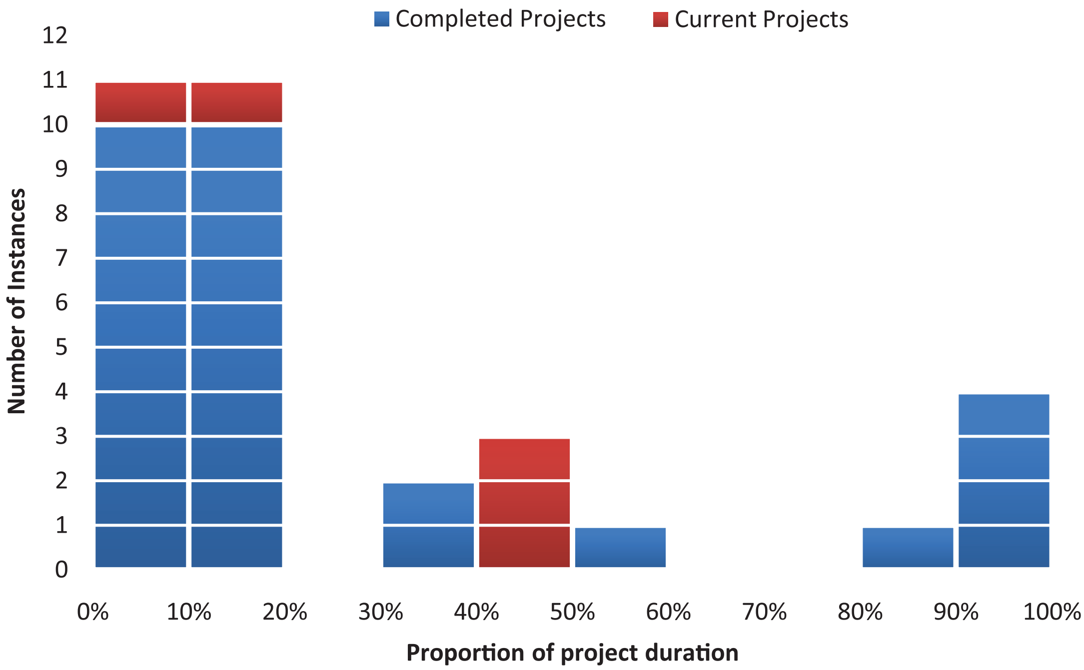



*Figure 87: Plot showing the number of instances of knowledge access as a function of the project duration*

The plot indicates that the majority of interactions occur in the first 20% of a project's development cycle. This confirms the commonly held view that knowledge use primarily occurs during early and conceptual design stages.

Five interactions occurred towards the end of the project's lifetime and correspond to knowledge capture activities. But the plot also indicates several knowledge interactions during the middle of the projects, indicating that some knowledge is sought during the design and development of projects. The roughly 4:1 ratio of initial knowledge interactions and mid-project interactions indicates that in the majority of cases designers either do not need or do not wish for codified knowledge during the design process.

### 5.4.7 Knowledge use across Multiple Design Iterations

Over the course of the study, due to a highly complex set of requirements, one project went through three major design iterations – where a design iteration is defined as the design, manufacture and trial of the product (Ulrich and Eppinger, 1995). A total of over 700 hours was invested in the technical design activities of the project (including knowledge access), the breakdown of which can be seen in Figure 88.

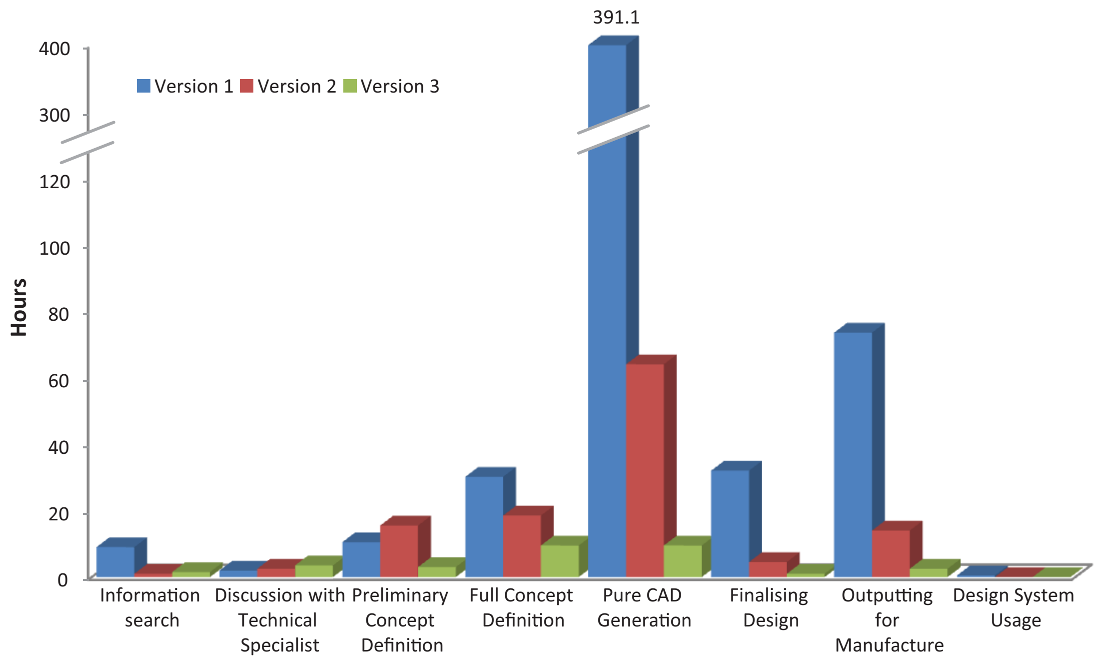



*Figure 88: Comparison of activities over three design iterations*

Several observations can be made from the plot. Clearly the first version required a significantly higher investment of time compared to the other versions, notably for CAD generation. The CAD generation work can be attributed to the high level of upfront CAD detailing work, such as establishing parametric models of the parts to facilitate subsequent modifications. The three other modelling activities – full concept, finalising and outputting all demonstrated decreasing investments of time as the versions evolved. This is to be expected as fewer large scale changes were required and the product became more refined.

From a knowledge utilisation perspective the changes across the three versions are significant. During version 1, a large period of time is invested in accessing prior codified knowledge (approximately 9 hours). During the second and third design iterations this drops considerably. Conversely discussions with the technical specialist were low during the early development work but increase to 4 hours by the third iteration.

Overall, the knowledge utilisation still appears proportionally less than expected as a total of just 12 hours was spent utilising codified knowledge, compared to 90 hours spent in discussions with colleagues and the technical specialist. In comparison, the project consisted of a total hourly investment of 1300 hours. Codified knowledge access therefore accounts for less than 1% of the total time invested.

It would appear that codified knowledge is typically only perceived as useful for providing an initial understanding of the project, reinforcing the findings of the preceding section. Personal knowledge sources such as discussions with colleagues and experts are more sought after during design future iterations(Daft and Lengel, 1984) supporting the findings of Yitzhaki and Hammerslhlag (2004) that verbal knowledge use increases during mid-project knowledge seeking. This is perhaps to be expected, given the need for designers to access more detailed knowledge and the accepted richer provision of knowledge through verbal discussion.

### Summary

This section has utilised a combination of system logging and user diaries to determine the designers' typical behaviour and usage patterns of the Design System. Both methods of knowledge capture yielded a large volume of data, but each had drawbacks. The diaries in particular provided a useful insight into the daily knowledge activities of the engineers, yet were found to underreport interactions with the Design System. The system logs provided a more reliable indication of the system access, yet the length of time spent accessing the system had to be inferred, incurring some degree of error. A number of conclusions can be drawn from the analysis:

- Both system logs and diaries demonstrated regular usage of the system by the engineers, although not all designers report seeking knowledge.
- Discussions with colleagues remain the most common form of knowledge transfer activity, and exceed that of interactions with the expert.
- Interactions with the technical specialist appear to be problem driven and typically include multiple interactions over a short period of time.
- The use of the Design System fulfils a different role to that of the expert. The expert does not just provide upfront knowledge, but provides iteration-based feedback and discussion.
- The system is regularly used for short periods of time, often less than 15 minutes, but is occasionally used for longer sessions lasting up to two hours.
- The system is primarily used during the first 20% of a project's development cycle, but occasionally midway through the cycle as well.
- Designer's activities over three product iterations indicate an increased reliance on the technical specialist and a decrease in the role of codified knowledge over progressive design iterations.

## 5.5 Interface: User Perceptions

As Davenport et al. (1997) argues, a KM system may be deemed successful through increased use. Clearly the propensity of the engineers to use the system is dependent on their perceptions of the system and the ease with which they can use the system.

This section consists of three sections: the first presents an analysis of the user's views of the system using a two stage survey. The second section discusses themes and issues raised through semi-structured interviews with the engineers. The final section presents the engineers' views on different knowledge types, using a knowledge ranking exercise conducted with the engineers.

### 5.5.1 User Perceptions of the System

One of the primary failings of the initial system was its lack of use and adoption by the designers. There are numerous factors that may account for this reticence or inertia against inputting data and also against accessing and using the existing codified knowledge. One factor that may account for this inertia is the designers' perceptions of the system value and the knowledge contained within. The aim here was to quantify this perception of the Design System and to examine how this changes over the eight month study.

Observational and anecdotal evidence suggested that users felt the software and construction of the system was sufficient, but that the system's content was either not relevant or not seen as valuable. A survey was designed therefore to quantify the users' perceptions of these two different facets:

- System design and usability
- System content and its value to designers' work

The survey was consciously designed to be brief and was launched early in the evaluation period as prior to encouraging and supporting the system uptake. This provided an indication of perceptions prior to the system's large scale use. The survey was then repeated at the end of the eight month study.

#### Survey Design

The Likert scale is a psychometric scale developed by psychologist Rensis Likert (Likert, 1932). It is arguably one of the most commonly used methods of measuring attitude and subjective opinions of survey respondents (Cummins and Gullone, 2000).

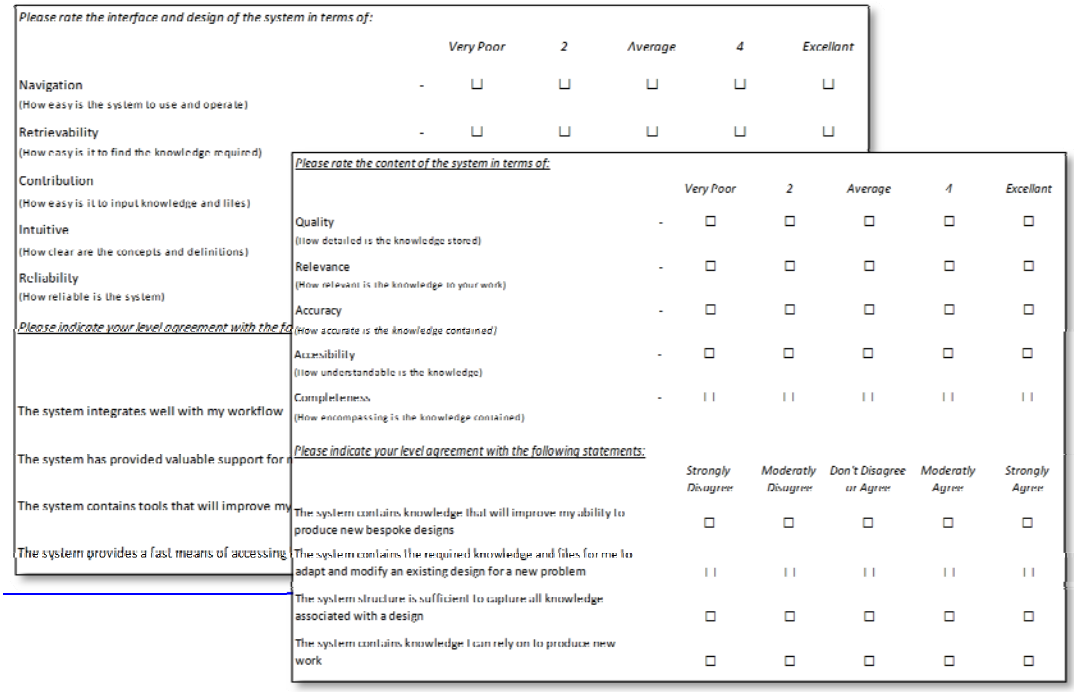
Respondents to a Likert survey are asked to evaluate their level of agreement (or disagreement) with a particular statement, typically a five point bipolar range using labels such as "strongly disagree, disagree, neither agree nor disagree, agree and strongly agree”. There has been much debate on the optimum number of scale points (Matell and Jacoby, 1971). Some argue that four or six point scales are more informative as they remove a middle option, others argue for five or seven (Cummins and Gullone, 2000). Essentially however, the scale simply needs to be sufficiently defined to maximise the spread of response types, thereby maximising the information content of the data.

There are two disadvantages of the Likert scale. Firstly, respondents are often tempted to be biased or try to answer as they think they ought to. This is a consequence of using leading questions (which are clearly required to generate an opinion). However, using basic ratings will still engender some bias as the preferred response is often clear. Second, the Likert scale consists of essentially discrete labels. This is open to some subjective interpretation by the respondent. What constitutes ‘strongly agree’ for example? It also means the scale is non linear (Jamieson, 2004), that is to say the categories cannot be considered equally spaced from each other. This will be addressed by utilising the study by Braunsberger and Gates (2009) to attribute values to the terms and by using a pure rating system in the questionnaire.

As described, the survey here was split into two sections, one addressing the system functionality, the second addressing the system content, with each section further split into two parts. The first part assessed against single quantities, such as accuracy, quality and content using a purely linear scale (1 to 5). The second used a Likert scale to assess the designers’ feelings towards the system’s integration with their work and the relevance and quality of the knowledge captured.

### Survey Questions

The survey questions were set out as follows:


Please rate the interface and design of the system in terms of:

| | Very Poor | 2 | Average | 4 | Excellent |
|---|---|---|---|---|---|
| Navigation (How easy is the system to use and operate) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Retrievability (How easy is it to find the knowledge required) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Contribution (How easy is it to input knowledge and files) | | | | | |
| Intuitive (How clear are the concepts and definitions) | | | | | |
| Reliability (How reliable is the system) | | | | | |

Please indicate your level agreement with the fo

The system integrates well with my workflow

The system has provided valuable support for

The system contains tools that will improve my

The system provides a fast means of accessing

Please rate the content of the system in terms of:

| | Very Poor | 2 | Average | 4 | Excellent |
|---|---|---|---|---|---|
| Quality (How detailed is the knowledge stored) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Relevance (How relevant is the knowledge to your work) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Accuracy (How accurate is the knowledge contained) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Accesibility (How understandable is the knowledge) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Completeness (How encompassing is the knowledge contained) | ☐ | ☐ | ☐ | ☐ | ☐ |

Please indicate your level agreement with the following statements:

| | Strongly Disagree | Moderatly Disagree | Don't Disagree or Agree | Moderatly Agree | Strongly Agree |
|---|---|---|---|---|---|
| The system contains knowledge that will improve my ability to produce new bespoke designs | ☐ | ☐ | ☐ | ☐ | ☐ |
| The system contains the required knowledge and files for me to adapt and modify an existing design for a new problem | ☐ | ☐ | ☐ | ☐ | ☐ |
| The system structure is sufficient to capture all knowledge associated with a design | ☐ | ☐ | ☐ | ☐ | ☐ |
| The system contains knowledge I can rely on to produce new work | ☐ | ☐ | ☐ | ☐ | ☐ |

Participants were requested to simply tick which ever they felt appropriate. They were informed that one section was on content and one section on the system usability. The Likert responses were then weighted according to results published in the study by Braunsberger and Gates (2009) and translated to a 5 point scale. Braunsberger and Gates  assessed descriptors on a 9 point scale, (-4 to +4) corresponding to greatest dislike through to greatest like. Their weightings are shown in Table 17 together with the translation to a positive 5 point scale (+1 to +5), which, in the author's opinion is conceptually a much easier scale with which to present results.

| | *Strongly disagree* | *Moderately disagree* | *Don't disagree or agree* | *Moderately agree* | *Strongly agree* |
|---|---|---|---|---|---|
| **9 point bipolar surveyed weighting** | -3.21 | -1.65 | 0.00 | 1.62 | 3.05 |
| **5 point positive translation** | 1.40 | 2.18 | 3.00 | 3.81 | 4.53 |

*Table 17: Weights of terms from Braunsberger and Gates (2009) and the corresponding translation to the five point scale used here.*

### Results – Round 1

The first round of surveys was completed by the manager and four designers. The technical specialist and manufacturing engineer declined to respond having too little experience with the system. The full results are presented, together with the mean and standard deviation in Table 18.

| | M | D.a | D.b | D.c | D.d | Mean | StDev |
|---|---|---|---|---|---|---|---|
| Navigation | 4 | 3 | 4 | 4 | 4 | 3.8 | 0.45 |
| Retrievability | 4 | 3 | 4 | 3 | 3 | 3.4 | 0.55 |
| Contribution | 3 | 3 | 3 | 3 | 4 | 3.2 | 0.45 |
| Intuitive | 3 | 3 | 3 | 2 | 3 | 2.8 | 0.45 |
| Reliability | 4 | 4 | 5 | 3 | 3 | 3.8 | 0.84 |
| The system integrates well with my workflow | 3.8 | 3 | 3 | 3.8 | 3.8 | 3.5 | 0.44 |
| The system has provided valuable support for my work | 3.8 | 3.8 | 2.1 | 3.8 | 3 | 3.3 | 0.73 |
| The system contains tools that will improve my ability to work | 3.8 | 3.8 | 3 | 3.8 | 3.8 | 3.6 | 0.36 |
| The system provides a fast means of accessing knowledge | 3.8 | 4.5 | 3.8 | 3 | 3.8 | 3.8 | 0.54 |
| Quality | 2 | 2 | 4 | 5 | 4 | 3.4 | 1.34 |
| Relevance | 4 | 3 | 4 | 3 | 4 | 3.6 | 0.55 |
| Accuracy | 3 | 4 | 4 | 3 | 3 | 3.4 | 0.55 |
| Accessibility | 3 | 4 | 4 | 3 | 2 | 3.2 | 0.84 |
| Completeness | 1 | 3 | 3 | 3 | 3 | 2.6 | 0.89 |
| The system contains knowledge that will improve my ability to produce new bespoke designs | 3 | 3.8 | 3.8 | 3.8 | 3 | 3.5 | 0.44 |
| The system contains the required knowledge and files for me to adapt and modify an existing design for a new problem | 3.8 | 2.1 | 3.8 | 3.8 | 3.8 | 3.5 | 0.73 |
| The system structure is sufficient to capture all knowledge associated with a design | 3.8 | 3.8 | 3.8 | 2.1 | 3.8 | 3.5 | 0.73 |
| The system contains knowledge I can rely on to produce new work | 3 | 3.8 | 3.8 | 3.8 | 3.8 | 3.6 | 0.36 |

*Table 18: Results from the first round survey of the Manager (M) and four designers (D.a-d), showing the mean and standard deviation.*

With such a small population of responses, it is important not to place too much emphasis on precise numbers. However themes can be drawn from the results.

A comparison of the four different section means indicates a higher rating between sections 1 and 3, and between 2 and 4. This suggests respondents rate the system higher than its content.

| | Mean | StDev |
|---|---|---|
| **Section 1** | 3.4 | 0.6 |
| **Section 2** | 3.6 | 0.5 |
| **Section 3** | 3.2 | 0.9 |
| **Section 4** | 3.5 | 0.5 |

Section 3 has a significantly higher standard deviation. This indicates differing views on the system's content. For example, designer C rates the quality of content as a 5, while the manager and designer A rate it at just 2. This may be explained by examining the individual question. The lowest mean is calculated by the 'system completeness'. It is therefore hypothesised that those who found required knowledge rated the system highly, while those who did not ranked the content poorly.

The highest question mean is given by system reliability and navigation. This encouragingly demonstrates positive feeling towards the systems interface and constructions. Importantly it highlights the success of the new system interface and operation developed in response to the initial trials.

### Results – Round 2

The survey was repeated at the end of the eight month evaluation period. This time it was completed by the manager, five designers and the manufacturing engineer. The questions were kept constant to allow comparison. Table 19 lists the difference between responses.

| | M | D.a | D.b | D.c | D.d | Sum |
|---|---|---|---|---|---|---|
| Navigation | | | | -1 | -1 | -2 |
| Retrievability | -1 | | | | | -1 |
| Contribution | | 1 | | | | 1 |
| Intuitive | | -1 | 1 | 1 | | 1 |
| Reliability | | -1 | -1 | 2 | 1 | 1 |
| The system integrates well with my workflow | | 1 | | -2 | | -1 |
| The system has provided valuable support for my work | 1 | | 2 | 1 | 1 | 5 |
| The system contains tools that will improve my ability to work | 1 | | 1 | 1 | | 3 |
| The system provides a fast means of accessing knowledge | | -2 | | 1 | -1 | -2 |
| Quality | | 2 | | -3 | | -1 |
| Relevance | | 1 | | | -1 | |
| Accuracy | 1 | | | 2 | | 3 |
| Accessibility | | 1 | -1 | 2 | 1 | 3 |
| Completeness | 1 | -1 | | -1 | | -1 |
| The system contains knowledge that will improve my ability to produce new bespoke designs | | | | | -1 | -1 |
| The system contains the required knowledge and files for me to adapt and modify an existing design for a new problem | | 2 | -1 | | | 1 |
| The system structure is sufficient to capture all knowledge associated with a design | -2 | -1 | -1 | -1 | -1 | -6 |
| The system contains knowledge I can rely on to produce new work | 1 | | | 1 | | 2 |

*Table 19: Table showing the difference in individuals' responses between the two surveys*

Two results are noticeable from Table 19 – the two large movers. The greatest increase was in response to question 7, 'has the system provided valuable support?' Four of the five respondents improved their response to this question and the average moved from 3.3 to 3.8. This result should not be underestimated. After eight months of support, 6 of the 7 respondents agreed that the system had provided them with valuable support (either moderately or strongly).

The greatest decrease was in question 17, 'the system is sufficient to capture all knowledge associated with a design'. All respondents felt that additional means was required to capture sufficiently all the knowledge and this is further supported during the interviews in section 5.5. What is important for future system development is that this result has changed significantly over the study, the mean dropping from a positive 3.5 down to 2.9. This demonstrates the importance of system use to support development. Not all use cases can be predicted in advance.

Results from section 3 are mixed, indicating a continuing disparity of opinions on the system's content.

| | Round 1 | | Round 2 | |
|---|---|---|---|---|
| | Mean | StDev | Mean | StDev |
| Section 1 | 3.4 | 0.6 | 3.5 | 0.6 |
| Section 2 | 3.6 | 0.5 | 3.6 | 0.7 |
| Section 3 | 3.2 | 0.9 | 3.3 | 0.9 |
| Section 4 | 3.5 | 0.5 | 3.4 | 0.7 |

Comparing the overall mean between the two different rounds, there appears to be subtle improvement in the respondents' views, yet also increased variation. A comparison of these values from round 1 and round 2 using the t square test, gives a result of 75%, suggesting that no significant change in perception occurred.

Overall, respondents rate both the system and its content positively. There does remain a difference in perception of the system's content and usability. The quality and content (particular the completeness) of the system needs to be addressed rather than modifications to the software system. Some modifications are required to the system, however, notably to increase its capacity to capture knowledge.

### 5.5.2 Semi-Structured Interviews

This section presents an analysis of a series of semi-structured interviews with the Design System users. The intention was to gain a deeper understanding of the interactions of the users with the Design System, specifically how and why the designers interact (or don't) with the system, what they feel the effects and benefits of the system have been and how it could be improved.

The interviews were conducted with six engineers and the manager, six months into the evaluation period. The exception was designer E who, having only recently joined the business, was interviewed the following month.

A semi-structured interview approach (as defined by Robson (2002)) was used. Questions were predefined and structured enabling comparative analysis between interviewees, but the interviewer (the author) modified or adapted questions during the interview to enhance understanding.

The interviews typically took around 25 minutes, and consisted of 17 separate questions with an additional ten follow-up questions, depending on the initial responses. Questions were separated into four sections, corresponding to:

- Accessibility and understanding
- Workflow and knowledge use
- Perceived benefits
- Usage and management

Interviews were conducted one-to-one and the interviews recorded using a dictaphone and written up in full. The transcripts of the interviews can be seen in Appendix A. The questions were developed in order to meet the objectives above. A combination of closed and open questions were used. In the final section the questions were consciously worded to be provocative in order to encourage the interviewees to provide more detail in their responses. The interview questions are listed in Table 20.

| Accessibility and Understanding |
|---|
| 1) What do you feel are the main aims and objectives of capturing and storing knowledge? |
| 2) Do you feel that the Design System supports these aims and objectives? |
| a) If yes, how? |
| b) If no, why not? |
| 3) Do you feel you have been given enough guidance on how to use the system? |
| 4) How would you improve this? |
| 5) How often do you access the system, and how long do you typically spend using the system? What was the knowledge you sought? |
| **Workflow and Knowledge Use** |
| 1) What information and knowledge do you need the most when working and working on a project? |
| a) Do you feel the Design System captures this knowledge? |
| 2) Where do you believe the major bottlenecks occur during the design and manufacturing process? |
| 3) How well you feel the Design System integrates with your existing workflow? |
| **Benefits** |
| 1) Has the system provided tangible benefits to your design and manufacturing activities? |
| a) If yes, how has the system provided these benefits? |
| b) What effect did the knowledge have? |
| c) If no, why do you think this is? |
| 2) What effect has the use of the system had on your workflow? |
| 3) When during the design process do you find you use the Design System the most? |
| 4) Has the system been able to save you time, for example suggesting ideas or helping to avoid mistakes? |
| 5) Do you feel the benefits of the system are worth the effort of documenting your work? |
| **6)** What has been the most valuable function or aspect of the Design System and why? |
| **Enquiring Questions** |
| 1) The system wasn't used much prior to this summer, why do you think that is? |
| a) If you were managing the use of the system |
| b) How would you improve it? |
| c) How would you encourage its use? |
| 2) How else would you ensure knowledge is stored and utilised? |
| 3) Would you recommend a new Chief Executive to continue using the system and why? |
| 4) The system is still not utilised very much, why do you think this is? |

*Table 20: List of predefined questions for the semi-structured interviews*

## Results

The interviews were analysed using a grounded theory approach (Glaser and Strauss, 1967). An open coding system was used to extract the key points and themes from each of the questions, which is the method advocated by Glaser rather than the micro-analysis, word-by-word approach recommended by Strauss and Corbin (Allan, 2003). Answers to each question were reviewed and keyword codes determined that summarised the feelings, problems or benefits raised. Results were then reviewed again and keywords integrated. An example of a coded answer is show here:

> *What do you feel are the main aims and objectives of capturing and storing knowledge?*
>
> So that we have a centre point from which other people can obtain that knowledge without having to go to one particular specialist to get that knowledge. In terms of the joint venture and the future of Pro-laser the idea is that it should help with up-scaling the business.
>
> *[+Business growth, Minimise expert reliance, +Central store of information]*

Where comments or themes could be interpreted as positive or negative, keywords were prefixed with either a + or - for example here the idea of a 'central store of information' was seen as a positive. A basic frequency analysis was performed on keywords. The results can be seen in Table 21. The incident count lists the number of times the key word or theme was mentioned. The second column lists the number of different interviewees who raised the theme.

| Key Word | Incident Count | Distinct Respondents |
|---|---|---|
| Poorly populated | 7 | 4 |
| Avoid mistakes | 6 | 4 |
| Lacking detail | 6 | 4 |
| Poor usage | 6 | 3 |
| Reap and sow | 6 | 5 |
| Self benefit | 5 | 3 |
| Archive | 4 | 2 |
| Beginning | 4 | 3 |
| Initial understanding | 4 | 3 |
| Resentment of current practice | 4 | 2 |
| Business image | 3 | 1 |
| Lacking knowledge | 3 | 2 |
| Lessons learnt | 3 | 2 |
| Poor search function | 3 | 1 |

*Table 21: Table showing the most frequently cited (>3) key words*

Several themes are immediately apparent. Most noticeable is the number of times concerns were raised about the lack of knowledge content (poorly populated) and the system's lack of use. Yet the interviewees themselves are those responsible for using the system and populating it sufficiently. Associated with this is the theme termed 'reap and sow'. This code was used to describe the argument given by many of the interviewees that if the system was used more or had provided more benefit, they would have been more willing to spend time populating the system. If they could see the benefit being reaped, they would sow more knowledge. But a large body of knowledge had been created and had provided value. It therefore becomes a cyclic argument, that to gain more value they must sow in order to reap.

Despite this, the positive benefits perceived by the designers are also discernible, notably the avoidance of mistakes (the most commonly cited benefit of the system), support for initially understanding a new problem and the role of the system as a design archive.

The 'distinct respondents' column listed in Table 21 also provides some additional insights and highlights the occasional issue put forward strongly by a single interviewee. For example, 'business image' was mentioned three times by just one interviewee – the manager. This represents a key role of the system, but is not shared by the other engineers. Conversely, it illustrates the permutation across almost all interviewees of the 'reap and sow' issue.

Specific themes and details were also extracted from the interviews. Table 22 illustrates the answers given in response to the question about how often the participant used the system. Participants' responses were given estimates of depth and frequency, based on the relative times and descriptions given.

| Frequency | Depth | | |
|---|---|---|---|
| | *Low* | *Average* | *High* |
| *Low* | 1 | 1 | 3 |
| *High* | 3 | - | - |

*Table 22: A matrix illustrating the different usage patterns by users, here depth refers to the level of detail sought, while frequency is how often the users access the system.*

One unintended response to this question was the different interpretation of the question. Some interviewees automatically assumed the question was referring to inputting knowledge, while others assumed it referred to knowledge seeking. Only designer C gave a balanced answer, while the manager gave no preference. The responses are summarised in Table 23. The unexpected result is that there is no correlation between the designers' experience or capability and their perception of the system as a knowledge receptacle or knowledge provider. For example designer A, the most experienced of the team, perceived the system as a provider. Designer E, the least experienced, perceived the system as a receptacle.

| | Knowledge In | Knowledge Out |
|---|---|---|
| Designer A | | × |
| Designer B | × | |
| Designer C | × | × |
| Designer D | | × |
| Designer E | × | |
| Manufacturing Engineer | | × |

*Table 23: Matrix illustrating the differing interpretations to questions on system access*

Detailed examination of the interview scripts demonstrated how different designers perceived and used the system differently. Some designers such as designer A focused on project specific knowledge and used the system to supplement and improve their existing knowledge of one product and its application. Conversely designers C and D sought cross product lessons and advice for solving problems encountered on unrelated projects.

When asked what the system was for and how they utilised it, many different themes were suggested. These are shown grouped into rough themes in Figure 89. The diagram illustrates the varied role the users feel the Design System should play. This ranges from a 'dumb' archive and information repository to a system aimed at supporting the learning and development of engineers. What becomes apparent through these interviews, therefore, is just how wide the scope and user patterns the system must address.

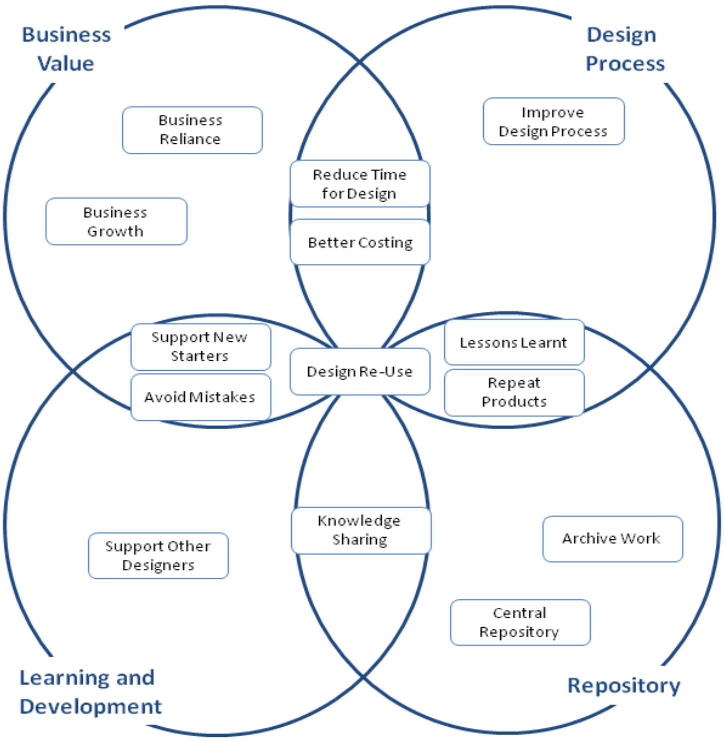



*Figure 89: diagram showing the key themes cited when discussing the system's aims and objectives*

To elicit further themes, the binary questions were analysed and codified using a five scale category system: positive ●, negative ●, positive with caveat ●, negative with caveat ●, and neutral ●, where those with caveats imply positive or negative responses but with qualifiers. This is summarised in Table 24.

| | Manager M | Designer A | Designer B | Designer C | Designer D | Designer E | Manufacturing Eng. |
|---|---|---|---|---|---|---|---|
| Do you feel that the Design System supports these aims and objectives? | positive | positive | positive | positive with caveat | positive with caveat | positive with caveat | positive with caveat |
| Do you feel you have been given enough guidance on how to use the system? | positive | positive | positive | positive | positive | positive | negative |
| Do you feel the Design System Captures this knowledge? | negative | positive | positive with caveat | negative | positive with caveat | positive with caveat | positive with caveat |
| How well you feel the Design System integrates with your existing workflow? | negative with caveat | negative | positive | positive with caveat | negative | positive | negative |
| Has the system provided tangible benefits to your design and manufacturing activities? | positive | neutral | positive | positive | positive | positive | negative with caveat |
| Has the system been able to save you time, for example suggesting ideas or helping to avoid mistakes? | negative | positive with caveat | positive | neutral | positive | negative | negative with caveat |
| Do you feel the benefits of the system are worth the effort of documenting your work? | positive | positive | positive | positive | neutral | positive | positive |
| Would you recommend a new Chief Executive to continue using the system and why? | positive | positive | positive | positive with caveat | positive | positive | positive |

*Table 24: illustrated summary showing the results of binary questions.*

The result to identify from this table is the generally positive feelings towards the system. In particular:

- The system is believed to support the aims and objectives (as perceived by the designers)

- It is seen as providing tangible benefits
- There is an almost universal agreement that the system is worth the effort of investment and should be continued
- The system remains poorly integrated into the designers' workflow
- Few of the designers perceive it to have saved them time, the ultimate goal.

Overall the interviewees responded enthusiastically when discussing the system and its role in their work. It is apparent, however, that despite the effort made to create an interactive and accessible interface, the system is still distinct to the workflow. Most designers only access it at the start and end of a project and it is not viewed as a concurrent tool. Designer A for example describes it as "more of a repository to put everything in at the end".

While knowledge capture is a primary aim of the system, its subsequent reuse is crucial to actually gaining benefit from the system. Thus the perception of the system as an 'archive' or inert repository represents a concern and may result in lower re-use than intended.

### 5.5.3 Knowledge Ranking Exercise

As an additional closing exercise to the structured interviews a 'card sort' was completed by the interviewees. The aim was to compare and rank the knowledge the designers find most valuable to the knowledge captured and provided by the Design System. This provided an indication of the degree to which the system addresses and captures the knowledge required.

A set of 17 cards were created, each with a different type or category of knowledge printed on and based around the knowledge types relevant to the designers' workflow and Design System. Additional blank cards were also made to allow participants to add their own. A two stage approach was taken, and participants were not told why they were completing the exercise. Their first instruction was:

> *"Please can you rank the various categories of knowledge and information in the order of how valuable the*

> *information is? Any other types you feel have not been included can be added."*

The result was then photographed and the following instruction given:

> *"Please can you now rank the various categories of knowledge and information in the order of how well they are captured and stored by the Design System? Any other types you feel have not been included can be added."*

An example of the sorted cards is shown in Figure 90.


*Figure 90: Photograph of the sorted knowledge types during the 'card sort' exercise*

**Results**

All of the interviewees completed the task. There was some feeling that some types of knowledge were of equivalent value and some suggested that it depended on the context. However when pressed and encouraged, nearly all admitted that, given a choice, there would be a preference.

Only one additional knowledge type was added, this referred to the knowledge associated with the manufacturing process fixtures were designed for e.g. five-axis laser cutting or welding. According to designer C, this can influences design decisions, such as material choice, far more than the actual part does. This knowledge type was then used in subsequent interviews.

The participants' lists were entered into two matrices, using an ascending value for each knowledge type, shown in Table 25. Here the top and bottom 10% of values are highlighted in green and red respectively.

| How Well is the Knowledge Captured | Manager M | Designer A | Designer B | Designer C | Designer D | Designer E | Manf. Eng | Normalised |
|---|---|---|---|---|---|---|---|---|
| Previous Design Requirements | 10 | 4 | 5 | 5 | 1 | 4 | 5 | 1.0 |
| Photos | 2 | 1 | 1 | 10 | 4 | 2 | 17 | 1.0 |
| Cad Renders | 3 | 2 | 2 | 11 | 2 | 3 | 15 | 0.9 |
| Previous Design Rationale | 7 | 7 | 12 | 1 | 10 | 16 | 2 | 0.7 |
| Previous Design Materials Used | 12 | 12 | 6 | 8 | 7 | 8 | 3 | 0.6 |
| Video | 4 | 14 | 3 | 12 | 3 | 7 | 16 | 0.6 |
| Previous Design Costing and Lead Times | 9 | 13 | 8 | 6 | 9 | 13 | 4 | 0.5 |
| Previous Design Ideas | 11 | 5 | 13 | 7 | 15 | 5 | 7 | 0.5 |
| Previous Design Benefits | 8 | 10 | 14 | 2 | 11 | 14 | 6 | 0.5 |
| Cad Geometry | 1 | 15 | 4 | 13 | 18 | 1 | 14 | 0.5 |
| Lessons Learnt Design | 14 | 8 | 11 | 3 | 12 | 9 | 9 | 0.5 |
| Lessons Learnt - Manufacture | 15 | 6 | 15 | 4 | 13 | 10 | 10 | 0.4 |
| Numerical Tools (i.e. Spring designer) | 17 | 3 | 10 | 15 | 5 | 15 | 12 | 0.3 |
| Case Studies | 13 | 11 | 7 | 17 | 6 | 17 | 8 | 0.3 |
| Common Features | 6 | 16 | 9 | 14 | 17 | 6 | 13 | 0.2 |
| Lessons Learnt - Other | 16 | 9 | 17 | 9 | 14 | 11 | 11 | 0.1 |
| Manufacturing Processes | 5 | 17 | 18 | 18 | 16 | 12 | 9 | 0.0 |
| Methodology Tutorials | 18 | 18 | 16 | 16 | 8 | 18 | 1 | 0.0 |

| How Valuable is the Knowledge? | Manager M | Designer A | Designer B | Designer C | Designer D | Designer E | Manf. Eng | Normalised |
|---|---|---|---|---|---|---|---|---|
| Previous Design Requirements | 3 | 6 | 1 | 4 | 6 | 5 | 7 | 1.0 |
| Previous Design Rationale | 5 | 2 | 2 | 7 | 5 | 6 | 11 | 0.9 |
| Previous Design Ideas | 4 | 7 | 3 | 8 | 4 | 4 | 10 | 0.9 |
| Previous Design Benefits | 1 | 8 | 4 | 6 | 8 | 7 | 8 | 0.9 |
| Lessons Learnt Design | 8 | 3 | 6 | 5 | 9 | 9 | 9 | 0.8 |
| Manufacturing Processes | 7 | 9 | 11 | 1 | 3 | 12 | 9 | 0.7 |
| Cad Geometry | 11 | 13 | 9 | 2 | 18 | 1 | 6 | 0.6 |
| Lessons Learnt - Manufacture | 14 | 5 | 14 | 3 | 11 | 10 | 4 | 0.6 |
| Photos | 17 | 11 | 5 | 12 | 12 | 2 | 2 | 0.6 |
| Common Features | 13 | 14 | 10 | 9 | 1 | 13 | 3 | 0.6 |
| Numerical Tools (i.e. Spring designer) | 12 | 1 | 17 | 16 | 2 | 11 | 16 | 0.4 |
| Lessons Learnt - Other | 9 | 4 | 15 | 15 | 10 | 18 | 5 | 0.4 |
| Cad Renders | 16 | 18 | 7 | 10 | 17 | 3 | 6 | 0.4 |
| Previous Design Materials Used | 15 | 10 | 13 | 14 | 7 | 8 | 13 | 0.3 |
| Video | 18 | 12 | 12 | 11 | 13 | 17 | 1 | 0.3 |
| Previous Design Costing and Lead Times | 2 | 17 | 8 | 13 | 15 | 16 | 15 | 0.2 |
| Case Studies | 6 | 15 | 18 | 17 | 14 | 14 | 14 | 0.1 |
| Methodology Tutorials | 10 | 16 | 16 | 18 | 16 | 15 | 12 | 0.0 |

*Table 25: Two matrices showing the interviewees' ranking of knowledge value (a) and the extent to which knowledge types are captured (b). High values indicate low ranking.*

The first matrix indicates a degree of agreement between interviewees in terms of knowledge that is not valuable, but shows a wide response to what knowledge different engineers consider most valuable.  This is perhaps to be expected.

Some concern should be raised over the lower ranking knowledge types. In particular, neither the 'case studies' nor 'methodology tutorials' are believed to have been used to much extent by the designers. Their low ranking is perhaps a reflection of a lack of understanding rather than of lack of actual value.

Reassuringly, the most valuable knowledge types are those associated with previous design rationale and requirements, which the Design System was created to capture.

One interesting observation is that several of the designers listed CAD geometry as highly valuable, (1, 2, and 6th). Yet few of the engineers have uploaded CAD geometry and often omit it even after completing the majority of other entries and uploads – usually preferring to maintain the files on the working drive with its own structure. This again highlights a gap between what the users need and what they actually share.

The second matrix indicates some level of agreement between engineers for both the knowledge types that are captured well and those that are not. The exception to this is the manufacturing engineer, who lists the photos as poorly captured, whilst other engineers list these as the most successfully captured. This difference can probably be attributed to his requirements from the system, described in the interview, in which he argues that he wants to use it to support manufacturing, but cannot as it's not updated until after the project has been completed, stating:

> *"The Design System is one of the last things to be updated, with regard to the project, and it's like the horse has already bolted. Its then the lessons learnt from that - I can't learn anything from the system."*

In his view and the authors, photos should be uploaded from the previous solution or of the component to be manufactured during the start of the project. This was one intended role of the 'specification' tab.

By combing the results of the two matrices above, an indication can be sought of the most important types of knowledge not currently being successfully captured. To calculate this, the sum of each knowledge type was taken from the two matrices and normalised, giving an index from 0 to 1 for each knowledge type. Taking the value index of $\mu_n$ and the capture success of $c_n$, for each knowledge type $n$, a metric $v$ was constructed using the following equation:

$$v = \mu_n(1 - c_n)$$

Therefore a high value of $v$ indicates an important, but poorly captured knowledge type. The normalised results can be seen plotted in Figure 91.

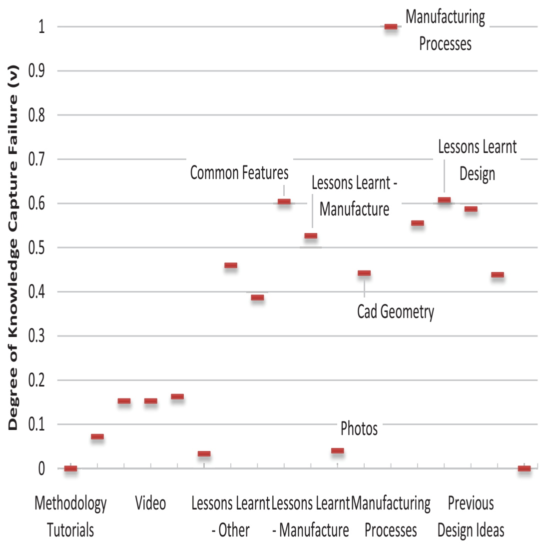



*Figure 91: Plot of an abstract metric highlighting the types of knowledge that need to be better captured.*

The plot highlights a clear deficiency in failing to adequately capture knowledge associated with manufacturing processes, suggesting the system should contain not only a database of solutions, but also a database of manufacturing processes to provide context.

The high positions of lessons learnt and CAD geometry are also a concern. Here, however, there is provision to capture this knowledge, yet they are perceived as both valuable but not fully captured. Again this suggests a gap between what the engineers want and what they actually input into the system. Designer D discusses this and suggests that there is a need better to close the iterative loop between benefit gained and effort invested, stating:

> *"If people are using it more often and getting great benefits from it then other people can see the worth. I suppose it's only as useful as the information that's put in, but if you find it difficult to access that information after it's in there, I suppose you might resent putting it in."*

Thus, the question of how to encourage continued input and knowledge reuse remains. When asked in the interviews, a variety of responses were given. The primary themes apparent were; 'discipline', 'routine' and to a lesser extent 'benefits'.

Discipline was by far the most cited theme. Five interviewees described a need for greater management and authority over its use. In particular, Designer B argued it needed a group leader to operate reviews and ensure it was correctly populated. This is further supported by the manager, who agreed that the existing passive approach to encouragement had not been successful.

Three of the respondents argued that it ought to be routine, that it should simply become 'part of the job'. Finally, two designers argued that better demonstration of the benefits would encourage the system's use.

### Summary

This section addressed and assessed the users' perception of the system, critically to understand how they have used the system, if they believe it has provided benefits and if it correctly meets the Design System aims and objectives.

A variety of qualitative and analytical methods were used to elicit as many opinions and perceptions of the system and its usage as possible. These were largely successful and a number of conclusions can be drawn. These are:

- Both the survey data and interviews show that the system is viewed positively by all the users.
- There was no significant change in user perceptions over the evaluation period.
- The system adequately captures the knowledge most valuable to designers, but additional knowledge capture is required
- All users view the system as valuable and worthy of investment
- There exists a wide and varying perception of the system's role
- The system is only partially integrated with designers' activities
- A strategic gap exists between knowledge input by designers and the knowledge they seek
- The system's value is agreed by all users, yet is primarily criticised for its lack of content

- Proactive management methods are seen as necessary to encourage its use and population

## 5.6 Products: Analysis of the Completed Products

The primary outputs from the design and manufacturing process are of course, products. Regardless of the presence of the Design System, they are the value-generating artefacts.

This section examines some products as case studies to complement the business wide view of the balanced scorecard examined in the following section. Three case studies will be examined, loosely adopting the Brinkerhoff success case method discussed in section 3.7.6. Here, an example will be given of successful knowledge utilisation, and an example given of a failed use of knowledge. Both studies in fact refer to the same product, highlighting the disparity that can exist. Finally a third proactive comparative study was conducted comparing two designers' solution to a problem, the first without the Design System, the second with.

### *5.6.1 Failure Case Example*

Designer A was asked to produce a series of 24 devices to support the welding of blades. A similar device had previously been produced some time before by the technical specialist.

Designer A was made aware of the previous design and consulted the technical specialist, requesting previous geometry files and discussing the project with him. An initial total of three hours was spent by designer A in the company of the specialist. When interviewed, designer A indicated that he did not look at the Design System, on the grounds that information provided by word of mouth from the expert would surpass anything recorded.

When it was suggested that there was a record, the designer actively searched for the product, with the first search returning one result - the correct record. Relevant media consisted of:

- Video - One hour interview with the expert detailing the previous design
- Case study – 11 page report detailing previous design
- Gem of wisdom – detailing concerns when interfacing against a complex surface, specifically written to aid development of blade interfaces

This illustrates the benefits the system could provide; it is possible that most if not all of the time spent with the expert could have been avoided. In particular the basic search and transfer of files should not be the occupation of the lead technical specialist. The designer clearly chose what he believed to be the easiest and most profitable route to the knowledge. Yet so much knowledge could have been obtained at his desk, from a system designed specifically for its accessibility and ease of use.

This example highlights the potential inertia faced when encouraging engineers to reuse design knowledge. It could be argued that the source of knowledge is irrelevant, yet utilising the specialist consumes twice the resource than necessary – the specialist's time and the designer's time.

Failure to search and gain from the system also means the designers will not see the benefit of the system and will be less inclined to store knowledge themselves. Secondly, without the designers using the captured knowledge, they will not appreciate the quality of required knowledge stored, potentially resulting in irrelevant or poor knowledge being stored. Following this, four hypotheses can be proposed as the rationale behind the failure of knowledge reuse:

- Designers do not believe it is valuable enough
- Information obtained does not provide them with the knowledge they require
- Not invented here syndrome (unwillingness to use knowledge from others and trust)
- There is an easier route to source information

The first two of these hypotheses may indeed be applicable for a poor knowledge base. But as shown in section 5.3, the knowledge base is not trivial. It is more common, as in the case here, that the designers make a judgement call prior to searching.

The third point above is a recurring issue in knowledge reuse and engineering (Suresh, 2002). It can be argued that people typically prefer to work with ideas or objects they are familiar with. There may also be technical limitations when reusing geometry created by others. Here however, the intention is to present designers with examples and experiences and allow them to decide whether they are relevant and if the lessons learnt or the geometry is applicable for the new design. This has been made clear to the designers and while some geometric reuse is intended, adopting large sections of geometry was not intended unless it was a repeat product.

The fourth hypothesis is applicable, since as described in the case study, designers do seek information from other sources – primarily the technical specialist or each other. However, the role of the knowledge system is not to replace these interactions, rather to make the majority of the discussions redundant and supplement and enhance those that remain. This final argument, coupled with the lack of a critical knowledge base, probably corresponds to the reason behind user inertia. Rectifying this inertia will require a wider and more reliable knowledge base, but importantly, designers must perceive the knowledge base as relevant and valuable.

The positive outcome from the case study was the greater understanding of the system and the system's potential by the designer. Furthermore, prior to moving forward he documented his understanding in a 'How To' document supplementing the existing knowledge base.

### 5.6.2 Success Case Example

Due to other customer requirements the product above was in fact shelved for a period of time. When the product was restarted, it was transferred to two other engineers – designer B and designer D.

Both designers utilised knowledge in the early stages of the project. Designer B spent the first four hours reviewing prior knowledge, whilst designer D spent five hours, spread over the first week, including reviewing the video and technical documents. In comparison, during the product's first development stage, 1.5 hours were spent in discussion with the technical specialist.

Both designers discussed the knowledge use relating to this product during the semi-structured interviews. Designer D, cited the rationale for its use, following the question "What was the knowledge you sought?":

> *"[what] I wanted to do was to try and find out the reasons why everything had been selected or done. Quite often things that seem quite an arbitrary figure or a very particular way of doing something, it's not immediately apparent why it's been chosen sometimes it's been chosen because of discussions with operators"*

This quote is of particular interest when examined in comparison to the previous section. The designer is citing a need for precise and detailed rationale behind the current design. Yet the quote refers specifically to the knowledge sought from the Design System. It is therefore inferred that the designer believed the system would have been capable of providing that knowledge and was therefore motivated to seek it. Returning to the four hypotheses above, each point has been satisfied:

- The designer wanted a known and valued knowledge type
- The designer believed the system contained the knowledge
- The designer was prepared to trust the knowledge

Finally, the designer chose the route to obtain this knowledge – at this point both the expert and designer A were present in the office and could have been approached. As it was, designer D did not approach the expert before completing almost 20 hours of technical work, indicating that the knowledge sought was sufficient to at least begin design work.

The figures above were generated through the diary study and therefore may underrepresent the discussions with the expert but they do indicate that the reliance on the expert has been successfully reduced.

However, both designers cited some frustration with the lack of detail supplied by the system. Designer D indicated that operator feedback was missing from the captured knowledge, representing a valuable appraisal of the current design. Designer B stated:

> *"Designer A produced a document that said how to design gas shields and generally it gave you a very good overview. But it didn't give you the nitty gritty, the finer detail of what you actually had to do and the problems you had to be aware of. Just to get [some] basic geometry, it was relatively straight forward, but then detailing that basic geometry up, [the knowledge] didn't scratch the surface. But that's not to say in the future, as part of the lessons learnt from a project that we won't populate it and do that and for new starters [sic] "*

The quote highlights the need for detailed knowledge to be captured, but also the iterative "reap and sow" concept. Having identified a knowledge gap, the designer would in future aim to supplement and fill that gap.

The use of the codified knowledge from the Design System clearly did not replace that of discussions in the case study. However, it did provide a valuable upfront source of knowledge. Furthermore the utilisation of the same knowledge set by two designers clearly demonstrates the scaling potential of the system, exactly as intended to support business growth.

### *5.6.3 Comparative Case Study*

In order to understand the product specific benefit provided by the Design System, a comparative study was conducted using a design task to establish the difference between novel design and adaptive design.

Similar to the approach taken in section 4.6, a design task would be undertaken by two designers with differing resources. In this case, a design task would be undertaken by the author and another designer was given the task of redesigning and improving the solution utilising the knowledge-based system.

As discussed in section 4.6.1 there are disadvantages to comparative studies. As in many studies no environmental variables would be measured. However, in this case the environment would be held relatively constant with the designers working under the same conditions, but around two months apart.

Naturally the most significant uncontrolled variable would be the experience and expertise of the two designers. Both can be classed as novice designers, neither being experienced with design and manufacture using the specialist technology. However, the initial designer (the author) is familiar with the capability of the technology, while the second designer has a large degree of experience (eight years) working in design. Both designers were sufficiently capable with CAD software, the author being experienced with Solidworks and AutoCAD, the second designer with UniGraphics.

The design task was provided by the technical specialist. The task was to produce a sprung clamp for centralising and circularising the ends of two pipes, so that a minimum of three tack welds could be made between the two pipes. Figure 92 shows the brief as received from the technical specialist.

**INTEROFFICE MEMORANDUM**

**TO:** DESIGNER

**FROM:** TEHNICAL EXPERT

**SUBJECT:** PIPE CLIP

IKEA 1.doc IKEA 2.doc IKEA 3.doc IKEA 4.doc IKEA 5.doc IKEA 6.doc 2.00 Clamp Clip 4.00 Clamp Clip

Hi,

We would like you to produce a design for a 3.50" (three and one half inch) diameter pipe clip. I have attached some files that may help you to achieve this:

IKEA 1 - 6 are assembly drawings that also show the internal construction of a 2" diameter clip;
2.00 inch Clamp Layout is the scheme that produced the 2" clip;
4.00 inch Pipe Clamp Layout is the scheme that produced clips for the Eaton Catastrophe of last year. Clamp No 2 on this scheme is for 4" ducting.

In addition to the attachments I think you will need to know the following:

- The Latching Mechanism for clips between 2" and 6" diameter is the same for all clips.
- The width of the clips is the same for all clips.
- There are Struts joining each side of the clip together.
- These Struts give the clip form and structure (as an assembly) and assist in maintaining concentricity between each side of the clip.
- The number of Struts joining the sides of the clips depends on circumferential availability. There is no upper limit.
- The gap between adjacent Struts around the diameter should be a minimum of about 25mm - this allows sufficient space for 'tack-weld' access without damaging the clip.
- A minimum of three equally spaced 'tack-welds' around the pipe circumference is ideal - however, you will see from the 2" version that this is not always possible. Just get as close to it as you can.
- The general radial height of the clip-sides around the Strut area is the same for all clips (~6mm).
- The Link should be designed with spindle centres of 21.00mm.
- The Link is the means of adjusting the 'clamping' force of the clamp - reduced centres = tighter clamp - this allows easy tuning without major changes to the clamp and mechanism (0.25mm reduction on diameter = ~0.75mm reduction on Link centres).

Regards,

*Figure 92: Screenshot of the task brief as given by the technical specialist*

The attached files included two AutoCAD files and 6 3D exploded CAD views of two existing designs. No further product knowledge was given.

## Methodology

The study was conducted in two stages. Initially a new design was produced by the author, utilising the limited knowledge provided by the technical specialist. Although all the geometry files were provided, no rationale had been captured around the design and a reasonable period of time was required to understand the previous design. Once the new solution had been created and its knowledge captured in the knowledge-based system, the second designer was requested to redesign the solution for a larger pipe reusing the prior knowledge.

Both designs represent adaptive designs. However, the author's version was intentionally a heavily modified version of the specialist's, adopting the basic principles and layout but redesigning the clamping mechanism. In contrast, the second designer was asked to produce a design based entirely on the author's version (purely adaptive design). The intention was therefore to observe differences between a relatively novel design and a variant design, in particular focusing on the process of development and time spent on different activities.

Both designers kept minute based logs of their thoughts and processes. These actions were then classified according to the same structure derived for the diary study discussed in section 5.4.

**Design 1:**
The first design (by the author) is shown in Figure 93. The redesign was prompted due to the complexity of the specialist's design. As the clip was intended as a high volume product, simplification of design would aid both assembly and future modifications.

The design's principle is to load both pipes (left and right) using two opposing arms around each pipe and using a clamping mechanism at the top of the clip to provide the load. A sprung element links the two arms and when the handle is rotated a 'cam' loads the spring so that the arms are driven together, restraining the pipes.

*Figure 93: Photograph of the first design version of the pipe clip*

The design took 34 hours to develop and manufacture. Extensive knowledge searching and access was undertaken at the start and during development of the spring. Several files were accessed, in particular the spring designer, other clamping projects and a 'how to' develop clamps. Little benefit was gained from these, however. The spring designer is limited to compression springs, and does not support development of tension springs as required here, once again demonstrating the disadvantages of a tool with limited scope. Of the other projects, none were specific or detailed enough to provide valuable advice.

The concept and utilisation of a cam was a novel idea by the designer, which had not been tested before using the technology. The design therefore represented something of a prototype. The design was drawn primarily in AutoCAD, remodelled three-dimensionally in Solidworks to ensure correct assembly, and then exported for manufacture.

While the concept may have been correct, the actual design had many failings:

- The spring stiffness was exceptionally high, so that significant effort was required to operate the device and deformation was observed.

- The orientation of the cam caused the arm to ‘climb’ out of the load surface when rotated.
- Finally, significant effort was required to assemble the device. Notably the pivot holes were cut undersize, despite reaming and the device still required significant time to assemble.

Several issues were encountered by the designer during manufacture. In particular some parts were required to be redrawn and recut due to an issue of scaling incurred following their export form Solidworks. While assembly time was therefore longer than typically expected, issues commonly arise in day to day production and the problems were therefore not necessarily any different to those faced by designers.

The design was fully written up into the Design System and all associated files uploaded. Sketches were scanned and uploaded, key photos were annotated, and all CAD and cutting files included. Screenshots of different parts of the knowledge can be seen in Figure 94.

Rolls-Royce

3.5 inch Pipe Clip

The basic principle of the design is the need to create a displacement over the length of a sping linking the left hand half of a clamp to the right hand half of the clamp around a pipe. i.e. stretching the spiring which in turn pulls two halves of the clamp together. In the previous version by Jeff he achieves this through the use of a double pivoted over centre clamping mechanism. This creates a easy and smooth operating mehanism, but at the expense of complexity. As an experiment a simpler method was developed which would place the spring under load using a cam rotated by a user.

*Available Files*

Requirements
Specification
CAD
Render
CAD
Geometry
Photograph
Laser
Cutting
Files
Sketch

*Requirements*

**General Requirements** To design a 3.50" clamping device or clip, to align and secure two seperate pipes of equal nominal diameter, concentrically to each other such that they can be welded together.

**Interface** Device is not required to interface with an existing or pconceived fixture, but will remain free.

**Additional / Other** Design is to be based on Jeff Bishop's previous design for the 4" and 2" pipe.

| | |
|---|---|
| Ref # | 407 |
| Version | 1 |
| H x W x D (mm) / M (kg) | 200 x 200 x 40 (0.5) |
| Status | Development Version Complete |
| Category | Device |
| Customer | Rolls-Royce Sheffield |
| Started | 03/08/2009 |
| Completed | 30/10/2009 |
| Security | UNCLASSIFIED |
| Processes Used | Laser Profiling, Manual De-Burring, Drilling, |
| Complexity | Medium Runner |
| Project Engineer | Jeff Bishop |
| Organisation Unit | Manufacturing Technology |
| Product Application | Any Application |

*Design Detail*

**Design Analyses Used** Some spring calculations were attempted using the Spring Designer, but no design was appropriate for the usage here. The spring was therefore estimate.

**Reasons for New Design** To create a equivalent design to Jeff's preceeding design, but which allowed for simpler construction.

**Concepts Rejected** Other overcentre clamping mechanisms were considered, butwould again require more than one pivot point and thus multiple parts.

**Design Detail** Cam was developed to provide a 1mm exntension to the spring over its rotation. It was also developed such that when the cam was rotated past 90 Degs, tyhe point of maximum extension, it would relax very slightly creating a local energy minima and thus a stable position.

**Design Detail** Many of the other concepts used in Jeff's preceeding design were adopted in the new design.

**Design Detail** The current design maintains Jeff's structure, which uses four arms two either side of each pipe and mirrored accross the weld line, i.e. each pipe is clamped by two arms, which are themselves linked.

**Design Detail** Note that the distance of the arms either side of the weld line app no specific rationale, it might be better to adjust it slightly to make and use of components easier.

*Benefits of Design*

| Quality | Cost | Delivery / Lead |
|---|---|---|
| Little benefit from quality. Jeff's orginal provides smoother and easier operation. | Expected to be less expensive than original design both through construction time and through material and component usage. | N/A |

*Made With*

| Devices | Features | External Parts | Material |
|---|---|---|---|
| | Slot Rivet, | M5 Silver Steel Rod, M5 Starlock Washers, | EBM 574 TCA 604 |



*Figure 94: Screenshot of the summary page of the 3.5" pipe clip and inset, an annotated photograph detailing some of the issues with the design*

**Design 2:**

The second design was completed and manufactured within 37 hours. It utilised the same concept as design 1, but addressed many of the failings of the earlier version. Reassuringly the designer referred heavily to the documented knowledge on the Design System and this is reflected in many aspects of the design. No additional verbal information was given to the designer by either the technical specialist or the initial designer. The designer was also not given access to the previously manufactured design. The design can be seen, unclamped around a 'dummy pipe' in Figure 95.

*Figure 95: Photograph of the second design version of the pipe clip*

The designer made several adaptations, notably the cam mechanism was flipped so that it rotated down into the mating face, avoiding the 'climbing' action seen in the first version. The designer redesigned the spring to give a much lower spring rate. The designer also cut the holes slightly bigger, reducing the amount of reaming required.

**Analysis of Approaches**

Based on the total time taken to design and produce a new design, there were clearly no significant time savings achieved during development of the second version. However, important observations can be made from a comparison of the different approaches and the time spent on different activities.

Figure 96 shows two pie charts illustrating the breakdown in time of each of the designers and demonstrates a similar proportion of time spent on several activities, noticeably manufacturing and assembly, despite both designers encountering issues.

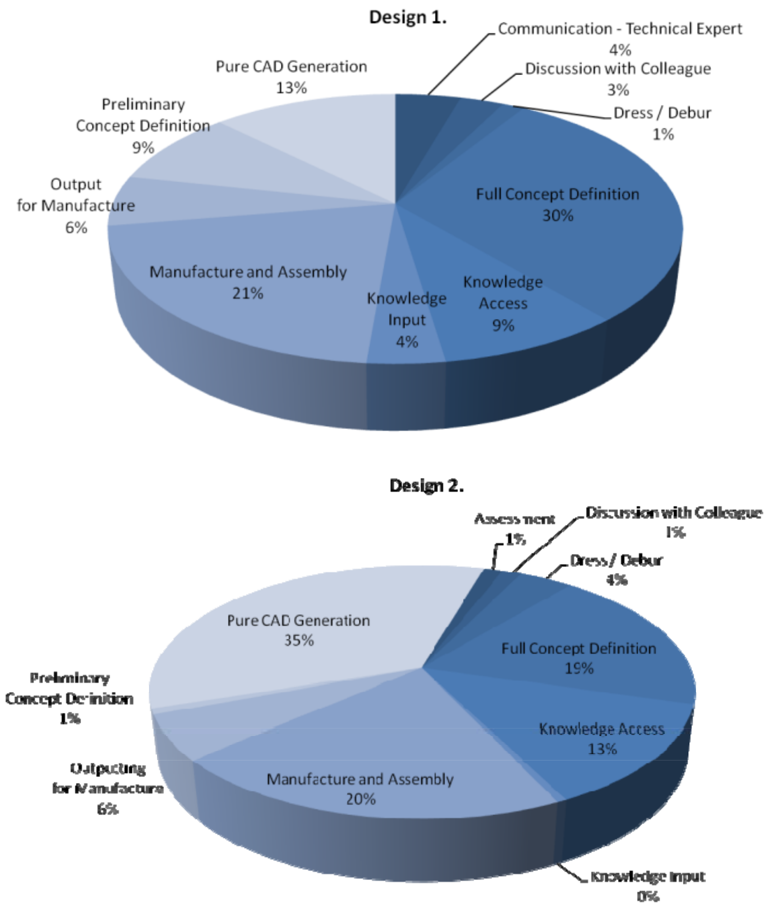



*Figure 96: Pie charts illustrating the breakdown of time for each of the designs.*

However, actual differences can be better illustrated by comparing the hours spent on technical activities, as shown in Figure 97.

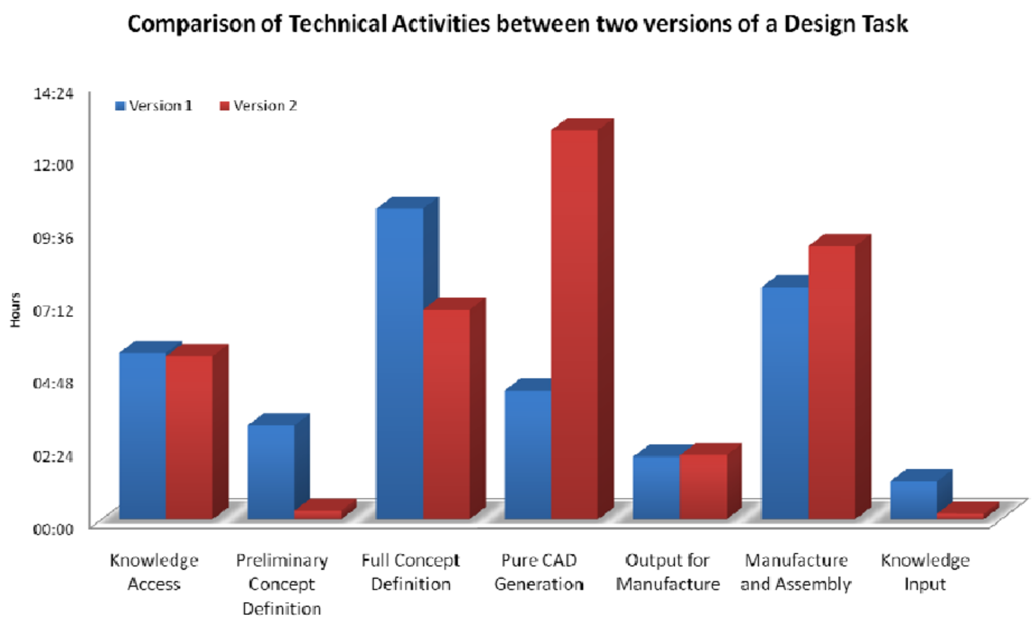



*Figure 97: Comparison of hours spent on technical activities*

Several interesting observations can be made from Figure 97. First, despite the emphasis given to the second designer on reusing knowledge, the time spent accessing knowledge (which includes reading and understanding) is approximately equal. Yet it was expected that the second designer would have spent much longer, having access to more knowledge. This result is thought to be due to the additional time required by the author to interpret and understand the experts CAD files and design without the additional rationale.

As expected, time spent on 'preliminary concept definition' and 'full concept definition' was significantly less than the first version. The unexpected difference was the increased time creating and developing the CAD models, classified as 'Pure CAD Generation'. This category is intended to capture time spent purely modelling, with little or no time spent developing and detailing the design. Consequently, this ought to be lower during the second design. In discussion with the second designer, it became apparent that importing the geometry into a different CAD package (UniGraphcs) required considerable effort and time due to the unconstrained nature of AutoCAD drawings.

**Analysis of Designs**

Further examination of the designs illustrates several interesting points. For example, minor issues were not addressed despite their documentation – in particular the distance (depth wise) between the arms. The issue was documented as follows:

> *"The distance (depth wise) between the two arms was an arbitrary value, this should be modified to a value easily divisible by the depth of the spacer rings. i.e. spacer rings can be 5 or 10mm deep, a depth of 20 or 30mm is suggested rather than the current 26mm."*

The designer did reflect other comments in the same dialogue box (Lessons Learnt – Manufacturing and Assembly", yet he did not alter the distance and this required the additional manufacture of spacers, taking around 30 minutes. When discussed, the designer remembered the comment relating to a standardised distance, but had not remembered its relevance during design and manufacture. This suggests the designer had successfully absorbed and stored the knowledge but was not able to factor in all the documented issues into the design. It is further suggested therefore that this could be an indication of the natural limitations to short term memory processing, the limit of seven ‘chunks’ as described by Miller (1956). Clearly this could be overcome by reducing the information channels and thus the chunks that need to be currently handled by the designer through better knowledge structure and a summary of the key issues.

The second observation relates to the reuse of (potentially) incorrect geometry. The lower pivots are spaced at 21mm apart, assuming a perfectly nominal diameter for the clamping arms. The first design incorrectly used a shorter plate, with a pivot distance of 20.5mm. This was not realised during manufacture and consequently was not documented. The second designer correctly identified the difference but assumed that this was intentionally undersized and reused the geometry. As a consequence the cam does not align well with the opposing arm. This highlights the documented danger of design knowledge reuse – the over reliance or trust placed on the preceding design (Busby, 1999).

**Feedback from Semi-Structured Interview**

To further support the case study, the semi-structured interview conducted with the second designer was extended to incorporate some discussion relating specifically to the design task. A full transcript can be found in Appendix A but the important points will be highlighted here.

Overall the designer did not find the task particularly challenging, apart from developing the mechanism for which little numerical support could be found. Besides this, however, the designer cited the knowledge support as excellent, stating:

> *“I felt like I knew – having read the information on the Design System – the previous design very well, having not seen the thing in the flesh, I felt that I knew an awful lot about it, the techniques and the sort of things hitherto I thought you would only learn and get from getting hold of it and using it. That was quite a surprise. When you offered me to see it, I didn’t need to”*

Two benefits were repeatedly referred to in the discussion. The first, the benefit of having something to start off with: “you felt like you weren’t starting from scratch”. The second was avoiding mistakes or pitfalls and as discussed above, this was largely achieved.

When asked about drawbacks, the designer highlighted (without prompt) the danger of overly trusting or being led, as discussed above, stating:

> *“there is a tendency to be led by it, and maybe having not seen the cam in a latch before, I would not have gone down that route”*

The designer suggests that rather than not using prior designs at all, a designer should be encouraged to sketch and brainstorm a set of solutions prior to reading existing designs. The designer can then choose to adapt or modify as they wish.

The interview highlights how detailed and fulfilling the Design System knowledge can be – to the extent of almost removing the need to see the physical object. The designer viewed the system positively and believes that without the prior knowledge, the design time would have been longer.

**Discussion**

The use of a single case study, with demonstrable limitations, restricts any claim that the behaviours and observations made in the study hold for all cases of reuse, both generally and within the studied business. However, several conclusions can be made from the study and in particular from the issues encountered in the study.

The large time investment by the second designer in CAD generation emphasises the importance of accessible and reusable geometry. The need to remodel geometry in a differing software package drastically reduces or even removes the benefit of adapting previous geometry.

The natural limits of human information capacity must be acknowledged in the design and presentation of knowledge. Designers should not need to 'learn' a large quantity of knowledge and be expected to reflect all they have read. Knowledge must be provided sufficiently structured so that all of the key issues can be reviewed regularly and throughout the design without being memorised.

The over reliance on and trust in previous designs has also been highlighted. While this case study could be artificial, it emphasises the need to encourage and maintain innovation and for designers to continually critique prior designs.

### *Summary*

The preceding section presented three product specific case studies, specifically discussing the use (or the lack of use) of knowledge during the design process. The first two studies demonstrated two differing attitudes and scenarios from anecdotal and diary-based evidence of knowledge use. The third study presented a comparative study of the design process for an original and adaptive design, with and without knowledge.

These studies clearly represent a limited sample set and the conclusions drawn may not be applicable to the general case. However, some conclusions and indications can be drawn:

- Having established a reasonable knowledge base, the inertia against reusing knowledge is dependent on the designers' willingness to value and trust the knowledge and to believe that the knowledge is accessible.
- The second case study demonstrated that dependence on the technical specialist could be reduced (in this case halved) through the use of the codified knowledge.
- The knowledge was not sufficient, however, to remove all communication with the expert.
- The comparative case study found that reusing past knowledge did not (as expected) result in a lower product development time. In the example here this appears largely a result of CAD incompatibility but preliminary and full concept definition stages were reduced.

- The use of prior knowledge did successfully avert a repeat of mistakes made in the earlier design but was observed to cause an over reliance on the previous design rather than encouraging the designer to develop new ideas.

## 5.7 Value: Balanced Scorecard Assessment

The final analysis of the knowledge strategy and Design System examines the value the system has had on the business. Section 3.7 introduced the different approaches that can be used to measure the status of a business, such as the balanced scorecard [BSC] or the Skandia Navigator [SN] measure of intellectual capital. Here the BSC will be used due to its flexibility and focus on internal process measures. It was also felt use of the SN's reductionist approach would not be appropriate given the infancy of the business case study.

As previously described, the BSC is populated with a series of metrics, referring to four different perspectives on the business. This section begins with the rationale and approach taken to develop these metrics, followed by a discussion on the data used to populate the scorecard. Finally the scorecard is presented and a discussion on the implementation given.

### *5.7.1 Development of the Balanced Scorecard*

In Kaplan and Norton's (1992) original paper the choice of metrics are discussed and chosen for a fictitious company with reference to the strategic direction and goals of the company. However, in the paper the link between strategy and the metrics are simplistic and in reality it is often much more complicated. This has led to the evolution of success maps' – "diagrams that show the logic of how the objectives of the organisation interact to deliver overall performance" (Bourne et al., 2003). They attempt to map the key factors that drive business value, which in turn can be used to populate a performance management system such as the BSC.

Derivations of these maps are not easy. In the much cited study of Sears, Rucci et al. (1998) a large mass of data was used, based on employee surveys, customer feedback and store-based data together with specifically development strategic management teams. Most success maps are theoretical in nature, although Bourne et al. (2003) report that some companies such as Shell are using historical data to test the maps and in particular the correlation between measures.

Here an exercise was completed with several employees to gain a view of what factors they felt were the dependent measures and value generating changes. Rather than simply surveying participants and establishing a set of unstructured measures, a top down exercise was developed to encourage the participants to develop their own success map. The exercise was split into several different instructions, each given after the previous stage and these were:

1. List any measures or metrics applicable to Pro-Laser that you feel should improve over the following year to add value to the business (clarification was added that the metrics were not necessarily factors that could be measured).
2. Rank those metrics in terms of importance (this was modified and limited to the top 4 due to the number of metrics listed).
3. Divide the measures into four sections, finance, customer, internal processes and learning and culture.
4. Write the relevant metrics in the different sections and link dependent measures with value ascending.

The exercise was completed in April 2009 and was completed by two designers (A & B), the senior manager (M), and a leadership graduate (L). At each stage, an example was given by the researcher to provide a better understanding of the desired response and to seed ideas in case the participants were stuck. It is expected these will have minimal influence.

All responses were scanned and can be seen in Appendix A. A list of the measures given is shown in Table 26, but does not show the specific causal links between measures.

| | *Manager M* | *Designer A* | *Designer B* | *Graduate L* | *Author* |
|---|---|---|---|---|---|
| **Finance** | ▪ Target product family<br>▪ Seamless P & L | ▪ Profit: income / design time (3) | ▪ Improvement on profitability<br>▪ No of jobs taken on | ▪ Number of projects – throughput (1) | ▪ Turnover<br>▪ Gross margin<br>▪ Mean cost per product |
| **Customer** | ▪ Clear product family (1)<br>▪ Better customer engagement (4)<br>▪ Business image<br>▪ Global reach<br>▪ Limitations | ▪ Customer satisfaction (1)<br>▪ Elapsed time as opposed to design time | ▪ Customer feedback response<br>▪ Customer enquiries | ▪ Customer satisfaction (3)<br>▪ Reduction in timescales from enquiry to delivery<br>▪ Brand image | ▪ Customer satisfaction<br>▪ New customers<br>▪ Delivery cycle time<br>▪ Customer profitability |
| **Internal** | ▪ Quick to best practice (3)<br>▪ Autonomy over IT<br>▪ Purchasing<br>▪ Methods<br>▪ Target exploitation of product families (2) | ▪ Design time to complete (2)<br>▪ Lead time to start<br>▪ Design time available / day (a kind of efficiency)<br>▪ Time to establish requirements | ▪ Average time for design<br>▪ Improvement right first time (design)<br>▪ Population of design system<br>▪ Improvement in manufacturing time<br>▪ Reduction in delayed projects (due to response)<br>▪ Reduction in overtime | ▪ Number of products directly involved in gas turbine delivery (2)<br>▪ Evaluation of cost (4)<br>▪ Time required during design phase<br>▪ Resource required for a project (people)<br>▪ Conceptual evaluation of consumables from evaluated stages<br>▪ Evaluation of effective workload and bottlenecks<br>▪ Assessment of price<br>▪ Visibility of Pro-Laser as a viable solution within RR<br>▪ Numbers of new vs regular runner designs / products | ▪ Reduce scrap rate<br>▪ MCE (design throughput)<br>▪ New product development<br>▪ Geometry reuse |
| **Culture and Organisation** | ▪ Improved use of individual skills<br>▪ Stability of workforce | | ▪ No of personnel<br>▪ Improvement in patent opportunities | ▪ Balance of internal RR vs external work | ▪ Patents launched<br>▪ Employee turnover rate<br>▪ Design system usage<br>▪ Design system population<br>▪ Employee skill level incr |

*Table 26: Results of the success map exercise*

The measures listed under the author were those derived primarily from the other responses synthesised together with KM-orientated measures given the intentions of the resultant BSC.

## Discussion of Metrics Given

Of the four (five including the author's) completed success maps, two were similar (the two designers). Designer A listed very few metrics overall (seven) and it was noted that of any of the responses his differed only slightly from ideas seeded by the author.

Noticeably both designers listed a large number of metrics orientated towards the reduction in lead times, both in design and manufacture and the response or reactivity of the business was also listed by both designers. Designer A also listed resource, suggesting the business should be over resourced to cope. These suggest an overriding concern by the designers on the demands placed on their time. This is further supported by designer A's metric "design time available per day" suggesting that he feels there is a loss of efficiency due to administrative or other duties and by designer B's listing of "reduced overtime". Importantly, both designers listed design time as a metric for improvement, implying that both believe it is possible to reduce this time. It could be assumed that if the designers felt this was a given constant they would have disputed it as a measure of improvement.

The leadership graduate L was at the end of a six month placement with the team in Rolls-Royce Sheffield. His primary role during this placement has been to devise and implement a quality management procedure for the design and manufacture of products on the Sheffield site. L is highly commercially aware due in part to his background and current role in the team and this is clearly reflected in his responses. His list of metrics is noticeably different to those of the designers and contains a large number of customer and brand-orientated measures. He has also listed several metrics orientated towards process improvement such as "prioritisation of work" and tellingly the metric "willingness to follow procedures" – a clear consequence of his recent work implementing new procedures.

Manager M completed the task after the other employees in a separate workshop (due entirely to time constraints) but M had not seen or been given access to any of the previous work. The brief was given in a similar manner to before, however the metrics listed by the manager are strikingly different to any of the previous results. The researcher seeded two ideas, namely "brand image" and "profit" in order to prompt the scale and level of metric sought after. "Brand image" was adopted, "profit" however, was not, on the grounds that it represented too high a level.

It is possible that the researcher influenced the response by describing the metrics as "measures of the business that should improve over the following year" which could be interpreted as binary measures of "what has improved". However, a similar description was given to the other employees (although word for word cannot naturally be guaranteed). As the workshop progressed, the researcher did try to direct the responses to a longer term strategy. But it was felt that too much influence would bias the list towards a preconceived idea, which was not the aim of the exercise.

It is apparent that the measures listed represent the current issues and limitations to the business. For example, the corporate constraints on purchases have in the past prevented purchase of tooling or materials, inhibiting the flexibility of the business to respond to different product requests rapidly. These therefore represent the changes in the culture and organisation required to cascade up through the success map to ensure improvement in customer facing measures and financial benefits. In this sense, the manager is anticipating the changes that are required for the business. However, the difficulty in eliciting long term strategic measures from the manager is a concern. In an ideal world these measures should have been uppermost in the manager's mind and implementation and the need to support them should have been secondary.

#### Discussion of Success Maps

The second stage of the exercise required participants to structure their metrics according to the tiered scorecard categories: financial drivers, customer drivers, internal processes and culture and organisation. Due to the number of metrics listed by the participants, only the most important metrics were asked to be placed within the scorecard.

Generally, participants placed the metrics in the appropriate categories but there was a tendency to place items too low in the hierarchy, particularly around "internal processes". The consequence of this was that very few actions were listed that the participants believed would directly initiate improvements in higher measures.

Manager M produced the most uniform map, for example stating "improved use of skills" and the "stability of workforce" as enablers to support improvements in customer engagement. This was closely followed by designer B, who also listed measures such as "population of Design System" under culture.

The graduate L produced a heavily process-orientated map, which confuses the map slightly. For example "evaluation of costs" is listed under financial measures. But his map does offer some useful measures not listed by the others. These include a direct thread focusing on measures to support Rolls-Royce gas turbine production (a worthy inclusion should the business not launch as an independent venture) and metrics focusing on how we measure success and as mentioned before the willingness to follow procedures.

**Development of Final Success Map**

Overall key themes can be distinguished from the success maps and the metrics given. These are:

- Business image
- Product development and placement
- Customer base
- Customer perceptions and engagement
- Design and manufacturing efficiency
- Improving workforce and capability

Of these, branding will not be addressed in the scorecard simply because limited activities have been undertaken and data is not available. However, customer feedback will be used; this is a limited but arguably a more direct measure of business image.

The other aspects were combined and developed into the following success map, shown in Figure 98.

*Figure 98: The Developed Success Map*

The relatively short lifetime of the company and limited data available precluded the possibility of historically testing the model. However, the model does address many of the measures given by the exercise participants.

**Discussion of logic path**

For the purpose of the research here, increased use of the Design System and an increasing system population should correspond to more efficient working practices (MCE), increased geometry reuse, a reduction in scrap which ultimately should lead to reduced delivery time, increased customer satisfaction and efficiency savings, reducing gross margin. The case studies also indicate that increased system usage may also correspond to a reduction in new product development so care must be taken that this does not happen.

These relationships are to some extent theoretical assumptions. Without extensive data to establish correlations between metrics they cannot be proved beyond reasonable doubt. However, the preceding sections indicate that many of these relationships can be inferred with some confidence.

The most difficult to infer is the implied efficient working practices, leading to reduction in design and manufacturing times - one of the primary aims of the knowledge strategy. Efficiency savings have been inferred through the minimising of expert reliance indicated by the diary studies and case studies. However, during the interviews many of the designers stated that while the system had provided tangible benefits, only three of the five designers stated that it had saved them time. This was further supported by the case study in section 5.6.3 in which the overall time was equivalent to the bespoke solution.

Results from both the interviews and case studies indicate that the system *is* capable of reducing errors and specifically mistakes prior to manufacturing. The relationship between system use and reduced prototyping is therefore assumed.

Given the product field (fixtures and tooling), lead time is often a customer's primary concern and consequently their measure of a project's success. Reduction of MCE and design time should inherently lead to better customer satisfaction, although this assumes sacrifices have not been made to product capability.

Finally, assuming no loss of business, reducing the mean project duration should result in increased turnover as more projects are completed over a fixed period. Maintaining or lowering variable costs through consumables and materials while increasing turnover will lead to higher gross margin.

### 5.7.2 Data Set

Data used to calculate and populate the BSC metrics was obtained from four different sources:

- The Knowledge repository
- Design reviews (following project completion)
- Diary study
- Business analysis

The system database and diary study have already been discussed in the preceding sections. The design reviews were established by the author to supplement project data. Completed projects were reviewed and additional data captured including the number of prototypes manufactured, the extent of geometry reuse, and knowledge used.

The business analysis includes basic data on the business status, for example number of employees (shown plotted in Chapter 2), number of patents launched and employee skill analysis (from section 5.2) combined with financial data taken from the profit and loss accounts over the evaluation period.

Clearly all the data has some degree of uncertainty associated with it. For example, the design reviews are entirely reliant on accurate responses from the designers. However, the project-based data is of particular concern. Only 14 design projects were completed over the evaluation period. This sample is too small to remove large scale deviance and represents a concern when simply comparing averages such as project duration.

It should be remembered that this is a young SME with little established historical data. One of the key arguments for the chosen approach to business evaluation was the limited potential for comparative studies between like for like projects. The combination of multiple metrics from a variety of sources remains the only means to minimise overall reliance on a single, limited data set.

The ultimate intention of the design time metric is of course to correlate knowledge use with reduced design time. The varied nature and complexity of different jobs renders this impossible with such a small sample size. An attempt was made to develop a correction for project complexity and thus to allow a comparison of two equally complex products.

Prior research has been conducted to quantify complexity, such as Bashir and Thompson (1999a) and to link it with cycle time, such as Griffin (1993). But generic measures and metrics have been limited. The more accurate attempts usually require a detailed analysis of the product's function and often the measures derived apply for a limited domain. The product set captured here is disadvantaged by the wide ranging geometric variations, yet relatively similar functional behaviour of the products. For example, nearly all of the products locate and restrain a component as their primary function yet have vastly different degrees of complexity depending on the geometry of the component and tolerances required.

Here, experiments focused on using aspects of the end geometry to generate different measures such as the number of 'features', the number of operations used to create the device in CAD and finally a surface area/volume ratio. No measure was sufficient and it was accepted that the project times would have to be taken 'as is'

### 5.7.3 Implementation

Typically, the BSC is implemented together with targets and the metrics assessed each month against these targets. Two differences were made here: first, the implementation was to some extent exploratory and no targets were set, rather the like for like changes were derived. Second, due to the small data set and high variance, the metrics were generated over four months and the two phases of the evaluation period were compared against each other.

The actual equations used to calculate the metrics are shown written up in Appendix B.

The result of the scorecard is shown in Figure 99. It is important to acknowledge that the percentage values are the like for like changes. For example, Design System population improved from 267 to 300, therefore showing a 12% increase. The traffic light system has been geared to show the desired responses – red lights always indicate a poor result regardless of a positive or negative swing.

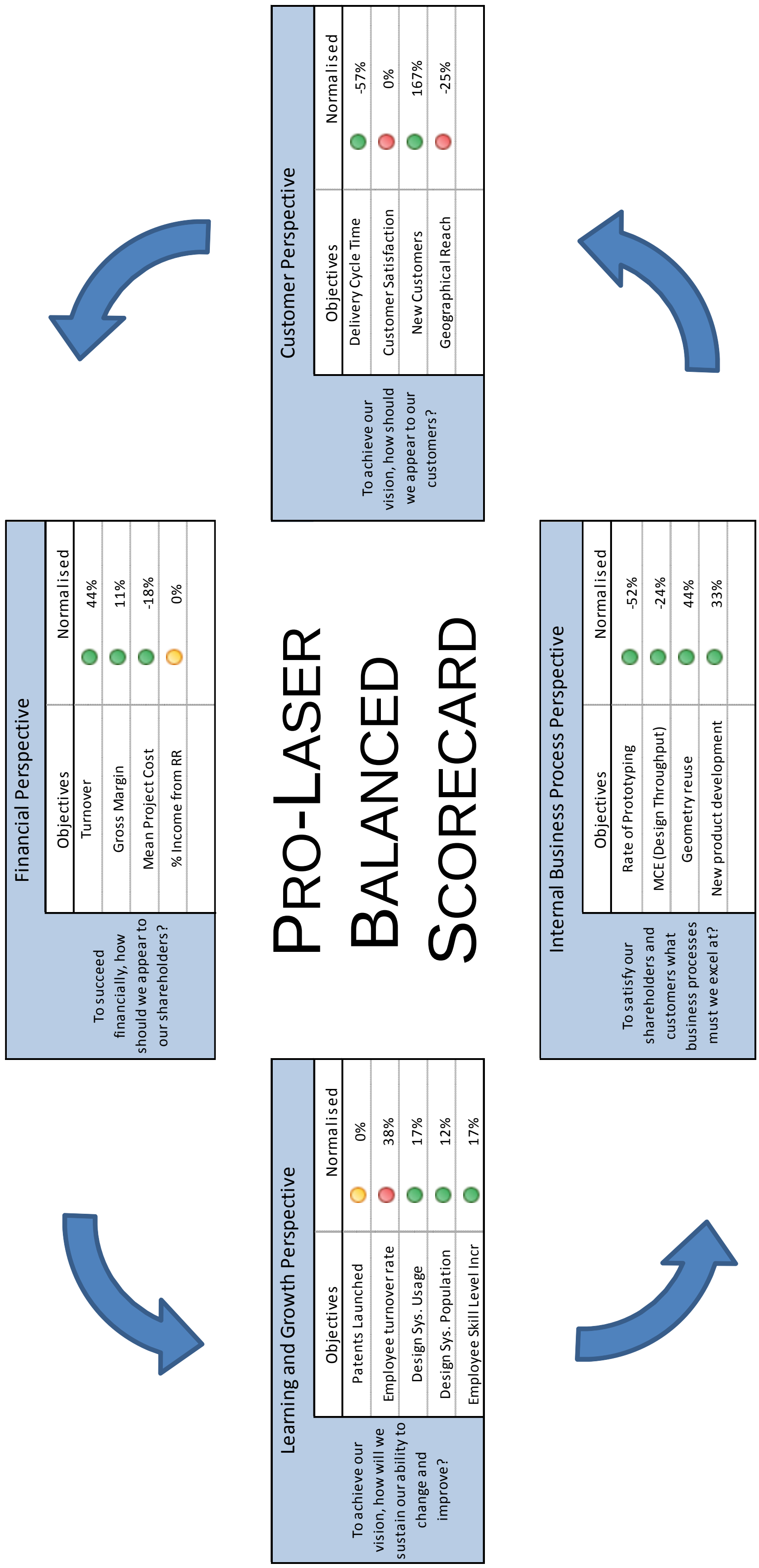

PRO-LASER BALANCED SCORECARD
Financial Perspective
To succeed financially, how should we appear to our shareholders?
Objectives
Normalised
Turnover 44%
Gross Margin 11%
Mean Project Cost -18%
% Income from RR 0%
Customer Perspective
To achieve our vision, how should we appear to our customers?
Objectives
Normalised
Delivery Cycle Time -57%
Customer Satisfaction 0%
New Customers 167%
Geographical Reach -25%
Internal Business Process Perspective
To satisfy our shareholders and customers what business processes must we excel at?
Objectives
Normalised
Rate of Prototyping -52%
MCE (Design Throughput) -24%
Geometry reuse 44%
New product development 33%
Learning and Growth Perspective
To achieve our vision, how will we sustain our ability to change and improve?
Objectives
Normalised
Patents Launched 0%
Employee turnover rate 38%
Design Sys. Usage 17%
Design Sys. Population 12%
Employee Skill Level Incr 17%

*Figure 99: (overleaf) The completed balanced scorecard assessment for the business*

The most important and reassuring result is the overall green response – most metrics demonstrate an improvement over the evaluation period. In particular, turnover and gross margin have both improved. Turnover was expected to increase in the second phase due to the influx of two new designers in September and November respectively. Yet the addition of new starters unfamiliar with the company should have resulted in slower production per person, both by the new starters themselves and the additional overhead they will have caused to the more experienced designers. Yet the opposite occurred – gross margin improved significantly, an indication of better or more efficient working practices.

Income from Rolls-Royce remains at 100% as the business has still not spun out from the main company. This also accounts for the decreasing geographical reach as the majority of customers are based out of Derby. Customer feedback remains at zero simply due to insufficient data to generate this metric. This in itself indicates some degree of failure to improve customer engagement. Employee turnover also moved to red following the departure of the expert in the second phase.

The main features to highlight from the scorecard are the positive changes with project-related metrics, notably decreasing delivery cycle time, decreasing design throughput, increasing geometry reuse and finally decreasing rate of prototyping – all metrics which are believed to be directly influenced by the knowledge strategy.

Naturally it must be accepted that these metrics are somewhat crude. For example, the rate of prototyping could be argued to be entirely dependent on the type of projects undertaken (runner, repeater and stranger) and not as a result of avoiding mistakes through knowledge use. This is a fair argument, yet proportionally the second phase saw more strangers produced than the first.

The skill level of the designers has also improved as shown in section 5.2. Thus perhaps the improvements in efficiency are from greater personal knowledge and capability? This is a valid argument, yet the gross margin improvement is significant and individual capability improvements are unlikely to generate such a large response over such a short period. Extending this argument it also follows that use of the Design System is unlikely to be solely responsible for the improvement in efficiency and gross margin.

Clearly over the eight month evaluation period a number of changes have occurred that have resulted in lower variable costs relative to incoming revenue. The variable costs are:

- Payroll
- Lasing gases
- Travel costs
- Materials
- Rates (water, electricity)

All except payroll are directly linked to the manufacturing volume, which has increased. For the gross margin to have increased, the rate of revenue increase has risen faster than the corresponding variable costs. It is possible that some economy of scale was achieved, for example lasing gas incurs a fixed loss regardless of the usage. Yet this is still of a significantly smaller magnitude than the cost of labour, materials and actual gas usage required to remanufacture an entire fixture following a failed prototype. It is therefore argued that the improved gross margin is as a result of better working practices, fewer errors and reduced project times as opposed to savings due to economies of scale. It is further argued that these improvements can be attributed in part at least to the increasing influence of the knowledge strategy.

### *Summary*

The preceding section has presented the final facet of the evaluation method, the evaluation of business value and an estimation of the influence and effect the knowledge strategy has had on the business over the eight month evaluation period.

It is accepted that the evaluation approach demonstrated here does not show conclusive evidence that the knowledge strategy is responsible for business improvement. It does, however, indicate a number of points from which conclusions can be drawn. These are:

- The business has undergone a significant disruption during the evaluation period – the technical specialist has retired while two novice engineers have joined the business.
- Despite the departure of the expert, the business has not suffered, turnover has greatly increased and the gross margin also increased.
- Average design time and design throughput has decreased. However, these values are based on a limited sample size and cannot be confidently attributed to a fundamental change in working behaviour.
- Geometry reuse has increased over the period, while manufactured prototypes/errors have decreased despite a higher proportion of strangers produced in the second phase.
- The nature of the operating costs (primarily labour) suggests that the improvement in gross margin cannot be a result of economies of scale.
- It is argued that improved working procedures have led to a greater efficiency and higher throughput of designs relative to the labour investment. This is attributed in part to greater knowledge use and the proactive knowledge strategy.

# Chapter 6

## Discussion

The purpose of this study has been to evaluate if a 'software-based' design support system is capable of providing value added support to a business. The preceding two chapters have presented in turn the development of the Design System and the evaluation of its effects.

The intention was to establish if the knowledge strategy taken provided value to the business. The aims and objectives of the study therefore relate to two different aspects. The first relates to the suitability and design of the Design System. The second relates to the findings of the evaluation to establish what effect the system has had. The first two sections of this chapter examine these two objectives. The third discusses the overall research methodology – was the theoretical rationale correct, could the method be improved and what were the limitations of the study?

### 6.1 Discussion on Design System

The Design System was developed through an iterative process based on the requirements and needs of the business but was influenced through reported experiences and the wider literature domain. The result is a largely hybrid solution, operating primarily as an explicit knowledge base, not to the formalised extent of ontologies, but nor to the unstructured input of CoPs or common reports. The system also contains geometry design tools with some rules but not automated to the extent of KBE-based systems. Characterising the approach is therefore a little difficult. It does not aspire to be a fully automated optimised system but is intended to be more targeted than a 'dumb' repository of text. A brief study was conducted to try and characterise the system using different categorisation and comparison to other common strategies.

In order to understand how the work presented here fits with other systems several different metrics are gathered together from different authors. Several of the most common approaches are then considered and rated for each classification. Given time and access to resources this approach could be scaled up - asking many KM users not only to rank existing projects, but also to include their own projects, would provide a database of projects with a series of attributes. An analysis of the data to find the covariance between metrics could then be used to identify a subset of distinct metrics. Surveys across practitioners have been successfully implemented (Chase, 1997, Wiig, 1994, Skyrme and Amidon, 1997) but these are typically geared towards reflective and motivational perspectives rather than benchmarking. In the absence of such a study, a brief analysis of the most common approaches has been completed, with an explanation of the source of the metrics given.

A collection of measures or scales has been made from a variety of sources, and some generated, these are:

- Tacit vs. Explicit (Polanyi, 1966)
- Personalisation vs. Codification (Hansen et al., 1999)
- Informal vs. Formal (Hicks et al., 2002)
- Process vs. Factual knowledge (Briggs, 2006)
- Automative vs. User driven
- Centralised vs. Distributed
- Novice user vs. Expert user

Five different generic strategies or systems were selected for study: Communities of practice, yellow pages, ontologies, knowledge-based engineering and product lifecycle management systems. All were described in detail in 3.5. Each strategy was given a rating from 1 to 5 for each of the measures described above, shown in Table 27.

| | Communities of Practise | Yellow Pages | Ontologies | Knowledge Based Eng. | Product Lifecycle Management | Design System |
|---|---|---|---|---|---|---|
| *Tacit vs. Explicit* | 3 | 1 | 5 | 5 | 5 | 4 |
| *Personalisation vs. Codification* | 3 | 1 | 5 | 5 | 5 | 3 |
| *Informal vs. Formal* | 2 | 1 | 5 | 5 | 5 | 4 |
| *Process vs. Factual Knowledge* | 3 | 5 | 5 | 5 | 5 | 4 |
| *Automotive vs. User Driven* | 5 | 5 | 2 | 2 | 5 | 5 |
| *Centralised vs. Distributed* | 5 | 5 | 1 | 1 | 5 | 4 |
| *Novice user vs. Expert user* | 3 | 5 | 2 | 1 | 2 | 3 |

*Table 27: Matrix of the different strategies against categorisations*

This can then be plotted as shown in Figure 100.

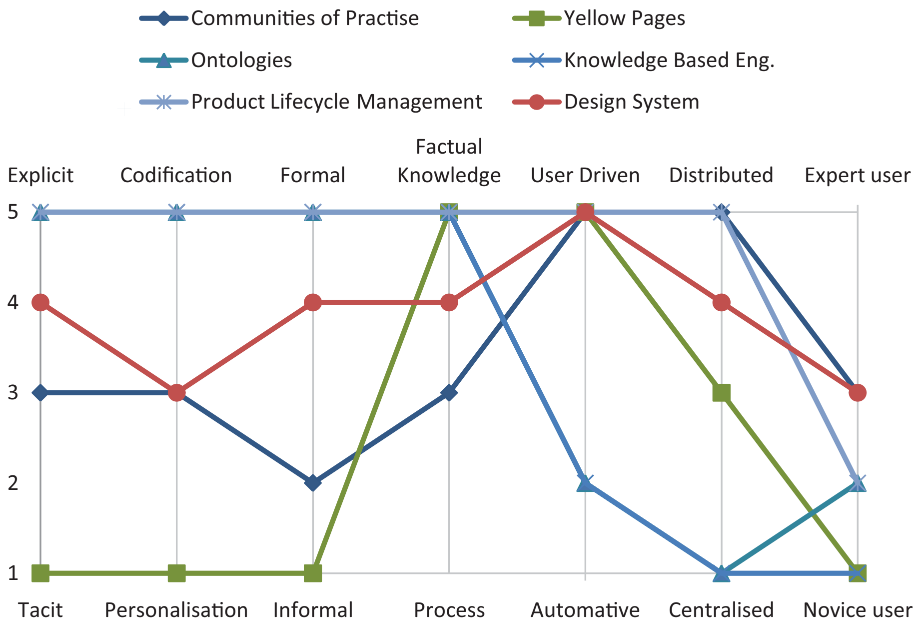



*Figure 100: Plot of the different strategies against classifications showing the relatively unique approach the Design System (red) demonstrates*

Figure 100 demonstrates that most other approaches represent more of the extremes – such as traditional KBE or ontologies with highly formalised and codified strategies. On reflection the closest approach is likely to be PLM systems, yet these typically do not support more general process-based knowledge nor do they support more tacit-based knowledge (as discussed in 3.5). The Design System created here should not be viewed as a 'watered down' version of any of these approaches, rather, an approach design for low volume products in a small business environment using elements from the different strategies.

### *6.1.1 Aims and Objectives Evaluated*

The question remains however, 'to what extent does the system meet its objectives?' In order to answer this, a series of hypotheses were created, based on the initial intentions of the system discussed in Chapter 1 and the 'vision' developed in Chapter 4:

The system meets the requirements as set out in section 1.1 to:

H1.1: Mitigate against knowledge loss

H1.2: Support rapid business growth

The system provides support for the activities required to complete the theorised user scenarios suggested in section 4.1.7:

H2.1: Replace (remanufacture) an existing product

H2.2: Modify an existing product

H2.3: Redesign an existing product

H2.4: Design a new product

H2.5: Quote for a new product

The system provides adequate support for users identified in section 4.1.3:

H3.1: Expert designers

H3.2: Novice designers

H3.3: Manufacturing engineers

H3.4: Salespersons

H3.5: Management administrators

The system is sufficient to capture all knowledge associated with:

H4.1: The Design process

H4.2: Individual projects

**Examining each of the hypotheses in turn:**

*H1.1: The system meets the requirement to mitigate critical knowledge loss.*

That the business continued, apparently without change, throughout and following the departure phase of the technical specialist demonstrates that no critical loss occurred. That this is as a result of the Design System or wider knowledge activities is a point of discussion.

The question is of course "what knowledge?" Much of the experts past product knowledge was captured and embedded in the system. However, section 5.4 highlighted that much of the value adding role of the expert is in fact advising others. His own capacity to design and manufacture solutions is substantial, but this can be emulated by others with his advice or in the case of repeat products, past products. But it is acknowledged (and widely accepted) that the richness of interpersonal knowledge transfer cannot be replicated with IT systems (Daft and Lengel, 1984). Furthermore his own ability to teach and guide others is also lost – as argued by Ahmed and Wallace (2004) novice engineers often do not know the knowledge they need and require the guidance of an expert.

It is argued that the wider knowledge strategy has done much to ensure knowledge and business continuity – but not necessarily due to the knowledge contained in the system. The process of mapping expert knowledge both in section 4.5 and 5.2 highlighted deficiencies in the knowledge transferred to other engineers, prompting proactive transfer activities, such as the writing of 'how to' documents, and presentations given to the other engineers by the expert. These findings lead back to the SECI model of Nonaka and Takeuchi (Nonaka and Takeuchi, 1995) model and the arguments of Hertzum and Pejtersen (2000) that optimum knowledge transfer strategies need a combination of both inter personal transfer methods and IT systems.

Thus in one respect the knowledge strategy has been valuable – ensuring the most appropriate subjects are taught and transferred. But the strategy can never replace his guidance. Therefore while product-based knowledge has been successfully captured by the system, the system could not hope to achieve continuity of all knowledge in agreement with the arguments of Hahn and Subramani (2000) that no expert can truly be replaced.

*H1.2: The system meets the requirement to support rapid business growth.*

This hypothesis can be separated into two distinct aspects: First, does the system encourage or aid rapid growth and second, is the system developed capable of scaling with a rapidly growing business.

The underlying theory behind knowledge utilisation to support rapid growth is based in the Penrosian view that firm growth is inherently limited by the time and cost of converting new employees into business assets through the transfer of knowledge (Penrose, 1959). Thus if knowledge transfer is achieved solely through personal communication, the ‘boarding’ process is limited by the availability of expert resource. Using a knowledge-based system should break this dependence and permit large scale recruitment, without draining existing resource.

The system provides two functions to support new starters: product-based knowledge in the repository and the process-based knowledge embedded in the ‘handbook’.

The principle of product-based scaling was highlighted in the ‘success’ case study section 5.6. The two engineers were observed to utilise the same set of codified knowledge independently, thus sharing knowledge at a rate greater than the consumption of expert resource. The successful boarding process is demonstrated by the knowledge mapping exercise, showing the clear improvement the new starter achieved largely without the technical specialist and with a high interaction with the Design System. In particular much of the new starter’s activities focused on adapting existing designs to gain experience and much of the existing design knowledge was obtained from the system. However, there was still interaction from other designers, particularly the more experienced designer A. Based on observations this appears to be mostly feedback and discussion-based interaction as theorised in section 5.4. Thus the system has not completely replaced the role of the specialist but has demonstrated a capacity to decrease the reliance on the specialist, an approach accepted and discussed by Hahn and Subramani (2000). The system does not therefore allow unrestricted recruitment and training but does successfully improve the potential rate of recruitment.

The second aspect – scaling of the system – is believed to be entirely supported. The server-client framework and development of the system to improve its operation, establishing a distinct database and efficient server procedures and file management, should allow unlimited growth.

In conclusion, rapid growth of the business has been successfully supported, but as expected the system cannot remove all dependence on experts and verbal discussions.

*H2.1: The system provides support for the activities required to replace (remanufacture) an existing product.*

This hypothesis clearly has been met by the system design. All CAD files and laser cutting files can be uploaded allowing the manufacturing engineer to easily download and recut the fixture. Photographs of the completed fixture and/or CAD renders should allow the engineer to understand and construct the product.

The hypothesis fails, however, when examining the actual content of the system. Section 5.3 found that just 11% of recent products contained CAD files. It is well documented that not only do design systems require a 'critical mass' of knowledge (Stenmark and Lindgren, 2004) but knowledge must be valuable and relevant (Kankanhalli et al., 2005b). Thus while the system developed supports the objective, the designer's use of the system and knowledge capture activities do not.

*H2.2: The system provides support for the activities required to modify an existing product.*

This hypothesis is again supported by the system's design, but is flawed by the same issue as above. The issues here demonstrate a recurring theme when comparing sections 5.3 and 5.5. That is to say a gap exists between the knowledge requested by the users and the knowledge they actually input and upload. The users appear not to reflect strategically on their interaction, so as to ensure they input the type of knowledge they themselves would need from the system. This is best highlighted in the interviews by the almost universal agreement that more detail is required particularly on design rationale whilst the engineers continue to input minimal amounts of design knowledge, despite the facility to input more. This represents a clear concern for the future of the work given the findings by Jones et al. (2009) who cite lack of co-adoption as the third most common reason for system abandonment.

*H2.3: The system provides support for the activities required to redesign an existing product*

Here the system does meet the requirements. Accepting the caveat above - that the effectiveness of the system is dependent on the knowledge captured for a particular product, the case studies demonstrated that the system can provide sufficient knowledge to allow a product to be entirely redesigned and improved without additional personal knowledge.

*H2.4: The system provides support for the activities required to design a new product*

The system contains support knowledge for the design of strangers through the provision of the tools, tables and the knowledge repository. Of these, the common features and joining techniques tool are widely used but are not sourced from the system directly.

The knowledge types sourced directly have met with some limitations. The spring designer was found to be insufficient to support the complex designs – as found by designers in the comparative case study (section 5.6.3). Most striking, however, are the findings with the knowledge repository. Designer D reported that the search function was not sufficient to find 'solutions' to the individual problems he encountered during the design of a stranger. Although the repository sufficiently captures product knowledge at a high level to support entire redesigns it does not capture low level problems and solutions to support adoption and adaptation of different ideas and solutions highlighting the question of what knowledge should be captured. The decision to capture product level description was taken early in this project, but as reviewed by Regli et al. (2000) there is a wide range of approaches and corresponding tools for managing design rationale and this system could benefit from more detailed approach.

Based on the evidence from the interviews and case studies, the system does not provide adequate support for strangers. Clearly provision exists, but a better means for the search and presentation of knowledge to support the creativity of designers, as proposed by Schneiderman (2007), is required. Perhaps, as suggested by designer D the system needs to be restructured to capture problems and solutions as subclasses of entire products. The concern with this approach would of course be the overhead required to input this knowledge.

*H2.5: The system provides support for the activities required to quote for a new product*

The intention here was to ensure a more accurate means for quoting by comparing new problems to past problems with known times and costs. Again, the system provides for this knowledge, capturing not just the costing and design times but also classifying the product (both prior to and after design) to allow like for like comparison. However, the author is not aware that this has ever been utilised. This is possibly a combination of time versus need. While based within Rolls-Royce, overrun on a quote (although undesirable) can usually be accommodated. When the business ventures out quotes will be binding and the need to produce accurate quotes will become critical. It is therefore to be seen if this function of the system is utilised.

*H3.1 & 3.2: The system provides adequate support for expert designers and novice designers*

In the original requirements set out for the system, a strong distinction was made between expert and novice designers given the acknowledged differences in approach between the two classes (Ahmed et al., 2003). One growth model discussed was the use of more numerous novice designers, supported by a few experts. The reality has been a much more traditional approach to growth, with engineers of mixed experienced employed. Significantly, no designer currently employed would be classed as a true novice. Furthermore, the intention was to provide novices with tools to rapidly produce runners and repeaters, yet this has not been the required role of the system.

The system has evolved into one designed to support engineers during design rather than generating variants. By default therefore the system provides support for experienced designers but does include knowledge for new employees as demonstrated by the high utilisation by designer E.

*H3.3: The system provides adequate support for Manufacturing Engineers*

As before, the system has the capability to provide valuable support to the manufacturing engineer but is currently lacking. The incomplete knowledge captured was raised as a problem by the manufacturing engineer during the structured interviews. His role necessitates up to date knowledge and geometry, so that he can manufacture components designed by other engineers with minimal dependence on the designer. As the system is typically updated after some period of time, it does not currently provide the support it could. This issue demonstrates the common problem of managing knowledge and data across and through design and manufacturing processes – the very task PLM systems have been designed for (Liu et al., 2009). Furthermore as previously discussed by Jones et al. (2009) this will compound the co-adoption issue as the engineer will be less motivated to support the system adoption.

*H3.4: The system provides adequate support for salespersons*

As of writing the business has yet to employ a dedicated salesperson. Typically initial project scoping and discussions are completed by the team manager and as he is both proficient technically and financially there has been no need to use the system in this role.

Currently system access is restricted to the local secure network. This represents the only technical limitation to meeting this original hypothesis. However, it is thought that the nature of the business growth and style of customer interaction will mean that a technical lead will always be involved early in the scope of projects and thus render the system redundant in this role.

*H3.5: The system provides adequate support for management administrators*

This refers specifically to two aspects of the system. The rapid output summarising capability of the system and the costing, material usage knowledge included in the database. Of these, the summary sheet has been used, but not nearly as often as expected. Typically the manager produces monthly summaries to the board reporting on recent products. It was expected that the summary sheet would be ideal for this role, yet it has not been used as such. Anecdotal evidence suggests that this is because of the poor formatting and rigid structure of the output sheet. Furthermore, in the interviews the manager does describe using the system for accessing images, just not using the output sheet.

The second role, the use of costing and material usages have not been utilised at all. Yet this may be simply as a result of the inability to produce summary data from across multiple projects. One idea therefore would be to allow data mining from within the admin function perhaps to output monthly reports, generating financial knowledge (Dhar, 1998) or to provide cross-sales knowledge (Anand et al., 1998).

*H4.1: The system is sufficient to capture all knowledge associated with the design process.*

This is perhaps the weakest of hypotheses 4.1 and 4.2. The system was intended to support multiple knowledge types as per Lundvall's (1996) classifications. In reality, despite the success of previous process orientated research (Baxter et al., 2007, Blessing, 1994), in this research the captured process knowledge is little used. The creation of a system structured around individual projects is inherently product-orientated and despite its alignment to the methodology, three points of interaction do not seem sufficient to capture experiences throughout the more detailed design stages.

It has been suggested that a function be created to record events and experiences as a 'log', in other words to capture small events throughout the design process using a free text field, automatically time stamped. This would de-emphasise the need to record a large amount of detail post design, but would also lead to greater knowledge capture about the process by which the final design was created. This is much more akin to tools such as DReD (Bracewell et al., 2004) which was discounted due to the overhead required to complete. However, using the system as a 'logbook' – an approach that has seen value (McAlpine et al., 2006) - at a more abstract level than DReD may encourage greater use. Undoubtedly it would require training and encouragement from team leaders to make it effective. It is suggested therefore that some work is required to meet this objective fully.

*H4.2: The system is sufficient to capture all knowledge associated with individual projects.*

That the system can capture a vast amount of structured data and in theory unlimited files and unstructured knowledge suggests that this hypothesis has been met. Yet during the interviews, many of the designers sought more detailed knowledge than is currently captured. It is strongly believed that this is dependent primarily on poor knowledge input. However, some steps could be taken to support longer and more detailed entries such as larger text boxes, pre-suggested formats and prompts and the logging function suggested above. Beyond these relatively elementary changes, the dependency on high quality input remains an issue of motivation and encouragement. The system has therefore met this objective.

### 6.1.2 Future Developments of Design System and Approach

The hypotheses and conclusions above suggest that overall the system is adequate in most respects. But a number of changes are proposed that would address some of the issues encountered, these are:

**Search Improvement:**
Currently the users can search the catalogue of existing designs using one of two methods: a free text search or a filter search based on a single category and corresponding term. Both of these approaches require the user to have a preconceived idea of the solution they require.

A more proactive solution is proposed that will use a nearest neighbour (Mitchell, 1997) or proximity based search to find products similar to an existing entry allowing users, as proposed by Hoare and Sorensen (2005), to better 'forage' for knowledge. The idea would be for users to enter the specification and requirement details, and then press a search button to draw up a list of similar products. The intention would be to proactively promote and demonstrate the potential knowledge available.

**Concurrent Logging:**
As previously discussed, a more concurrent means for capturing process knowledge throughout a design's development is required. The suggestion is a free text input with a time stamp allowing events, decisions and rationale to be logged. Ideally some form of indexing or data mining could be implemented to allow specific problems and solutions to be retrieved.

**Expansion of repository:**
Linked to the above, the concept of more knowledge, focusing on other aspects of support than product related knowledge has been highlighted.

During the interviews it was suggested that a similar repository be created populated with guidelines and knowledge related to different manufacturing processes. Should a user be requested to design a fixture for a process they are unfamiliar with, for example water cutting, the repository would contain the necessary guidance to support the engineer. Long term a relational database could be constructed, linking a series of different repositories modelled on the existing one, allowing many aspects of knowledge such as manufacturing processes, products, material qualities and customers to be retrieved simultaneously based on any new specification.

**Data Mining and Reporting:**

Finally, with the expansion of knowledge captured or contained, so the provision of knowledge extraction should be expanded, in particular to automatically derive and extract reports based on product costing, dates of completion and customer feedback. In short, the Design System could be utilised even further to become the primary management and design support system to the business.

## 6.2 Reflection on Results

This section will discuss the findings and implications of the results presented in Chapter 5, in particular the aims and objectives of the research will be tested and key themes and lessons learnt extracted.

The primary hypothesis of this research was:

*A Design System can provide value to a business by supporting knowledge reuse by designers.*

In section 5.7 it was argued that business value had increased given the indicators from the balanced scorecard, but the value could not be attributed entirely to the system. Examining each of the Design System facets provides the following evidence:

**People:** Over the eight month evaluation period, individual core capability increased marginally, but overall competency fell as a result of the expert's retirement. The number of employees increased, but two novices started while the expert retired. On this evidence turnover would be expected to rise, but profitability to drop.

**Content:** Knowledge was continually captured over the evaluation period and most new projects were entered. Knowledge content over the period greatly increased despite poor completeness in some fields, leading to an increasingly valuable system.

**System use:** The system was used regularly throughout the evaluation period both for input and access of knowledge and the number of distinct 'sessions' rose through the latter period of the evaluation. It is therefore expected that any effect the system has either draining resource or adding value would be enhanced during the latter evaluation stages.

**Interface:** All interviewees reflected positively towards the system indicating a degree of acceptance and satisfaction towards the system. All users agreed it was valuable, thus indicating that some benefit was perceived at the working level. No significant change in perception occurred over the evaluation period, thus any effect this may have on the ultimate value to the business will be unchanged.

**Products:** The analysis of three case studies demonstrated that use of expert resource could be reduced, which should in theory improve the profitability of the expert. It was also found that knowledge use does not necessarily imply shorter design times, but can avoid errors, therefore reducing costs and lead times.

**Value:** Finally, the BSC indicated increased turnover and increased profitability together with reducing lead times and throughput.

That the system is thought to improve the very metrics that have increased suggests some degree of reliance and dependence – given that working practices have not changed significantly nor have the employees.

On critical reflection, however, the magnitudes of improvement in gross margin and lead times cannot be entirely as a result of knowledge use, or rather as a result of direct cost savings given by error avoidance and reduced discussion time. This can be adequately demonstrated when it is considered that of the nine products analysed for phase 2, only four utilised the system. Making the assumption that the others received no effect suggests that those four products had individual savings in lead time of 34% – clearly unreasonable.

Conversely, that the increased use of the system does not correlate to a negative effect, which would suggest that some return on the increased use (and investment) has been achieved. The alternative explanation is that an additional factor has changed significantly over the study without being captured – unlikely given the wide array of metrics assessed.

In the author's view a number of factors may explain this contradiction: first, the dataset used to populate the BSC is insufficient to allow like for like comparison. Hence the adoption of different types of products could have caused a change in the gross margin. For example, overall the time spent per product has decreased. This is of course desired for two equivalent products but it is possible that the products in the second phase may have simply required less time. This in turn may have allowed for greater efficiency, but equally likely, it could cause profitability to decrease. This factor can neither be confirmed nor discarded with the data available. In future a longer study (or one based on a high product volume company) is required to examine and resolve this factor.

Second, despite the use of the diaries, actual design processes have not been examined in much detail. In particular the structure of projects, interactions with the customers and delivery mechanisms have not been considered. Two telling metrics are the MCE (design throughput) and design cycle time. MCE reduced by 57% from phase 1 to 2, significantly more than the actual design time reduction. Thus the team has become significantly better at delivering and completing projects. This will undoubtedly be part of the learning and organisational knowledge established over time, but it will also have been influenced by the increasing structure provided by the quality procedures and Design System. The Design System in particular requires upfront logging of new products and as demonstrated by section 5.3, this was usually completed. It will have therefore provided a visual structure and point of reference from which to pursue and complete the project. It is therefore argued that the knowledge capture activities themselves could be responsible for improving working practices.

Third, the system usage analysis demonstrated a much higher use of the system than reported by both the diaries and the design reviews from which the BSC is constructed. The possibility therefore exists that the system has provided supplementary support such as that cited by designer D in the interviews (quoted below) far in excess of the reported support and may well have improved all the products.

> *"...for example, yesterday I was talking to Designer C about a particular project and there was an example on the design system of a similar solution and he was able to pull it up and show me several photos very quickly - that just doesn't happen in a usual design office. You can describe it and you could pull up the number of the drawing."*

Most likely both the second and third points both contribute to the overall improved business, while the error created by the sample size significantly blurs the causality of the improvement.

### 6.2.1 Theoretical Advancement

The important question remains:

*"Is the system and approach developed appropriate for adoption and application by other companies wishing to improve their own businesses?"*

It has been argued that the approach taken is a hybrid approach and while no one component is unique, the system developed is. Thus does the approach represent an improvement over past approaches and are the existing frameworks such as Hahn and Subramani's (2000) incomplete?

Firstly, the approach and system is bespoke to the business. But it would be incorrect to argue that this represents a new and unique theory of KM. The approach has utilised an array of previously established methods each best suited to the role, for example the codification of knowledge and use of storytelling, to develop the system.

The common problem with most of the previous approaches individually is simply that they represent extremes. For example CoPs as demonstrated in Millen et al. (Millen et al., 2002) offer an excellent means for capturing cross company discussion, but would simply not add value in a small scale environment. KBE can encode extremely complex geometry through parameterisation and optimisation, yet requires expert training and is too time consuming for one off products (Sandberg, 2003). This need to develop a strategy effective across a small team without specialist knowledge is perhaps the distinguishing feature of an SME's knowledge requirements.

Could and should the approach be adopted by other SMEs? It was argued in Chapter 3, that in the modern era, no business can afford not to implement some form of Knowledge Management (Bose, 2004). Reflecting on the research experiences, this view remains unchanged. The benefit of accumulating knowledge over time cannot be underestimated, particularly for an expanding business. However, the decision to implement a knowledge strategy should not be viewed as binary, rather as a continuum ranging from low investment to high.

Most modern businesses have some degree of IT technology, often product or customer databases, ordering systems and document storage. As highlighted in Chapter 3 these are usually dumb systems which add little intellectual value to the business. The basis to the system developed here could be argued to be little more than an extended database, but it is the establishment of a structured means for capturing additional knowledge associated with the products that is important in part representing the process support argued for by Baxter (2007). The study here has demonstrated that with a relatively low investment, a long term benefit can be gained as a knowledge base is established and expanded. The example for other companies should be that where possible even small steps should be taken to ensure the growth of a knowledge base - as Liebowitz (2008) puts it "weaving in KM into the organisation fabric". For example, simply marking up customer transactions with notes and advice on customer preferences would ensure better or more targeted customer handling.

The important caveat to the widespread adoption of KM is its role. As argued above and by Davenport (1999), any strategy must be aligned to the business. Using the example above, little value would be created by capturing individual customer preferences in an Estate Agent for example. The infrequency of interactions with the same customers would negate any benefit. Instead, better knowledge or meta-data could be captured about the properties, the area, experiences by residents, in turn allowing for much more targeted house viewings.

Here, the instigation of a knowledge strategy was motivated by a very real and potentially critical event – the retirement of the expert. But two interesting points should be remembered. First, the majority of knowledge actually accessed was from the more recent (+400) projects entered by the designers themselves – designer C even stated that his input was primarily for himself as an 'aide-mémoire'. Second, while a large quantity of knowledge was captured and codified from the expert, it is likely the most effective aspect of the knowledge strategy was actually the systematic identification of knowledge gaps prompting tacit knowledge transfer.

The first point reinforces the evidence that KM activities can be effective when operated as part of existing routines and practices. The second point leads to the inevitable conclusion that mitigation against knowledge loss should be established long before the issue ever arises. Knowledge mapping and strategic development of employees should be seen as part of the resource planning activities of the business from its very establishment – the very principle of the Knowledge Based View of the Firm (Grant, 1997). The departure of any employee on a small team is likely to be disruptive but clearly it can be minimised with foresight and a strategic approach to handover. That proactive methods caused a positive response to core competencies demonstrates the value of accurate mapping and practical responses.

Perhaps the most significant theme throughout the implementation is that of individual motivation and the inertia against adoption of new practices and processes, particularly when sharing knowledge. Prior studies have observed the inertia of individuals against knowledge sharing (Sveiby, 2001). It is often against individuals' natural instincts to share knowledge openly. Furthermore the observations also suggest another potential issue – designers are typically highly creative and goal-focused. Their primary objective is to solve a problem through design. It should be unsurprising therefore that they find recording the rationale behind their decisions a distraction to the design process.

As presented in section 5.3, designers are initiating the storage of jobs and several entries have a completed first page and some with minimal uploads. On the whole the knowledge required to meet the user scenarios described at the start is not being captured. Six suggestions as to why this may not be happening are:

- A lack of defined expectations
- Knowledge is seen as too valuable to share
- Other tasks are consciously prioritised
- Inputting information is too much of a burden
- Knowledge cannot be codified
- Confidence of work

The initial two suggestions are, in the author's opinion, unlikely reasons on their own in the study presented. Firstly, there has been a high level of understanding and dialogue with the end users throughout the development of the system and in explaining the rationale behind the system. Workshops have been run in order to obtain input from the designers on how to improve the business and how best to utilise the knowledge. Second, the designers are willing and at least appear happy to share their knowledge – they have never shown unwillingness to share knowledge via other means. This would agree with the findings of Kankanhalli et al. (2005a) in which the authors found that the loss of 'knowledge power' did not appear to affect knowledge codification.

The third and fourth suggestions above provide interesting discussion points. At the time of the systems implementation into the workplace, the design team underwent an annual review. The importance of the role of knowledge transfer in the organisation was made clear to the team by senior management and furthered by the author in June. The team were encouraged to support the knowledge transfer programme, with 30% of their time nominally aligned to this activity (of which the Design System is one aspect). This was designed as an aspiration target, in order for the designers to balance their requirements and improve their prioritisation of knowledge tasks.

Despite this allocation, designers spend very little of their time on knowledge related tasks and always prioritise design and manufacturing related tasks over those of knowledge transfer. This was in fact the commonly cited reason when asked during the interview. It cannot be due to the burden of inputting knowledge alone, as the designers are all typically well motivated and remain committed in all other activities and tasks. It does appear true, however, that despite encouragement from management, as engineers they see notation and paperwork (and therefore knowledge transfer) as an aside to their primary role – an observation made in prior studies (Marsh, 1997). In the developing knowledge-based economy, this view must change. Companies cannot afford for individuals (regardless of their ability) to operate in isolation and not support the company's knowledge base.

As per Polayni's theory of tacit knowledge and knowing, it is possible that designers are simply not able to codify the knowledge required in the system. It would seem that the study supports this, of the 'knowledge' entered, the most common inputs were the initial specification page. This is arguably the most explicit knowledge and easily codified. Despite this, throughout the study the designers the designers were regularly encouraged to describe and document the issues they encountered and solutions they developed. This level of detail is regularly captured as part of improvement programs and customer feedback, in many organisations. Furthermore, much of the knowledge captured refers to descriptions of the product, its operation and key requirements. It is not felt that this reflects the 'un-teachable' knowledge described by Polayni (1967).

During the interviews, the interviewees were asked what steps they would take to encourage knowledge capture. Four (including the manager) responded that greater discipline should be used to ensure that the system is completed as per policy. How this is achieved is not necessarily obvious.

Authority and management lead is required, together with a means for encouragement, either monetary or other. But as part of this a more procedural approach should also be used. Currently, the business does not currently enforce a formal interim or close-out review of every design project and feedback is generally delivered via the client after delivery. Therefore if formal review meetings were established scheduled after delivery and designs reviewed by a senior designer, a defined point by which all documentation must be completed is created. Furthermore the review would encourage reflection and discussion supporting the knowledge capture and perhaps confirming the views of the engineer on certain matters.

No single reason can be attributed to the reluctance of designers to implement the knowledge transfer programme described to the required level of detail. The engineers all appear positive towards the programme, and would like additional detail during reuse yet the lack of genuine commitment to knowledge capture remains a significant issue in the implementation of knowledge programmes.

It is therefore argued that any strategy must be implemented in accord with a concerted effort to change practices and fundamentally alter the beliefs of employees to encourage sharing and view the strategy as a necessary ‘part of the job’. It is further argued, based on the increased use of the system following June, that the presence of a local ‘champion’ is significant in encouraging the adoption of new systems and practices. Both approaches have been previously identified as ‘critical success factors’ (Wong, 2005, Soliman and Spooner, 2000) but in the authors view represent the former represents ‘the’ critical factor for any system integration.

## 6.3 Reflection on Research and Avenues of Future Study

The final section of this chapter reflects and discusses on the methodology used to test the research hypothesis. In particular the limitations of the study and conclusions drawn above are examined and aspects for future studies to improve upon are given.

The study here represents an advancement to the field of KM and design reuse. It has crucially demonstrated a link between business value and the advent of a KM Strategy, previously lacking. However, the causality remains unclear and statistically the study is weakened by the small size of the business. A number of avenues of further research are therefore opened, both to further clarify the hypothesis and to advance the field beyond that covered here.

Fundamentally the study is weakened by the simple premise that the study has examined just one business. It is believed that the business can be thought of as representative of many small manufacturing businesses; however, there could be aspects of the environment that are unique and which could affect the business in such a way as to cause an unrepresentative response. Given the opportunity, a series of studies need to be undertaken across several businesses and ideally across different sectors. The resource problem that this raises is non-trivial however. In particular the need to develop a bespoke tailored and the resources required may preclude the detailed, multi-faceted approach that has been conducted here.

Two streams of research therefore emerge: the need to confirm (or disprove) with greater confidence the level of causality between the knowledge implementation and the need to establish if the findings here apply to SMEs in general.

Realistically, the issue of cross business applicability and value would need to be addressed through a high level approach of the type discussed in section 3.7. However, the study has demonstrated that if the causality and effect of a new process is to be understood, a series of measures need to be taken examining the actual role the process or strategy actually has. It is not enough to simply survey the opinions of a manager or chief executive as per Darroch (2005). The study must take into account the degree of uptake or adoption, the quantity and quality of knowledge utilised and the mechanism or effect the knowledge has on the value generating activities of the business.

To confirm with greater confidence the hypothesis that knowledge activities generate value will primarily require a much extended study but also a greater number of detailed studies examining exactly how knowledge is reused. It is argued that in engineering in particular, a study should examine the degree of 'cross pollination' of ideas and if the products that reuse ideas and geometry have a statistically significant lower cost rate, without a corresponding drop in quality or innovation. The extension of this research therefore expands out of the field of Knowledge Management into the fields of innovation, creativity and design.

To advance the field of KM further, the key research directions lie in the issues of implementation and long term effects. Implementation as discussed often in this study is the key to the success of a KM System. Without the support and interaction of individuals and without an accessible system, the strategy will simply not be effective. But while this research has achieved a degree of success, it is not clear what the primary motivating factors are and how best to encourage future strategies. A number of factors were beneficial, the presence of a researcher, the well motivated team and the potentially damaging knowledge loss supporting the work of Wong (2005) and Soliman and Spooner (2000). Yet much could be improved and it could be argued that full support and engagement was never achieved. Could a study deduce if an array of methods could guarantee engagement? Are financial incentives necessary or is it simply a matter of time before processes are accepted? This avenue of research expands into the fields of organisation behaviour and psychology, but it does represent a major 'gap' in the field of KM.

The long term effects have also not been demonstrated by the study. The intention throughout has been to establish a complete history of products and past knowledge which the business can utilise and profit from with increasing returns. This four year study, of which the final system was only on site for a year is not long enough to conclude if this would be the actual outcome. It is possible that as a business becomes more established and employees stabilise the need and impetus to capture and reuse knowledge drops. As argued throughout, the aim of KM is to utilise knowledge to generate value (Edvinsson and Malone, 1997), not to create an archive (Demian and Fruchter, 2006). If the knowledge is not reused, the continuation of a knowledge strategy may well become a hindrance.

## Summary

This chapter has reflected and discussed on three different aspects of the proceeding work, the suitability of the Design System measured against its aims, the outcome of the research and conclusion against the original hypothesis and finally the limitations to the study and avenues for future work.

The hypotheses in the first section clearly demonstrate the need to ensure the developed system is aligned closely with the business strategy. For example, the system design has evolved (correctly) away from supporting novice engineers and high volume runners to the more repeater-orientated repository. Yet the business's increased emphasis on strangers (44% of products completed during phase 2), was perhaps not sufficiently anticipated, rendering the system weaker in this role. Although many of the aims and objectives of the system have been met two lessons can be drawn: first the high dependence on knowledge capture has clearly been demonstrated, as without adequate knowledge the system is simply not valuable. Second, while codification can minimise expert reliance, mitigating knowledge loss and supporting scale up, other knowledge sharing activities are still required and verbal discussions cannot be replaced.

The second section reiterated the rationale behind the positive conclusion for the research hypothesis and debated the theoretical implications and advancements that this might entail. It was concluded that while no new theoretical approach was undertaken, the bespoke implementation of a collection of methods tailored to the issues facing an SME demonstrates a novel approach that could be adopted by other SMEs faced with similar issues.

Finally the third section acknowledged the limitations inherent in a study based on a single case study and highlighted the two divergent directions of future research necessary to conclude the hypothesis. Furthermore, it described other aspects of KM that still require research, namely the long term sustainability and effect of such policies and specific research addressing the issues of implementation and adoption by employees.

# Chapter 7

## Conclusions and Future Research

This chapter presents the main conclusions of the research presented in the preceding chapters. It opens with a summary of some of the significant findings, followed by key contributions to the field of research. Recommendations for the case study business and potential areas of research requiring future study are presented before the final concluding remarks.

### 7.1 General Conclusions

This thesis has concluded that a knowledge-based Design System is capable of providing value to a small to medium enterprise through the reuse of design knowledge, successfully protecting the business from critical knowledge loss.

Both the implementation and evaluation of the Design System led to a number of findings, some presupposed, others that became apparent over the course of the research. The most significant findings are summarised here, prefaced by the relevant area of the study:

- System design: The role of a knowledge system must be clearly aligned to the business objectives, end users and long term vision. Functionality that does not support these objectives is significantly underused and often becomes redundant.

- Implementation: Individual inertia or reluctance to input knowledge represents the single biggest issue when implementing a knowledge strategy. This can be reduced by aligning capture with existing processes, but as time passes, inertia increases.

- Implementation: A strategic gap was observed between the knowledge shared by designers and the knowledge sought. They did not appear consciously to link the two. No solution to this paradox was found, but it is believed that as knowledge re-use increases, so will knowledge capture.

- Knowledge transfer: Accurate Knowledge mapping – identification of key knowledge – forms a necessary and valuable part of a knowledge strategy. Used to guide pro-active teaching, a measurable improvement in understanding can be created.

- Knowledge capture: It was found that of the methods trialled with the technical specialist, structured interviews were the most productive capture method, efficiently providing a rich and structured output compared to time consuming storytelling and shadowing.

- Design tools: KBE tools appear to fall on a continuum trading between capability and ease of use. Tools must therefore be designed with the end users in mind and acknowledge that designing for a large problem domain is likely to result in a complex, expert driven tool.

- Knowledge use: Knowledge reuse was not found to reduce design and manufacturing time but was successful in reducing and avoiding errors. Evidence suggests, however, that designers can overly trust prior knowledge, potentially reducing innovation.

- Knowledge use: Codified knowledge use was primarily utilised during the first 20% of a project's development cycle, and during early iterations of a project. Conversely the technical specialist was typically sought by engineers during later product iterations and when faced with specific problems.

- Knowledge use: Use of the Design System was found on average to account for 2% of a designer's time, compared to 7% for verbal communication. Furthermore, the latter figure is believed to under represent the true figure.

- Evaluation: It is believed that the use of the Design System led to improved working procedures, attributed to the increased process awareness and formalisation. This resulted in more efficient project throughput and reduced lead times.

## 7.2 Contributions to Knowledge Management Research in Design

This thesis has demonstrated a suitable knowledge strategy for an SME founded on a knowledge-based Design System. The extensive literature review in Chapter 3 demonstrated the breadth and variety of approaches that have been trialled to support businesses, in particular those in design and manufacturing via management of business knowledge. Despite the wide ranging research in KM it was argued that there was little research to support small scale businesses and furthermore little evidence demonstrating the actual effect KM has on businesses. The research here has addressed this deficit by developing a bespoke knowledge strategy designed to support an SME facing potentially critical knowledge loss and using a multi-faceted evaluation approach to understand the role a Design System can have within the business.

While this approach and system developed was developed specifically for the specific business studied, the strategy is not limited to this business. Rather, the research demonstrates an approach that could be applied to any SME requiring a KM strategy to maximise the use of prior knowledge and safeguard against potential knowledge loss.

Some caveats to its application exist:

- The approach has been tailored to a project-orientated company, and typically for individual designers – the lack of collaborative or concurrent engineering support represents a weakness of the system which could be developed.

- The approach was specifically designed for a small team, where individual discussions were prevalent and an online discussion forum was not required; again this could be rectified.

Overall, however, the research should demonstrate how a relatively simple strategy, strongly tailored and integrated with the business strategy can provide valuable support for the business.

## 7.3 Recommendations for Pro-Laser

Within the case study business, the research has had a profound effect. Not only is this a result of the development and launch of the Design System itself, but from the acquisition of data and increased understanding and formalisation of products and processes. As of writing, the business continues to flourish and develop with consistently high demand for fixtures and tooling and an ever widening portfolio of products. Reflecting on Greiner's growth model discussed in section, the business continues to evolve through stage 2 moving towards a more decentralised mode of operation.

Throughout its development, the knowledge strategy must remain a pivotal component of the organisational structure and behaviour of the business. Despite the successful mitigation of the specialist's departure, the business must continue to maximise its existing knowledge base through the Design System. The study therefore recommends a number of actions to maintain business growth:

- As discussed, a series of alterations are recommended to the Design System, importantly the inclusion of better data mining, concurrent logging of decisions and design rationale and the potential expansion of the knowledge repository.
- Greater structure and discipline should be applied to the designers to encourage more complete knowledge capture of products. It is further

suggested that this incorporates a review and signoff procedure by senior staff to ensure adherence.

- The strategic management and development of core competencies should be maintained. As argued above, successful mitigation against future loss can be minimised through long term strategic planning. This could take the form of tutorials by different team members, ensuring particular lessons learnt are shared and transferred.
- Finally it is also recommended that the balanced scorecard be maintained to further monitor the business and to advise strategic decisions.

## 7.4 Recommendations for Future Research

There are limitations to all research. Every aspect of this research has attempted to utilise numerous different resources and methods to minimise the study's limitations. Throughout, a mixture of quantitative and qualitative data was gathered, opinions garnered and pro-active experiments completed. However there remain fundamental limitations:

- The study has only examined one specific case study. Attempts have been made to highlight any aspects specific to the business studied such as the emphasis on fixtures and tooling. But no evidence has been gathered to establish the validity of the findings to other businesses.

- The evaluation period, although conducted over a reasonable time span (eight months) did not produce a sufficient data set to correlate statistically the effects of knowledge on final products.

This study therefore recommends that two avenues are pursued. First to establish if (as supposed) a causal link between knowledge use and product cost exists. The second is to establish if design systems such as the one developed here provide value to all design and manufacturing SMEs.

The field of study examined here focused primarily on the effect KM activities can have. While best practices and experiences were utilised throughout, there remain two aspects that deserve further study:

- Implementation: Throughout the study steps were taken to encourage adoption by employees. Largely these steps were iterative trial and error. In future clear factors need to be identified to guide future implementations.

- Long term effects: Despite the extensive evaluation, eight months is not sufficient to establish the long term role and effects knowledge support may have on a growing business.

## 7.5 Concluding Remarks

The ever increasing power and affordability of computing has already revolutionised much of how we live and work. Yet it remains unclear how this capacity can be best used in creative domains such as design, a field traditionally driven by the decision making capability of designers. The research here has demonstrated and evaluated one possible method of support – supplying designers with timely knowledge from a repository to allow better and more informed decisions. Much work remains to be done however; ultimately design capacity is still limited by the availability of experienced and well trained designers. It is likely that this will always be the case, but ensuring this resource is utilised efficiently and effectively is paramount to establishing competitive advantage and ensuring business growth. The field of Knowledge Management therefore continues to be an area of significant importance, not least within design and manufacturing.

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