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PROVIDING VALUE TO A BUSINESS USING A LIGHTWEIGHT DESIGN SYSTEM TO SUPPORT KNOWLEDGE REUSE BY DESIGNERS

Nicholas Reed[1], James Scanlan[1], Gary Wills[1] and Steven Halliday[2]
(1) University of Southampton, UK (2) Rolls-Royce plc, UK

ABSTRACT

This paper describes an alternative approach to knowledge based systems in engineering than traditional geometry or explicit knowledge focused systems.
Past systems have supported product optimisation rather than creative solutions and provide little benefit to businesses for bespoke and low volume products or products which do not benefit from optimisation. The approach here addresses this by supporting the creativity of designers through codified tacit knowledge and encouraging knowledge reuse for bespoke product development, in particular for small to medium sized enterprises.
The implementation and evaluation of the approach is described within a company producing bespoke fixtures and tooling in shorter than average lead times. The active support of knowledge management in the company is intended to add value to the business by further reducing the lead times of the designs and creating a positive impact to business processes.
The evaluation demonstrates a viable alternative framework to the traditional management of knowledge in engineering, which could be implemented by other small to medium enterprises.

Keywords: Engineering Design, Knowledge Management, Knowledge Based Systems,

1. INTRODUCTION

It is broadly acknowledged that the post-industrial economy is rapidly becoming the knowledge driven economy suggested by Bell in 1974 [1]. Due to increased emphasis on innovation to provide a business' competitive edge [2] knowledge has now become the key asset in many companies relative to the diminishing primacy of capital and labour [3]. This new economy now requires companies to effectively manage and exploit their knowledge, in order to maintain a competitive advantage and maximise their returns [4].
This is particularly important for companies in manufacturing and engineering. Traditionally limited by factors of production such as materials, labour and money, companies are now being forced to consider knowledge as their key competitive advantage, it is unsurprising therefore that Knowledge Management (KM) in engineering is seen as the new step change since CAD/CAM introduction [5].
The impact to the manufacturing environment is potentially immense. With the increase in rapid and repeatable production techniques, such as laser cutting, water jet cutting and rapid manufacturing processes requiring minimal fixturing and setup, many products are becoming knowledge-based goods. These goods "obey a law of increasing returns, once the cost of designing or making the first has been absorbed" [6] With the addition of modern rapid manufacturing this statement can hold to any manufactured item providing the value is inherent in its design, not the material, generating the potential for high returns.

2. REVIEW OF KNOWLEDGE MANAGEMENT

Knowledge is usually described as the additional contextual understanding of facts that provide the foundation for our decisions [7]. A loss or lack of knowledge relating to a particular decision can lead to unnecessary rework, increased costs from acquiring the required knowledge or an incorrect decision to be made. Knowledge is therefore a valued commodity.

Knowledge Management (KM) is a relatively recent discipline, the term coined in 1986 by Karl Wiig, at a Swiss conference sponsored by the United Nations – International Labour Organisation [8]. Wiig defined KM as managing the deliberate and systematic process of building, renewing and applying knowledge to maximise an enterprise's knowledge-related effectiveness, i.e. to realise the best of its knowledge assets and to provide a competitive advantage [9].
Since its first inception, Knowledge Management has generated a burst of activities and investment in projects, indeed in 2002, 80 percent of fortune companies had Knowledge Management staff [10]. Today the terms encompass an array of issues and approaches, from social networking activities to the development of software systems to aid or support decision making. The systems can be generically termed Knowledge Based Systems.

2.1 Knowledge Based Systems

There is an entire array of tools that fall under the classification of Knowledge Based Systems, ranging from knowledge repositories and basic filing systems to expert systems intended to replicate or replace human capabilities [8]. In the past systems were defined as Knowledge Based if they consisted of an inference engine and a separate knowledge base, from which the engine could determine solutions. This definition, however, was formed from the Computer Science perspective, evolving from Artificial Intelligence research stemming back to the 1950's [11] and recently, this distinction has become blurred as more systems are developed under the Knowledge Based System term.
Traditionally too, this field is where the majority of knowledge management work has occurred in engineering. A subset of Knowledge Management termed Knowledge Based Engineering which combines a codified rule and knowledge base with computer-aided geometric design [5]. They are generally developed using formalised knowledge of relationships to assist or automate tasks to ensure faster design or production.
Yet many knowledge based systems in engineering are highly orientated towards geometry production, such as parameterised CAD models, [12]. The emphasis of these systems is typically on codifying knowledge to support automation and non creative design tasks, where geometry is the output. While often very capable, these systems are targeted at 'well-known' highly optimised products. As with any intelligent system, they are limited to the domain they have been designed for and widening the domain usually causes a decrease in capability. While suited to solving "complex, highly structured problems" [12] these systems are simply not capable of developing novel or new products.

2.2 Design Reuse

Design reuse describes the application of past concepts, ideas or geometry to a new problem thereby minimising the time and effort required to develop the new solution. Conceptually it is easy to understand the benefit to the design process by the efficient application of design knowledge; Busby [13] lists four key benefits:

- Use of existing designs avoids the use of resources consumed in the original design
- It helps avoid error and uncertainty associated with new development
- It helps familiarise production staff with the design
- It helps clients maintain consistent ways of using and maintaining the product

Studies indicate that experienced designers rely heavily on past designs [14], yet these designers rely on past designs of their own, those that they are familiar with and remember. Yet despite the benefits to the business, design reuse on an organisational level is remarkably low.
In the study conducted by Busby, he utilises anecdotal evidence to establish themes which underpin the failure of design reuse, both its failure to take place and the failure of attempted design reuse. While the findings highlighted the specificity of individual cases of failure, at a high level it was possible to discern particular themes. Notably, constraints associated with the organisation and processes represented 40% of all failure cases. There is also strong influence of designer's individual preferences (and perhaps prejudices) which can preclude against reuse. Yet Busby does conclude that an effective database of designs would remedy much of the issues observed. It is assumed that the database would attempt to encapsulate the rationale required (and often observed to be missing by

Busby) aiding reuse. Based on the study, however, it would also need to be established with a process for reuse to mitigate the organisational problems encountered in failure.

2.3 Types of Systems

In this paper, systems will be generally categorised into two different families under the headings of lightweight and heavyweight systems. These terms are intended to correspond to the degree of automation, knowledge and intelligence embedded in the system together with the implementation cost and effort required for implementation and are best illustrated by expert systems that "embody expertise" [15], but require significant investment to capture and embed the knowledge before the system is suitable for use [11]. These systems symbolise the heavyweight approach, ideal for optimising high performance components or multi-part systems where performance is crucial and the investment in the system is realised by the end product. Conversely a lightweight system offers less automation, intelligence and capability but requires lower upfront investment. This classification is not intended to be rigorous, but to indicate the difference between the common approach to knowledge based systems and to that taken here.

3. APPROACH

Here the disadvantages of the current approach are presented, the solution advanced in this study is presented and the approach taken to evaluate the solution outlined.

3.1 The Problem

When considering past knowledge management studies in engineering, the majority appear to be aimed at embedding knowledge to produce 'heavyweight systems'. Often they facilitate the production or development of a product that could not otherwise have occurred without the system such as multi-objective optimisation functions or, they are designed to mimic or replicate human behaviour in order to vastly scale up speed or volume. Today's system builders have the capability of deploying vast computational power, yet the primary benefit of these systems lies in repetitive computation. Creative decision making, however, is at least currently, better left to designers.

In a low volume design environment with a high emphasis on bespoke products, these systems offer little if any value to the designers. Yet the need to actively manage and utilise knowledge is just as important to maintaining competitive advantage.

There are of course tacit orientated knowledge management activities such as the establishment of communities of practice that seek to support interaction of individuals, and in particular sharing of less codifiable knowledge between individuals. The emphasis of course is that knowledge can be transferred between a vast numbers of individuals irrespective of department or indeed location.

Two problems exist with this approach. First, knowledge transfer still requires time and effort from the provider. While communities are often searchable, the knowledge is not captured in a structured or robust manner and conceivably duplicate problems do still arise. Second, it inherently requires a pool of 'experts' which can contribute to the community. In a small business this is unlikely to provide any value to the company.

The problem therefore exists, how can small firms producing customised or low volume products be supported through knowledge management? In this study it is argued that an alternative emphasis is to support the creativity of designers by providing them with relevant knowledge through the design process, and utilising the advantages provided by computational functions such as rich media and indexed searches.

3.2 Proposed Solution

It has been argued that in order to re-use knowledge, designers must have the ability to *find* the relevant knowledge and *understand* the knowledge presented [16], while Rouse states, that to be useful in supporting innovation, systems must "record, organise, reuse and curate knowledge" [17, 18]. As Marsh puts it, benefit can be achieved by supporting designers with timely and relevant information [19].Here it is argued that this concept can be applied to the reuse of experience by creating a Knowledge Based System that will store captured past design experience in a structured manner to allow efficient retrieval, reuse and subsequent capture. The emphasis on this system, as opposed to more typical heavyweight Knowledge Based Systems, is that the system acts solely to

deliver relevant knowledge to designers to *support* the designer's creativity and decision making and not to replace them.
This is supported by Marsh's extensive ethnographic study on designer's use of information. The study observed that designers primarily use information from other designer's memories and information is primarily supplied to provide awareness of alternatives [19]. Marsh finally concludes that with current technology capture and utilisation of past experience should be targeted at "information provision to support designers".
It is further argued that due to the required investment in heavyweight systems and their typically specialist role a lightweight system designed to support designers existing work flow and creativity could provide more value to a business. If correct, this would support Porters argument that innovation is a business discriminator should occur in all stages of the business [20].

3.3 Research Approach

In order to evaluate the proposed theory, a system has been created and launched in an industrial design environment. The system created will be a bespoke system that will endeavour to implement the recommendations of past studies, and provide designers with as valuable support as possible. The system will address each of the functions discussed in the section above, namely supporting designers 'search', 'reuse' and the subsequent 'capture' of newly generated knowledge. A proactive experiment evaluating the benefits of the system has been completed and the results discussed below.
Finally a twofold approach will be taken to evaluate the effects of the system. Proactive studies will be conducted to measure the impact to designers' workflow and behaviour, while long term metrics will be established before and after the implementation of the system to determine any effect on the business as a whole.

4. INDUSTRIAL STUDY

This study is supported by industrial partners who utilise a unique approach to the design and manufacture of fixtures and tooling in the Aerospace sector. Coupling state-of-the-art laser-cutting processes with unique design methods the company excels at providing bespoke, customer solutions in ultra-short lead times compared to traditional machined 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 etc. They are production devices that maintain the a relationship between the tool and the workpiece facilitating the manufacture of duplicate parts [21, 22].
Fixtures and tooling are crucial to the production of components, not least in aerospace where low volume, high optimised parts often require bespoke fixtures to ensure the components correct production. Tooling can rarely be produced prior to a components final design, therefore the lead time of the tooling directly impacts on the lead time production of the final component. Consequently there is always a demand for shorter lead times in the production of fixtures and tooling.
The company studied here has addressed this by having created a step change design method. With the addition of rapid manufacturing the products are highly knowledge-orientated, drastically cutting lead times. However the design approach was primarily developed by a single highly experienced expert. New designers have been successfully seconded into the business; however, a large quantity knowledge capital remained as tacit knowledge and only accessible through the single expert. This situation not only limits future growth, but also creates vulnerability for the company with over reliance on the expert.
From an academic perspective the company represents an ideal case study for which to test the proposed methodology on. Having operated for just over two years, and with only six employees, traditional knowledge based approaches would be too time consuming and costly to the small company, and would provide low returns. Due to its short history there are less established processes and greater flexibility compared to a more mature company. This ensured much easier implementation of the approach.
A system was therefore created to meet two criteria: first, to capture, manage and protect existing tacit knowledge and second, to reduce product lead times and improve the quality of designs by re-using expert knowledge. These functions should provide a tangible and valuable benefit to the business. The system is a lightweight system and focuses on providing knowledge on demand for non expert designers.

4.1 The System

In prior studies a recurring problem with any Knowledge Transfer program is the inertia of individuals against knowledge sharing [23]. It is often against individuals natural instincts to share knowledge openly and within engineering, designers are typically goal focused often finding recording the rationale behind their decisions a distraction to the design process.

The intention with the system here was to be able to support both the design process and individual design activities, while recording and reusing the design rationale. Existing strategies detailing frameworks and/or methodologies for Knowledge Based Systems were examined, however no one individual strategy or system was adequate for the proposed environment. Hahn's[24] framework, for example, (based heavily on Nonaka and Tekeuchi's model) supports knowledge transfer using systems such as Knowledge Mapping tools (the so called yellow pages) and communities of practise. Both of these systems require relatively large user populations to be effective. In the current environment of one expert and several designers, these would be ineffective. As described traditional codifying systems would not provide the benefit required.

The actual system proposed is a hybrid system containing three types of knowledge; 'best practice' methodology, a 'meta-data' type knowledge repository and unique numerical design tools.

4.1.1 Repository

The repository is a SQL driven database storing codified information and rich media about previous designs, including the design drivers, product requirements and materials, together with relevant CAD files, photographs and video files. Studies indicate that experienced designers rely heavily on past designs [14] the intention therefore to provide a semi-structured meta-data style knowledge base detailing past designs. By structuring the knowledge, and recording the most important aspects of the designs, designers will easily be able to access and assimilate knowledge. However, the uploading of more detailed reports and CAD files is vital to providing the level of detail and depth required by the designers.

4.1.2 Methodology

The methodology was derived from the experiences of the existing designers following time spent discussing past designs and observing their approaches to new designs. The workflow provides the basis of the system structure (detailed below) but also exists as training documents and handbooks suitable for new or novice designers.

4.1.3 Toolkit

The third section is a toolkit encompassing a series of different tools, primarily orientated around the CAD engine, to support and accelerate future design work for example parametric components. Initially experiments were completed on full product parameterisation. This required large upfront investment in coding but offered no cross product value. More value was seen by parameterising the most commonly used parts and creating user defined features.

4.1.4 Implementation

To further support accessibility and improve usage it was also acknowledged that designers would need access to the system from their own workstations. As the business would likely become a multi site business model, the system was constructed using the latest web technologies allowing pervasive access to the system.

The system structure is such that it behaves as a gated process, with webpages (requiring and displaying different information) corresponding to each gate. The pages are separated as:

- Preliminary information: displaying the job description, the designer associated to the project, the requirements of the client and finally any specifications relevant to the job.
- Post design: 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: displaying information received following the completion and of the project, modifications that were required, feedback from the clients and the designer.

Figure 1 shows screenshots showing the various stages of the system, including the current search function, design summary and design specifications page.

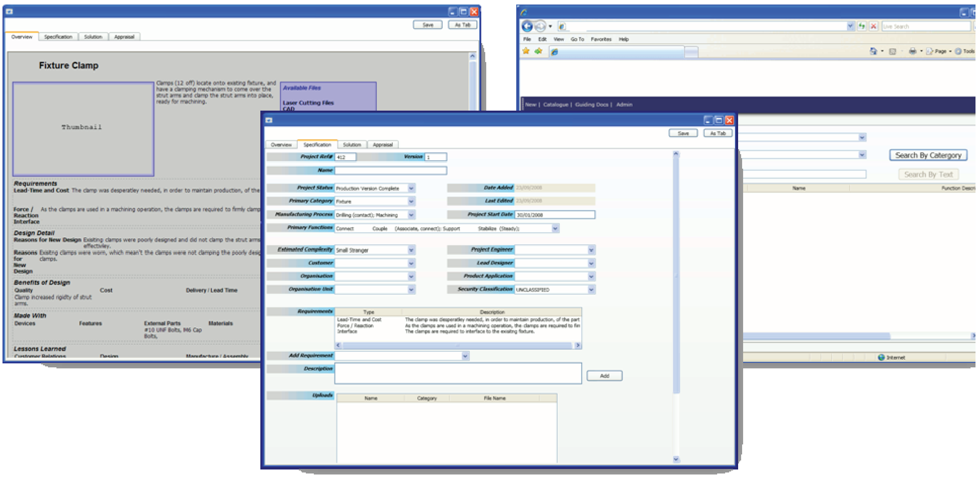

Figure 1: Screenshots of the system in use at various stages of the design process

Each stage is given a traffic light system, turning to green when completed, providing an at a glance view of the level of information stored on a particular project – a crucial requirement identified by Marsh - to make designers aware of the information available.

This can be roughly thought to support the Lundvall's [25] classification theory of the forms of knowledge transfer, described as: know-what, know-why and know-how. In short, designers need to:

- have the knowledge of designs
- have the rationale behind the designs
- have the knowledge of how to design.

Over these webpage sits a search page to find prior designs, offering both a free text search and a category search function. The designer's intended workflow with relation to the system is illustrated schematically inFigure 2.
Finally an additional section was added to provide access to best practice design documents, including the methodology, individual design case studies and 'how to' documents.

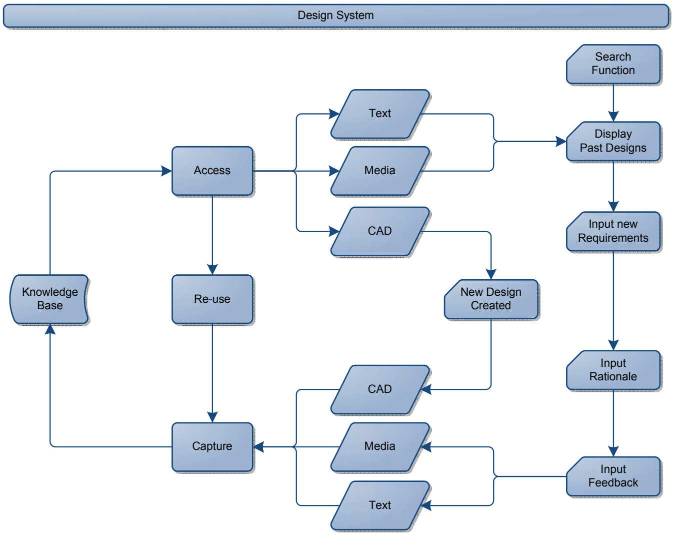

Figure 2: Schematic illustration of the system's role in knowledge reuse, showing designers activities on the right moving from top to bottom.

4.2 System Evaluation

Jennex [26] defines two forms of success for Knowledge Management activities: process orientated success – the implementation of efficient processes using Knowledge Management principles to improve communication and utilisation of Knowledge, or outcome success – tangible benefits to the business or processes, such as enhancement of products, services and productivity.
In the study presented here, the motivation is clearly an outcome success, lower lead times and improved products. The implementation of the system will require and intends to improve current design methodology but this is a facilitator to the primary goal of the project and not a measure of success.

4.2.1 Method

Following implementation of a trial system an experiment was conducted to test if the system provided a measurable benefit to the designer's solutions. The aim was defined as: *"To assess the effectiveness of the current design system, training and associated knowledge in the full development and production of a fixture design"*.
The system is primarily designed to provide past designs and experience to engineers with little or no prior knowledge of the design technology. These were termed novices, although it should be noted that this does not reflect the engineers overall experience. In theory, the perfect knowledge based system would support a novice engineer with enough knowledge to design a solution equal to that of an experienced engineer. A test was therefore constructed to test this proposal, by comparing the solutions of novice and experienced engineers for the same design problem.
Six engineers took part in the experiment. Two experienced engineers, three novice engineers and the technical expert. Each engineer was asked to produce a 5-axis laser fixture, for a two stage laser operation, which prior to the experiment, no solution had been produced. A week was allowed, for the test, a two day training period was given to all engineers and the engineers were given three days to produce a solution.

4.2.2 Assessment

Two modes of assessment were used; the first was an observational study of the designers followed by an open question interview. The second was a metric based assessment of each of the solutions. The metrics were derived prior to the week and were based on 'best practise' design principles such as quantity of material used, number of external parts used, conscious use of symmetry together with a 'fit for purpose' assessment of the design.

An alternative method was originally proposed which would assess the time it took for the engineers to complete a solution. Although simpler to evaluate, it was believed that designers would simply rush to create a solution and not utilise the knowledge base. The time taken to design would also become heavily influenced by the individual designer's ability in CAD, rather than their understanding of the technology.

4.2.3 Observations

Each of the designers successfully completed a design in the time designated, and a wide variety of different solutions were produced. Noticeably the expert's solution was markedly different to the others, and was the only solution to support both stages of the laser operation with the same fixture.

Two issues were encountered, not all of the designs could be built and therefore their feasibility not evaluated and, due to the wide range of solutions developed the metrics devised were not appropriate for all solutions. Alteration of the metrics following the test would almost certainly been influenced by the solutions produced and not a fair evaluation.

The interviews were useful, however, in understanding the benefits and more importantly the limitations of the system. All novice engineers stated that they found the knowledge repository useful in providing the basis for design solutions and the experiment indicated that this knowledge base did facilitate concept creation (or reuse) by new designers. There was evidence of both attempted and successful reuse of geometry. Geometry reuse was hampered, however, by the different CAD systems that were being used.

Two problems or inhibitors to effective use of the system were encountered and described by the designers: firstly, designers were not aware of what to search within the system. They knew the requirements but not the terminology to describe them. One designer simply looked through all past 5-axis laser fixtures, but this is much too time consuming. Second, once appropriate designs were found, designers struggled with the implementation of geometry reused from other designs, the problem attributed to not having a 'feel' for scaling of the material or geometry.

5. DISCUSSION AND FUTURE WORK

The evaluation of the system was not successful in proving that knowledge based support provided by the system was effective. Although the observations suggest that the approach taken is capable of providing value. In a separate study, it was found that 75% of the time spent from request to delivery was spent by the engineers designing and design capacity remains the primary limiting factor to company growth. The study demonstrated that concepts and geometry from past designs can be adopted by other engineers, reducing the need for rework. But a different method of evaluation is required to achieve quantifiable results. The evaluation week was, however, useful in identifying two issues with the system and in supporting development of a further test.

5.1 Issues with the system

According to Battelle [27] knowing what users actually want is considered the 'Holy Grail' of search engines, but is still greatly sought after by companies such as Google. The difficulty faced here by designers was typical of the problem faced when users try to articulate their needs using keywords or text. The problem of searching has been highlighted in past engineering studies, in particular by Marsh's study on designer's use of information. It was observed that in the majority of cases, written reports were accessed by their authors rather than engineers unfamiliar with the work [19]. Thus reports were used to confirm or supplement a designers own memory.

One solution to this could be a proactive search function based on prior input of the requirements.

Online sites as 'Amazon' or 'lastfm.com' utilise relatively advanced recommender systems which can analyse the behaviour patterns of similar customers and recommend new content or products. Alternatively a nearest neighbour algorithm could be employed to find designs with similar customer requirements and specifications. There remains the problem however of finding sub components, for example functions within the overall solution. This is limited, however, by the degree of detail provided by the designers. Implementation of an updated or proactive search function remains as future work.

The second issue observed is perhaps more difficult to solve. The issues associated with adaption and implementation of design was observed in the study by Busby. In this study errors were seen when designers tried to scale or adapt designs incorrectly. The most common problem seen in the current study was assessment or understanding of the mechanical performance of structures or shapes. This is particularly important within the industrial context studied as the design methodology uses a novel approach to, often employing critical geometries to hold and position components for further operations. It was therefore proposed that additional numerical tools be developed to support detailed geometric design, thus supporting novice designers to produce accurate designs, for example in calculating bend angles as a function of material thickness. These tools would be accessed through the design system, supporting the concept of a single source of knowledge and would be based on validated structural data. As of writing one tool has been completed and others are in development.

5.2 Future Evaluation of the System

The long term aim of the project is to establish a measure of the effect of the system to both the designers and the wider business. Analysis of performance and business benefit is the least developed field of Knowledge Management and little proof of the value the systems provide has been completed [4, 28].

In the attempted evaluation presented in this study a method was used that attempted to solve the problem of measuring the typically intangible benefits of a knowledge based system, such as improvement in designs by attempting to define a measure of the 'best' design. Using a fixed set of metrics each with numerical or binary result, the intention was to remove the subjectivity from the experiment and allow a fair evaluation of the solutions. In reality, the metrics were too fixed and did not allow for novel solutions.

Further proactive experimentation, similar to the experiment above will be used to assess the direct usage of the system by designers. In future however less formalised metrics will be used. Instead, a category system is proposed whereby activities such as successful geometry reuse, successful searching, unsuccessful reuse and unsuccessful searching will be used. Ethnographic studies of designers will be undertaken and an evaluation made as to the impact (positive or negative) to the designers.

Due to the difficulties of evaluating the direct benefit to designers, an alternative approach is also proposed that will evaluate the long term effects of the system to the business. It is proposed that an appropriate Balanced Scorecard [29] assessment of the company could be implemented, populated with metrics for which the system is intended to improve (such as average lead time, scrap rate, customer complaints), and evaluated annually.

It is acknowledge that, the company's growth and development may obscure the results from being conclusive, but by including factors not directly affected by the system (such as number of staff, staff development etc.) an assessment could be made as to the improvement relative to company growth. A scorecard has been produced and will be trialled in parallel to the above proactive experiments.

6. CONCLUSION

The work presented here demonstrates an alternative approach to the creation of a Knowledge Based System in engineering than traditional geometry orientated solutions.

A lightweight user driven system was produced with low initial cost and investment (relative to an automated knowledge based system) and demonstrated within the industrial context of a small to medium enterprise. The system combined a searchable knowledge repository with a collection of tools to provide guidance and support for specific aspects or functions of the design process such as access to previous design rationale, CAD files and manufacturing information. Integration of the system, with the methodology supports the find, understand and reuse process of knowledge deployment.

An experiment was completed to evaluate the benefit of the system to the designers and the wider business. The evaluation of the experiment was found to be flawed and could not prove quantifiably for or against the hypothesis. However the observational evidence demonstrated that designers were willingly to reuse concepts and geometry, suggesting that value could be seen by reducing the time taken to design. Further anecdotal evidence from designers identified benefits from the system and issues for improvement. The experiment demonstrated the potential for future evaluation of the system, but also highlighted the need for high level and flexible assessment of the benefits.

An updated system has been launched within the company full time. It is in regular use and continues to receive support from designers and management, both types of users identifying functions that are beneficial to their work.

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Contact: Nicholas Reed
University of Southampton
Computational Engineering and Design Centre, School of Engineering Sciences
Highfield Campus
Southampton, SO19 1BJ
UK
Tel: +44 2380 598359
E-Mail: nreed@soton.ac.uk
URL: http://www.soton.ac.uk/ses/people/pgr/ReedNJ.html

Nicholas Reed is a postgraduate research engineer at the University of Southampton, studying for the completion of an EngD. The research is jointly funded by EPSRC and Rolls-Royce plc. to create a Knowledge Based System with emphasis on the evaluation and impact to the business. Prior to the EngD Nicholas completed a Masters in Physics from the University of Warwick.

Contact: Gary Wills
University of Southampton
Learning Societies Lab, School of Electronics and Computer Science
Highfield Campus
Southampton, SO19 1BJ
UK
Tel: +44 (0)23 8059 2831
E-Mail: gbw@ecs.soton.ac.uk
URL: http://www.ecs.soton.ac.uk/people/gbw

Dr Gary Wills is a Senior Lecturer in Computer Science at the University of Southampton. He graduated from the University of Southampton with an Honours degree in Electromechanical Engineering, and then a PhD in Industrial hypermedia systems. He is a Chartered Engineer and a Fellow of the Higher Educational Academy. Gary’s main research interests are in Personal Information Environments (PIEs) and their application to industry, medicine and education.