CRANFIELD UNIVERSITY

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A PROCESS-BASED APPROACH TO ENGINEERING DESIGN KNOWLEDGE REUSE

SCHOOL OF APPLIED SCIENCES

PhD THESIS

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A process-based approach to engineering design knowledge reuse

Supervisor: James Gao

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List of publications

Conference proceedings

Baxter, D.I., Gao, J.X. and Roy, R. (2007) "Design process knowledge reuse challenges and issues." CAD07, Honolulu, Hawaii, 25-29th June 2007

Baxter, D.I. and Gao, J.X. (2006) "Development of a Process Based Data Driven Engineering Design Knowledge Reuse System." CAD06, Phuket, Thailand, June 19-23rd 2006

Baxter, D.I. and Gao, J.X. (2005) "Formalising Customer Requirements as an Input to a Design Knowledge Reuse System." Proceedings of the 3rd International Conference on Manufacturing research (ICMR 2005) Cranfield, UK, September 6-9th 2005

Gao, J.X., Baxter, D.I., Mountney, S., Bradfield, D. and Sackett, P.J. (2005) "Knowledge Management for New Product Development: Keynote Paper." International Conference on Manufacturing Research (ICMR2005) Cranfield, UK, September 6-9th 2005

Baxter, D.I. and Gao, J.X. (2005) "Process based design knowledge reuse through process and product representation." Proceedings of the 12th CIRP Life Cycle Engineering Seminar (CIRP LCE) Grenoble, France, April 3-5 2005

Baxter, D.I. and Gao, J.X. (2004) "Process based representation for design knowledge." Proceedings of the 2nd International Conference on Manufacturing research (ICMR 2004), Sheffield, UK, September 2004

Journal publications

Baxter, D.I., Gao, J.X., Case, K., Harding, J., Young, R., Cochrane, S. and Dani, S. (2007) "An Engineering Design Knowledge Reuse Methodology Using Process Modelling." Research in Engineering Design 18: 37-48

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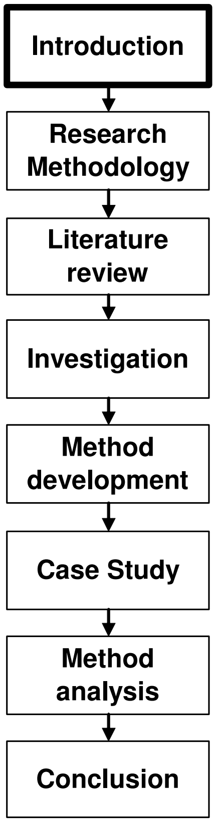
Glossary

php	HyPertext Pre Processor A web technology to enable provision of dynamic web pages. Forms part of the html code in a web page that is read separately by a php processor that interfaces with a database.
SQL	Structured Query Language A language to interface with databases. Provides commands such as ‘create table’, ‘create entry’, and so on.
mySQL	An open source database that applies SQL
DevPHP	An open source application for developing php code
CAD	Computer Aided Design: generally refers to computer based design packages used to create 2D or 3D drawings of products
CAM	Computer Aided Manufacture: refers to computer based packages to support manufacturing analysis
TRIZ	Theory of Inventive Problem Solving (Acronym taken from the Russian: also known as TIPS)
FMEA	Failure Modes and Effects Analysis: a method to assess the likely causes and the seriousness of the effects of potential product failures, frequently applied to the assessment of product safety and reliability.
QFD	Quality Function Deployment: a quality tool used to show map product requirements and solutions.

Abstract

Manufacturing enterprises are under increasing pressure to produce products of higher quality at lower cost in shorter time frames if they are to remain competitive. Engineering design support methods can help companies to achieve these goals. One such approach is design knowledge reuse. Industrial requirements have been identified as (i) the ability to rapidly create product variants; (ii) the ability to capture and re-use design knowledge, and; (iii) the capability to support the design effort across a distributed enterprise. The research aim is developed to assist the manufacturing enterprise in meeting the industrial requirements in the following way: a design solution to a new product requirement can be supported using an application package that is developed for a specific product domain. The application package consists of knowledge about previous products and projects, and procedures for using the knowledge to achieve a new solution. An initial investigation showed that design reuse in practice is lacking in specific areas: access to relevant and contextualised captured design knowledge; the relationship between design reuse and the product development process; integrated engineering and business objectives. Literature gaps were also identified. They include: (i) knowledge reuse for the whole product life cycle (particularly early design); (ii) integrated product and design process models; (iii) a 'how-to' element of the product design process. The aim of this research is to provide a method for reusing engineering design knowledge. The research method is 'interview case study', which supports a flexible approach and enables the research to develop according to the findings. The research was carried out with four companies, one of which took part in a detailed case study, providing case data to develop, populate and validate the proposed system. The outcome of the research is a proposal for a process based engineering design reuse method. The method consists of a combination of product, process and task knowledge to support the design process. Product knowledge is represented using a product ontology. Process knowledge is represented using the Design Roadmap method. Task knowledge is represented using a template developed to record the critical aspects of the task, including 'how-to' knowledge. Case studies are used to validate the proposed framework and the developed prototype system. The proposed design knowledge reuse framework is applicable to a range of industries in which mature, complex products are developed.

Chapter 1: Introduction



This section will first describe the initial observations that prompted this research, including the challenges to be faced in the manufacturing domain. A preliminary investigation into challenges and issues with design knowledge reuse in practice will then be described. The findings of this preliminary investigation are used in defining the research aim and objectives. Finally, the structure of the thesis document will be outlined.

1.1. The manufacturing environment

This section describes the context within which the research was started, and describes some general research aims to support the manufacturing enterprise. These general aims will be built on following an industrial investigation and literature review.

Manufacturing enterprises are under increasing pressure to produce products of higher quality at lower cost in shorter time frames if they are to remain competitive. The design challenge is to create products that meet these needs. In a globally distributed production environment in which outsourcing to economies with low cost bases is commonplace, global standards of engineering are ever increasing, and customer expectations are rising along with standards, design is the key differentiating factor in producing products that can win orders.

Even in industrial markets with a well defined product requirement, specification of product performance is extremely complex. Multiple performance elements must be optimised, many of which are conflicting. A well cited example is high quality and low cost. Other apparent contradictions include high performance and low energy consumption; light weight and robust; small and powerful. Managing these factors and creating a product that meets the requirement at the market and builds a solid commercial case is the challenge of product development. Doing it quickly whilst meeting these complex goals is crucial. Time lost to a competitor product influences not only today’s sales, but the whole shape of the future market. The combined complexity of the design challenge, time pressures, and improved communication methods has led to an increase in design and component outsourcing. The automotive industry is an extreme example, in which they are effectively assemblers and project managers rather than traditional manufacturers. Other industries are less extreme, but still there is a trend towards increased outsourcing and supplier involvement in product design.

Trends noted in the manufacturing environment include:

(1) Time pressure is increasing in product design;

(2) Manufacturing enterprises are outsourcing a greater percentage of component manufacture and services to their supply chains;

(3) The customers, suppliers, business partners and departments of an enterprise are globally dispersed;

(4) The trend towards project based contracts and a global demand for engineering expertise has reduced the length of time employees spend in an organisation, and led to an emergence of a growing number of consultancy companies.

The following requirements are therefore identified:

(1) The ability to rapidly create product variants that meet the same basic functional and performance requirements. These product variants are sold to the different markets and product applications supported by that company;

(2) The ability to capture and re-use design knowledge to strengthen the position of the project based organisation, currently at risk of losing their design knowledge along with their personnel;

(3) The capability to support the design effort across a distributed enterprise. This capability should include project management, resource allocation, design data and communication among team members via a globally accessible platform.

1.1.1. Current design support technologies available

Knowledge management (KM) is now a well developed research area, and several methods and technologies are available. The majority of KM tools and methods are intended for managing strategic level knowledge, rather than operational knowledge at the task level for product development. As such, KM systems are not well integrated into the design environment. Focused applications and technologies to support design have become more widespread, with increasing capability to provide document management, distributed access, visualisation, and workflow. A few technologies stand out in their capability to support reuse of one or more aspects of design knowledge, including knowledge based engineering applications and parametric design. However, several limitations exist to limit the widespread reuse of design knowledge:

(1) There is little focus on the re-use of the knowledge that goes into the creation, development and integration of design artefacts;

(2) Knowledge structures supporting design applications are not well suited to distributed environments;

(3) There is little focus on ensuring design methodology represents best practice;

(4) The development of conceptual design structures and the various modelling techniques required are not well supported;

(5) Early design is widely recognised as the most significant determinant of product cost, yet remains the least supported area;

(6) Effective design reuse is a whole-system issue, yet design processes, information management, and product development knowledge are not effectively integrated.

1.2. Preliminary investigation: company A

This section describes the preliminary investigation of industrial problems, requirements, and product development methods and tools. The organisation structure, product type, product complexity, design tools and methods, development strategy, and manufacturing will be described. Design reuse will also be discussed.

1.2.1. Organisation structure

As a project led organisation, the approach to design has significant differences depending on the project type. Variations in budget lead to differences in design project management, and the product applications have differing needs for quality control and documentation. Project managers also have a large influence on the way a design project operates. Engineering personnel will also have their own preferences. Small projects can include 5 people, and very large projects can include 50. The published and audited company process is a stage gate method (Cooper 1994) that is applied to all projects which have a budget above a certain threshold. This is to ensure that projects do not progress past the gates (e.g. concept, feasibility, technical demonstrator) unless the commercial aspects of the project are satisfactory.

1.2.2. Products

Company A design and manufacture vacuum pumps for the semiconductor industry. They are a medium sized company with medium production volumes.

1.2.3. Product complexity

Company A produces highly engineered electro-mechanical products with challenging requirements: high expectations of reliability, often in harsh operating environments. There is a range of electronics sophistication, from a very basic interface through to a fully networked product with remote monitoring and advanced warning / potential failure detection capability.

1.2.4. Design tools and methods

Company A have a variety of design systems and methods in place. Parametric product modelling is applied to key components. At the start of this project there was not a common PDM / PLM system in place across the global enterprise, however at site level the PDM system was used to store all CAD data. Due to a global and growing business there are a variety of CAD systems in use across the various design sites. There is not a common approach to design knowledge management or reuse.

Product performance is closely related to clearances. Dimensional control systems are used to model geometry and assemblies, supporting performance analysis. The system is not currently integrated with the CAD system. Product performance analysis is also carried out using in-house Excel / VB based tools.

Associative design practices are applied in a limited fashion. The current approach to sharing parameters is an Excel spreadsheet. Performance analysis and simulation packages can export the result to the CAD system as a input parameters, and generate an accurate component form.

No KM methods were in place. Decision processes and best practice methods are not technology supported.

1.2.5. Product development strategy

Product development takes place in a modular fashion. A pump product line will consist of a number of variants, to meet the needs of a variety of applications in a customer site. The intention of the modular strategy is to increase market coverage whilst reducing the total number of components. Across product lines, products are segmented based on application severity: light, medium and harsh duty. Within the product lines, two main splits occur: pump capacity (measured in litres of gas pumped per hour) and chemical resistance (fluorine resistant versions – this is used in some semiconductor processes for cleaning).

In the main, the vacuum pumps are sold to support large scale, high tech industrial processes. The application requirements are generally clearly defined in terms of required pumping capacity and performance. Exact specifications of the chemical composition of the gases to be removed may not be provided, however the main composition of the process gas to be removed by the vacuum pump is known. Innovation in the market is driven by system issues: pump interface, reliability, and life cycle cost (unit cost, service cost and frequency, power consumption, heat generation).

The strategy is a combination of technology and market driven. New product requirements are identified in terms of customer applications. Technology solutions are developed to meet those needs. Technology solutions already developed will be considered for new customer applications.

1.2.6. Manufacturing: volume and location

Manufacturing location and method varies by product type, and suppliers are located globally, however a significant amount of the manufacturing operation is based in the UK.

1.2.7. Design reuse

In this context, design reuse is taken to mean design knowledge reuse and component reuse. Design reuse is carried out at a variety of levels. Knowledge is applied within design through KBE systems. These are developed in house to model product performance. Parametric design tools for key product components also support design knowledge reuse. Knowledge reuse is otherwise carried out in a variety of means, often personal to the designer or engineer and through informal means such as design notebooks and storage of information and data in personal folders or on individual PCs. The use of standard components does take place but is not strictly practiced. Within product families, common components are often used across several variants.

1.2.8. Observations

There is limited standardisation. In previous projects, the cultural focus on engineering excellence has allowed substantial variation for performance reasons. The control of the design process has also been engineering biased in previous projects. The stage gate process has been viewed as a hurdle rather than a barrier.

The rate of NPI is vital to the company due to market conditions. This creates a conflict between the engineering bias and the commercial awareness.

1.3. Preliminary investigation: company B

1.3.1. Organisation structure

Company B is a project based organisation. Groups within the design group will serve a specific customer on a specific project. They will use CAD tools specific to the customer.

1.3.2. Products

Company B supply a range of automotive systems. This investigation is taking place within latch design, part of the access control systems division.

1.3.3. Product complexity

Car door latches are apparently relatively simple electro-mechanical systems. Their design is a significant challenge due to hidden complexity. This complexity arises from two aspects: strict regulation and high reliability. Latches are rigorously tested for both elements. In reliability testing, a car door latch must be demonstrated to withstand 1 million open / close operations. In meeting regulations, one example is crash testing. An identical latch design must be shown to pass crash testing criteria for each of the four doors on a vehicle. Latch systems vary from mechanical only to some fairly sophisticated electronics. For example, keycards that unlock vehicle doors (and enable the ignition) based on proximity.

1.3.4. Design tools and methods

The customer driven design organisation structure, which is common in automotive suppliers, requires multiple CAD and PDM systems. The systems are specified by the automotive customer. Technical and management issues make sharing between customer projects difficult. ‘Sharing’ refers to data, systems, knowledge, and components.

The initial feedback on the research was that the advanced proposals represented a level beyond that which the company would be ready to build into. There was also some scepticism relating to the use of automated systems. Excel spreadsheets are often used to carry out product analysis. It was noted that it is dangerous to reuse such tools without expertise to judge whether the output is sensible. Several ‘known’ constraints are not formally known, however experience has shown that ‘due to the variety of constraints this is the best size’. As such, designer expertise is necessary for operating these analysis tools, in order to make assessments of the validity of inputs and outputs.

1.3.5. Product development strategy

Company B organises their design in a modular fashion, developing products with common mechanical components with electronics variants for high end product lines. The ideal approach to design starts with a best practice design booklet, which was under development in the design group, representing an effective approach to the tasks required and points to be remembered for those tasks. The designers also use some analysis tools developed in Excel.

1.3.6. Manufacturing: volume and location

Manufacturing is high volume. Assembly takes place at the design site in the UK, and components are globally sourced.

1.3.7. Design reuse

There is not a common approach to design knowledge management or reuse. It was considered that the development of an agreed design methodology would be valuable. Design notebooks are in use, and the most common method of design reuse. Common components are used for a variety of product lines, however it was recognised that component variation was currently high: an internal investigation in the company identified that the use of common components could be much improved. Currently, each new product results in a new family of fixing screws, since there is no process in place to standardise parts. A previous placement student exercise found that a set of 150 fixers could be reduced to 3 or 4, if minor design changes were made to accommodate them. The customer driven design organisation structure and multiple CAD and PDM systems makes reuse more complex.

A current project in the company was taking place, capturing and recording design information. The result is a large, unstructured collection of information. This project has highlighted the additional issue of design knowledge structure and potential recall issues where large volumes of information exist. A suggested method was that the document is structured according to product sub-systems.

The reuse of parts was reported to be problematic, however the reuse of knowledge was suggested to be much more difficult.

1.4. Preliminary investigation: company C

1.4.1. Organisation structure

Company C are a large organisation with several thousand employees. They undertake major design projects which are high investment, large scale, safety critical and highly regulated. As a result, the management of design projects is a major challenge. The company is structured according to the product structure – it is organised based on product modules (compressors, fans, externals, etc.).

1.4.2. Products

Company C supply a range of gas turbine engines for aeroplanes, from business jets to wide body airliners.

1.4.3. Product complexity

The product is classically complex. That is, large scale (size) with many thousands of highly engineered components in a tightly controlled system with multiple electronics interfaces (redundancy is required), complex hydraulics systems, and complex thermal and gas flow characteristics. They are tightly regulated and safety critical devices: the consequences of failure mid flight are potentially very severe. As a result, product development is a serious challenge.

1.4.4. Design tools and methods

There are common design systems in place, with a variety of advanced knowledge based engineering tools for design analysis and manufacturability analysis. Design processes are well documented through a series of flowcharts, which are available via the company intranet. A major company initiative was taking place at the time of this research project into design best practices and design process mapping. There is a company wide CAD and PLM strategy, with advanced systems in place across the organisation. The CAD tools do not readily support feedback to the design team on machine tool capability.

During the detail design stage there are more people that need support. At this stage the design is more constrained, and so more amenable to knowledge capture and analysis. However, there is less potential for impact at this stage.

A major consideration of this organisation is the impact and scope of change: any design (product) change, software change, method change, or manufacturing change represents a major undertaking. Safety and engineering integrity can not be sacrificed for time savings.

1.4.5. Product development strategy

Products are developed for a range of aircraft. Design projects are generally customer led: a new engine will be developed for a new airframe. Innovation takes place at each generation in terms of fuel efficiency and noise. There is a major drive to improve product development performance and reduce product development time within the organisation.

1.4.6. Manufacturing: volume and location

Manufacturing is relatively low volume and highly specialist. Materials are critical to the performance of a gas turbine engine, since higher temperatures can lead to higher efficiency. Manufacturing tolerances are also very tightly controlled in several aspects of production. Assembly takes place in the UK, and is collocated with design. Manufacture of key systems also takes place in the UK. Components are globally sourced.

1.4.7. Design reuse

Design reuse is carried out at a variety of levels. Knowledge is applied within design through extensive use of advanced KBE systems for performance analysis and manufacturing simulation. One example is an analysis tool to evaluate product shape after manufacturing, in order to define manufacturing parameters including mould shape. These are generally developed in house by KBE specialists. Parametric design tools are also applied.

Regarding experience and lessons learned: ease of use is a barrier to knowledge capture and search, limiting reuse. The intranet system used for experience capture and lessons learned is extremely large, and much of the content reflects the view of a single user; a 'mind dump' rather than a structured, managed, categorised entry. This is a barrier to reuse in two ways: retrieving the relevant entry is difficult due to the volume, and the relevance of a particular entry to another user is variable.

A general question relating to organisational memory in knowledge management that the organisation is aware of is "how to be more scientific about what to remember".

1.4.8. Observations

A key issue for the organisation is 'how to structure captured knowledge'. The intranet system was used as a knowledge base, but was not regularly accessed or used. It is a place to store everything, with user driven content.

A structured design process was in place. The design process prescribes events at the macro level, but not at the task level.

There is a concern with the amount of effort required to populate a design reuse system. The ideal approach would operate using an 'over the shoulder' approach.

1.5. Company comparison

The companies are compared using the using metrics described above. For most of the metrics, the scoring is restricted to high', 'medium' or 'low'.

	company A	**company B**	**company C**
Design complexity	Medium	Low	Very high
Design technology	Medium	Low / medium	High
Design process detail	Medium	Low	High
Knowledge management maturity	Medium	Low	High

	company A	company B	company C
Specification source	Application driven	Application driven	Application driven
Product family	Wide range of variants	Small number of variants	Small number of variants
Regulation	Medium	High	Very high
Production volume	Medium	High	Low
Production investment	Medium	Low	Very high
Relative customer power	High	Very high	High
Development time	3 years	2 years	3 years

Table 1.5-1: comparison of companies in initial investigation

Design complexity is different across the three companies, and corresponds to the level of design technology and also the level of design process detail. It is not clear whether there is a causal relationship between design complexity, design technology and design process detail.

Knowledge management maturity also corresponds to the design complexity and technology. In this sense, knowledge management maturity is judged on the basis of technology rather than strategy. Only company C has a knowledge management strategy or department.

Specification in all three companies is common: it is application driven. In each case, the company supplies a product to an industrial client that forms part of a larger system. Company A supplies products that support a manufacturing system, companies B and C provide modules to fit onto vehicles and aircraft. In each case, the specification of the larger system dictates the specification of their product.

Company A develops products as part of a large product family. Companies B and C typically produce only a few variants.

Regulation appears high in all companies; the level indicated is in a relative sense. Automotive is highly regulated, aerospace is very highly regulated.

Production volumes are different in each company. Note that investment in production equipment does not correspond to volume, but to complexity.

Relative customer power is high in all cases. Only in company B does the company not have the option to bypass the customer and go to the end user for specification of their product as part of the system.

Development time is approximate and similar across the companies. This is consistent with the product complexity vs. design technology and design process detail: a highly complex product with a high level of design technology and detailed design process can be developed in the same time as a low complexity product with low complexity design technology and a low detail design process. This is clearly a simplification and does not measure relative complexity, technology or process detail. However, this relationship certainly warrants further investigation.

1.6. Summary of the preliminary investigation

The preliminary investigation will guide the research aim and objectives. Research methods will then be defined that are appropriate to the aim and objectives.

The preliminary investigation suggests that design reuse is lacking, and that there are several limitations to design knowledge reuse in practice. There was not a clear design reuse strategy in any of the organisations. Design reuse practices that were in use were not part of a wider coherent structure, and this limited the potential to share good practice.

The main source of knowledge reuse was designer personal notes (notebooks), shared documents and intranet. Each one has problems associated: personal notebooks are not shared, so can only be reused by the original author. Intranet use presented a similar challenge, largely due to the user driven content: whilst the notes are available, they are not easy to find and they are not presented in a way that makes them easy to reuse. Shared documents provided a level of design reuse in one company; however the value of the document seemed to diminish as its size increased. These knowledge reuse methods, where they are available for reuse, lack context.

Where design knowledge capture takes place locally, for instance in Excel models, there is a significant challenge in terms of reuse by a novice. Since these models tend to be created as a ‘quick calculation’, the limits of applicability are not defined, and the main assumptions are not documented. Reuse of such models can therefore provide unworkable solutions.

In the product development processes, there seemed to be an engineering bias. Whilst there is a business process structure in place in each case, the apparent focus of the design team is on the achievement of the engineering goals. Since engineering goals can be met better with a new solution (rather than an existing solution), this tends to be what happens. The engineering focused applied practice was not in line with the commercially focused prescribed practice. There is an apparent gap between the two. It was considered by one of the organisations that the development of an agreed design methodology would be valuable.

There appears to be a need to reconcile engineering and business objectives in a single coherent design method that includes design knowledge reuse as an integral element.

In summary, the challenges to design knowledge reuse in practice are:

- Access to relevant and contextualised captured design knowledge. Storage methods do not support reuse in context: centralised and unstructured vs. locally held and unavailable.
- Developing a relationship between design reuse and the product development process.
- Integrating engineering and business objectives.

1.7. Research aim and objectives

The aim of this research is **to provide a method for reusing engineering design knowledge**.

The requirements of the manufacturing environment described in the prvious section include: the requirement to rapidly and easy create product variants; the ability to capture and re-use design knowledge; and the capability to support design across a distributed enterprise. The aim of this research will support the first two requirements through supporting the reuse of design knowledge, which will reduce the time taken to carry out design. The third requirement should also be addressed when developing the method to reuse engineering design knowledge.

Several limitations to effective design knowledge reuse have been identified through an initial investigation. Three key areas in which this research project seeks to develop solutions are: the conflict between the engineering view and the business view; the difficulty in enabling shared understanding; and the difficulty in access and retrieval in large knowledge bases. A further objective is to support knowledge reuse for early design. The research objectives can be summarised as:

- To propose a design knowledge reuse framework that combines an engineering view with a business view;
- To propose a method that promotes shared understanding of the product development knowledge content;
- To propose a method to improve design knowledge access and retrieval; and
- To propose a method to support knowledge reuse for the whole product life cycle, particularly early design.

The research objectives must be considered in the context of an existing academic body of work. Therefore an additional objective is:

- To identify research gaps through a literature review, and to propose a method that meets those research gaps.

The final research objective relates to the industrial context of this research:

- To test and evaluate the method in an industrial case study.

The research aim is focused on the development of a method for design knowledge reuse. That method must take account of both academic literature and industrial findings, particularly the industrial challenges identified: access to relevant knowledge; a relationship between the design knowledge reuse framework and the design process; and a method that integrates business and commercial objectives.

The organisations taking part in the research will provide the industrial context. They will take part in defining the scope of the case studies. The investigations with the participating organisations will also contribute to the understanding of the industrial environment. This understanding, combined with the case data, will be critical elements in the development of the method.

1.8. Research scope and focus

The research is taking place in the context of variant design in mature domains. Variant design refers to the design of a new product within an existing product family. The development of the method for reusing design knowledge will be considered within this context. The resulting method will therefore be tested for suitability within the context of a variant design in a mature domain. As well as limiting the organisational context, the scope of the research will also be limited in terms of the focus for investigation: the case studies will focus on a limited set of company data relating to product design. That set may relate to a specific product, component, designer or project. The case study scope will be defined in collaboration with the participating companies.

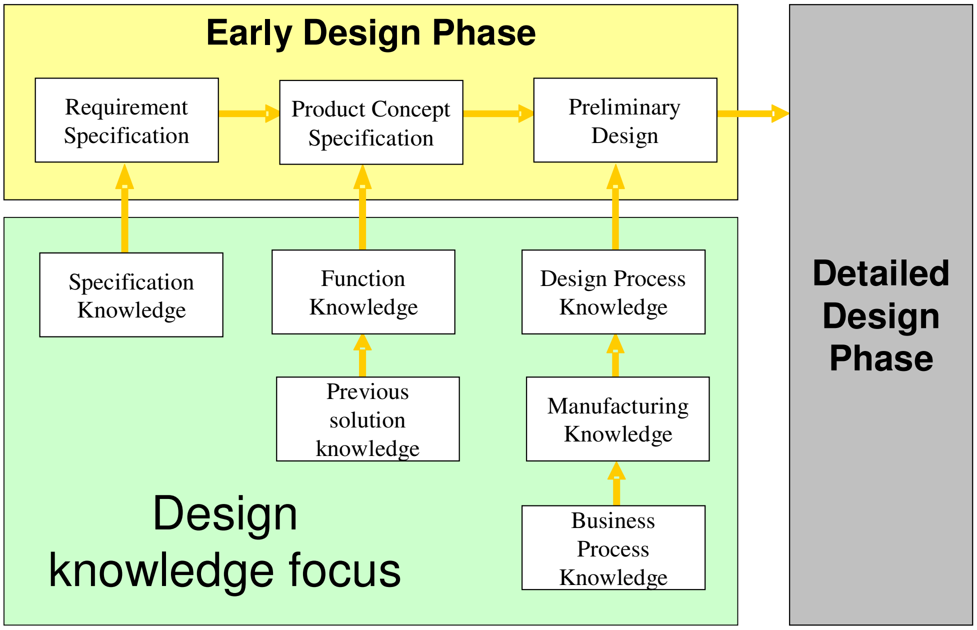


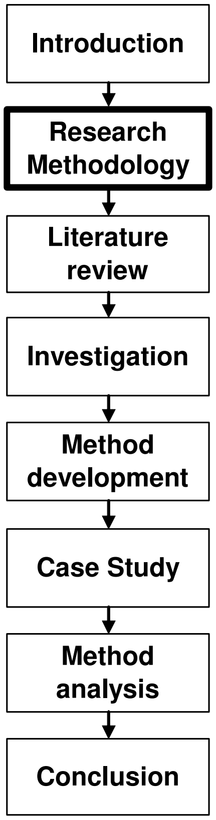
Figure 1.8-1: knowledge inputs to early design

The early design phase is the focus area for investigation. Early design is the name given to the requirements generation, concept specification and preliminary design activities (see Figure 1.8-1).

1.9. Document structure

The document structure is as shown in the diagram on page 1. Chapter 1 described an preliminary investigation that sought to identify challenges to design reuse practice. Chapter 2, research methodology, will describe the foundations of the research methods and describe in broad terms how the research will be carried out. Part of the research method is a literature review, which is described in chapter 3. The review of the literature will position the research and identify potential contribution through proposing research gaps. Chapter 4 will describe the detailed industrial investigation and knowledge capture that provides an initial case for developing the design knowledge reuse framework. Chapter 5 brings together the literature and preliminary investigation which together contribute to the proposal of a method to reuse engineering design knowledge. In chapter 6 the proposed method is developed in a prototype system. That system is analysed in a detailed case study in chapter 7. Chapter 8 contains the conclusions of the research.

Chapter 2: Research Methodology



This chapter will describe the method and justification for how the research will be carried out. First, some definitions and a description of methodology will be provided. Second, a description of how methodology relates to this research project. This is followed by an overview of research methods, then a description of the research method adopted in this project.

The aim of the research and the environment in which the research is being carried out are important factors in deciding how the research should be carried out. The aim of this research is to provide a method for reusing engineering design knowledge.

2.1. Research method

The research method is related to the research aim. The aim and objectives described in chapter 1 were developed according to the initial company findings. This was enabled by the adoption of a flexible strategy, which allowed focus on important issues highlighted by the insight developed and the analysis of the combined data sources. The selected research approach is interview case study. The basis of the selection is in part due to the research aim and in part due to the epistemological stance adopted: critical theory (knowledge is created through interpretation). The research aim represents applied research, since the provision of the method is the main focus. Interview case study provides a means to investigate the participating organisations, to validate the findings of that investigation, and to assess the proposed application or method. Qualitative statistical analysis methods are not appropriate, since the two foundational assumptions of a normal distribution and a random sample do not apply.

2.2. What is methodology: definitions

Methodology is itself a term which provokes debate. What the term methodology means to a research project varies across disciplines. The importance assigned to the study of methodology also varies across research disciplines. First the word will be defined, then the meaning within the context of this research. It is partly due to the nature of this research field that such effort is devoted to the definition and justification of methodology.

The Cambridge dictionary defines methodology as:

> “A system of ways of doing, teaching or studying something”

From a semantic perspective, the word methodology is constructed from the two parts method and ology. The suffix ‘ology’ is derived from the Greek ‘logos’. In the context of the word it means ‘reason’. Method–ology therefore means reason of method, or study of method.

Lehaney and Vinten carried out a review on how the word methodology has been used in various research papers (Lehaney & Vinten 1994). From their review, they identify six definitions of research methodology:

- The ways in which hypotheses become theories – scientific methodology;
- The ways in which techniques are chosen to address a particular problem;
- The ways in which problems are chosen, which addresses the question of sponsorship;
- Methods or techniques;
- The modelling process, which include hard and soft systems approaches, and the ways in which the relevant variables are chosen for a model, and how reality is concomitantly simplified;
- The chronological planning of events – the research programme.

Combining the various view of methodology with the semantic perspective, "research methodology" will be taken to mean the study, selection and justification of research approach. This is close to Lehaney's category "the ways in which techniques are chosen to address a particular problem". "Research approach" refers to the selection of methods that will be applied to the research. "Research method" refers to particular tools and techniques applied to the research. This is demonstrated in Figure 2.2-1.

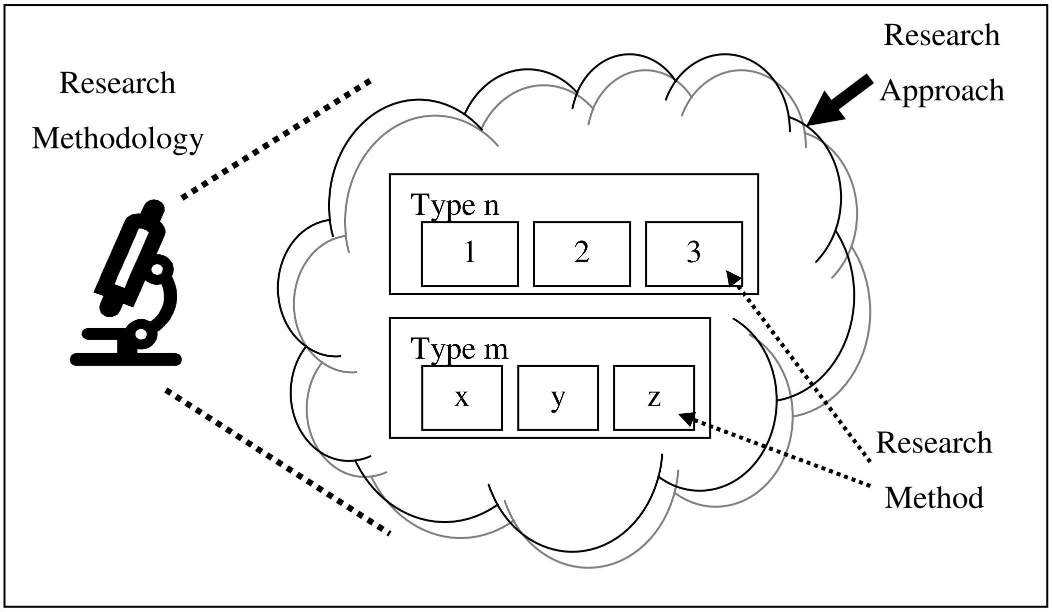


Figure 2.2-1: Description of methodology related terms

2.2.1. How research methodology relates to this project

The aim of this research is **to provide a method for reusing engineering design knowledge**. Along with the aim of the research, the research environment is important in deciding which methods should be applied. The organisations sponsoring the research were defined in advance. Each of the participating organisations designs and manufactures mature, highly engineered, safety critical products in global competitive markets.

The research aim and environment provides a basis for methodology selection. This section will describe the planned research approach, including methods for data collection and analysis and a discussion of how the chosen research approach relates to the research aim. Before the research approach is defined, we will take a brief excursion into the murky waters of epistemology. Knowledge will be addressed to some extent in the literature review, since this project seeks to propose solutions for ‘knowledge reuse’. The theory of knowledge subscribed to in the research must also be discussed, since it has an influence on method selection and justification.

2.3. Epistemology

Definitions of epistemology include:

> “The branch of philosophy that studies the nature of knowledge, its presuppositions and foundations, and its extent and validity” (dictionary.com)
>
> “The part of philosophy that is about the study of how we know things” (Cambridge online dictionary)

For the purposes of this chapter, “epistemology” also refers to the selection and justification of a particular theory of knowledge, or epistemological stance. The rational or logical discussion of epistemology becomes somewhat difficult if we assume an open mind at the outset, and do not immediately reject any of the most radical theories. Strong holism and critical theory, for example, reject the notion of objective fact or the assumption of rationality in the comparison of phenomena. As such, the comparison of epistemological stances becomes an exercise devoted not to some satisfactory conclusion on the appropriateness of a given epistemology, but a dialogue whose only purpose is to show something about how the sociohistorical bias of the author influences the debate.

The purpose of addressing epistemology is not to contribute to the wider philosophical debate. Rather, it is to describe how the nature of knowledge and understanding influences the selection and justification of research methods. For example, how to justify the interpretation of an interview? Is it adequate to make notes, or should tape recordings be kept? How to validate captured knowledge? Is a discussion sufficient, or must a mathematical proof be obtained? Although not strictly within the domain of epistemology, this is the eventual purpose of its study here.

2.3.1. Epistemological extremes: where do we stand?

Meaning and reality: are they stable logical constructs or transient social constructs?

Positivism would have it that reality is a logical construct, whilst social constructionism suggests that reality is in the interpretation: each actor has a different view, and their basis for that interpretation changes over time and with context.

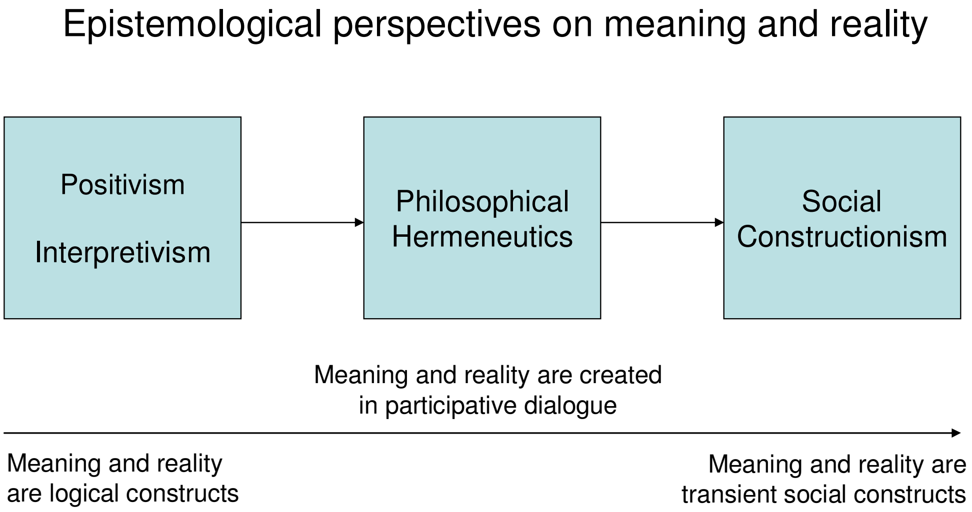


Figure 2.3-1: Epistemological perspectives on meaning and reality

One other important epistemological argument is that of comparison: can we make comparisons on any sound basis?

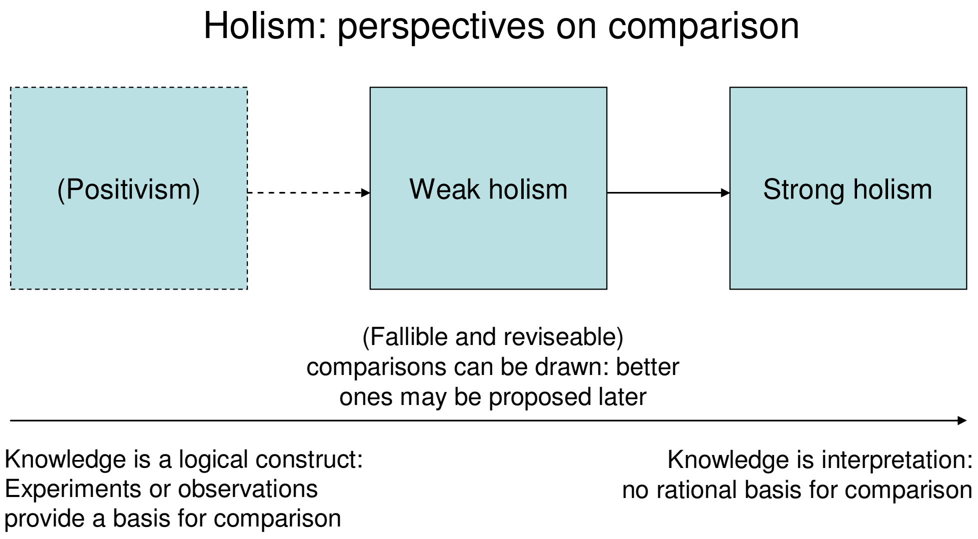


Figure 2.3-2: Holism - perspectives on comparison

Positivism allows a comparison of logical constructs through experiment and observation. Strong holism rejects any rational basis for the comparison of concepts, since all knowledge is interpretation there can be no rational basis for comparison. The discussion of which (if any) stance will be adopted in this research is discussed in the following section, in which epistemology is discussed alongside ontology in the context of selected social science approaches.

2.3.2. Defining epistemology by comparing social science approaches

A limited selection of literature has been used to determine the nature of epistemology. Here the interplay of epistemology, ontology and social science approaches will be addressed. Table 2.3-1 shows a comparison of some social science approaches:

Comparison of social science approaches

	Positivism	Critical Rationalism	Interpretevism	Critical Theory	Realism	Structuration Theory	Feminism
Scientific method?	Yes, all scientific explanations have the same basic structure	Yes, to try to disprove a hypothesis: theories which survive critical observation are provisionally accepted	Yes, rigorous method enables logical deduction of social phenomena	No: objective observation is not possible due to observer assumptions or bias. Truth is based on consensus	Yes, in terms of empirical = actual therefore real: to explain the observable through underlying mechanisms	No, this theory is focused more on the needs of the interaction than its measurement.	No. Objective reality is replaced with a dual reality: Integrated thoughts + feelings, logic + intuition, rationality + intuition
Experience	Phenomenalism: experience as the only reliable basis for knowledge	Observation is theory dependent	Interpretation rather than sensory apprehension	Interpretation rather than sensory apprehension	Observation of the actual, explained by the real (underlying structures)	Immersion in the social world	Natural and social worlds are social constructions. Interpretation with feelings.
Knowledge creation	Passive model of knowledge. Separation of facts and values	Active (deductive) model of knowledge	Passive and deductive model of knowledge: reality is all interpreted	Observer is actively involved but embedded in rich context	Deduction of the laws (from the real) that cause events (actual)	Observer must use the same skills as the social actors to derive meaning	Feeling and experience together, knowledge based on shared vision
Ontology: Social Reality	A complex set of *causal* relations between variables. Only that which can be observed is real.	A complex set of *causal* relations between variables. Theories account for observation, but are not derived from them	Meaning is negotiated by social actors – meaning (reality) is interpretation	Meaning is negotiated by social actors. Embedded assumptions are crucial	Social episodes are the product of cognitive resources social actors bring. Distinct empirical, actual and real domains.	Produced by skilled social actors but not necessarily in the conditions of their choosing. Social structures influence and are created by human agency.	Multiple realities exist – and are dependent on the observer
Epistemology	Knowledge is derived from sensory experience by experiment or comparative analysis	Knowledge is derived from observation and deduction: it remains tentative and subject to critical evaluation	Knowledge is derived from everyday concepts and meanings: negotiated through a social process	Causal laws and interpretive understanding: Knowledge through interpretation of embedded meaning	Laws expressing tendencies of things. Models and structures are created to account for observed phenomena	To understand this world it is necessary to know what the social actors know, through a process of immersion	Women have a privileged position in their ability to understand the social world due to caring labour

Adapted from Schwandt (2003)

Table 2.3-1: Comparison of social science approaches

The approach adopted for this research is critical theory. Some elements of realism are also accepted, such as the ability to explain the way things work by creating models. Critical rationalism is another approach with some similarities. It accepts an active, deductive knowledge model that remains subject to evaluation. Theory accounts for, but is not derived from, observation.

Interpretivism is rejected as its primary aim is to generate theory about social phenomena. The aim of the research is to provide a system for design knowledge reuse, and whilst not pre-empting an IT emphasis we should also not assume in advance that its method will be derived from theory about social systems: some logical structures may play a part. The ontology of interpretivism questions the value of this research in a fundamental way: if all reality is interpreted and negotiated by social actors, then this process of negotiation should be a central aim of a ‘knowledge management’ system. Since meaning *is* interpretation, the content of the system would also be fluid and subject to interpretation.

Positivism is rejected on the basis of its ontology: that relations are causal and that only the observable is real, and its epistemology: that knowledge is derived only from experience or experiment. Positivism rejects the concepts of negotiated meaning, tentative theory, and the importance of context or embedded assumptions, and as such it will not be accepted.

Structuration theory will not be adopted since its primary aim is to study social structures, which differs from the aim of this research. Its ontology and epistemology are not clearly stated. It focuses on the social structure being created by and simultaneously influencing social actors.

Feminism will not be adopted. This is in part due to the gender of the researcher. Whether one must be female in order to apply feminism will not be addressed here, however it should be noted some of the concepts of feminism are accepted: knowledge is based on shared vision; thoughts and feelings (or rationality and embedded context) have a dual influence.

A summary of the adopted epistemological stance:

- Causal laws may be identified through interpretive understanding;
- Knowledge is created through interpretation: embedded meaning and context play a major role in this process;
- The embedded assumptions of the researcher may change during the process, although they are not necessarily known.

2.4. Research approach: qualitative or quantitative?

> “This distinction between quantitative and qualitative methods is a matter of emphasis – for both are mixtures.” (Stake 1995)

There are several arguments showing a strong tendency for the application of quantitative methods in qualitative research. Quantitative methods are essential in many research practices, and can support and benefit some qualitative research designs. What must be considered is the appropriateness of a given method in the context of the research. Some authors advocate the use of quantitative methods in all research. The claim is that these methods allow testing of hypotheses which allow the findings to be made applicable to a wider context. This perspective is typified by Remenyi, who argues that where qualitative methods such as case studies are used, quantitative analysis methods are essential:

> "Thus, even if a case study protocol has been used to collect data, if the researcher wishes to claim that the results have a degree of generality then quantitative techniques for hypothesis testing will be essential." (Remenyi & Williams 1996) p144

The initial point that the paper makes is excellent: that the formation of a narrative helps to understand the scenario in early stages of the research, and that such methods can increase the innovativeness of the results. The conclusion, however, is based on slippery foundations: in order to show generality, quantitative techniques are essential. In fact, such methods *require* the assumption of generality as an *input*. The concepts of populations and random sampling assume that input data has been selected at random from a large population. In the context of this research, the 'population' is made up of a relatively small number. Individual participants are carefully selected based on their expertise. Any attempt to assign a 'random' label to them is surely flawed. This must be understood in the application of quantitative methods.

Quantitative (experimental) methods require a high degree of control. Interviews within the epistemological stance accepted by critical theory, the adopted research approach, cannot be 'controlled' to a high degree. Observer 'bias' (or background) is an essential element of understanding. Meaning is negotiated by social actors: any other researcher in the same situation may have a different understanding, and create a different conclusion. Quantitative (survey) methods require large populations. Aside from issues relating to survey design, which are widely cited as being extremely important, the issue of response rates will be briefly addressed. An acceptable response rate is 2%. There is an obvious argument that the 2% who do respond may not be representative of the total sample. Statistical analysis methods may account for this in part. With such a low response rate the effect of an unrepresentative sample skewing the results could be so great that the meaning of the analysis is lost.

It is important, when using statistical techniques, to understand the fundamental assumptions that they make in order to produce a meaningful result. Many statistical techniques assume not only a random input but also a normal distribution.

An alternative way of characterising two different types of research has been proposed by Wright (quoted in Stake (1995)). The distinction is between inquiry for making explanations (in this context, allied with a quantitative method) and inquiry for understanding complex relationships (more similar to a qualitative method). The actual data types or methods are not defined: it is the purpose of the research which brings about the difference. Quantitative research seeks to determine the relationships between a small number of variables. The approach actively seeks to limit interpretation until after the analysis has been carried out. Qualitative research seeks to examine relationships within a particular case, with modifications to the research as a result of unexpected elements and an active approach to interpretation as two essential elements for ensuring that the research can adapt to identify and explore the relationships that matter. "…dependent variables are experientially rather than operationally defined." Stake (1995) p41.

The aim of this research project is to provide a method for reusing engineering design knowledge. This method should be suitable for the participating organisations. The suitability will be judged by a small number of participants representing those organisations. The measure of suitability will be sought by consensus, through participation. The method for design knowledge reuse is not known at the beginning of the project, and this will form the main body of work. Aside from the method for reuse, a secondary element (arguably of equal or greater importance) is what knowledge to include and why. IT tools are not specified, design methodologies are not fixed, and the definition of 'knowledge' in the context of the system remains up for debate at the outset.

2.4.1. Fixed vs. flexible

Fixed research designs require a developed conceptual framework or theory so you know in advance what to look for. They also require extensive pilot work to establish feasibility of the methods and a high degree of control over the environment to ensure experimental validity. Social research methods, or qualitative designs, are often flexible. They make extensive use of qualitative data, such as words. A flexible research approach requires less pre-specification. Because many of the details of a flexible research design are not be specified in advance, the researcher can adapt to the unexpected.

Robson (2002) focuses on research to initiate change. The aim if this research project is not to initiate change, but to propose a system that *could* be applied within the current operating environment. It must reflect issues faced by practitioners. Another advantage of a flexible study is that it permits validation through triangulation. Multiple sources, methods, investigators or theories can be used for this triangulation process.

2.4.2. Applied research vs. qualitative and quantitative

A typical research design for applied research is different from both qualitative and quantitative traditions. The research study begins with a detailed area of interest. The researcher then makes use of a combination of academic literature and initial investigations with the sponsor organisation to identify a ‘problem’ within the organisation and possibly a ‘gap’ in the literature. These two elements then form the basis of the detailed study. This is not like a pure qualitative approach such as grounded theory, in which the researcher uses research methods to explore issues, and uses data to create theory. It also differs from quantitative research in which experiments and data analysis enable hypothesis testing. The applied research model represents a middle ground. The main focus is not on the testing of a hypothesis, or creation of theory, but the development of a method or system. Since the emphasis of the research is shifted, so too is the relative emphasis on methodology, method and analysis. Both qualitative and quantitative approaches require a robust methodology, since this provides justification for the research methods applied to the gathering and analysis of data, which represents the outcome of the project. A major outcome of the applied project is the work itself, and as a result the justification of the method used to gather and analyse data typically receives less focus. This is illustrated in Figure 2.4-1. The shaded areas represent the focal element(s) within each approach.

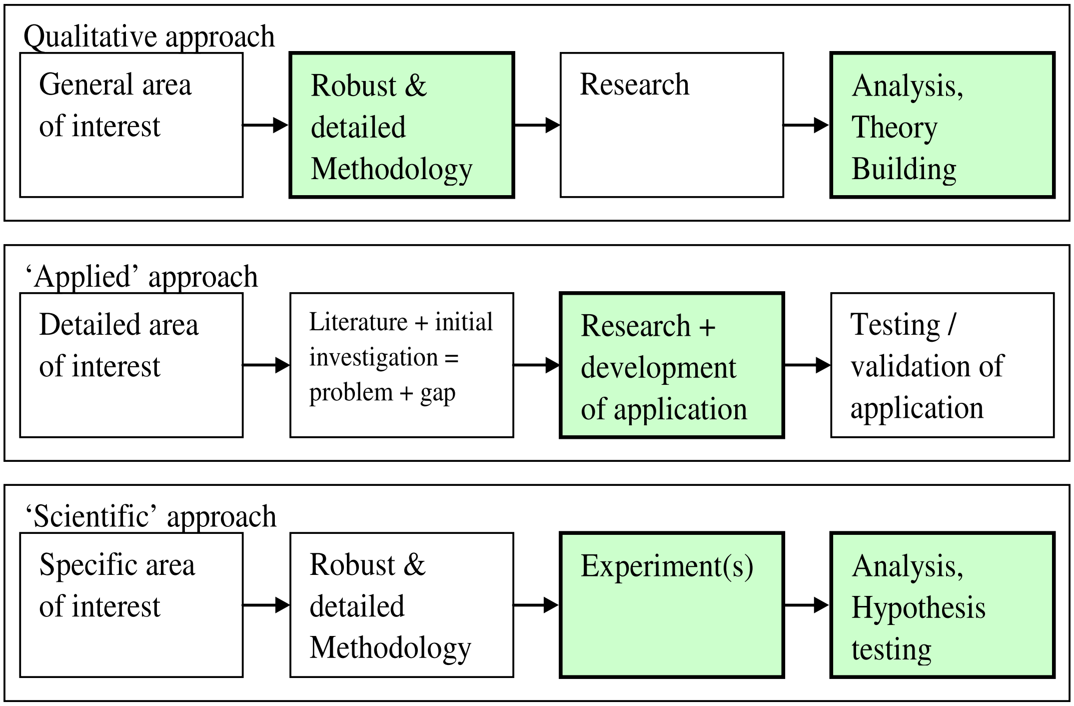


Figure 2.4-1: comparison of research approaches

In both the qualitative and scientific (quantitative) models, the methodology plays a critical role in ensuring that the outcome of the research is valid. The applied approach differs in methodological and substantive content. The methodology is typically less strictly defined, since part of the substantive content is derived from the additional 'application' element. The outcome of this type of research is a specification of a system alongside a commentary on its applicability. A primary method of verification will come from the sponsor organisation(s) through their participation in the testing and validation of the application.

2.4.3. Research strategy

The research strategy, or approach, is related to the research aim. The research objectives were expected to develop as the project progressed, and the actual research questions were not clearly defined at the outset. The use of a flexible strategy means that this evolution of research objectives and questions actually makes the research richer, more able to focus on important issues highlighted by the combinations of data sources. The general approach can be defined in advance by examining the initial research aim.

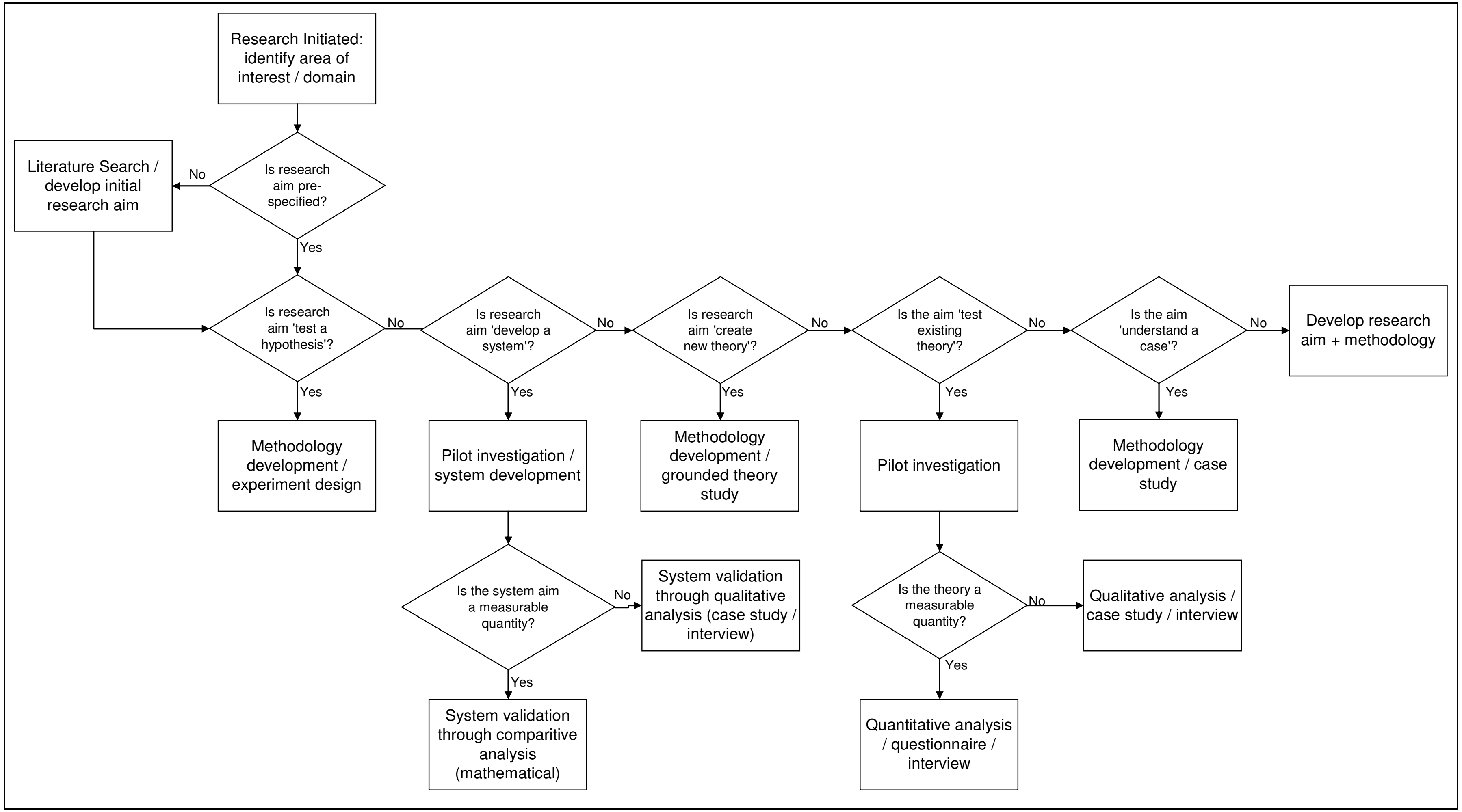


Figure 2.4-2: Research strategy

Figure 2.4-2 is an attempt to describe the method selection process for the qualitative, scientific and applied research domains. It shows that the research strategy for several of the research aims has a similar foundation. The initial research aim must be defined in advance in order that a general strategy can be selected. Pilot studies form a constituent part of most strategies, and this helps to guide the selection of method through the concurrent development of the research aim.

2.4.4. Validity

In this section it is assumed that interviews and workshops are the primary data sources. Validity of the research is threatened by two main elements: description and interpretation. In terms of description, reliability is threatened by inaccurate recording of data. If tape recording is not feasible, the quality of note taking is important. If participant responses are subject to researcher interpretation, they could also be considered invalid.

	Threat to validity		
Strategy	**Reactivity**	**Researcher bias**	**Respondent bias**
Prolonged involvement	Reduces threat	Increases threat	Reduces threat
Triangulation	Reduces threat	Reduces threat	Reduces threat
Peer debriefing / support	No effect	Reduces threat	No effect
Member checking	Reduces threat	Reduces threat	Reduces threat
Negative case analysis	No effect	Reduces threat	No effect
Audit trail	No effect	Reduces threat	No effect

Table 2.4-1: Strategies for dealing with threats to validity: from Robson (2002) p174

There is an argument, following the discussion of epistemology, that would reject the notion of reducing researcher bias since this is also the source of insight and the filter through which analysis takes place. The deeply embedded context through which the environment is viewed provides the only source by which the account of the situation will be provided. The bias *is* the mechanism through which this occurs. However, it is considered that the validity threats described above do have intrinsic value. Prolonged involvement enriches the contextual filters of the observer, providing the capacity for greater insight. Triangulation and member checking reduces the risk of factual errors.

It is not the intention to remove researcher bias, but to reduce the risk of an inaccurate or incomplete story with factual errors.

The threats to validity in this research project will therefore be managed in three ways: triangulation, audit and member checking. Triangulation of data and theory will be the main sources. Audit refers to keeping data throughout the research, including notes, transcripts from interviews, field notes, documents, etc. Data collected will also be tested through member checking: asking the participants to comment on notes, models or records produced as a result of the interviews or workshops.

It is also important to make a judgement on the generalisability of research results from a philosophical perspective: can the proposed system which is suitable for company X be said to be suitable for every company, or even every company in a particular domain? The insights gained from comparing the suitability of the proposed application across multiple organisations will help to identify some aspects of the application and the participating organisations that affect the suitability.

2.5. An overview of research methods

Robson (2002) states that real world research can combine both qualitative and quantitative methods. This section will describe a selection of research methods and tools.

Three methods are commonly applied to flexible design research: case study, grounded theory study and ethnographic study. Ethnographic study is not appropriate to the research objectives, since it focuses on description and interpretation of culture and social structure of a social group. Case study and grounded theory will be described, and the methods evaluated for use in this research project.

2.5.1. Case study

The use of a case study in research is to provide two things: a detailed study of a particular subject (person, organisation, program) and an extensive interpretation of that case.

> "A case study is expected to catch the complexity of a single case." (Stake 1995)

The case study typically applies multiple methods, which may include observation, interview and documentary analysis, amongst others. Details of the case study design may not be known in advance if it is a new or little understood area. An important feature of case study is the context:

> "Case study is a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence." Yin 1994, quoted by Robson (2002) p178

Stake (1995) describes the case study as a method for understanding issues within the case, for gaining insight into the interactions and relationships that influence the case, and for interpreting the social mechanisms that are important to the issues. The aim of this project is not to unravel the social mechanisms within the case, it is to provide a method for reusing engineering design knowledge. The purpose of the case study is to identify the necessary components for such a system. This deductive approach could be considered as somewhat removed from the complexities of the organisations in question. In part this is true. However, the detailed focus on the methods and needs of the organisations taking part in the study will be referred to as a case study. It is a case study with a systems focus rather than a social focus. Stake refers to two distinct types of case study: intrinsic and instrumental. Intrinsic case study means the case is given. In this type the CASE is dominant. Instrumental case study means the case is sought out to help understand a research question. In this type the ISSUE is dominant. This research involved pre-specification of both the issue and the cases, however the cases were sought out in order to assess the issue. The case type in this research is therefore instrumental: the issue is dominant.

Considering a dominant issue within a case alongside the comments on the validity of assigning generality across cases, the purpose of the case is not obvious. It is assumed that some of the principles derived from the cases studied in this research will be applicable to other situations, although not necessarily and not without careful consideration of context. By extracting shared contextual elements of the cases it is considered that any conclusions made that suit the studied cases will also be relevant to cases in a similar context. This is in part achieved through the instrumental case study: focusing on the issue rather than the case.

Within a case study, proper data gathering is crucial. This should be planned according to the research questions, and properly recorded. The data gathering plan will be shown in the investigation and case study chapters.

2.5.2. Grounded theory study

> "The central aim is to generate theory from data collected during the study. Particularly useful in new, applied areas where there is a lack of theory and concepts to describe and explain what is going on." (Robson 2002) p90

The focus of the grounded theory method is to create theory in new or relatively unknown domains. The research domain is well known; it is the application that is new. An investigation into the effectiveness of the system, or the factors leading to successful use of the system may be suitable areas for a grounded theory study.

2.6. Analysis of qualitative data

> "There is no clear and accepted single set of conventions for analysis corresponding to those observed with quantitative data… there are ways in which qualitative data can be dealt with systematically." (Robson 2002)

An accepted view of data analysis requirements is that where qualitative data is used to support quantitative data, it is not necessary to perform detailed and complex analysis. If the data collected during the study is primarily qualitative, then attention must be given to their analysis. Alternatively, analysis may be rather more tacit and informal:

> "…the carefully structured approach that we discuss here is not always necessary. For some qualitative researchers, even quite inexperienced ones, it is entirely feasible that data analysis may simply be a matter of finding a quiet corner, spreading out the field notes without a laptop in sight, and writing about what was seen and heard. Many times we know instinctively, from our sensitive immersion in the particular culture being investigated, what needs to be said, and how." (Gorman & Clayton 1997)

The major influence governing the choice of a method for data analysis is that the research conclusions can be demonstrated as having come from the data. Poor reliability and validity caused by the researcher making conclusions based on informal interpretations of the data are a potential risk to this process. Formal analysis methods could help to reduce these risks. Alternatively, it is entirely feasible that those same biases may be carried through the more formal data analysis approach (as they are generally based on decisions, selections and value judgements made by the researcher), so the risk remains. The method for data analysis will be decided upon based on the perceived need: if understanding is lacking, then formal methods can be drawn upon to help tease out meaning from the data. The need for such tools, according to Rice-Lively (in Gorman & Clayton, 1997) arises “If your data prove too great in quantity or too complex to carry in your head…”. Therefore, if the understanding is apparent, and supported by alternative methods such as triangulation and member checking, then formal analysis methods will not be applied. Details of any analysis mechanisms applied will be provided in the analysis chapter.

2.7. Description of the adopted research method

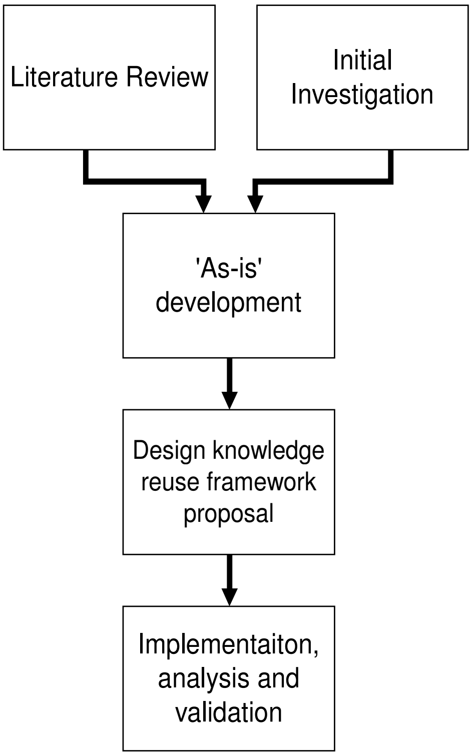


Figure 2.7-1: Development approach

In summary, the development approach includes a field study (initial investigation) and literature review, which guide the development of the research aim and objectives. A detailed investigation (‘as-is’ development) is followed by a design knowledge reuse framework proposal. That proposal is implemented, then tested and validated with industry. The approach is shown in Figure 2.7-1. Although this represents the overall sequence, a degree of iteration took place in the process particularly with regard to literature: the analysis of the initial framework together with further investigation and further review of the literature prompted changes to that framework.

The purpose of this research is to make proposals for new methods within well understood domains, rather than to generate theory. The strategy adopted will therefore be case study. The (data gathering) methods applied within that strategy will include interviews and observation. This strategy could be referred to as interview case study (Gorman & Clayton 1997). Secondary data sources will also be used, including company documents.

Data gathering begins immediately: the researcher is collecting and interpreting data from the very beginning. First impressions, background, literature, initial interviews and observations all contribute to ‘data gathering’ insofar as they are changing the background, or interpretive filters, of the researcher.

2.7.1. Interview

Interviews will be described in terms of the degree of planning and control: to what level of detail the topic is defined in advance and to what extent the conversation is kept within those defined boundaries. Commonly referred to interview types are structured, semi-structured and unstructured. A highly structured interview (such as a survey interview) has pre-defined questions and a limited set of answers. Fully structured interviews have predefined ‘open response’ questions with fixed wording. Semi-structured interviews have predefined questions. The order of questions may be changed (and questions may be omitted) based on the interviewer’s decision of what is appropriate. Unstructured interviews have a general area of interest.

Less defined interviews provide more scope for the respondent to influence the discussion. This may result in less definable detail. It may provide more insight into diffuse elements such as culture, context or trust. With a greater degree of freedom, a richer response is possible. The context of the response may be included, or derived. This type of interview will be applied by nearly all researchers in early stages, where the aim is to try and understand the domain. Informal discussion is also used in these stages, the main difference being that the informal discussion is often not recorded.

Within this research project, the majority of interviews will be semi-structured. The degree of structure will vary depending on the requirement. Interviews carried out during the early stages of the research will be unstructured, with the aim of developing an understanding of the environment. Insight gained from these interviews will lead to the creation of semi-structured interviews. That is, the context and purpose of the semi-structured interviews will be derived from the unstructured interviews.

The use of interviews fits into two categories described by Robson (Robson 2002) as suitable situations for interviews: studying individual perceptions of processes within a group, and for exploratory work in advance of a more focused study. This view is shared by Oppenheim, who suggests that the two kinds of research interview are ‘exploratory’ and ‘standardized’. Where their views may diverge is in the nature of interviews: Oppenheim suggests that if an interview is not a 1-way process, then researcher bias will mean that it loses much of its value. (Oppenheim 1992) This is written from the perspective of questionnaire design, which is a quantitative approach. A lack of quantitative content in a framework that only accepts quantitative input clearly causes problems. The view that there is no other framework is not accepted.

In summary, Robson’s view on the advantages of interviews are that they are a flexible and adaptable way of finding things out, which give deeper understanding of responses and motives than questionnaires. The disadvantages include the difficulty of carrying them out in a professional manner that avoids bias, and their time consuming nature for both carrying them out and the analysis that is required.

2.7.2. Observation

Observation will not be carried out in a formal sense. There will not be records of particular behaviours or events on a time chart. Informal observations made as a result of being in the workplace of the organisations taking part in this research project may become important to the research. Where this is the case, they will be investigated, possibly in interviews. They may also have an influence on the analysis of results. The main reason for not including observation as a major source of data is the type of data being sought: the aim is to provide a system, so the main data requirements relate to questions for the future: what should be included? Study of existing methods, including current design practices, could be carried out using observation, however time limitations dictate that this need will be better served through interviews relating to historical events.

2.7.3. Other methods

Telephone conversations, email, informal discussion, meetings, and a variety of documents will also be used within this research as sources of data. Issues relating to the use and any formal analysis of these additional methods will be discussed in the analysis chapters.

2.8. Summary of research methodology

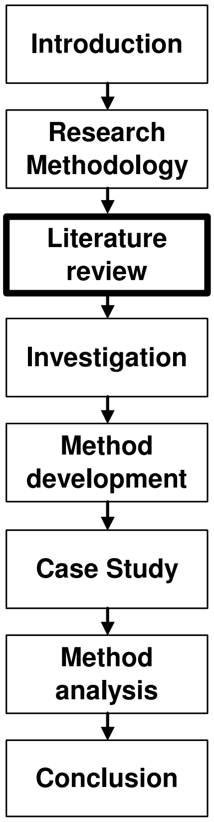
Research methodology is taken to mean the study, selection and justification of research approach. The selected research approach is interview case study. The basis of the selection is in part due to the research aim and in part due to the epistemological stance adopted: critical theory. Critical theory holds that:

- Causal laws may be identified through interpretive understanding;
- Knowledge is created through interpretation: embedded meaning and context play a major role in this process;
- The embedded assumptions of the researcher may change during the process, although they are not necessarily known.

The aim of this research is to provide a method for reusing engineering design knowledge. This represents applied research, and as such, the provision of the application or method is the main focus. Interview case study provides a means to investigate the participating organisations, to validate the findings of that investigation, and to assess the proposed application or method. Qualitative statistical analysis methods are not appropriate, since the two foundational assumptions of a normal distribution and a random sample do not apply. The perspective on bias follows the adoption of critical theory: the embedded assumptions of the researcher play an active role, and are not necessarily known. Validation and checking therefore forms an important part of the research approach.

The outcome of such a research project is significantly different from a commercial project, since the outcome must by nature represent something different and new (to contribute to knowledge), and is not required (in purely academic terms) to represent something successful. In attempting to ‘provide a method for reusing engineering design knowledge’, a perfectly valid solution may already exist. That solution is automatically rejected (at least in its current form or within its current domain) on the basis that it exists and has been applied. A second, similar issue is the innate assumption that the contextual framework within which the thesis is built is based upon an exhaustive literature review. This is neither true nor possible. There are a great deal of publications that are not readily available to researchers, including certain reports and particularly conference proceedings that are not indexed in an academic database or published on the Internet. Semantic mismatch within a domain may also rule out access to publications that do exist, where search phrases do not match but meaning does. In arguing that the research is not necessarily the best solution, and that it is almost certainly lacking in its contextual framework, it is wrong to consider that such a contribution is without value. The proposals made have been subjected to scrutiny by industrial practitioners, and this is the basis on which value of the proposal is judged. Given the epistemological stance adopted in this research, if two researchers had the same finite set of literature and each investigated the same case, they could still be expected, on an equally valid basis, to identify different literature groupings and gaps, draw different conclusions from the case and propose different methods. This relates to the adopted view that knowledge is created through interpretation.

Chapter 3: A review of the literature supporting design knowledge reuse



This chapter will describe the key sources from literature which have had a major bearing on the research in terms of theoretical foundation, current research status and significant related work. It will also provide definitions, assumptions, and a basis for classifying and positioning the research. The review also seeks to identify research gaps in order position the academic contribution of this research.

3.1. Literature Review: scope and purpose

The aim of this research is **to provide a method for reusing engineering design knowledge**. The context within which the aim is defined suggests that the research must also contribute to the research domain. The review therefore seeks to identify research gaps that the design knowledge reuse framework can contribute to. As such, the research aim guides the literature review strategy. The scope of the literature review began with defining the important concepts and terms (knowledge, knowledge management, engineering design) and to gain an understanding of other work in a similar domain (engineering design knowledge management, design reuse).

The purpose of the literature review is to identify existing work to form a theoretical foundation for understanding the domain, then to gain some insight into which domains are relevant in order to position the research, then to research existing work in the selected domains to gain an understanding of the status and progression of that work.

3.1.1. Method

The sources for literature search include the Cranfield library electronic catalogue, and more importantly the externally managed subject databases including Elsevier Science Direct, INSPEC, IEEE Explore, ABI/INFORM (ProQuest), Emerald, and ISI Web of Knowledge. Other Internet resources were used, particularly Google (Web and Scholar).

Aside from the directed searches, there was also a path through the literature defined dynamically. That is, relevant sources provided references which themselves provided more references. Following that path provides an appreciation of the underlying assumptions of the literature. Another important element of the literature review process is the discovery of appropriate terminology to direct further searches.

3.1.2. Key areas

The key areas for the literature review include:

- Knowledge management concepts
- Design knowledge reuse

- Design process support

The literature review will first examine knowledge management, defining important terminology and describing some essential theories of knowledge and knowledge management. The review of engineering design knowledge reuse will show that the design process is an important element of reuse from a variety of perspectives. This will lead to a new category of engineering design process support. Design reuse and design process support will be described, then analysed for similarities, trends and gaps.

3.2. Knowledge management concepts

The aim of the research is to provide a method for reusing engineering design knowledge. Reusing knowledge is one of the key aims of knowledge management. Within the knowledge management domain, along with proposed methods to manage knowledge there is also a great deal of work on defining knowledge, including classifications of knowledge types. This section will define knowledge and describe knowledge management.

Polanyi coined the phrase “we know more than we can tell”. There is some knowledge that we have that we are able to describe. This is referred to as explicit knowledge. There is some knowledge that we have that we can not describe, yet are able to use. With the right tools we can describe more than we knew we could, but still we don’t know how. An example given by Polanyi is our ability to recognise faces. We can not describe how this process works, yet we can perform it expertly without conscious thought. The knowledge of how to perform this face recognition is tacit: we are able to apply it yet we are unable to describe it. The definition of knowledge often includes segmentation into two types, tacit and explicit (Polanyi 1966).

Nonaka applies this distinction to a theory of organisational knowledge creation, in which knowledge is created through various modes. The knowledge evolves in a spiral from tacit to explicit as it becomes better understood (Nonaka 1994).

The SECI model is shown in Figure 3.2-1. This describes four types of knowledge creation. Socialization is the transfer of one person’s tacit knowledge to another person’s tacit knowledge through social interaction. Externalization is the transfer of tacit knowledge into explicit knowledge. This is the aim of knowledge capture exercises. Combination is the creation of explicit knowledge from another source of explicit knowledge. Internalization is the transfer from explicit knowledge to tacit knowledge, which may take place in activities such as reading.

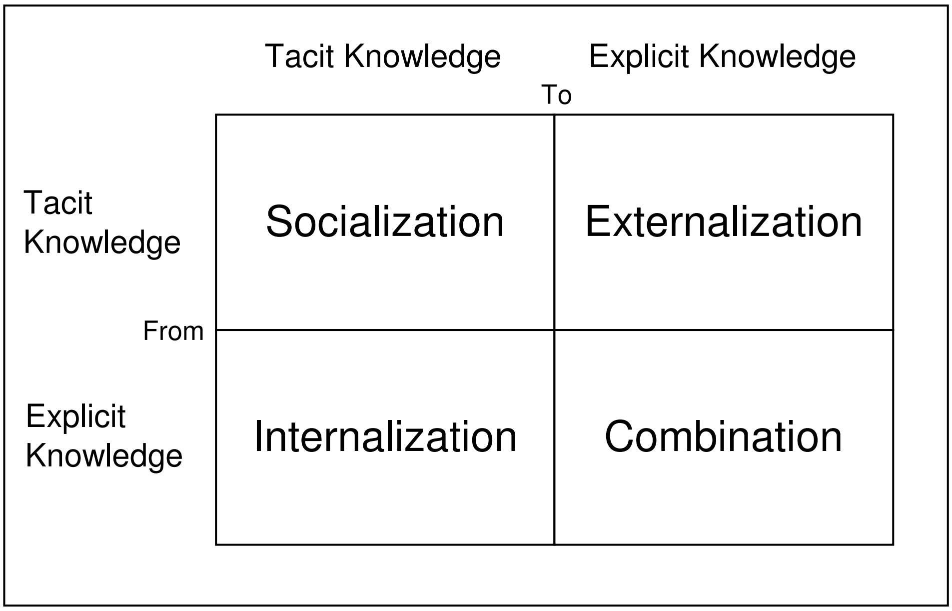


Figure 3.2-1: Modes of knowledge creation: SECI model (Nonaka 1994)

An important mode in the context of this research is externalization: creating explicit knowledge from tacit knowledge. This will be an assumed mechanism for knowledge capture. The central theme of the model of organisational knowledge creation assumes a dynamic interaction between these modes, as shown in Figure 3.2-2, the spiral of organisational knowledge creation. The fundamental theme of this model is that tacit knowledge, as it is shared and gradually becomes better understood, is formalised: becomes converted to explicit knowledge. At one level, the knowledge creation model is in keeping with the assumed nature of knowledge: the tacit elements are not currently formally understood. Where there is potential for conflict is in assuming that tacit knowledge can be converted to explicit knowledge. While tacit knowledge may be applied at some level it is not necessarily understood how this takes place or what actually happens, and as such there is a component of tacit knowledge that can not be included in this conversion process.

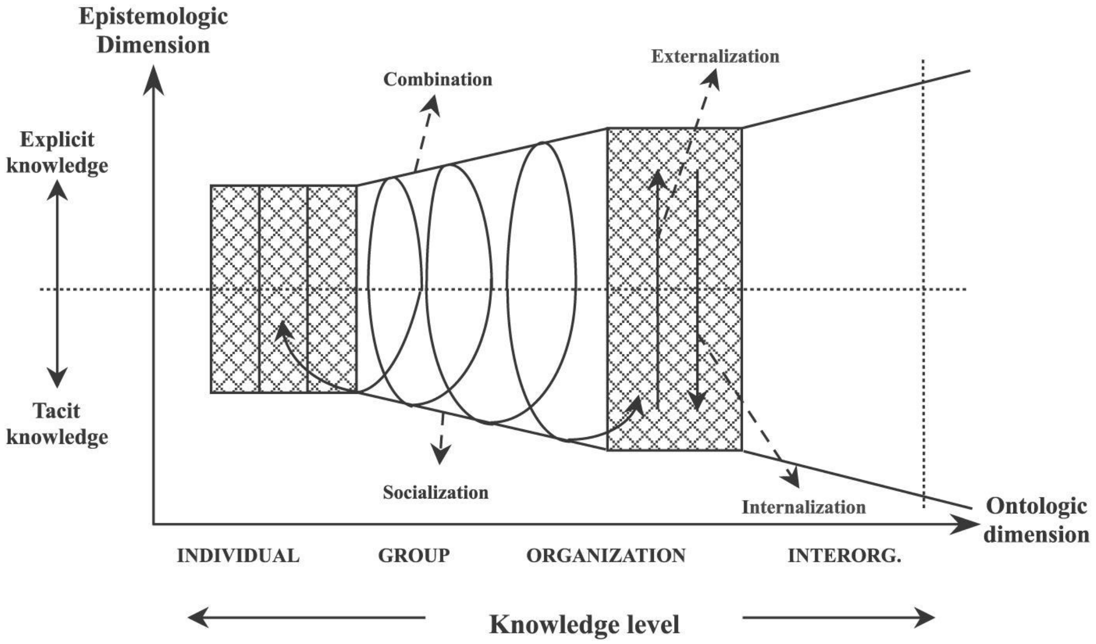


Figure 3.2-2: spiral of organisational knowledge creation (Nonaka 1994)

The spiral model appears to suggest that group interaction leads to the conversion from tacit, within-person knowledge to explicit, formalised and stored (shared) knowledge through the various combination, socialization, externalization and internalization processes. Knowledge is viewed here as a dynamic combination of explicit and tacit elements that we combine with existing knowledge, share through social interaction, externalise through documentation and internalise through processes such as reading. This says a lot about how knowledge operates, but not very much about what it is. Formal definitions of knowledge are varied and sometimes vague.

Nonaka defines knowledge as “justified true belief” (Nonaka 1994). Alavi describes various definitions, or perspectives of knowledge along with the implications for its management (Alavi & Leidner 2001). The main purpose of the classification is to put knowledge into context to understand how it might be managed using an appropriate system. The knowledge taxonomy is shown in Figure 3.2-3.

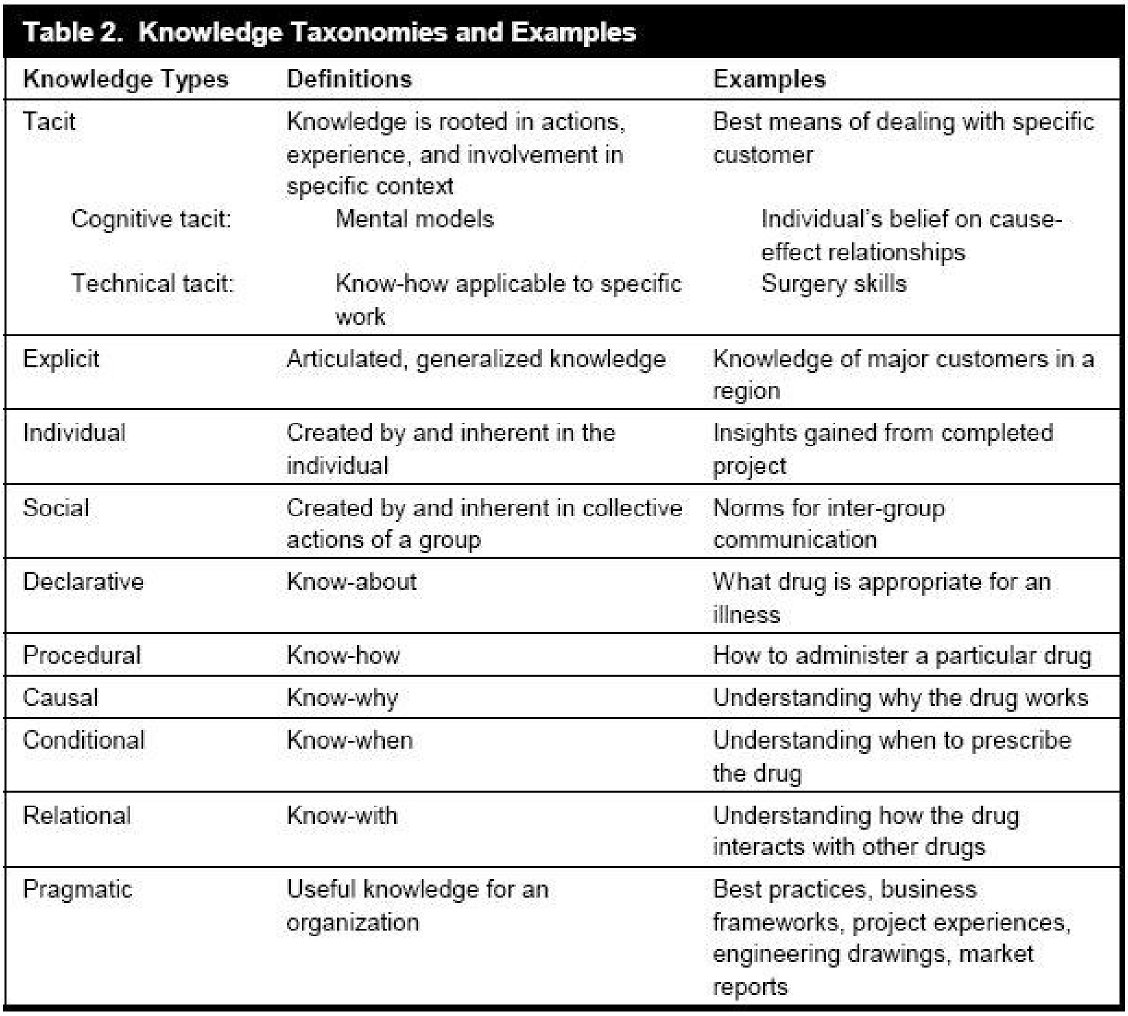


Table 2. Knowledge Taxonomies and Examples

Knowledge Types	Definitions	Examples
Tacit	Knowledge is rooted in actions, experience, and involvement in specific context	Best means of dealing with specific customer
Cognitive tacit:	Mental models	Individual's belief on cause-effect relationships
Technical tacit:	Know-how applicable to specific work	Surgery skills
Explicit	Articulated, generalized knowledge	Knowledge of major customers in a region
Individual	Created by and inherent in the individual	Insights gained from completed project
Social	Created by and inherent in collective actions of a group	Norms for inter-group communication
Declarative	Know-about	What drug is appropriate for an illness
Procedural	Know-how	How to administer a particular drug
Causal	Know-why	Understanding why the drug works
Conditional	Know-when	Understanding when to prescribe the drug
Relational	Know-with	Understanding how the drug interacts with other drugs
Pragmatic	Useful knowledge for an organization	Best practices, business frameworks, project experiences, engineering drawings, market reports

Figure 3.2-3: knowledge taxonomies and examples (Alavi & Leidner 2001)

The CEN (**C**omite **E**uropeen de **N**ormalisation, or European Committee for Standardisation) definition of knowledge makes extensive use of knowledge types:

> "A set of data and information (when seen from an Information Technology point of view), and a combination of, for example know-how, experience, emotion, believes, values, ideas, intuition, curiosity, motivation, learning styles, attitude, ability to trust, ability to deal with complexity, ability to synthesize, openness, networking skills, communication skills, attitude to risk and entrepreneurial spirit to result in **a valuable asset which can be used to improve the capacity to act and support decision making**. Knowledge may be explicit and/or tacit… individual and/or collective." CEN (2004) emphasis added

The important aspect of this definition is the phrase “can be used to improve the capacity to act and support decision making”. That is, it suggests that knowledge must be useable. It will therefore be assumed that knowledge represents something useable, which is closely aligned to the definition by Nonaka that knowledge is ‘**justified true belief**’. This will be adopted as the definition of knowledge. The type of knowledge used varies depending on the need. The classification of knowledge varies depending on the application. The representation of that knowledge, if it can be represented, also varies according to its type and application.

The theory of organisational knowledge creation (Nonaka 1994) implies a method for managing knowledge in the   of knowledge creation shown in Figure 3.2-2. The methodology is frequently cited in knowledge management publications. In June 2006, Google Scholar (http://www.scholar.google.com) lists 2416 citations.

The CEN definition of knowledge management is somewhat more precise than their definition of knowledge:

> “Planned and ongoing management of activities and processes for leveraging knowledge to enhance competitiveness through better use and creation of individual and collective knowledge resources.” (CEN 2004)

This definition will be accepted when referring to knowledge management. Knowledge reuse is a subset of knowledge management. In engineering design, knowledge reuse has been a subject of particular interest over the past few years. The next section discusses knowledge reuse in engineering design.

3.3. Design knowledge reuse

This section will describe and categorise current approaches to engineering design knowledge reuse. The analysis will show that:

- There is a lack of support for early design, or nondeterministic design problems.
- Effective design reuse is a whole-system issue: product design processes, information management, and the products must be considered together.

- Process (modelling) represents knowledge and can be applied to reusing design knowledge.

- Process models can be integrated with other aspects of design. A variety of approaches have been developed, however the integration is often not applicable to the whole design process.

3.3.1. Design reuse systems and frameworks

There are a variety of proposals and analyses of design reuse methodologies and systems in the research literature. They come from a variety of domains including engineering design science, computer aided design / computer aided manufacture (CAD / CAM), artificial intelligence, and knowledge management. This section describes a selection of design reuse methods, and attempts to highlight trends and gaps.

Lang et al suggest that in conceptual design, three types of design knowledge are important for reuse: intent, rationale and history (Lang et al. 2002).

> “Knowledge management issues in conceptual design are centred on information gathering, and the capture and use of design knowledge. The capture and representation of design intent, design rationale and design history is required for the purpose of (a) capture of design expertise as a corporate asset, (b) reuse of design expertise to accelerate future designs, and (c) facilitating backtracking during complex and ill-defined and ill-structured design problems. Currently, hard copy design notebooks are the most commonly used devices to record the design knowledge.” (Lang et al. 2002) p8

They go on to say that knowledge management systems will continue to have major limitations until cognitive aspects of design are thoroughly understood. They also state that even with large volumes of internally available reference and design documents, designers accessed knowledge predominately through colleagues. Most design decisions are still captured in design notebooks. Whilst intent, rationale and history are important, they are not enough on their own. The ‘how to’ element of design, design methodology and design process support should also be considered.

Andreasen describes a method to capture conceptual design through applying three product views: transformation, organ, and part structure (Andreasen 1998). The views could be loosely referred to as form, function and behaviour. The transformation view focuses on transformation of material, energy or data that occurs when operator and machine co-operate (behaviour). The organ view focuses on active elements that create effects, and their mode of action based on physical principles (function). The part view focuses on the materialisation of the machine in parts, so that every part solves its tasks based on its mode of action (form). The proposed method of defining conceptual designs enables a focused analysis on the required function of the product, without directly fixing the product structure. The models created could be reapplied to future designs. Again, the 'how to' element of design, design methodology and design process support should also be considered as part of an integrated approach.

Shahin et al propose a design reuse system which is primarily based on structuring the product information, which is similar to Duffy and Legler (1999). They suggest that structuring of design information is required to enable reuse. The design model used greatly influences this process. Within design Function Deployment, their selected approach, design should be structured as (a) product concept (b) solution concept (c) embodiment design and (d) detailed design, for efficient reuse (Shahin et al. 1999). The product concept is represented by a prioritised list of functions. Solution concept is represented by a function tree. Embodiment design is represented by a parts tree. Detailed design is represented by a geometric model. Whilst this approach does address the whole design process, design process models are not considered as an integral part of reuse. Also, it does not address design rationale.

CAD / CAE based design reuse methods include component reuse, parametric design (both generative and variant: see (Andrews et al. 1999)), and KBE systems. Most Computer Aided Engineering (CAE) systems (such as Unigraphics, Catia, Pro-Engineer and ICAD) provide parameter-driven knowledge modelling capabilities which are normally based on a geometric model. These systems have design rules embedded in the parameters, and are used for very specific engineering calculations. They are very well suited to solving complex, highly structured problems in which a level of optimisation is required. Andrews et al present two methods for reusing detailed designs, which they call generative and variant (Andrews et al. 1999). The generative method stores geometric features as constructive solid geometry (CSG) trees, which can be modified to generate a new solid model. The variant method relies on the creation of a parametric CAD model, in which parameters can be modified to create new members of a product family. Both generative and variant methods allow storage and reuse, through modification, of existing detailed designs. The authors comment that “their ultimate usefulness is dependent on the designers ability to store (and thereby retrieve) these designs systematically” p109. They suggest that a solution to enable design reuse must consider both technical and organisational issues. CAE based solutions are not appropriate to the whole design process; they focus on detail design.

Knowledge Based Engineering (KBE) is a term describing the application of knowledge to provide some level of automation in the engineering task. The term could be argued as being interchangeable with ‘intelligent design’ and ‘design automation’. KBE can be applied to a wide range of design tasks (Hew et al. 2001). Design knowledge, once embedded in KBE systems, is not accessible (for reuse) to non-programmers. This limits the potential to reuse the knowledge in other applications. In order to make this knowledge more generally reusable, the MOKA (Methodology and tools Oriented to Knowledge based engineering Applications) project provides a standard methodology for developing KBE applications, enabling reuse of the captured knowledge through a modified-UML (Universal Modelling Language – commonly used in modelling computer based systems) knowledge representation method (Sainter et al. 2000). Chao et al created a KBE platform to enable an agent based system to share common domain knowledge and apply rules (i.e. P2 should be near P3 and not near P5), and selection criteria to a design problem (Chao et al. 1998). The benefits of such a system include the automatic application of known design rules and constraints within a well known domain. Such systems are generally limited to detail design, and are very specific: in this case for a specific type of plant layout problem in the petrochemical industry. KBE as a general technology type can be applied to a range of problems. It can not be considered as a stand-alone design reuse solution; it requires a supporting methodology.

Dani and Harding suggested that technical solutions to reuse problems are not adequate, and propose that all factors affecting reuse are interdependent and should be addressed simultaneously (Dani & Harding 2004). They implement a value net approach to the reuse process, which takes account of multiple viewpoints and helps the organisation to identify appropriate reuse activities through interaction with a reuse agent and a knowledge base. The activities are represented in terms of process models, so provide a detailed, prescriptive, and structured activity framework. The methodology can be applied to a variety of knowledge reuse problems (though it was created to meet the needs of a design problem). This approach recognises that a range of reuse situations exist, and that several factors should be considered. Within the proposed framework, it is not clear how design object specific reuse could be supported, and as such it does not fully support the engineering focused aspects of design reuse.

In terms of shared understanding and knowledge representation, the development of ontology and its application to engineering design is providing a means to represent domain knowledge: understanding product (or manufacturing, service, or any domain) concepts, data elements, and relationships between concepts (Kerr et al. 2004).

CADET supports knowledge reuse in design. The system allows users to build their own knowledge bases through a paradigm called ‘AI as text’, in which they can describe rules and constraints that apply to particular products or user groups. WebCADET is an extension of the CADET tool, the ‘web’ part enabling distributed access through the Internet (Rodgers et al. 1999) (Caldwell et al. 2000). One application of the method was in developing a set of rules applicable to roll container trolley design, in which parameter values were defined in terms of requirements attributes such as ‘easy to push and pull’ and ‘doesn’t cause backache’. The flexibility of the tool enabled by having a user defined rule base means that it can be applied to a range of design problems, including conceptual design (Rodgers et al. 2001). The tool relies on a user search, and does not relate to design methodology.

A large research project on design reuse is taking place at NIST: the design repository project (Szykman et al. 2000) (Allen et al. 2000) (Regli & Cicirello 2000) (Szykman et al. 2003) (Regli 1999) (Szykman 2002). “A design repository is an intelligent, knowledge-based design artifact modeling system used to facilitate the representation, capture, sharing, and reuse of corporate design knowledge.” (Szykman et al. 2000). The intention of the repository project is to provide a complete, fully integrated (and searchable, reusable) representation of the design artefact including form, function and behaviour. Form, or geometry representation uses STEP AP203 and VRML for

Web based access. Function is represented through function structures, modelled using a generic schema including function name, documentation, and flow. These should be created using standard terminology to ensure interoperability. Mapping is provided between the physical and functional domains. The behaviour representation is still being developed. Another key feature of the project is the attempt to provide knowledge representations that are both human and machine interpretable. XML-based representations are being applied in order to facilitate interoperability and knowledge exchange among distributed designers. Whilst the design repository supports a range of design knowledge types, it does not integrate rationale or design methodology.

Another extensive design knowledge project is FIPER (Federated Intelligent Product EnviRonment). The approach describes an environment within which a variety of distributed services can be applied to an intelligent CAD master model. Software tools act as distributed service providers and service requestors (Röhl et al. 2000). Extensions to the project include a workflow model, developed to manage process definition, execution and resources (Wujek et al. 2000). The intelligent master model is most suitable for variant design in well known areas, where extensive product knowledge has been built up over many years and next generation will share much of the same geometrical relationships. It is also apparently a project with a focus on detail design, since the central element of the approach, the master model, is a CAD based representation.

3.3.2. Design knowledge reuse issues

Important issues in design reuse include the value of reuse, the need for focus on design as a knowledge process, and the need for integrated, user friendly solutions.

Finger, in her keynote speech to the 1998 Engineering Design conference with the theme ‘design reuse’, characterised the design reuse field (Finger 1998). She discussed the difficulty of function-form mapping, the instability of knowledge even in mature domains due to new technologies and new customer needs, and the current unsystematic approaches to knowledge capture and retrieval. She suggests that a more fundamental view is required in order to reuse design knowledge: we must recognise the nature of design, as a process of developing a theory of the artefact, in order to enable the activity of knowledge building to be captured along with the artefact theory. A further proposal for improving design reuse included capturing design failures. A comment on available tools shows that the current focus on detail elements is not sufficient, however whilst conceptual design is important for reuse it is difficult to capture:

> "…current design tools have the effect, on the practice of engineering design, of emphasising 'those parts of the process that were well understood and/or easily systematised' (e.g. detailed design, analysis, machine path planning), while minimising those parts that were less well understood (e.g. problem definition, synthesis and conceptual design) (Finger 1998)"

Smith and Duffy, in their paper "Re-Using Knowledge: Why, What and Where" (Smith & Duffy 2001) describe some important aspects of design reuse and make suggestions about the types of solutions required for effective design reuse. As for "why" they state that time, cost, quality and performance are key factors. They also demonstrate that without systematic reuse, design will become far too expensive. They show that there is significant value in reuse. To answer the "what": function, behaviour, solution concepts and 'how' and 'why' (rationale) must be provided in order to support reuse early in the design process. As to the "where": in the design process (that is, processes that support design for and design by reuse). In order to support reuse for innovative as well as variant design, they propose that abstraction and generalisation should be applied in order to enable the generation and modification of knowledge for more flexible reuse. Design for reuse is an integral element of design reuse. Design for reuse requires a strategic view of the product development process. It is considered to have the greatest potential for adding value when compared against other components of the design reuse process model (Lehaney & Vinten 1994).

Khadilkar and Stauffer carried out experimental evaluation of design reuse during the conceptual design phase (Remenyi & Williams 1996). Their goal was to determine the usefulness of design history information and to establish the need for providing conceptual level design information for future use. They found that about 50% of the queries made were related to conceptual stage information from the past design effort. They also found that 70% of the old design information was useful during redesign.

In response to the 1998 Engineering Design Conference on design reuse, Sivaloganathan and Shahin created an overview of design reuse (Sivaloganathan & Shahin 1999). They discussed seven categories of design reuse literature: focused innovation, cognitive studies, computational perspective, standard components, tools and methods, design reuse systems, and issues in design reuse. They suggested the design reuse tools they reviewed were effective in some areas and ineffective in others, indicating the developing nature of the design reuse paradigm. Future work proposed included: user friendly computational frameworks to aid storage and retrieval, knowledge models compatible with design reuse models, and design reuse tools integrated with other systems to provide more power.

Hicks et al (Hicks et al. 2002) argue that for effective information and knowledge reuse in design, formal definitions are required – and are often lacking. They also suggest that a problem for design reuse is the lack of formal guidelines for the reuse activity. As such, they propose some classifications for data, information and knowledge, along with their relationships and limits. Four generic classes of reuse are proposed: decision making (outcome, alternatives and basis), descriptive (classify an object, event or process), measurement (value of a particular aspect of an object, event or process) and distribution (formal information elements specifically for sharing). Alavi (Alavi & Leidner 2001) shows a variety of knowledge types along with knowledge management system approaches suitable for each. Hicks et al (Hicks et al. 2002) support the view that different knowledge types have different reuse requirements. The main limiting factor for reuse in their view is not the system, rather it is the increasing requirement for meta-knowledge as the knowledge level moves from the situation and context embedded ‘case’ to ‘specific’ to ‘general’ to ‘generic’. They propose a framework describing the limits of applicability for each knowledge type, and outline the requirements for acquisition, capture and electronic storage.

Much of the discussion on design reuse has focused on the framework: a systems perspective considering the requirements of the process and information model. Markus describes reuse as a system, but with a much greater emphasis on the actors in the system as contributors and consumers of knowledge. She defines reuse situations and success factors (Markus 2001). There are four types of knowledge reuser: shared work producers (produce and reuse their own); shared work practitioners (produce and reuse each other’s); expertise-seeking novices; secondary knowledge miners.

Each type of reuser has different requirements. They are differentiated by distance – in terms of the degree of shared knowledge. Several knowledge types are described: general and specific knowledge, declarative and procedural knowledge, rationale and analytic knowledge. Where a knowledge repository exists, it often requires rework to be useful for new reusers. Knowledge producers rarely have the resources and incentives to effectively repurpose the knowledge. Two major factors in repository quality are: who authors the entries, and for whom they author the entries: consideration of user needs is an important knowledge reuse success factor.

There is an emerging theme suggesting that not only the design process, but also the design article must be modified in order to incorporate effective reuse. That is, a product designed for reuse could be substantially different to a product designed by reuse, which itself is likely to be different to a product designed from a first principles perspective. Duffy and Legler (1999) propose a process by which designs are rationalised for reuse. The lack of formal guidelines is cited as a limitation to reuse. Their method consists of ten (iterative) steps such as initial evaluation, information gathering, objectives, information optimisation, create product structure, and evaluation for a decision on what approach to adopt. One of the key elements of this process is the proposed approach for structuring the information: product simplification, modularity, variant and part reduction, and standardisation are together considered as information optimisation issues. This perspective on the design process, as an information system to be optimised, does not commonly form part of design reuse or knowledge based system methods. A more usual approach is to create a method to address a specific optimisation problem (thus reusing knowledge of the optimisation, such as in knowledge based engineering or parametric design) or to propose methods to capture existing design data (including intelligent retrieval methods such as case based reasoning). This optimisation approach represents a major effort for implementation: fundamental redesign of the selected products to meet the optimisation schema. The level of implementation is evaluated as part of the proposed process, in which decision are taken based on measuring effort against reward.

3.3.3. Design reuse: benefits and problems

Around 20% of the designer’s time is spent searching for and absorbing information. This figure is even higher for technical specialists (Lowe et al. 2004b). Furthermore, around 40% of all design information requirements are met by personal stores, despite the fact that more appropriate information may be available from other sources. The type of information used changes during the design process (Lowe et al. 2004b).

Benefits of reuse were investigated by Duffy and Ferns (1999). They performed an evaluation, through interviews with designers, of their perceived benefit (in terms of time, cost, quality, and performance) of the design reuse process model. The Design Reuse Process Model is a cyclic process where knowledge is abstracted from a new design and used to build or enhance the domain model and reuse library, which in turn are used to support the new design. Design for reuse was considered to provide greatest benefits, followed closely with design by reuse, the reuse library and the domain model. Design for reuse is a more fundamental approach to design reuse than design by reuse, and requires greater change.

Design reuse, with all its perceived benefits, remains problematic. Busby carried out an investigation into the problems of design reuse (Busby 1999). Most reuse problems were cases of reuse not taking place: belief that reuse was desirable but not practised. The next most common problem was an unexpected amount of additional effort to reuse. Others include knowledge loss through inappropriate replication, and error where existing designs were reapplied to new purposes (performance failure). Most problems were caused by organisational factors (40%), followed by environmental (36%), engineering factors (29%), cognitive factors (19%) and finally motivational factors (16%). Organisational factors inhibiting reuse include: reuse of specific designs instead of standard designs caused problems, large numbers of designs make classification problematic, and project managers are accountable for project performance, so have no incentive to spend extra time making designs reusable. The application of design for reuse is made complex by organisational factors.

The benefits of reuse are provided by fast access to the right information, and hindered by organisational, environmental, engineering, cognitive and motivational factors. The proposed method to support reuse should take account of organisational factors through investigating current design practice. Engineering factors must also be considered. Cognitive and motivational issues will be partially assessed in the validation of the system.

3.3.4. Design knowledge reuse: summary

Design reuse has developed significantly in recent years (Sivaloganathan & Shahin 1999). Systematic reuse is necessary (Smith & Duffy 2001), however formal guidelines are lacking (Hicks et al. 2002). In order to meet the strategic information and knowledge requirements of engineering design, it must be considered not as a process of developing an artefact, but as a process of developing a *theory of the artefact* (Finger 1998). The selected design methodology drives the systems considerations: design *by* reuse requires support for retrieval of relevant design knowledge. Design *for* reuse fundamentally changes the product structure (through concepts such as modularity) and its supporting information and knowledge structures (Robson 2002). Conceptual design information is minimised by existing approaches (Finger 1998) and is important to design (Remenyi & Williams 1996). Knowledge models should be compatible with design reuse models, and design reuse tools should be integrated with other systems (Sivaloganathan & Shahin 1999). Effective reuse also requires much greater emphasis on the actors in the system as contributors and consumers of knowledge (Markus 2001).

In summary, it is crucial to consider design reuse within the context of design. The design reuse approach should be developed alongside the design methodology, since the methodologies are not mutually exclusive. Rather, design methodology and design knowledge reuse are reliant on one another: each leads the other. Conceptual design should be considered as an important element of design knowledge reuse. With that, it is also important to note that different knowledge types require different representations and reuse methods. Users of a knowledge reuse system must be considered.

3.4. Design process support

Figure 3.4-1, from Hicks p266, (Hicks et al. 2002) shows how the design process has information and knowledge requirements for each stage. Creativity and inventiveness are required along with adaptive skills through knowledge combination and evaluation. In-person processes and requires an extensive amount of meta-knowledge, more so as the generic-ness of the knowledge increases. This suggests that an appreciation of knowledge management principles is required in combination with knowledge of the engineering domain.

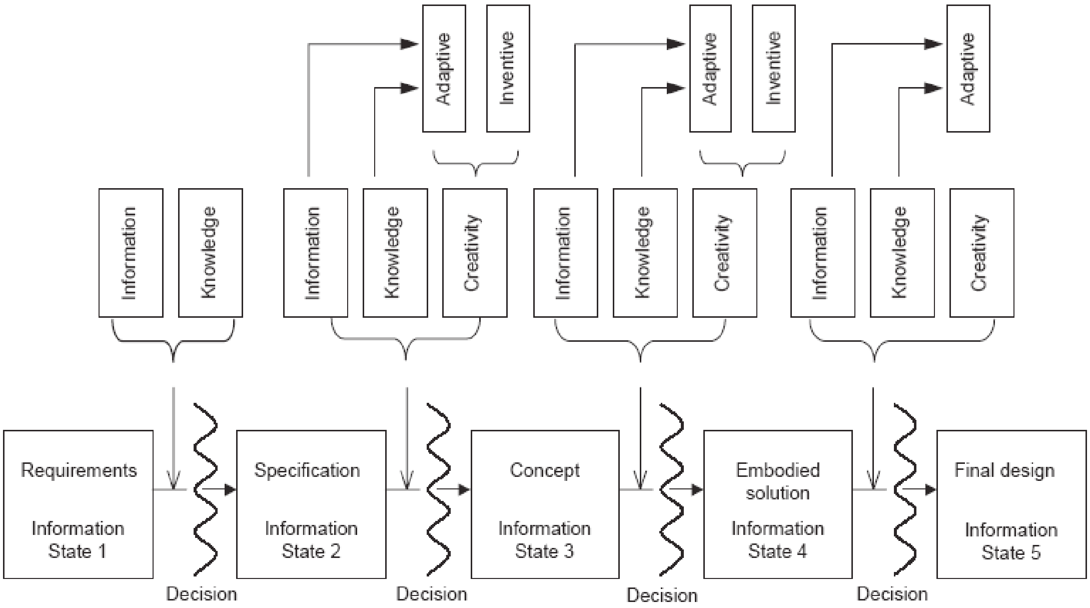


Figure 3.4-1: Design as an information-knowledge process (Hicks et al. 2002) p266

It has been suggested that the design process is a driver of design reuse for decision making at all stages of product development (Inns & Neville 1998). Also, that a representation of the design process is as important as representation of the artefact:

> “While our primary focus is on modeling the design products (artifacts), we believe that modeling the design process is at least as important for automating design processes and representing design histories” (Gorti et al. 1998)

Design reuse tools can support the design process either through guidance to reapply knowledge at the most effective time or through the capture and application of the knowledge embedded in the process itself. If these factors can be combined, the process can be used as a basis for design knowledge reuse (Baxter & Gao 2004) (Baxter & Gao 2005). The outcome of this section will be a proposal that the design process is a critical element for design reuse.

The review of process support papers resulted in a categorisation of the process support methods. Three main categories are proposed: methodology based design, business process modelling for design, and design process integration. A classification of the literature in the process support categories is shown in Table 3.4-1.

- Methodology based design: design process support systems with a design methodology guiding the process. The methodology is commonly systematic design. This category typically takes an engineering science view of the design process.

- Business process modelling for design: design process support systems with a view of the design process as a transactional business process, defining a series of tasks, inputs, and outputs. This category typically takes a management approach to the design process, focusing on process aims rather than systematic detail.
- Design process integration: design process support systems with the capability of integrating a model of the design process with one or more other aspects of product development. This category represents the developing nature of multidisciplinary design research, and the increasing recognition of the requirement for integration. It is also the category with fewest members.

Table 3.4-1: classification of design process support

Category	Reference
Methodology based design	• Tate & Nordlund 1996 • Shahin et al. 1999 • Hicks et al. 2002 • Blessing 1995 • Salminen et al. 2000 • Backer et al. 1995 • Gardam 1997 • Pavkovic & Marjanovic 2001 • Xu et al. 2002 • Paashuis & Boer 1997 • Clarkson & Hamilton 2000 • Hansen & Andreasen 2002 • Knott et al. 2003 • Li et al. 2004
Business process modelling for design	• Shooter et al. 2000 • Hayashi & Herman 2002 • Tate & Nordlund 1996 • Yassine & Falkenburg 1999 • Gorti et al. 1998 • Kalpic & Bernus 2002 • Pavkovic & Marjanovic 2001 • Huang & Gu 2006 • Park & Cutosky 1999 • Concheri & Milanese 2000 • Clarkson & Hamilton 2000 • Sim & Duffy 2003 • Pavkovic & Marjanovic 2000 • Eppinger et al. 1997 • Balasubramanian et al. 1999 • McMahon et al 2004b

Design process integration	• Lu et al. 2000 • Blessing 1995 • Gorti et al. 1998 • Huang & Gu 2006 • Park & Cutosky 1999 • Concheri & Milanese 2000 • Clarkson & Hamilton 2000 • Burge & Brown 2002

3.4.1. Methodology based process support systems

Tate and Nordlund attempt to address two questions that are generally not answered by typical design process models: How do I carry out the task? Who is responsible for the task? Their approach describes how to carry out tasks, and assigns responsibility. It also enables information flow between tasks (Tate & Nordlund 1996). It lends from the axiomatic design approach, and applies those principles for functional specification and analysis. The specific path taken between the start and end points is not predefined, but is the choice of the design team.

Shahin et al propose a design reuse system whose main function is to structure design information for retrieval (Shahin et al. 1999). It is based on the Design Function Deployment approach, and as such design information should be structured as (a) product concept (b) solution concept (c) embodiment design and (d) detailed design. They suggest that designers prefer to use concepts and lessons of past designs, particularly where the task is complex.

Li et al create a system based on the Analysis–Synthesis–Evaluation (ASE) design paradigm (Li et al. 2004). Their tool uses parametric design models and agents to carry out reasoning relating to role assignment and other expert systems tasks. They also propose a modular information exchange method for convenient design problem negotiation. The system aim is to support decision making. The authors recognise that the system can be applied to deterministic detail design problems, but not conceptual, nondeterministic problems.

Driven by their assertion that there is a lack of formal, consistent definitions for capturing, storing and reusing information and knowledge in engineering design, Hicks et al propose a framework to meet these challenges. They propose that inadequate definition is the key issue to be resolved before effective approaches can be developed for the acquisition and management of information and knowledge. Formal definitions are proposed, and a framework presented that categorises information (descriptive, measurement, decision making…) and knowledge (general, specific, case…), alongside requirements for their capture and storage (Hicks et al. 2002). They note that for the application of generic principles to a specific design case, extensive meta-knowledge is required. They also recognise that a lack of guidance for knowledge reuse is a hindrance:

> "A problem within design reuse in engineering practice is the lack of formal guidelines or approaches to enable designers to reuse design information" (Hicks et al. 2002) p11

Blessing describes the development of PROSUS, a computer supported process-based approach to design. "The core of the system is a model of the design process, rather than of the product, in order to be able to support the whole design activity." (Blessing 1995) p1 The system applies a design matrix to the engineering design activity, which serves a dual role as a means to record decisions and as a structure to retrieve past knowledge. The elements of the design matrix are five 'issues': problem, requirements, function, concept, and detail design. The product model is derived from the design matrix - through the description of each of the issues. The process model is derived from the systematic design methodology (Pahl & Beitz 1988).

Salminen at el developed a framework to support SMEs in product development. The framework provides a common set of tools, models and processes for the various partners in a collaborative enterprise to use. The architecture is described in terms of a multi-tier system, consisting of a physical IT layer, tools layer, strategic processes layer, people layer, and business environment (Salminen et al. 2000). It does not describe how to carry out the processes, but how to co-ordinate them from a strategic perspective.

Backer et al introduce Functional Design Excellence (FDI), an approach to managing technical design which encourages reuse through a standard design process. The process embodies several elements: working reviews; standardisation (of parts, materials and designs); and performance metrics for process improvement. Through applying standard design processes and components, the authors claim that the organisation can improve their 'right first time' performance and focus innovation on aspects of a design that are truly new (Backer et al. 1995).

Gardam and Burge question the validity of the established 4 phase design process model. They suggested that a two phase model may be more appropriate. With further development it may be possible to apply a single phase design activity, essentially an extended task clarification activity together with the application of standards. This reduction in design phases is taking place alongside developments in artificial intelligence and expert systems. They also report that the prescriptive process, as described in the literature, is often not applied in practice (Gardam & Burge, 1997).

Pavkovich and Marjanovich developed a computational model of the design process. They apply a design methodology developed by Hubker and Eder. The system is aimed at adaptive and repetitive design tasks. It is intended to support the creation of a design process model, and not to automate the design process. The design process is represented as a set of nodes with attributes and constraints. Each node may include an action function. The function may be performed manually or as a software process. They found that the design process is difficult to plan in an automated sense due to the iterative nature of the design problem (Pavkovic & Marjanovic 2001).

Xu et al view design as a mapping problem. They developed a method enabling design requirements to be translated into geometry through a mapping process. The mapping is top-down, from requirement analysis through functional requirement to layout to detail design. Their methodology is based on axiomatic design principles. Their view of product as a mapping process between domains extends through problem, requirement, form, process, and result – and the mapping is many to many and multilevel. Their system applies mapping between a function element library, function/form relationships, assembly, and function carriers. The provisional and uncertain result is then applied to a geometric reasoning system, resulting in the final form (Xu et al. 2002).

Paashuis and Boer propose a tool to support integration within a product development environment according to the prescribed needs of concurrent engineering. The framework is a step toward a complete concurrent engineering design and implementation methodology, describing relationships between the different areas as well as the approach, goals and planning. They address methods to integrate certain aspects of the new product development process, including strategy, process, technology and organisation. Integration by process requires reorganising the product development process such that all functions (or departments: marketing, design, manufacturing) are better integrated. **A limitation for the reengineering effort is the lack of tools to support process modelling**, and their lack of their ability to represent dynamic processes with iteration and feedback (Paashuis & Boer 1997).

Clarkson and Hamilton propose a ‘parameter based’ design method. The research initially set out to capture design knowledge; it was realised that the design process within the sponsoring company was not formally represented, and as such there was scope for improvement. A knowledge capture exercise took place to identify the stages in the design process, and a methodology is proposed to operate it in the future. Because of the dynamic nature of the process, they developed an intelligent system based around a ‘signposting model’. The design process is represented as a series of tasks. Confidence in design parameters is used as a basis for identifying, or signposting, the next design task. The signposting model allows a design process to be constructed from knowledge of individual design tasks. It does not build the design process in advance, since the inputs include design parameters and confidence levels. Instead, the system helps the design team to identify the next best task based on the current design state (Clarkson & Hamilton 2000).

Hansen and Andreasen describe an alternative view of the design problem (which impacts upon the design process). They suggest that a conceptual design may be seen from two sides: market oriented (how it solves the design task) and design oriented (how it creates the functionality and structural realisation). These two sides should be understood as a totality and solved together. In the literature, concept design focuses on solutions and functionality – there is no clarification of market need aspects. Concepts can be generated for each aspect of the life cycle: business concept, product concept, production concept, disposal concept - and so on, into more detail within each aspect. The implication is that conceptual design representations must be extended, and that the process should include these tasks (Hansen & Andreasen 2002).

Knott et al describe the use of an object oriented modelling method for capturing information system requirements. BORM (Business Object Relationship Modeling) is a development methodology used to store knowledge of process-based business systems. It is a combination of the object-oriented approach and process-based modelling. The study highlights the advantages of graphics in process modelling, providing easy and effective feedback to users. Clear rules of how to progress through the development process were found to be beneficial (Knott et al. 2003).

3.4.2. Methodology based design process support issues

Mechanical design is a well supported and documented process with several approaches, or methodologies. They are often prescriptive, systematic and described in detail. This ‘methodology based design’ category includes some of the better known design process approaches along with a number of other approaches described in the literature. Methodology based design is not an exclusive category: some of the approaches in the business process model and design process integration categories are also part of the methodology based design category.

Perhaps the best known approach to mechanical design is Pahl & Beitz’ systematic design methodology (Pahl & Beitz 1988). Their approach includes four stages: design specification, conceptual design, preliminary design and detailed design. The design specification method involves first defining the main objective and characteristics of the product, then breaking these down into sub-systems, functions, or assemblies. A checklist is provided to enable the generation of a complete specification, including headings such as geometry, kinematics, forces, energy, material, signals, ergonomics, production, and quality. This rigorous method is continued throughout the development process. Ulrich & Eppinger (Ulrich & Eppinger 2000) and Ullman (Ullman 2003) take a similar approach.

Reinertsen describes the design process with less emphasis on the mechanical system and more emphasis on the business. Where systematic design takes a finely detailed approach to specification, Reinertsen suggests that requirements are managed using a progressive approach, in which detailed elements that do not relate to the overall product requirement are fixed late on in the process, and only a limited number of performance characteristics are fixed early on (Reinertsen 1997). He proposes that the development team create a product advert at the start of the project as a concise statement of the product value proposition, or strategy. He gives an example of a product development team using a ‘catalogue-page’ specification, reasoning that if it’s not important enough to be in the catalogue, it’s not important enough for the product specification. A more detailed specification simply creates more constraints for the designers without creating more value for the customer. The rest of the development process is also described in terms of measures and targets rather than product functions and flow: the team should always be aware of the overall aim, with a keen eye on time and an unrelenting focus on quality.

Another key design methodology is not a complete systematic design process guide, but instead serves to support design analysis. Axiomatic design describes an approach to the analysis of design requirements that claims to enable optimal design through reducing conflict between functional requirements (Suh 1990).

3.4.3. Business process modelling for design

Shooter proposed an information flow model which can be used to map the design process. Its structure will enable the direct translation and understanding by computer systems, yet its flexibility (achieved though a low level of abstraction) will enable its application within a variety of design processes. It was created to support an agent based data exchange model to improve information flow across distributed design teams. The design information flow model is sufficiently formal to eventually support a semantics-based approach for developing information exchange standards (Shooter et al. 2000).

Hayashi and Harman propose a systematic method for exploring alternatives to a product design process for differentiated products. Their process model consists of three types of elements: resources, activities and dependencies. Co-ordination is defined as “managing dependencies among activities”. Their methodology provides a basis for viewing the process, selecting product differentiation methods, co-ordinating that process, and evaluating cost (Hayashi & Herman 2002).

Tate and Nordlund (also in the ‘methodology’ category) developed a method to enable information flow between tasks (Tate & Nordlund 1996). Important features include a description of how to carry out tasks, and assigned responsibility. It lends from the axiomatic design approach, and applies those principles for functional specification and analysis. It is not a prescriptive model: the specific path taken between the process start and end points is not predefined.

Yassine and Falkenberg suggest that major conflicts in design process management stem from specification conflicts (of design tasks). They propose a method to resolve specification conflicts to reduce coupling of design tasks. This is argued to produce a better design process through less iteration because of reduced coupling. "In conclusion, two coupled tasks can be de-coupled if, and only if, the fluctuations underlying the output of task j (feeding task) can be tolerated by the specifications of the other task i (being fed)." (Yassine & Falkenburg 1999) p233

Huang and Gu created an integrated development architecture based on coupling relations between the product model and a corresponding process model. The system works on the principle of a product controller and process controller working to optimise the states during coupling phases. Either one or other or both can be optimised at each stage. In the example, four main product parameters were identified, and four processes identified to optimise the parameters (position analysis, simulation, force analysis, and finite element analysis). An algorithm evaluates model coupling and guides the process iteration by testing against a satisfaction measure for the performance parameters, or evaluation factors (time, cost, quality, etc.) (Huang & Gu 2006). This work shows the critical relationship that exists between the product design process and the product model, and provides a means to optimise the process.

Concheri and Milanese developed a system that can create and dynamically modify a model of a design process with corresponding product data. The system applies two types of knowledge: parametric models with engineering rules, and design system rules for planning design strategies. The system provides assisted generation of project models and traces the design history (Concheri & Milanese 2000). The process models applied in the system are formal, detailed methods to apply knowledge based tasks. It does not support nondeterministic or informal methods, such as may be applied to manual tasks.

The approaches of Li, Concheri and Milanese, Huang and Gu and Yassine and Falkenberg are well suited to well understood, deterministic detail design problems, but not conceptual nondeterministic problems, as reflected by Li (Li et al. 2004).

Gorti and Kim propose an object oriented method to describe both design products and design processes. Using a combination of factors, including: relationships, constraints, context, methods, function, form and behaviour (and others), the product can be described. They suggest that form, function and behaviour are linked so closely that they must be considered together. The design process is described using the objects: goal, plan, specification, decision and context. The representation can then be used to assist a designer in finding relevant parts, products or knowledge, or to be applied to (semi-)automation of the design process. The design process is represented formally, in order to enable computational support. It does not include guidance for manual task completion or the assignment of roles and responsibilities (Gorti et al. 1998).

Kalpic and Bernus discuss the power of modelling in improving new product development. They develop a reference model for use in future projects. Process modelling is seen as a means to elicit and reuse working knowledge (tacit formalisable knowledge being cited as the primary aim of knowledge management systems). The main contribution of the method is improved project planning quality, which results in better project quality. BPR (business process reengineering) can enable the transformation of informal knowledge to a formal, structured form that can be shared throughout the organisation: process modelling and reengineering can be used as a knowledge capture exercise (Kalpic & Bernus 2002).

Pavkovic and Marjanovic consider the entities in the object oriented design process model (Pavkovic & Marjanovic 2000) as part of an effort to develop a formal, computer interpretable design process model for a process planning system (Pavkovic & Marjanovic 2001). The system is intended to support the creation of a design process model, and not to automate the design process. The design process is represented as a set of nodes with attributes and constraints. Each node may include an action function. The function may be performed manually or as a software process. They found that the design process is difficult to plan in an automated sense due to the iterative nature of the design problem. They developed their model with the understanding that existing design methodologies do not formal design process descriptions, and so can not easily be provided with (intelligent) computer support for process planning and execution.

Sim and Duffy argue that there is no shared understanding (i.e. an ontology) of the activities that designers perform in the design process. They identify and classify a generic set of design activities from published literature into three groups: design definition activities, design evaluation activities and design management activities. In an attempt to achieve a shared understanding of these activities, a set of consistent and coherent definitions of these activities are deliberated and presented. Design knowledge is classified as: input knowledge, design activity, design goal, and output knowledge. These categories are described for each design activity, from the range of distinct activities shown in systematic methods and research papers (Sim & Duffy 2003). This approach is distinct from the other attempts to formalise the process since it aims to provide a shared understanding of engineering design activities to people (researchers, practitioners and system developers).

Eppinger et al describe the use of signal flow graphs to model the design process, which were selected in order to enable the inclusion of iteration in the model. Their method provides an expected lead time with mean and variance. The signal flow graph structure essentially applies a task ID number with an expected time. The approach can deal with iterative and parallel tasks. Clearly, the value of the method is limited by the accuracy to which the task sequence and durations are known. They highlight dependency and critical path, but do not extend the knowledge of the process beyond representing task durations (Eppinger et al. 1997).

Balasubramanian et al propose a modelling schema for capturing decision making processes in product development. They developed the ThoughtFlow tool, which helps the project team to display the results of their decision making process in terms of traceable, actionable events. The main purpose of the tool is in supporting the decision making process through a visual mapping method (Balasubramanian et al. 1999).

McMahon et al (2004a) developed a best practice advice system to support engineering analysis processes by providing guidance on how to carry out tasks as well as providing examples of previous similar work. The system is part of a design environment called INTEREST that also applies a workflow system along with an activity description method. The activity description enables the system to search for and retrieve data from similar activities.

Park and Cutkosky developed a framework to model the design process. They argue that the growing need to collaborate within and between firms and the increasing number of tools to support individual tasks makes the collaboration effort more complex. Engineering process modelling methods proposed so far have serious limitations when applied to large scale complex design projects. Existing process modelling methods capture a partial process description, leading to deficiencies in modelling. Their proposed Design Roadmap (DR) enables the capture of process logic in a format that enables several views of the process for different needs: design matrix views for analysis, and various views to show process flow including a flowchart type representation and GANTT charts. The approach lends from IDEF, petri nets and design matrix methods. An important element of the method is the inclusion of data in the process model. This enables the design team to share data through the process model. Another important function is the addition of roles to the task objects, showing people responsible for a given task (Park & Cutosky 1999). The method mainly addresses project management issues, however has the potential to support a product data view if it were extended.

Various business process modelling methods are described in the literature. Solutions to deterministic problems are supported, including: agent based systems, cost analysis, information flow, conflict identification, design optimisation, process planning, and process optimisation. These methods are intended to provide a level of automation in the design process. Some elements that contribute to nondeterministic problems are addressed, including: relationship modelling (form, function and behaviour), process reference models, signal flow models, design task ontology, decision modelling schema, and process logic models. These methods are intended to improve the design process by enhancing understanding.

3.4.4. Design process integration

Lu provides an approach based on integrating the various communication methods and actors in the design process. It is achieved through understanding the relationships between designers and likely causes of conflict and the design process. The approach represents a model to identify the information needs of designers such that the process can be optimised. Social interaction is represented as a mechanism to transfer information between process objects, and considered as a critical part of the optimisation. Importantly, it also provides methods to manage the conflict (Lu et al. 2000).

Blessing integrates process (or design methodology) with a product model, a means to record design decisions (rationale), descriptive task support and design analysis tools. The core of the system is a model of the design process. The product model is derived from a design matrix – through the description of each of the five issues: problem, requirements, function, concept, and detail design. A procedure matrix provides task execution support, and a strategy matrix supports task sequencing (Blessing 1995).

Gorti et al describes an object oriented method to describe design products and processes. A combination of relationships, constraints, context, methods, goals, function, form and behaviour enables a description of the product development process, the product, and links between the design goals and tasks (Gorti et al. 1998).

Huang and Gu propose an integrated development architecture based on coupling relations between the product model and its corresponding process model. A product controller and process controller work to optimise the states during the coupling phases (Huang & Gu 2006).

Park and Cutkosky provide a method to model the design process that integrates the process model with product data, project management, and design analysis (Park & Cutosky 1999).

Concheri and Milanese's MIRAGGIO system also integrates the design process with product data. The system brings together rule-based parametric models and rule-based design strategies to provide design automation, assisted generation of project models and to trace design history (Concheri & Milanese 2000).

The signposting system integrates qualitative product knowledge with process knowledge, indicating the next best process step based on confidence levels in key design parameters (Clarkson & Hamilton 2000). McMahon et al (2004b) make the comment that research is beginning to address the issue of combining product and process representations, although almost exclusively in variant design. They cite Clarkson and Hamilton as an example.

Pavkovic and Marjanovic provide integration of design process modelling through object oriented representation and design methodology as part of an effort to develop a formal, computer interpretable design process model for a process planning system (Pavkovic & Marjanovic 2001). They developed their model with the understanding that existing design methodologies do not include formal design process descriptions, and so can not easily be provided with (intelligent) computer support.

Burge and Brown attempt to integrate design rationale with a process model (Burge & Brown 2002). Rationale can be generated to describe why certain tasks are necessary, and in what order they should be performed. Frequently considered alternatives could be included as rationale for certain steps.

3.4.5. Other work on design process support

Case-Based Reasoning (CBR) has been applied in a variety of ways to enable design knowledge reuse. Essentially, it involves creating an index of the problem area, then applying artificial intelligence techniques to find similar cases. One relevant example is the conceptual design information server, in which the cases are selected by the user from a wide variety of information sources to support conceptual design (Wood-III & Agogino 1996). Leake and Wilson suggest that a case-based reasoning design support system should provide three capabilities: capture of and access to design experience; support for new designers; support for adapting previous designs to fit new goals. Attempting to meet these aims, the DRAMA tool they developed allows browsing of past cases, and monitors the user during the design process. This adjusts relevance criteria used in the intelligent search operation applied to design knowledge retrieval (Leake & Wilson 2001).

Harding et al created a server based monitoring method with agent based support to provide the relevant party (designer, project manager, etc.) with details of any changes to the design database and an analysis of the effects of the change. The moderator operates with a flexible army of agents, chosen to reflect the project needs and to match the project team. The agents will have varying levels of automation depending upon the needs and capabilities of the software (Harding et al. 2003).

A key aspect of being able to manage knowledge is the ability to identify and capture it. Matsumoto et al describe the development of the Knowledge Capture Report. Its use in industry demonstrated a quick, effective and low cost approach to capturing project knowledge and events. It is essentially a documentation tool for project based knowledge management, describing the process of capturing and documenting lessons learned (Matsumoto et al. 2005).

Zdrahal et al describes a case study in which students are involved in a collaborative design project in order to assess the benefits of their tool in supporting knowledge reuse. The system allows the user to build queries which search the knowledge base to retrieve cases, examples and files that are relevant (Zdrahal et al. 2000).

3.4.6. Summary of design process support

A summary is presented for the methods proposed to support the design process that have been discussed in this section. Design process methodology is a critical element of design knowledge reuse methodology. Design process and design reuse methodologies should be developed in parallel. Several approaches for supporting the design process have been developed, some of which relate directly to design knowledge reuse. An analysis of design process support in the literature resulted in three categories of design process support being proposed: methodology based design, business process modelling for design, and design process integration.

Methodology based design includes general design methodology such as systematic design (Pahl & Beitz 1988), as well as analysis based methodologies such as axiomatic design (Suh 1990). Methodology based support systems provide additional detail support including how to carry out tasks (Knott et al. 2003) and who should carry out tasks (Tate & Nordlund 1996), information structure (Shahin et al. 1999), parametric design and reasoning (Li et al. 2004) (Pavkovic & Marjanovic 2001), coordination (Salminen et al. 2000), standard processes (Backer et al. 1995), computational task selection (Clarkson & Hamilton 2000), and conceptual mapping (Hansen & Andreasen 2002).

Business process modelling for design includes information flow models (Shooter et al. 2000) (Tate & Nordlund 1996), resource models (Hayashi & Herman 2002) (Park & Cutosky 1999), conflict models (Lu et al. 2000) (Yassine & Falkenburg 1999), process-product models (Gorti et al. 1998) and coupling (Huang & Gu 2006), parametric design modelling (Concheri & Milanese 2000), template development (Kalpic & Bernus 2002), best practice provision (McMahon et al. 2004a) object oriented models (Pavkovic & Marjanovic 2000) (Pavkovic & Marjanovic 2001), signal flow graphs (Eppinger et al. 1997), and decision capture (Balasubramanian et al. 1999).

There are also a variety of methods to integrate the design process with one or more additional elements, including: cross-discipline communication (Paashuis & Boer 1997), product model (Blessing 1995) (Huang & Gu 2006) (Concheri & Milanese

2000), form/function/behaviour (Gorti et al. 1998), project models (Park & Cutosky 1999), and rationale (Burge & Brown 2002).

3.5. Research gaps identified in design reuse research

This review has shown some issues for further research: the relationship between the design process and the design object is not well understood. Integrating rationale with the design process has relatively little work. Design process models as an integrated part of knowledge management requires further analysis to identify the limits and nature of applicability determined by the type of design process. Another area for further research is an integrated knowledge reuse framework for engineering design, in which a process model and product model are provided in a single framework.

Existing methods to reuse design knowledge are generally not compatible with the whole product design process: some are suitable in conceptual design; most are focused on detail design. There is a research gap in providing a knowledge reuse framework that is suitable for the whole product development life cycle. This includes the need for an integrated process and product modelling approach to integrate KBE and geometric knowledge types such as performance analysis and parametric design with non-geometric knowledge, including problem solving methods, solution generation strategies, design intent (or rationale), and history. An additional knowledge type is the design process, or methodology. This variety of knowledge types is associated with the tasks in today's dynamic design process.

In summary, the following research gaps were identified:

- Design reuse for the whole product life cycle;
- Integrated product and process models;
- A 'how-to' element of the product design process;

There is a lack of support for early design, or nondeterministic design problems. Furthermore, there are very few design reuse methods that support the whole product life cycle. Early design in particular receives relatively little attention in the design reuse literature. The reason could be that, as Finger reported, design reuse methods tend to emphasise the aspects of design that are well understood or easily systematised, while minimising the less well understood aspects (Finger 1998). Early design is less easily systematised. The few design reuse methods that do address early design do so with a functional representation. Andreasen developed a method to link product function to the method: a function-means tree (Andreasen 1998). This enables reuse of similar means. The function concept is also supported by Shahin et al, and in the NIST design repository project (Shahin et al. 1999, Szykman et al. 2000).

A number of integrated product and process models have been proposed to support design. Gorti et al propose a modelling method to represent a product, the design process and the relationships. Park and Cutkosky provide a method to model the design process that integrates the process model with product data, project management, and design analysis (Park & Cutosky 1999). Huang and Gu (2006) and Concheri and Milanese (2000) propose formal methods to represent product and process models. These methods are proposed either for modelling and analysis, or for process management purposes. A design process guide is not proposed: task level support is not part of the integrated models, and they do not provide support for the whole design process.

The 'how to' element was recognised as an important aspect of design process support (Smith & Duffy 2001), however it is reported to be missing from design support systems (Lang et al. 2002). There are some examples in which how-to is provided. Tate and Nordlund developed a method to show how design took place, to guide new designs (Tate & Nordlund 1996) however this method focuses on modelling rather than support. Knott et al suggest that clear rules of how to progress through the development process are beneficial, however their modelling was developed to support information systems development and not engineering design (Knott et al. 2003).

The research aim is to provide a method for reusing engineering design knowledge. The proposed method should address these research gaps.

3.6. Literature review: summary

The literature review was divided into three key areas: knowledge management, engineering design knowledge reuse and design process support. The knowledge management review sought to identify a definition for knowledge, which was defined as justified true belief. Knowledge management relates to activities for applying knowledge.

The review of engineering design knowledge reuse methods and systems showed that design reuse is a whole-system issue, yet there is a lack of support for early design. Design knowledge reuse frameworks and systems do not all consider the design process as a central element of design reuse. That the design process operates in a particular way is implicit in design reuse systems – they assume a position within the general framework of a design methodology such as systematic design. Process modelling can support design knowledge reuse, and can be integrated with other aspects of design, however it is not a common feature of design reuse systems.

The review of design reuse identified process support as a category for investigation. A representation of the design process is considered of equal importance to a model of the design artefact, particularly in variant design. A design process model provides knowledge of how best to do design, along with a structure within which information requirements can be met. Process support has been categorised as: methodology based design, business process modelling, and design process integration. Integration of the design process with the design object is not addressed, and the how-to aspect of task descriptions is not well addressed.

3.7. Summary of research issues

The research issues identified in the preliminary investigation and the literature review can be summarised as follows:

The research gaps identified in the literature review:

- Design reuse for the whole product life cycle;
- Integrated product and process models;
- A ‘how-to’ element of the product design process;

Issues identified in the preliminary investigation:

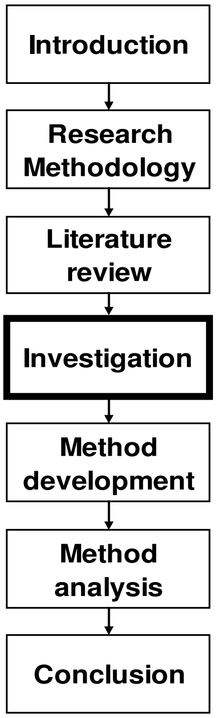
- Access to relevant and contextualised captured design knowledge. Storage methods do not support reuse in context: centralised and unstructured vs. locally held and unavailable.

- Developing a relationship between design reuse and the product development process.

- Integrating engineering and business objectives.

The research aim and objectives described in section 1.7 were developed in order to meet the above requirements.

Chapter 4: Industrial investigation: design knowledge capture



This chapter describes an industry investigation. It will show how design knowledge was captured from the participating organisations using an in depth example. The requirements for design knowledge reuse identified in the preliminary investigation and the gaps identified in the literature will be combined with the findings from this investigation in the next chapter: method development.

4.1. Purpose and method of the investigation

The industrial investigation is intended to capture design knowledge from the participating organisations through an in depth example. This captured knowledge will be used to support the development of, and then evaluate the proposal for, the design knowledge reuse framework.

The design knowledge reuse framework is intended to reflect a wider understanding of industry needs than the few companies participating in the research project. One of the contributions of the literature review is a recognition of a wider environment and a framework within which to position the research. The specific details and individual needs of the participating organisations will also be considered when developing the method. This performs two functions: to provide some insight into the design rationale of the knowledge reuse framework (for what specific purpose was a given aspect of the method created), and to maintain a high degree of relevance to the organisations, enabling them to perform more in depth and insightful analyses of any proposals. It is through comparison with literature that the wider relevance of the method will be assessed.

The case study approach will apply interviews and observation as primary data collection methods, with company documents as secondary sources. Following the assumptions of critical theory, it is assumed that *objective* observation is not possible due to observer bias. Knowledge is created in an active sense, whilst being embedded in a rich context. Understanding of experience is derived from interpretation. Meaning is negotiated, and embedded assumptions are crucial in this process.

The research approach is qualitative and flexible. Threats to validity are to be mitigated through triangulation, audit and member checking. Initial interviews will guide the selection of subsequent research activities. This results in a model that roughly follows the format: interview → checking → development → interview → checking → development etc.

4.2. Design support requirements identified

The preliminary investigation described in chapter 1 highlighted several limitations for the application of design support systems and design knowledge reuse in practice. The challenges to design knowledge reuse in practice were identified as:

- Access to relevant and contextualised captured design knowledge. Storage methods do not support reuse in context: centralised and unstructured vs. locally held and unavailable.

- Developing a relationship between design reuse and the product development process.

- Integrating engineering and business objectives.

4.3. Selecting a suitable target for knowledge capture

Company A suggested that a suitable approach to detailed knowledge capture would be to consider a single component: the pump headplate. This was decided upon in a group discussion with representatives from the company. The headplate was selected as it is sufficiently complex to warrant a detailed investigation, and it is critical to several of the product functions. It is also, as a single component, of sufficiently narrow scope to enable a detailed investigation within the time constraints of the project.

The vacuum pump is an electro mechanical product whose basic function is gas displacement. Specifically, the pumps are used to evacuate process chambers in a variety of semiconductor manufacturing operations. The product being investigated is a roots-claw configuration. This pump type is used by company A for a variety of applications.

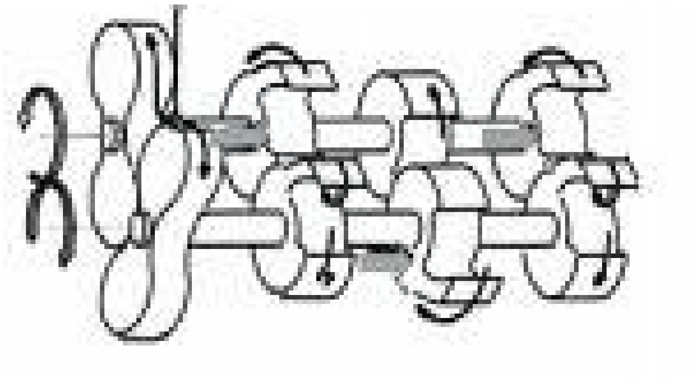


Figure 4.3-1: schematic of roots-claw pump

The diagram in Figure 4.3-1 shows the pump rotors and gas flow. Gas enters on the top left of the diagram and is compressed between the rotating lobes. As the lobes rotate, their edges form a barrier to isolate and compress the gas. The compressed gas is passed through a port. The rotors pass over the port to open and close it. Once the gas has been passed through the port into the first claw rotor, a similar process takes place. The interlocking rotating claws isolate and compress the gas, rotating to the next port opening where it is passed to the next stage. This continues until the gas is passed out of the final (exhaust) port. The combination of positive displacement and high compression ratios result in a pump capable of producing very low pressures in a closed chamber.

The headplate is a cast and machined component that performs several functions. It forms the low vac end of the vacuum envelope. One side represents part of a stator, as shown in Figure 4.3-3. The other side is one half of the gearbox enclosure, as shown in Figure 4.3-2. The gearbox side houses the shaft support bearings. The bearing housing can be seen in Figure 4.3-2. Lubrication channels are cut into the face above the bearing housings, to direct oil into the bearings. A complex static and dynamic seal arrangement exists between the two sides, to minimise gas and oil travel from the gearbox into the vacuum chamber. The slots between the two sides shown in the cross section view in Figure 4.3-4 represent the housing for static seals (rubber lip seals) and the dynamic seal (provided by gas flow directed through the central channel). Gas flow channels also provide nitrogen purge and pressure balance functions as well as the dynamic seals.

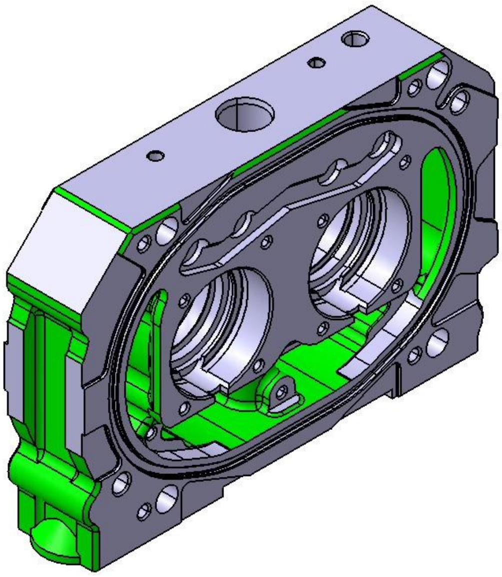


Figure 4.3-2: headplate, gearbox side

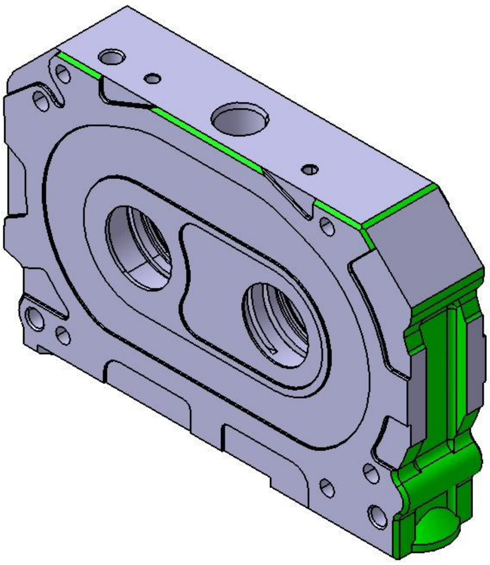


Figure 4.3-3: headplate, stator side

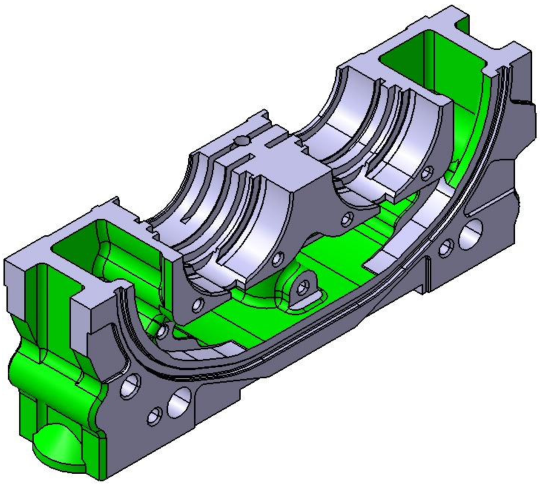


Figure 4.3-4: headplate cross-section, gearbox side

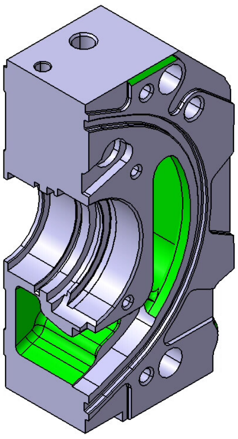


Figure 4.3-5: headplate cross-section, gearbox side

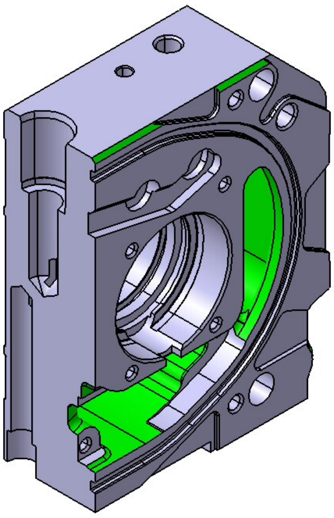


Figure 4.3-6: headplate cross section, gas flow channels

4.4. Design knowledge capture: introductory sessions

The initial sessions are intended to enable the researcher to better understand the design of the selected component. An early description of the process is shown in Figure 4.4-1. The process represents an overview of the engineering design process, including some of the knowledge types applied during the tasks. The diagram also shows how these company stages relate to the established design stages of ‘conceptual’, ‘embodiment’ and ‘detail’ (Gardam & Burge, 1997).

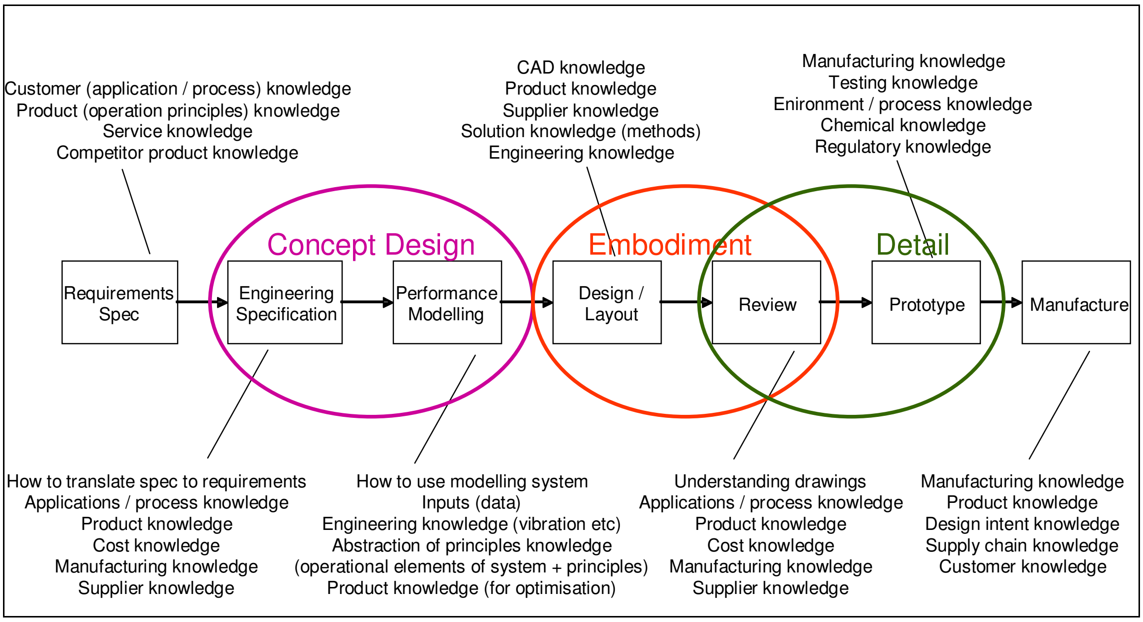


Figure 4.4-1: early stages of design knowledge capture

The first stage of the process is shown as requirements specification. The definition of a sound product requirement in this task requires knowledge of customer applications, product operating principles, service, and competitor products. Requirements specification falls outside the definition of ‘concept design’, in which a product concept is developed and its operating principles tested through (soft) modelling methods. The engineering specification task is translation of specification to product requirements, and it requires knowledge of customer applications, products, costing, manufacturing and suppliers. Performance modelling requires knowledge of the modelling system, engineering fundamentals, and the product. The embodiment phase develops the initial layout of the product: often this is a CAD model including all of the basic elements but not fully dimensioned or verified as manufacturable. There is some crossover between this and the detail phase, since they are essentially an iterative process forming the same basic elements: model, verify, adapt, model… with increasing detail towards a description that can be manufactured. The diagrams shows the knowledge types required by these stages, including CAD knowledge, manufacturing knowledge, engineering knowledge, regulatory knowledge, supplier knowledge, and so on. Prototyping is considered a part of the detail design stage, since building a prototype is essential for product validation and reliability testing – and this activity takes place within the product development process and may occur before the product definition is complete.

4.5. Design process capture and modelling

Because the headplate performs several critical functions within the product, modelling its design process requires a good understanding of the product system. Design of the headplate requires the interaction of several disciplines and engineering specialists. A common headplate may be used in multiple configurations within a pump family.

A series of interviews took place to capture the process. These interviews were followed by functional modelling, using IDEFØ (NIST 1993). The models were sent via email to the designers, which resulted in some changes. Follow-up interviews then took place to further validate the process models.

> “IDEFØ is a method designed to model the decisions, actions, and activities of an organization or system. IDEFØ was derived from a well-established graphical language, the Structured Analysis and Design Technique (SADT). The United States Air Force commissioned the developers of SADT to develop a function modeling method for analyzing and communicating the functional perspective of a system… IDEFØ is useful in establishing the scope of an analysis, especially for a functional analysis. As a communication tool, IDEFØ enhances domain expert involvement and consensus decision-making through simplified graphical devices. As an analysis tool, IDEFØ assists the modeler in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong. Thus, IDEFØ models are often created as one of the first tasks of a system development effort.” (Knowledge Based Systems, Inc.)

IDEFØ was used in this stage of the investigation to help capture and visualise the development process for the selected component. The intention was to capture the various functions applied in the development process, along with the activities and interactions. During the validation exercise, it was necessary to explain the IDEFØ notation to the participants in order that they could understand the model before checking its accuracy and completeness. This was supported by the use of the diagram shown in Figure 4.5-1.

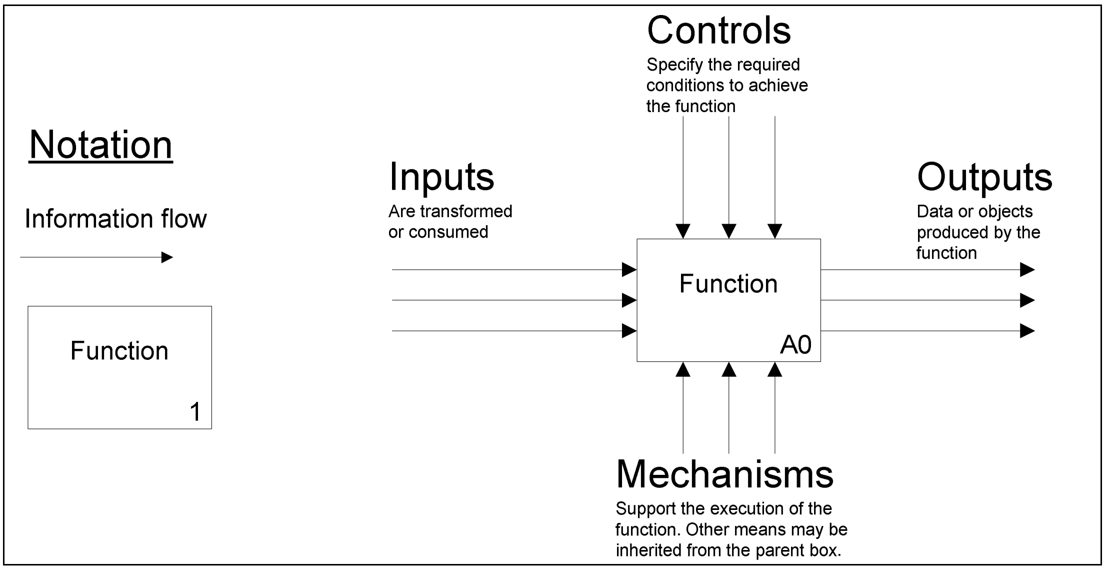


Figure 4.5-1: IDEF0 notation

The following diagram series describes the headplate design process, as represented using IDEFØ.

Figure 4.5-2 represents the top level node, or context diagram. This node describes the overall context and purpose of the model. The model purpose is stated as “analysis of the vacuum pump design process to enable structured knowledge capture and representation”. The process task is ‘vacuum pump design’. Inputs include commercial analysis, technical study and customer requirements. Controls are technical requirement, time scale, and financial management. Mechanisms include designers, peer review and technical / manufacturing. Outputs from the process include manufacturing infrastructure, operation instructions, and marketing documents. Whilst this diagram describes the overall process, its purpose is to set the remaining tasks in context. It is not the intention to model the whole process. For the following diagrams, inputs, controls, outputs and mechanisms will not be repeated in the text. The commentary will be limited to descriptions of context or scope.

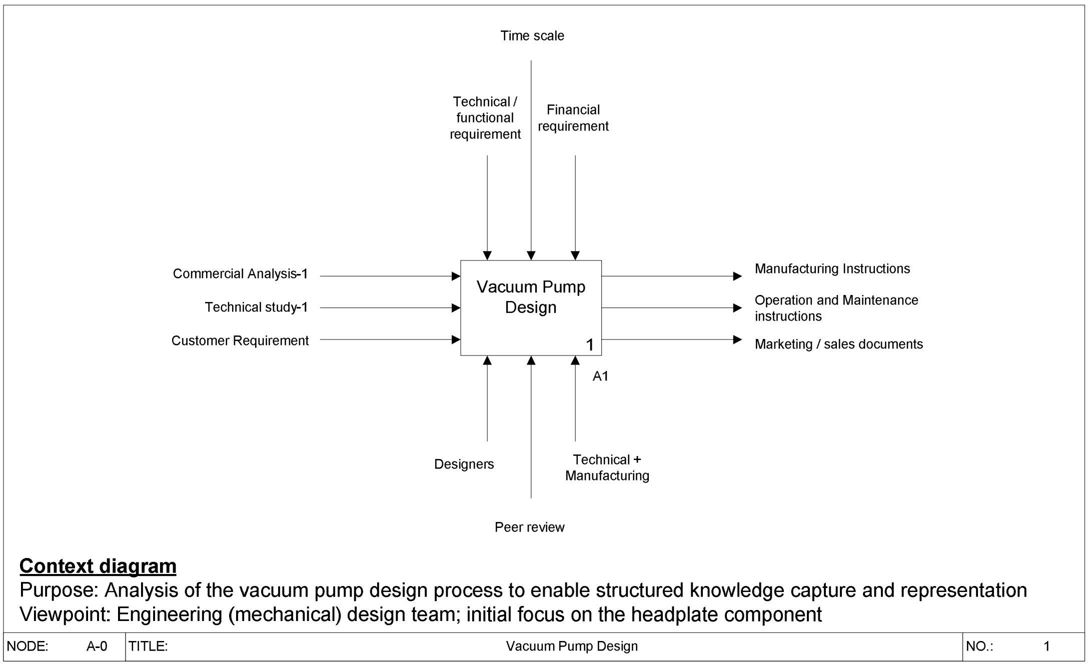


Figure 4.5-2: A-0 (context diagram)

Node A1 (Figure 4.5-5) shows the conceptual design process. The key outputs from the process are product parameters supporting the design specification. At this stage, the performance of the pump has been modelled and verified to meet the required targets as specified by the customer requirements. The output from the concept (modelling) stage forms the input to the embodiment design stage. Competitor product analysis is combined with market analysis and project planning to produce a technical product specification. This includes the expected project cost and duration as well as an initial definition of the product. The initial product specification (represented by ‘pump type, stage configuration, etc) forms the input to a mathematical model, which calculates the critical performance parameters of the pump. Many of the stages are interrelated, and as such iteration and feedback is expected to take place.

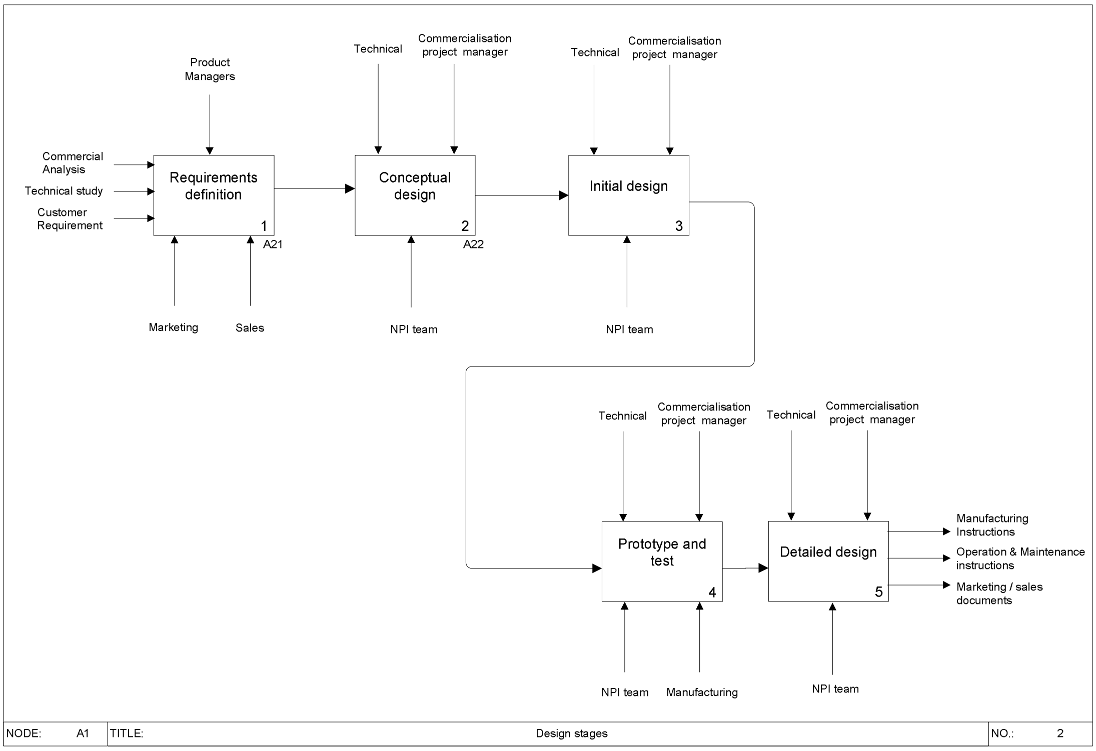


Figure 4.5-3: A1 vacuum pump design stages

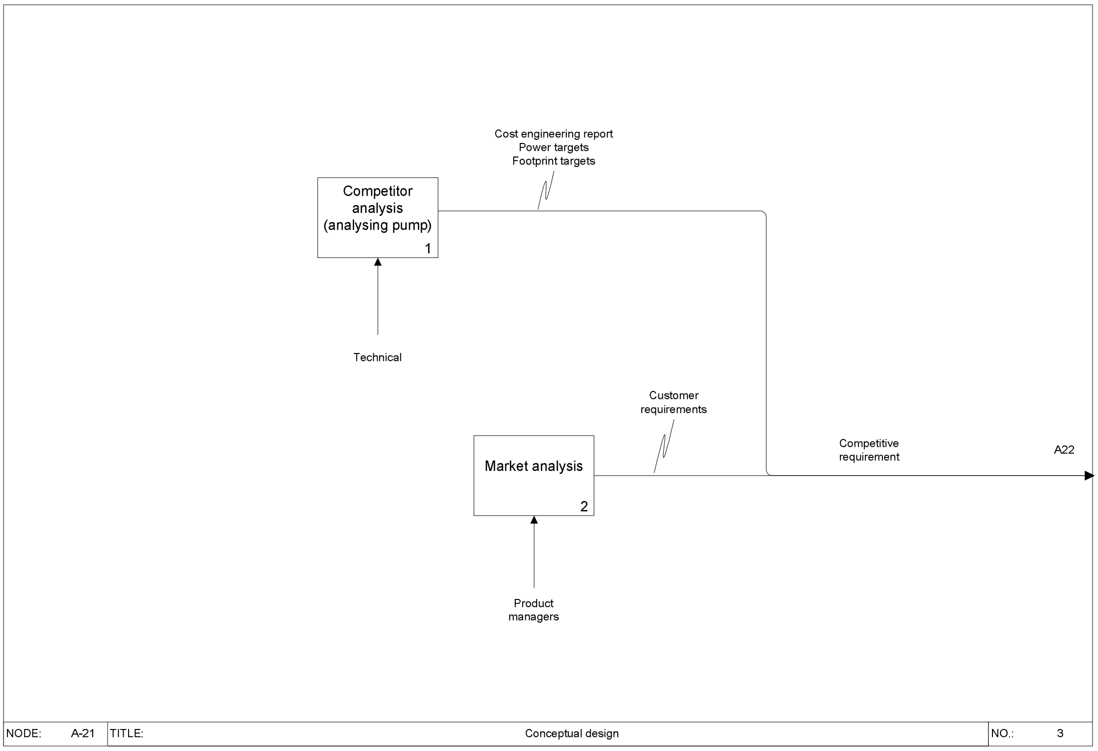


Figure 4.5-4: A21 requirements definition

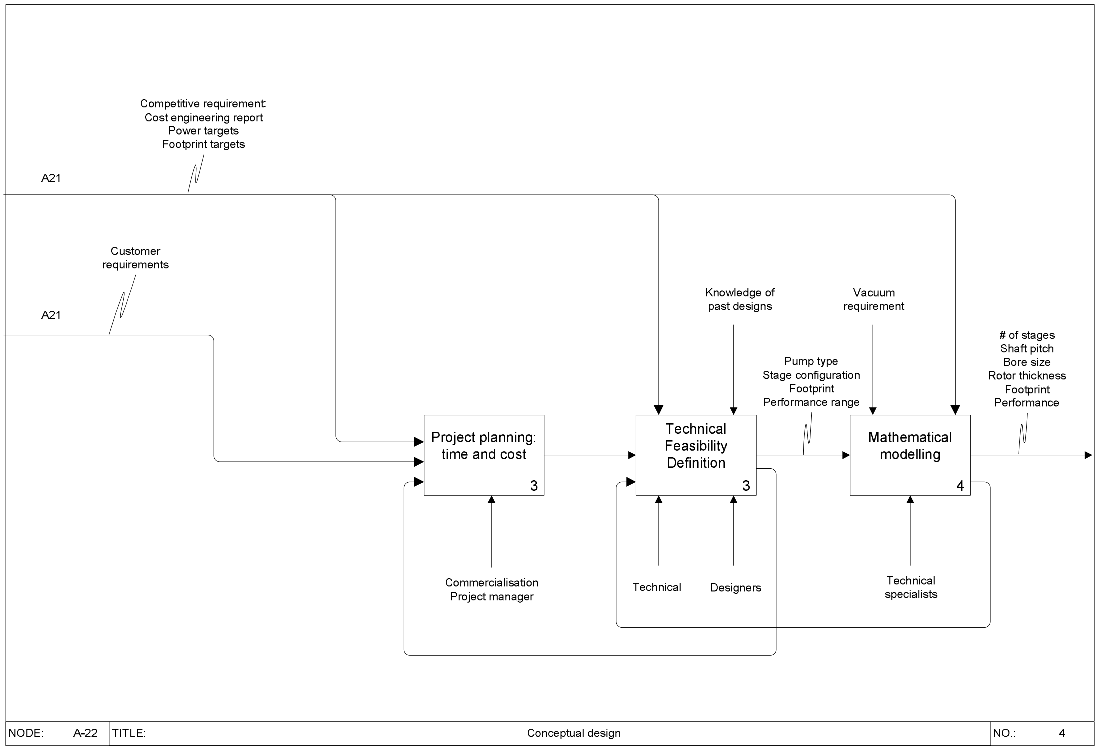


Figure 4.5-5: A22 conceptual design

After the product specification and modelling, an initial scheme of the pump is created (see Figure 4.5-6). This includes the shaft and rotor dimensions, mass and speed. This data is applied to a dynamics calculation to assess resonance. The layout design then takes place, building progressive detail – the bearings, gears and motor are specified. These inputs contribute to the pump cartridge layout, which specifies the key functional dimensions of the pump. In practice, it is likely that this layout is created in a CAD system to provide a visual input to early product review and analysis.

The pump cartridge represents the major functional mechanical unit that performs the vacuum pumping. Overall layout of the cartridge is shown in Figure 4.5-7. Some specifications for the stators are provided from stage A1. This stage represents the CAD layout of the cartridge elements and components. The various pump stages are created, including rotors and stators. The drive system is added, including the motor, gears and two main shafts. Bearings are added, based on the previous specification. A lubrication system is added for the drive side. Initial seal layout then begins, to prevent gas moving between the process chamber and gearbox.

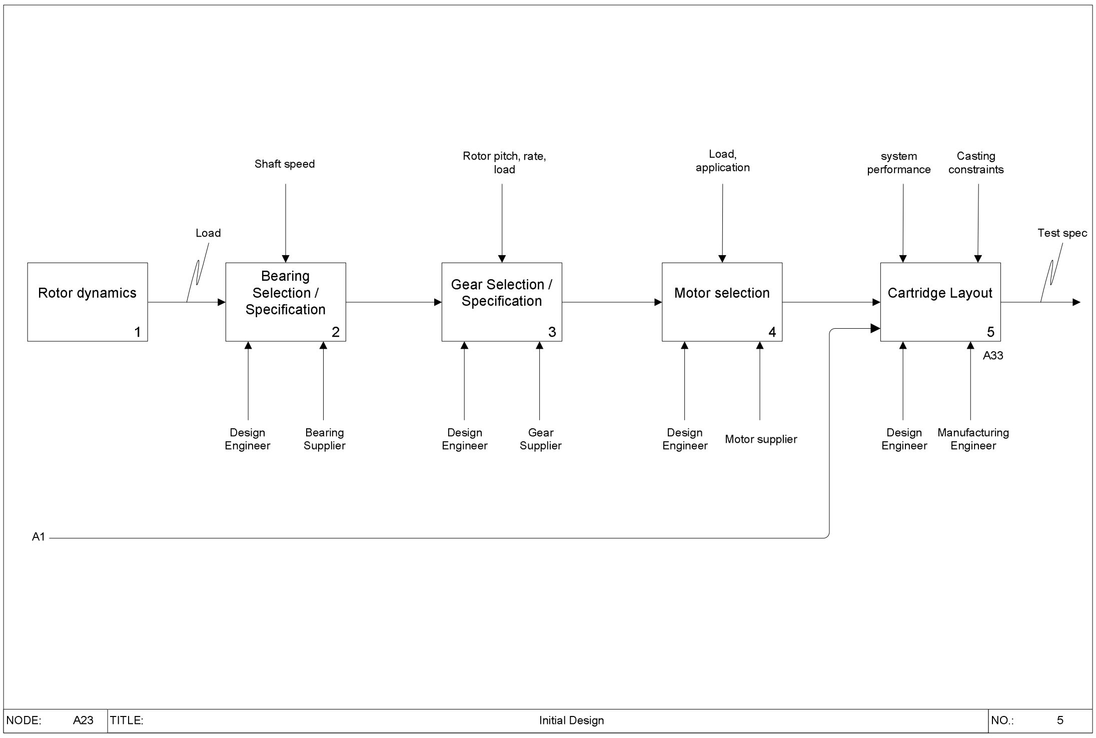


Figure 4.5-6: A23 initial design

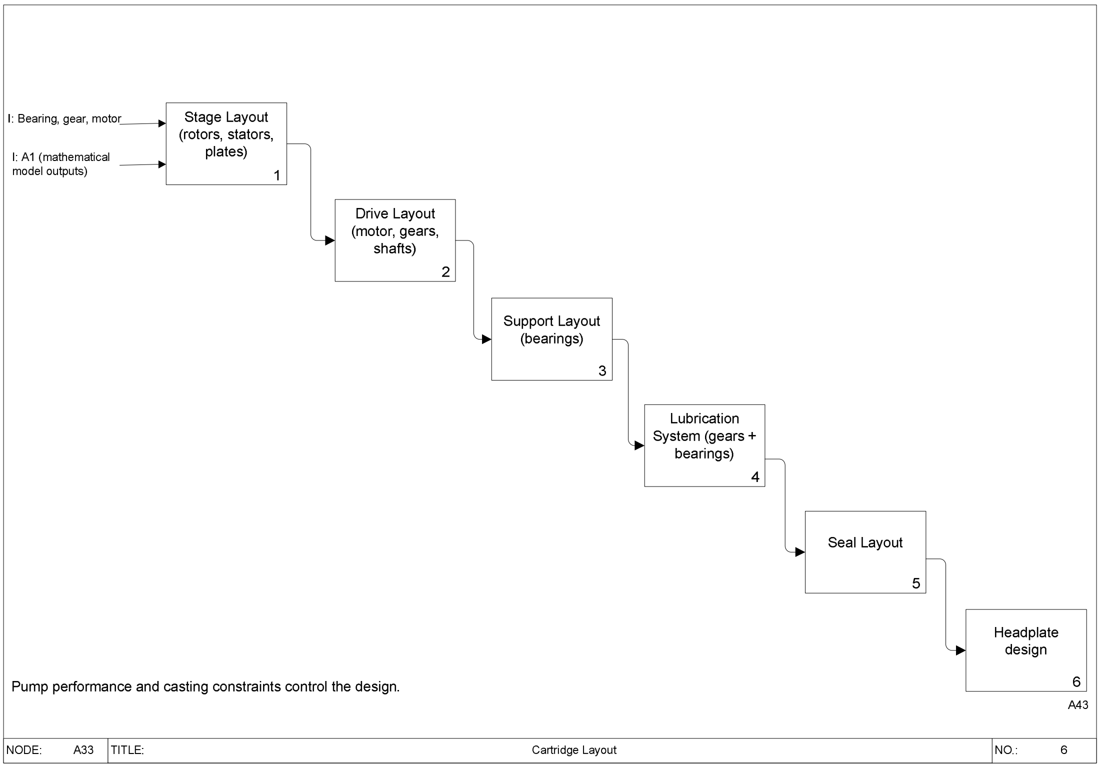


Figure 4.5-7: A33 cartridge layout

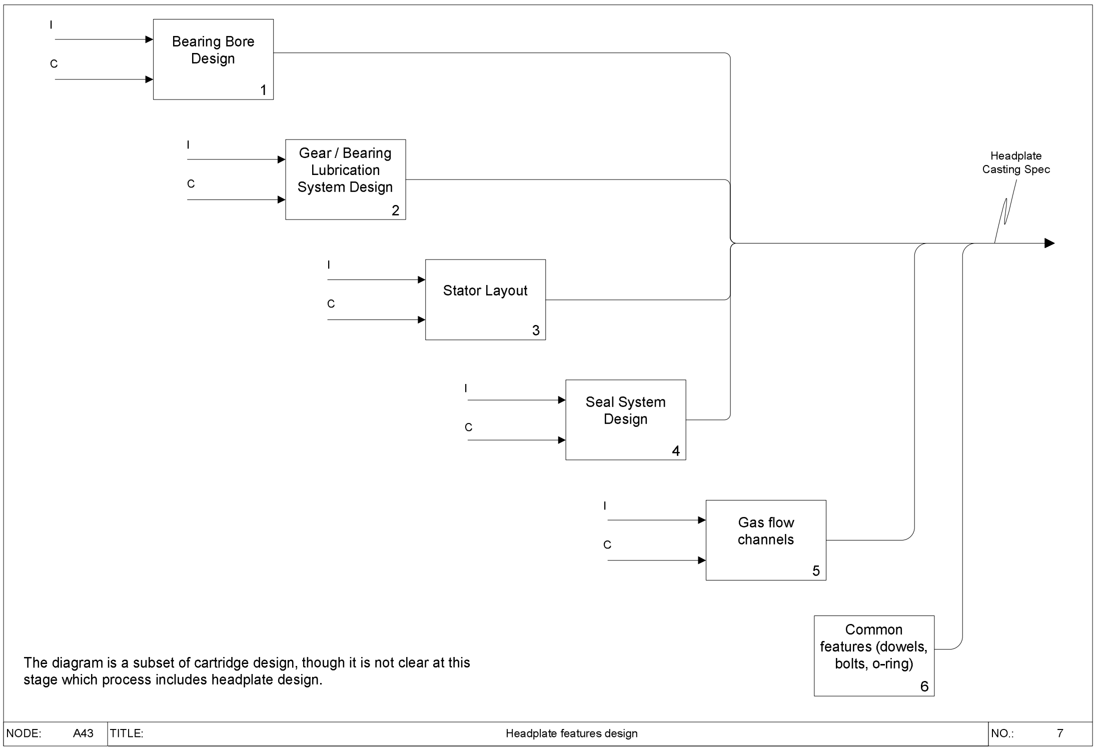


Figure 4.5-8: A43 Headplate design

The design of the cartridge includes design of the headplate, the selected component. As such, the design stage shown in Figure 4.5-8, in which headplate design takes place, represents a subset of the cartridge design process. This is denoted by the node number A211, which shows that it is the first child diagram of node A21. Headplate design includes design and layout of the bearing bore, stator, seal systems, gas flow channels and fixings. Many of these elements have inputs or constraints from previous activities. The product layout that precedes this stage acts as a constraint. For example, the selection of bearings is guided in part by the running speed, temperature and load. The size of the bearing housing is constrained by the shaft diameter and separation distance. Common features are defined by the group product strategy, a function not captured by this model. The design of the product functions and components is iterative and takes place in increasing detail. At the initial layout, the activities relate to the specification of overall product dimensions. At the component level, the activities relate to specific details of features. The component level activities are likely to influence the higher level activities – in some cases dimensions may need to change, affecting overall product dimensions.

4.6. Description and critical analysis of IDEFØ

The process capture exercise was carried out with the intention of modelling the design process using IDEFØ. This method is recognised as a valuable tool for capturing and communicating functional relationships in processes, and its relative simplicity combined with readily accessible knowledge base made it a valid choice for the initial stages.

A brief description of IDEFØ was included in section 4.4. This section will provide a critical analysis. IDEFØ is a hierarchically structured set of nodes. At the top level there is a single context node to describe the overall purpose and viewpoint. The context node may have a child node, containing up to six child nodes. Each child node may be described in more detail, as a single node containing up to six child nodes. There are four link types defined by IDEFØ: Input (which task(s) precedes this task), Output (which task(s) are subsequent to this task), Control (measures to control the output) and Mechanism (means of carrying out the task). Each of the link types can refer to a child node in the same node diagram or to an external node, by reference to the edge of the node diagram and an associated node ID.

Node A-0, the context diagram (Figure 4.5-2), shows a view of the whole (design) process as a single node. The diagram includes a brief statement of purpose, in this case: “analysis of the vacuum pump design process to enable structured knowledge capture and representation”. The viewpoint is defined as engineering (mechanical) design team, with initial focus on the headplate component. At this level, the description of the process is valid, understandable and easy to communicate. The next level is A-1, conceptual design (Figure 4.5-5). This diagram shows the sequence of tasks in creating a conceptual product specification. Key tasks include competitor analysis, market analysis, project planning, technical feasibility definition and mathematical modelling. This process model is the result of several interviews with a range of personnel, including sales managers, product managers, project managers, technical specialists, designers and engineers.

This hierarchical model applied by IDEFØ is useful in being able to describe a high level view of the process and a detailed function view. One limitation of IDEFØ is the specification of the maximum number of 6 child nodes in any parent node. This limits the description of a process to six nodes in a single diagram. Multiple nodes can be applied to represent a process; however this brings additional complexity and reduces the human interpretability of the diagrams. A further limitation of IDEFØ comes in describing processes with multiple feedback loops: the number of arrows shown in a node with multiple internal links can cause problems in understanding the diagram. In an engineering scenario, most processes have some relationship with multiple other processes.

The design knowledge reuse framework seeks to capture an engineering view of the new product development process. An important aspect of the engineering view is the creation and processing of data describing the product. A product data model has been defined as part of the product ontology. This product data model could be assigned relationships with the process. IDEFØ does not support the addition of product data.

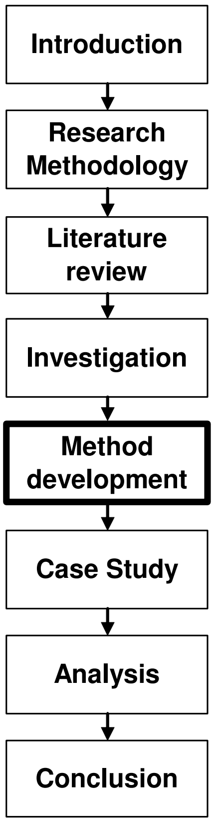
The representation of sequence in the model becomes more important as the design progresses to the detailed stages and more people are involved in the design process. IDEFØ represents a function level view of the process and is not intended to show task ordering, rather it shows functional interactions. IDEF3 is a process description method that represents temporal information; precedence and causality relationships. IDEF3 is well suited to describing enterprise processes, including manufacturing operations. The inclusion of product data is a key element of the proposed methodology, since it represents a key constituent of product knowledge. The process capture exercise identified that the product data is closely related to the design process: certain tasks create a specific data set. In order to support the inclusion of data in the process model, an alternative process representation was sought.

4.7. Summary

The design process capture exercise has helped to identify the design process context, including the nature of the product and the organisation, and the relative importance of automation and fundamental engineering that is applied in product development. The process had not been formally captured in such a way previously within the company. Certain elements of the engineering process were captured and formalised in knowledge based engineering tools. There was not a formally understood method to bring together the various techniques applied in product development. Each project manager would bring their own knowledge and skills to a new project in managing this process. One of the achievements of the process capture exercise, then, is the early stage of developing a best practice design process. The element of the process captured so far refers to requirements capture, commercial and marketing functions alongside a detailed engineering description.

One of the key benefits of the process capture exercise is that it opens a dialogue with the engineers and designers in defining the process in their view, exposing their requirements as well as capturing their methods. Representing the process then provides a model that can be used to communicate, understand and refine the process. Capture and modelling therefore provides the means not only to understand, but to improve the process. The next stage in providing a method for reusing engineering design knowledge is to define the requirements of the method. This can now be carried out with a better understanding of the environment into which it must fit. The process will be applied to the development of the design knowledge reuse framework as a test case. It will also be extended and refined as the method is developed.

Chapter 5: Principles and development of the proposed design knowledge reuse methodology



This chapter will describe the principles and development of the proposed design knowledge reuse methodology. The requirements of the method will be defined and related to the industrial challenges and research gaps identified. The proposed method will then be described.

5.1. Development approach

The previous chapters described the literature review and investigation. This chapter describes the development of the methodology, and the following chapter describes a case study to create a prototype system. The overall approach taken to the investigation was described in section 2.7. During the research, the 'develop, test' activities took place several times. Descriptions generally represent a combined view after several cycles of iteration. The events and resulting decisions or conclusions are not strictly described in the sequence they took place, since the understanding gained at the end is different to the views held at the beginning of the process. This is through insight from the case study implementation, validation and also new literature identified as part of the process.

5.2. Requirements of the design knowledge reuse framework

The aim of this research is to provide a method for reusing engineering design knowledge. It must also show that it has contributed to the research domain through an investigation of existing methods in the literature. Research gaps identified by the literature review include:

- Design reuse for the whole product life cycle;
- Integrated product and process models;
- A 'how-to' element of the product design process;

The challenges identified in the preliminary investigation are:

- Access to relevant and contextualised captured design knowledge.
- Developing a relationship between design reuse and the product development process.
- Integrating engineering and business objectives.

These gaps identified in the literature and the challenges identified in the preliminary investigation are also confirmed by the industrial investigation described in chapter 4. Therefore, the requirements of the design knowledge reuse framework are:

- To provide an integrated platform to enable the reuse of design knowledge, particularly early design, combining process and product knowledge with a business focused approach.

- To represent the design process, including how-to descriptions, such that it can be usefully applied, therefore enabling knowledge reuse.

5.3. Components of the design knowledge reuse framework

The knowledge elements that the proposed method will address are: product, task and process. For a given design project, product knowledge (requirements, dimensions, users, and a range of other parameters) is provided through a design process interface, along with task knowledge (how to carry out that task). Process knowledge forms a central element of the design project, by guiding the design personnel in their activities (what task happens first, which task is next). The process knowledge also includes links to relevant task and product knowledge sources.

Figure 5.3-1 shows how the interaction of these elements enables knowledge reuse. Assuming that the system is in place, and has been used for a previous project, the situation is as follows: the past project informs the current project, by providing product, process and task knowledge. The process knowledge is a formal process model, describing the product development activities and their sequence. Product knowledge includes a parameter set that is required by the design process. As each task is completed, the product parameters are updated. They are also provided to subsequent design tasks to show the task input and constraints. For each task, a how-to description is provided. Each element will be described in more detail below.

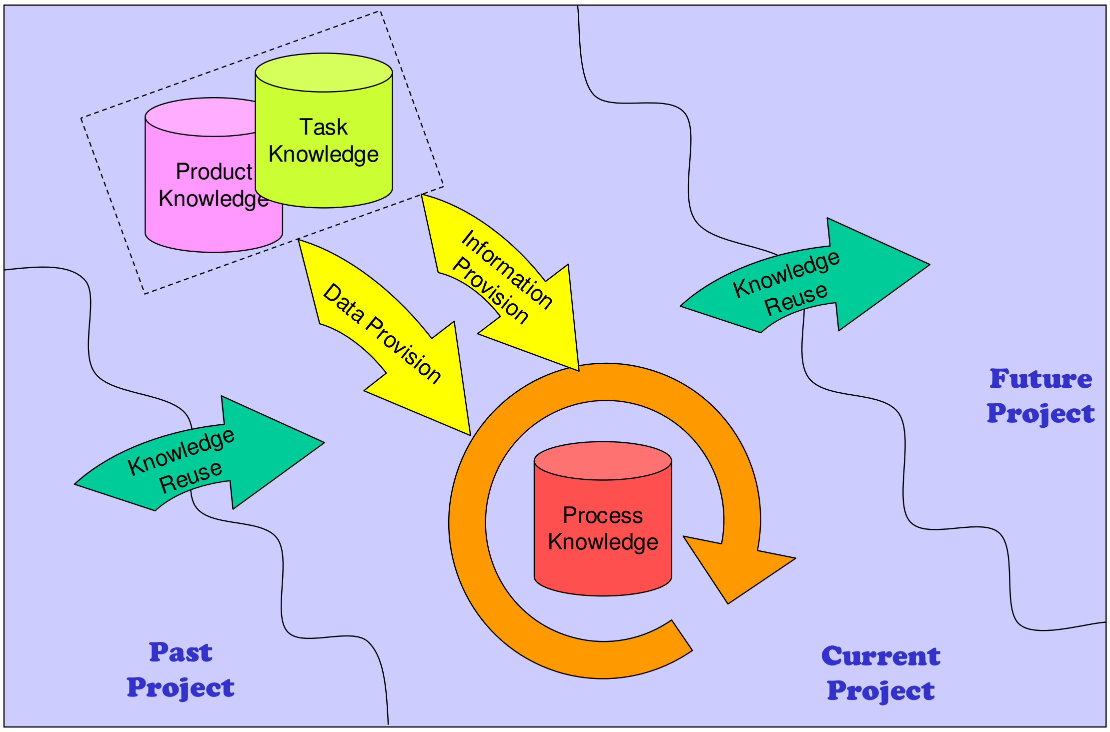


Figure 5.3-1: components of proposed framework

5.3.1. Process knowledge

Process knowledge will be described first, since it references the other knowledge types. Process knowledge essentially includes a process model, which consists of tasks and links between tasks. Link types include precedence, iteration, feedback, and feedforward. Through a series of iterations to create a detailed task model of the product development process, important knowledge about relationships between tasks and relationships between those tasks and product features can be identified, and the best practice methods for developing products can be applied to the next generation.

A detailed task model of a design process represents a great deal of knowledge about not only the product, but also the organisation, its employees and other stakeholders, the competitive environment, suppliers, customers and relationships. In this proposed method these additional elements are not explicitly addressed. In defining the process that is best suited to the development of a particular product type or family in a particular organisation, these complex environmental factors must be implicitly addressed. So, aside from the inherent complexities of the technical or engineering focused product development process, mapping a design process must also reflect additional non-technical constraints and influences. It is the combination of the technical product knowledge and the knowledge of additional environmental factors that gives rise to the specification of a product development process that is best suited to a particular product type in a particular organisation.

Once the process is modelled, the significance of environmental or specific technical factors that gives the process such value could be lost. These implicit elements can not be easily recorded in a process model. There are techniques, such as relationship diagrams or rich pictures, which can be applied to demonstrate the nature of the environment; however these are outside of the scope of this study. The capability to record additional information, whether environmental, social or technical, must be supported by the design knowledge reuse framework in order that sub-optimal decisions are not made in a later stage where important contextual factors have changed. For example, the selection of a 3-axis milling machine has a significant influence on the product design. If a company has substantial in-house capacity, then that method must be given consideration during design. Other manufacturing method selection influences may be due to production volumes or specific technical requirements, such as low cast porosity. Again, manufacturing method selection has a significant influence on design, so the rationale for the previous selection of a particular method should be visible in a new project. These manufacturing related factors are technical, and quantifiable. There are also non-technical factors that can influence product design, such as the release of a new competitor product, or a request from a large customer for a specific feature.

The combination of the technical and non-technical elements into a best practice product design process model should seek to capture the process along with some of the process rationale.

Additional knowledge referenced by the task model therefore includes product knowledge (including a data model), as well as task knowledge (how-to descriptions and supporting information). These are described next. The task knowledge allows recording of free text, which enables the description of historical and contextual factors that led to the definition of that process.

5.3.2. Product knowledge

Product knowledge includes a product data model: product elements and parameters. Every aspect of the product that is used or created by a design task must be included in the product data model. That is, where a product feature or parameter is referenced by a task, it should be included in the product data model. Some design tasks will include product data such as ‘customer’, ‘production volume’ or ‘location’, each of which have an indirect influence on the product design. Other tasks will reference product data such as ‘component x material’, ‘component x axial length’, and a range of other geometrical and physical descriptors.

It is not the intention that the product data model replaces (or includes) a full geometry description, since the complexity of this task would be very high for a limited return: CAD systems are already very good at representing product geometry and it is not the intention to replace them. The aim of the product data model is to support the creation of the product, by storing any additional data required for or created by design, engineering, manufacturing (and any other) calculations and analysis. From the earliest stages of design, a range of product data is generated. Requirements data, for example, is applied in very early calculations for product feasibility analysis, product costing and project planning. Capturing a shared view of the product data from a whole-life-cycle perspective will enable reuse of the data and the complex knowledge structures supporting them. A ‘whole-life-cycle’ perspective means that rather than considering just one stage of product development, all stages can be represented – from requirements capture to design, manufacturing, maintenance, remanufacture, recycling and disposal.

In order to enable concurrent application of the various elements of product data, including distributed access and updating, the product data model must be a centrally managed, shared model based on a shared understanding. Common access to product data is an important issue, and must be considered from a variety of technical and socio technical perspectives. This issue will be addressed to some extent in the method development and analysis stages. The more relevant issue at this stage is common understanding of the product data.

In order to enable shared understanding of the product model, an ontology will be developed. The ontology will primarily be applied to the definition of product parameters (a taxonomy of terms), including commonly agreed vocabulary. It will also be applied to the definition of data types, or slots, for each of the parameters. This product ontology will form the basis of all product data operations. It is crucial to pursue a common understanding of the product data if the knowledge is to be accessed by multiple users, particularly if they are distributed geographically. Even where people are co-located, they may use different terms for the same thing in their daily work. The creation of the product ontology will require that groups of users come together to define the product model.

5.3.3. Task knowledge

Task knowledge includes textual and graphical how-to descriptions, rules, and a full range of linking options to additional sources of information. It also enables the recording of contextual factors.

The content of the task knowledge will be dependent upon the needs of the user and the knowledge and experience of the author. It will also vary greatly depending on the nature of the task. The description could be a how-to description supporting a structured form to fill in, or a selection of images and text to describe the background of a task. Hypermedia provision through modern Office systems and Internet browsers provides a very flexible means to represent a wide range of data, information and knowledge. ‘Additional knowledge’ may refer to a detailed step-by-step task description, an online supplier parts catalogue, a British Standard document, a web page with information on a specialist subject, or a discussion group or wiki. The main requirement of this task knowledge method is flexibility; however it should also be structured to support knowledge capture and reuse. Task page templates will be developed during the case study.

5.4. How the framework aims to address research gaps

Formalising the design process and populating the model with product and task knowledge provides a method that can be followed in a new design project. Following that method represents knowledge reuse. Learning should be formalised at the end of each project and fed back into the system. This forms the basis of knowledge reuse for future projects.

The literature review identified that the design process is a key element of knowledge reuse, both through business process modelling and through the application of design methodology. There is a research gap in providing a knowledge reuse framework that is suitable for the whole product development life cycle, in particular early design. Few approaches describe a relationship between the design process and design object.

This research gap relates to integrating a product model with a design process model. There is also little work on the 'how-to' element in current process modelling methods. An engineering view of the design process, in which the design process is supported with product data as inputs to tasks and prompts for outputs from tasks, is also a novel element.

One of the objectives of this research is to develop a design knowledge reuse framework that meets the research gaps, along with the industrial needs. A summary of these research issues is shown in section 3.7. The proposed method should be suitable for all early design. The proposed framework aims to explicitly address a formal model of the design process as part of an integrated design reuse approach providing support for formal and informal knowledge reuse approaches: a formal product model and design process and informal 'how-to' task descriptions. The framework should support design analysis and KBE alongside problem solving methods, design intent, history and task support.

5.5. Process modelling using Design Roadmap method

The design roadmap method was selected as an alternative for modelling the design process, and is the chosen method for process representation in the proposed framework. This method supports the inclusion of product data in the process, and was developed specifically for engineering processes. As such, the method supports the modelling of common engineering process flow actions including iteration and feedback links. The basic notation for a DR model is shown in Figure 5.5-1. The blue rectangle with rounded corners represents a data set – in their terms, this is a 'feature'. The use of the term 'feature' has caused problems in explaining the DR process notation to research participants: their engineering perspective brings with it a strong association with the word feature that differs from its use in this context.

> "A feature, F*i*, is a unit of information or material upon which a task operates. It may represent data (e.g. scalar, vector, list, graph, etc.), an aggregate property (such as 'electrical properties', or 'geometry'), or an artifact (e.g. a schematic drawing). Simply put, features are input and output entities of tasks." (Park & Cutosky 1999)

The black rectangle with the angled corners represents a task.

> "A task, Ti, is the fundamental unit of a process. Hence, a process by definition is a graph of one or more tasks. The DR framework requires a task node to have at least one input feature, and at least one output feature." (Park & Cutosky 1999)

Three link types are shown – i.e. three methods of creating relationships between task and feature objects. Precedence indicates that one object precedes another, and that the preceding object provides an input. Feedback indicates that the result of a subsequent task is an input to a task, and that the link may require a task to be repeated. Feedforward indicates that the result of a previous task is an input to a subsequent task.

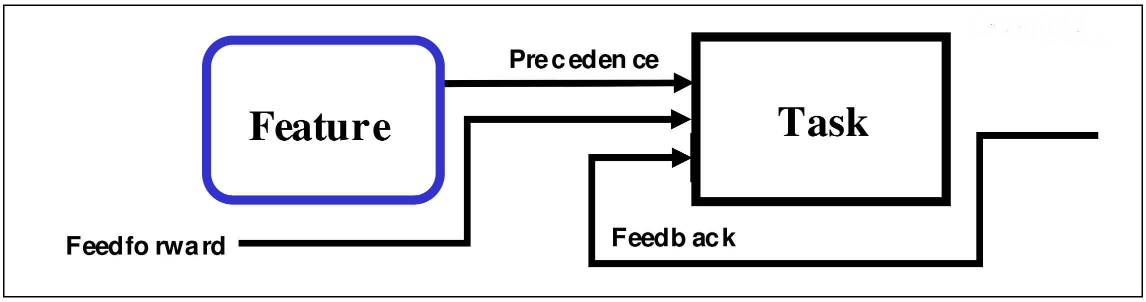


Figure 5.5-1: Design Roadmap (DR) basic notation

In order to successfully apply the process representation in the engineering design domain, it may be necessary to change the name of the data element from 'feature' in order to avoid confusion with engineering related uses of the word 'feature'.

The initial attempt to remodel the process using the Design Roadmap (DR) notation took place using the IDEFØ model as the basis: the researcher translated the IDEFØ model into a DR model. The initial model was taken to members of the design team. Interviews took place in order to validate the process description. As described in the preceding section, IDEFØ does not support task ordering or the addition of product data, where the DR method can support these needs.

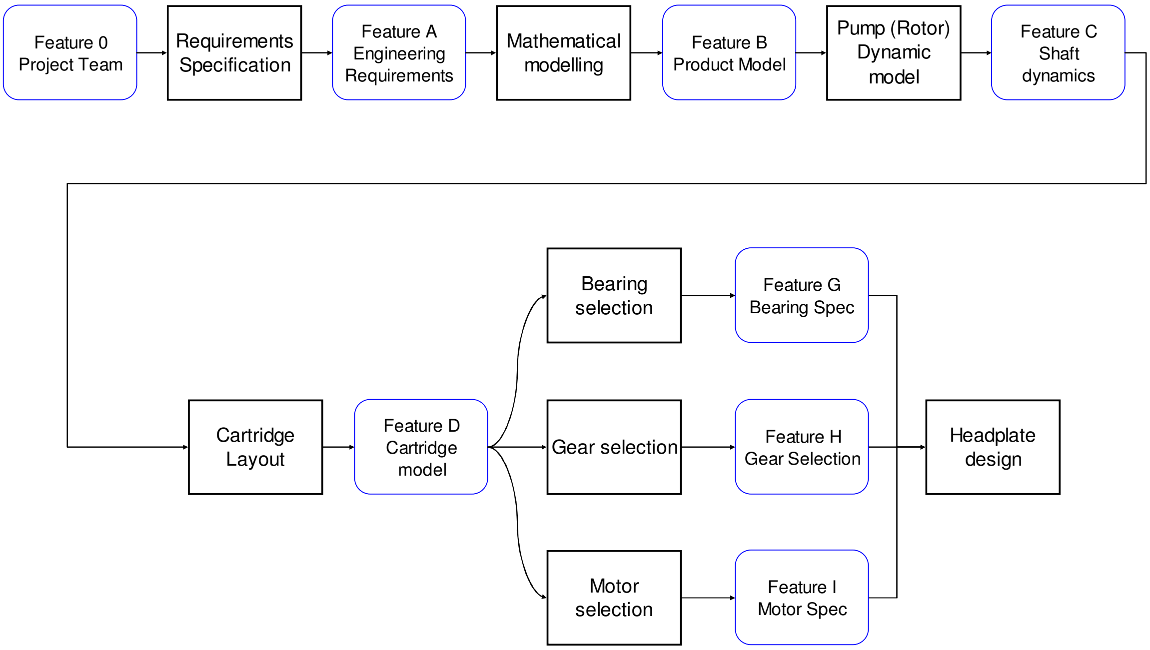


Figure 5.5-2: high level process model (design roadmap notation)

The process model shown in Figure 5.5-2 represents an overview of the headplate design process after validation. The model will now be briefly explained. Each blue rectangle with rounded corners represents a data set. Each black rectangle with square corners represents a task. Starting at the top left of the diagram and working in the direction of the arrows: ‘Project team’ is a data set that consists of the names of each project team member. ‘Requirements specification’ is a task to define the engineering requirement. ‘Engineering Requirements’ consists of a set describing the product requirement from an engineering perspective. This was reduced to a small number of variables, including: customer category, size constraint, power consumption target and prime cost target. Mathematical modelling is a process that applies a specialist engineering application to modelling the performance of a vacuum pump. The result is a more detailed product model, with critical feature dimensions, clearances, operating speeds and temperatures. The task pump (rotor) dynamic model takes a subset of that product model as an input to determine the natural frequency of the proposed pump. The output is a data set describing the shaft dynamics. This, along with the product model, forms the input to the cartridge layout task. This task defines the major parameters of the pump cartridge and creates an initial layout. The output data set is the Cartridge model. This describes the necessary parameters to define the following tasks: bearing selection, gear selection and motor selection. It is likely that each of these components will be bought in from suppliers rather than made in-house.

Each task (bearing, gear and motor) has a resulting data set describing the selected parameters. These data sets, along with the cartridge model, provide input to the 'headplate design' task.

The limited notation in Figure 5.5-2 makes the diagram simple to understand. The diagram is missing certain process elements including iteration and multiple inputs, in order to maintain a simple view of the process structure. The process actually contains several feedback loops, as shown in Figure 5.5-3.

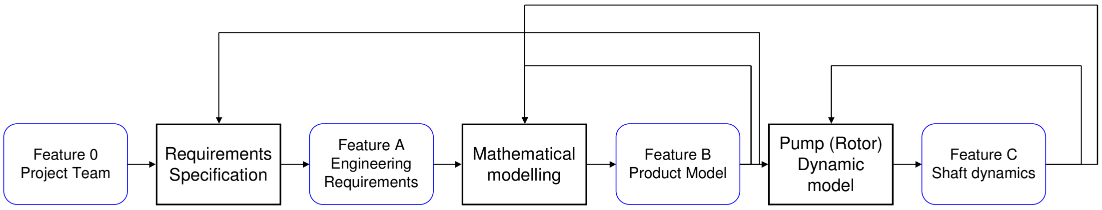


Figure 5.5-3: portion of DR model showing feedback loops

The product model data is fed back into the requirements specification: where the mathematical model shows either better or worse performance than originally specified the product requirement is updated o reflect an achievable figure. The product model data is also fed back into the mathematical model, since several iterations of the modelling process are expected to take place, refining and altering the inputs to optimise the output. The shaft dynamics data feeds back into the dynamic modelling and mathematical modelling tasks, again as an iteration loop to optimise the product characteristics.

The overall design process as modelled with the DR method is different, showing fewer process units than the IDEF model. This is a result of changes made during the validation exercise.

5.6. Modelling task and product knowledge

5.6.1. Task knowledge development

Having created the process model using the design roadmap method, task knowledge can be added. This is carried out alongside the development of a task template. Task knowledge will be described in more detail in the following sections, in which the development of the prototype system is described.

5.6.2. Product model development

Product knowledge is modelled using ontology. The first stage of the ontology development was to break down the vacuum pump into its constituent features and functions to show the location of the headplate in the component domain. This stage applied some of the phrases and definitions identified in the earlier knowledge capture stages, and combined this with a literature source on vacuum practice (Harris 1989).

A key requirement of the ontology is to create a shared definition of terminology used during the product development process. This includes the definition of product parameters, data types and limits or ranges where appropriate. The initial ontology describing vacuum pump types is shown in Figure 5.6-1. The Protégé system was used to model the ontology. Protégé an open source, platform-independent environment for creating and editing ontologies and knowledge bases, developed by Stanford University.

In the diagram, 'C' refers to 'Class'. 'A' refers to 'Abstract': an abstract class appears in the class hierarchy, but has no direct instances. A concrete class can have direct instances. 'M' refers to Vac_pump_types enables a definition of the product type in general terms: the types began as defined by Harris (Harris 1989), with some modifications to suit the target organisation. The pump types can be defined by an "is-a" hierarchy: a rotary vane pump is-a rotary pump is-a positive displacement pump is-a vac pump type.

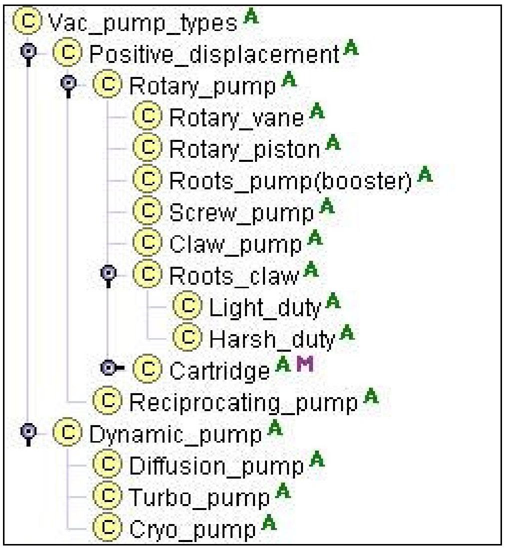


Figure 5.6-1: Ontology showing vacuum pump types

The “is-a” hierarchy is more difficult to apply to a product model showing component structures. Figure 5.6-2 shows the product structure for Vac_pump_components. They are represented in a hierarchy made up of composition links, which are more appropriate for this application. The ‘cartridge’ is shown to be composed of a ‘headplate’, ‘seal system’, and ‘lubrication system’.

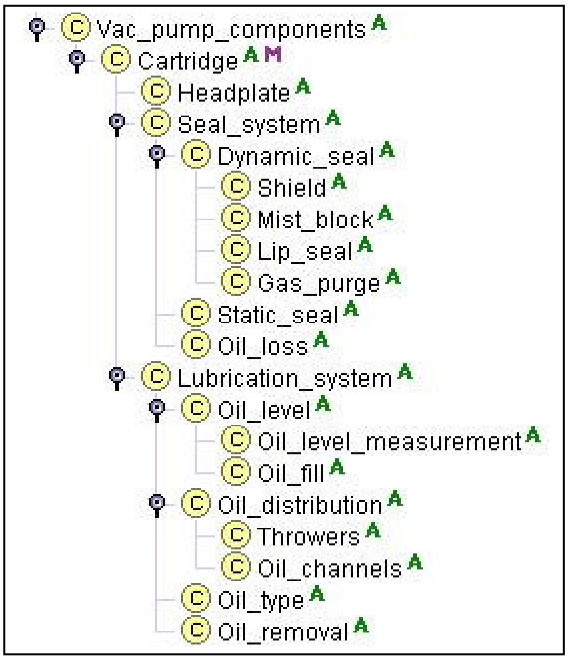


Figure 5.6-2: Product ontology showing components

The product model is incomplete, however its purpose at this stage is to position the headplate in a composition hierarchy showing related and constituent component groups. It shows that ‘headplate’ is part of the larger composition ‘cartridge’. The Protégé system enables the creation of slots for each object. This will not be completed within the Protégé system, since the product data will be migrated to the prototype system. The product knowledge hierarchy to be adopted will be implemented in the developed prototype system.

The ontology development consisted of capturing product knowledge to identify the product type and composition in terms of its constituent components.

5.7. Pilot implementation of the design knowledge reuse system: stage 1

The main purpose of this pilot implementation is to investigate how the combination of process and product knowledge translates into an information system framework, and to begin a review of the proposed concepts. The implementation takes place in two stages. The planned system architecture for the first stage is shown below in Figure 5.7-1.

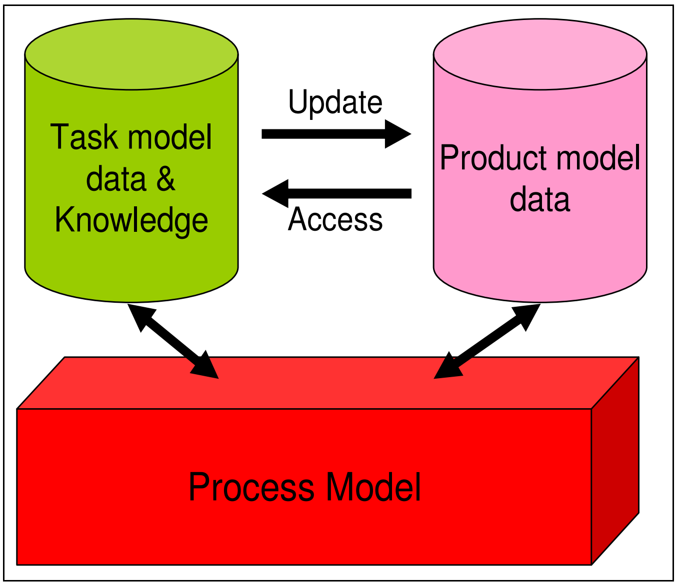
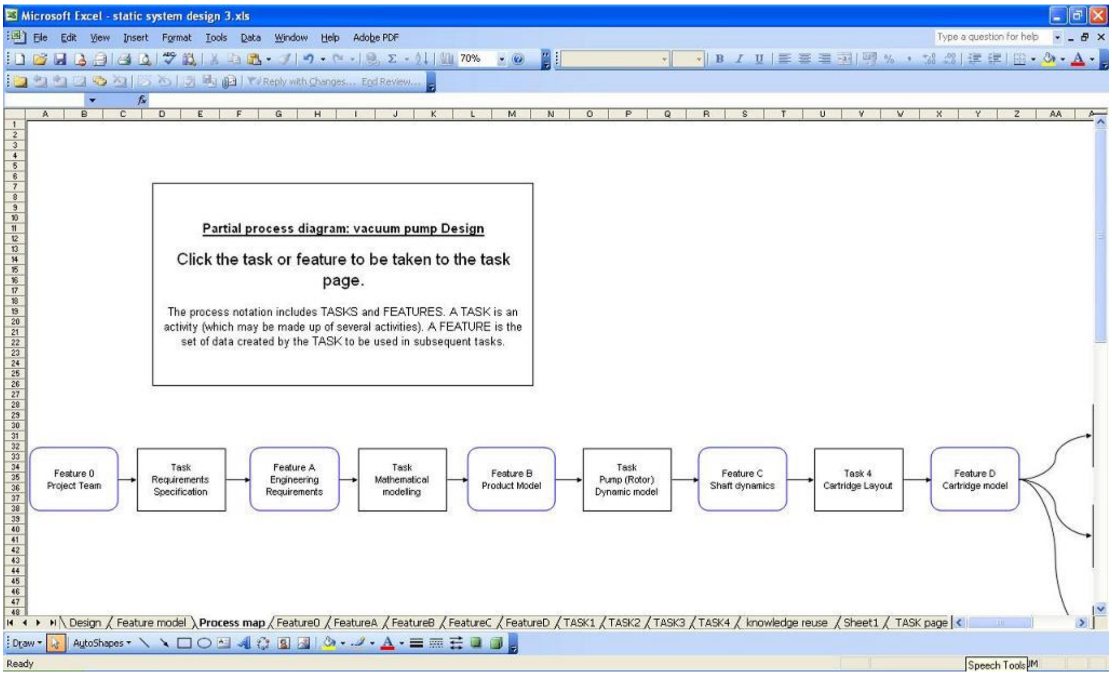


Figure 5.7-1: System Architecture of stage 1 implementation

The system architecture for the stage 1 implementation shown in Figure 5.7-1 shows three main components: task model, product model and process model. The interaction in the diagram shows that the product model is accessed and updated via the task model. Both product and task model are linked to the process model, which forms the central element of the system. The stage one pilot implementation involves implementing these data structures in a Microsoft Excel spreadsheet based system. Excel is very capable in terms of data storage and manipulation, however it is less capable in terms of the visual modelling of processes.

5.7.1. Excel prototype system: process model

The first step in the development of the Excel based system was creating the process model. Figure 5.7-2 shows a screenshot of the whole page; Figure 5.7-3 shows a scaled version of the process model, resized in order that the tasks can be identified in an A4 print.



Partial process diagram: vacuum pump Design

Click the task or feature to be taken to the task page.

The process notation includes TASKS and FEATURES. A TASK is an activity (which may be made up of several activities). A FEATURE is the set of data created by the TASK to be used in subsequent tasks.

Figure 5.7-2: Screenshot of main system page - process model

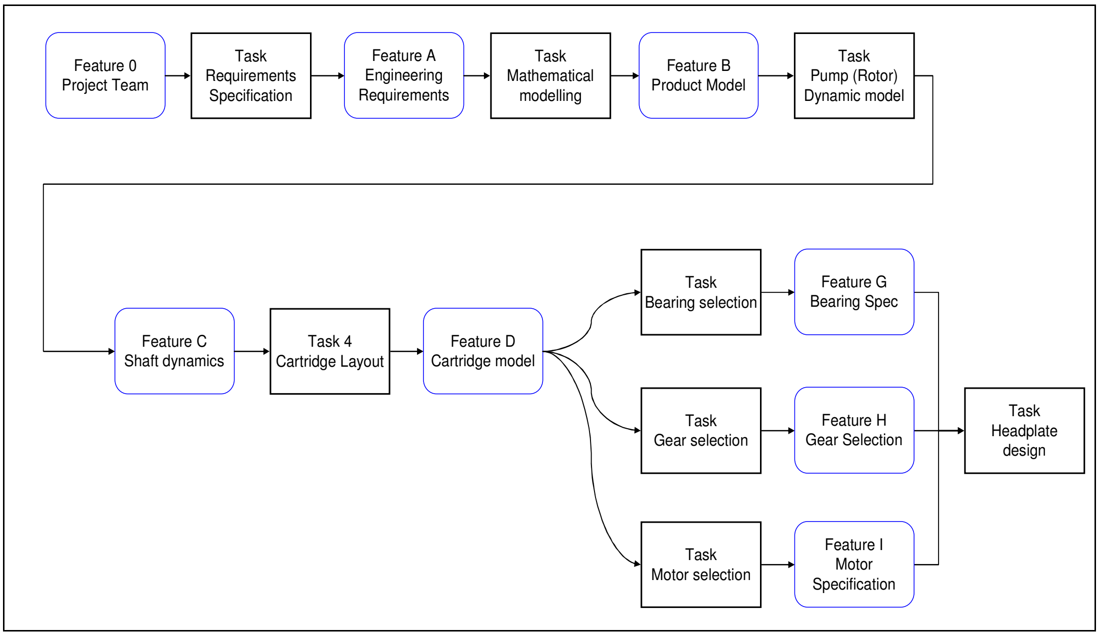
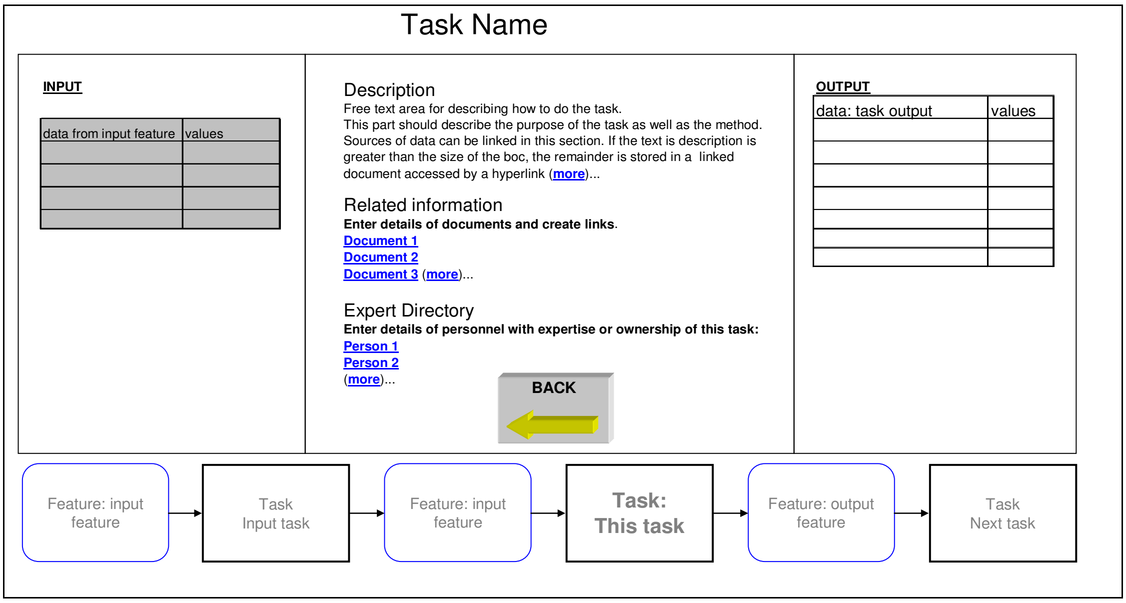


Figure 5.7-3: Edited version of process model, resized for printing

5.7.2. Excel prototype system: task model

The second step in the development of the Excel based prototype system was creating a task model. Each of the task objects in the process has an associated task page worksheet. The task objects contain hyperlinks to enable the user to navigate through the system by clicking the tasks. The task pages are a key element of the Excel model. Each task page displays the data required as an input (from the input feature). It then shows a task description, with text describing the task objective and method (the ‘how-to’ section). The description area also allows links to external documents. The page displays the data required as an output from the task on the right hand side. The data is entered on the page as the task is completed. In the Excel system, the data remains in the cells where it is entered. It is stored when the file is saved. A task page template is shown in Figure 5.7-4.



Description
Free text area for describing how to do the task.
This part should describe the purpose of the task as well as the method. Sources of data can be linked in this section. If the text is description is greater than the size of the boc, the remainder is stored in a linked document accessed by a hyperlink (more)...

Related information
Enter details of documents and create links.
Document 1
Document 2
Document 3 (**more**)...

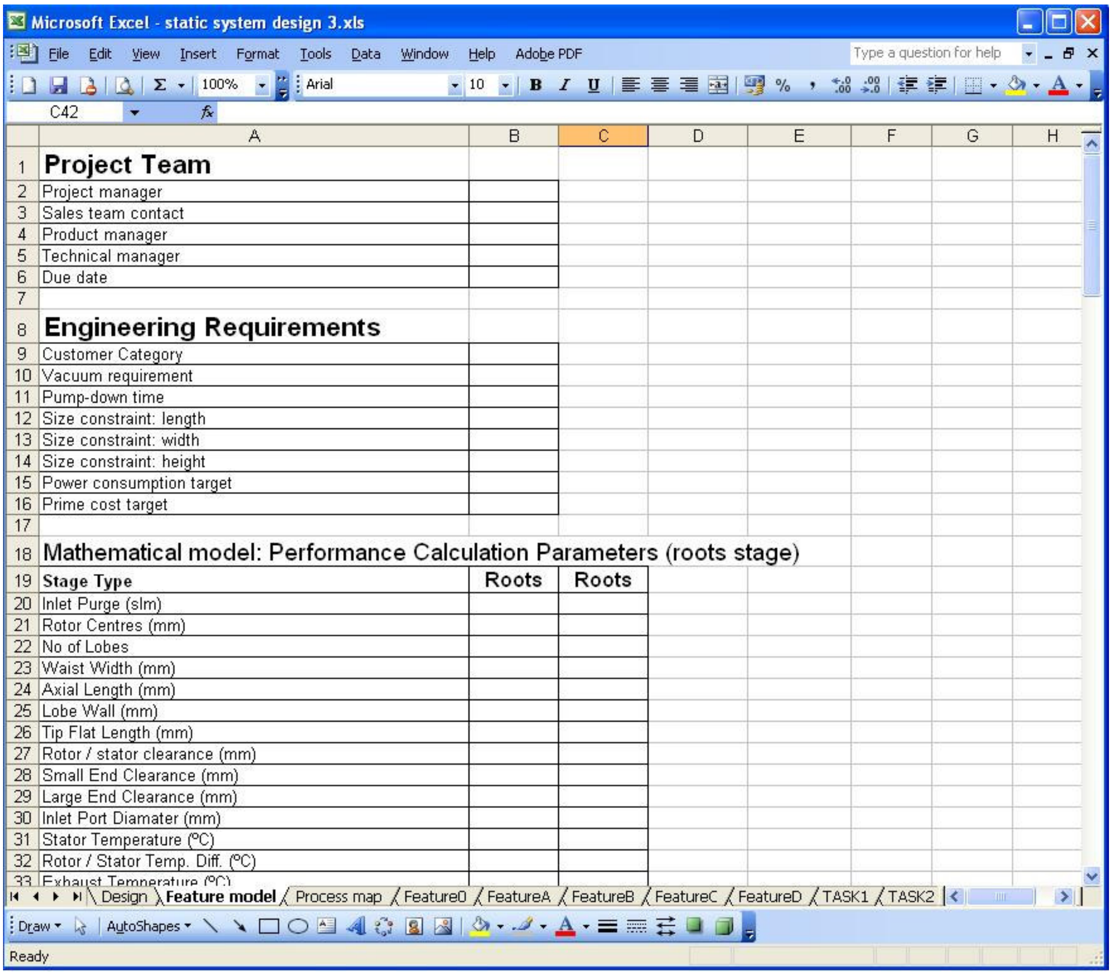
Expert Directory
Enter details of personnel with expertise or ownership of this task:
Person 1
Person 2
(**more**)...

Figure 5.7-4: Prototype 1 task page template

As a result of the validation process, additional features were added to the task page template. The task input (shown on the left hand side in grey) is read-only and can not be edited. Each task page also shows a section of the process model to provide some context: what took place in advance of this task and what will take place next. This is shown at the bottom of task page. The task ‘context’ objects also contain hyperlinks; the user can click through to previous or future tasks to see the description and any data that has been created. Providing the design process context diagram is a significant step in the design process representation, since it provides the user with quick access to the other tasks as well as a view of where the process sits in relation to those other tasks. The feature is currently static: it is created in advance of the process and does not change if the process sequence is edited. Dynamic methods should be implemented in a production version of the system.

5.7.3. Excel prototype system: product model

The data storage applies a centralised approach – all product data is stored in one worksheet. Other worksheets that access that data for display or updates refer to the original source. This enables a view of all of the product data from a single source, and maintaining a single source prevents duplication errors. A sample of the Excel feature model is shown in Figure 5.7-5. The data sets are organised according to the features they correspond to. The product model should be developed based on the product ontology. Whilst the view of the product parameters may not correspond to the hierarchical structure of the product ontology, the parameter names and their corresponding data are defined by the ontology. In the Excel prototype implementation the structure is defined according to the data sets applied by design tasks.



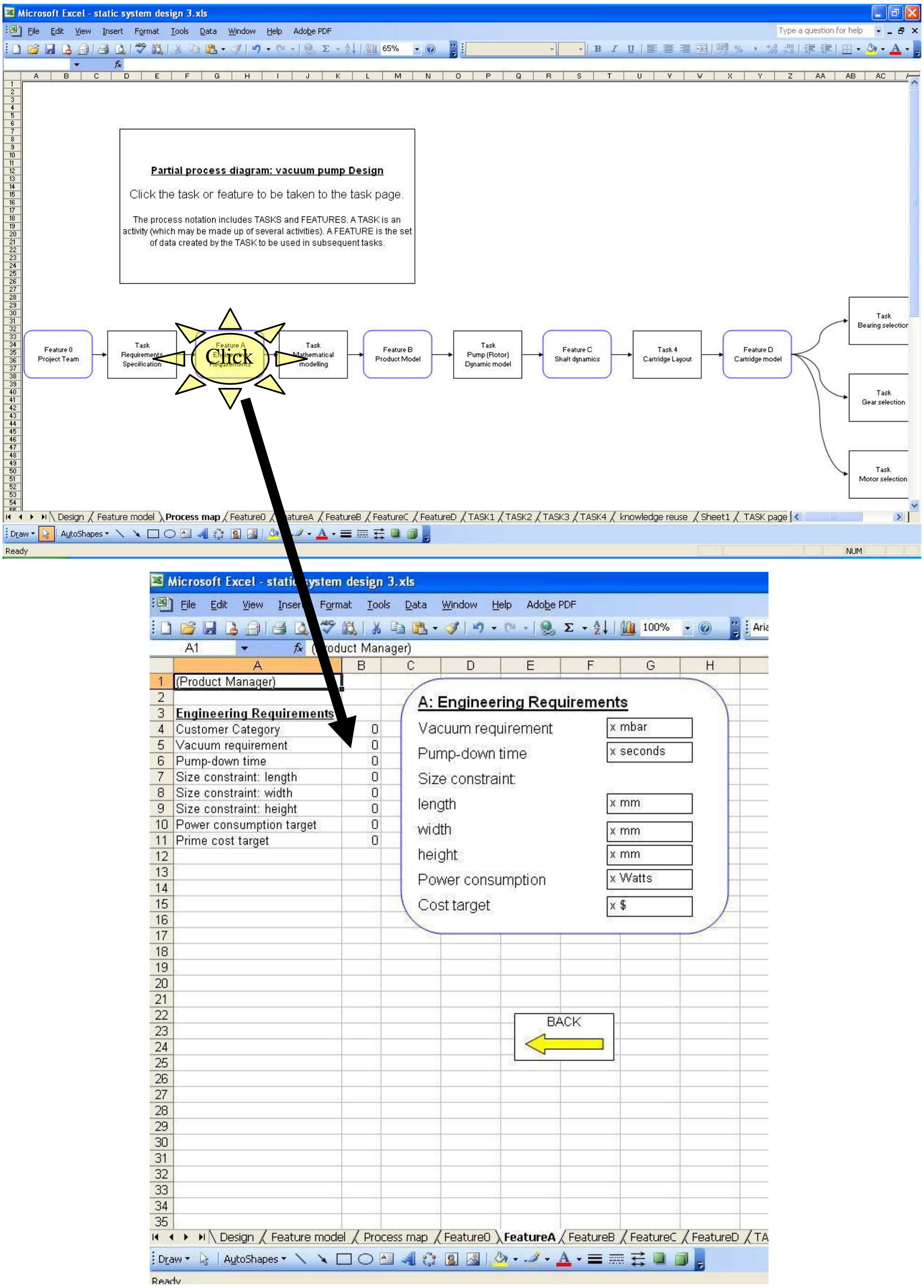
	A	B	C
1	**Project Team**		
2	Project manager		
3	Sales team contact		
4	Product manager		
5	Technical manager		
6	Due date		
7			
8	**Engineering Requirements**		
9	Customer Category		
10	Vacuum requirement		
11	Pump-down time		
12	Size constraint: length		
13	Size constraint: width		
14	Size constraint: height		
15	Power consumption target		
16	Prime cost target		
17			
18	Mathematical model: Performance Calculation Parameters (roots stage)		
19	**Stage Type**	Roots	Roots
20	Inlet Purge (slm)		
21	Rotor Centres (mm)		
22	No of Lobes		
23	Waist Width (mm)		
24	Axial Length (mm)		
25	Lobe Wall (mm)		
26	Tip Flat Length (mm)		
27	Rotor / stator clearance (mm)		
28	Small End Clearance (mm)		
29	Large End Clearance (mm)		
30	Inlet Port Diamater (mm)		
31	Stator Temperature (ºC)		
32	Rotor / Stator Temp. Diff. (ºC)		
33	Exhaust Temperature (ºC)		

Figure 5.7-5: Excel pilot development - screenshot of feature model

The spreadsheet shown in Figure 5.7-5 shows how the data is arranged in the pilot system. Each title in bold represents a feature, which corresponds to the features in the process model shown in Figure 5.7-3. ‘Project Team’ corresponds to Feature 0, and the data elements stored in that feature are shown as Project Manager, Sales team contact, Product manager, Technical manager and Due Date. ‘Engineering Requirements corresponds to Feature A, and ‘Mathematical Model: performance calculation parameters (roots stage)’ corresponds to Feature B.

All product data elements are created according to the product ontology, which was initially developed using the Protégé system in order to develop the hierarchy and ensure that the concepts were consistent. It was later implemented in the Excel prototype system, since the purpose of the product ontology is to provide a structure for the product parameters and data. There is a range of data elements associated with the product development process that go beyond specifying the product. As such, that the product ontology is also extended beyond the product, to include additional data from fields such as ‘product application environment class’, ‘customer’, ‘requirements parameters’ and ‘project team members’. By maintaining the structure and rules implied by the product ontology, the integrity of the product data is retained in terms of consistency, completeness and the maintenance of a shared view. Each data element must, therefore, be created and validated by peer review such that it reflects a shared view of the data particularly in terms of name, but also that it corresponds to an appropriate task, that it has all necessary data fields and is of the correct data type.

In the Excel pilot implementation each process object is represented by a drawing object. Each of these objects is associated with a worksheet by means of a hyperlink. For example, the process object ‘Feature A’ has a hyperlink to a worksheet named ‘Feature A’. The diagram below (Figure 5.7-6) indicates that when the user clicks the feature object, the worksheet opens. That worksheet provides access to and editing of the engineering requirements data associated with that feature. The feature worksheet has a button to navigate back to the ‘process map’ worksheet.



Partial process diagram: vacuum pump Design

Click the task or feature to be taken to the task page.

The process notation includes TASKS and FEATURES. A TASK is an activity (which may be made up of several activities). A FEATURE is the set of data created by the TASK to be used in subsequent tasks.

(Product Manager)

	A	B
1	(Product Manager)	
2		
3	**Engineering Requirements**	
4	Customer Category	0
5	Vacuum requirement	0
6	Pump-down time	0
7	Size constraint: length	0
8	Size constraint: width	0
9	Size constraint: height	0
10	Power consumption target	0
11	Prime cost target	0

A: Engineering Requirements

Vacuum requirement	x mbar
Pump-down time	x seconds
Size constraint:	
length	x mm
width	x mm
height	x mm
Power consumption	x Watts
Cost target	x $

Figure 5.7-6: links between objects in the Excel model

5.8. Pilot implementation of the design knowledge reuse system: Stage 2

The second stage of prototype development intends to overcome some of the limitations of the first. Planned features include an improved user interface, and Web-based distributed access.

5.8.1. Stage 2 system architecture

The second (Web based) prototype will provide the same basic functionality as the first (Excel based) prototype in terms of the process based design knowledge reuse system. That is, it enables design knowledge reuse through access to a process model that is linked to product knowledge through a formalised data model based on a product ontology, and task knowledge reuse through the provision of 'how-to' and contextual information. Figure 5.8-1 shows the planned architecture of the Web-based prototype system.

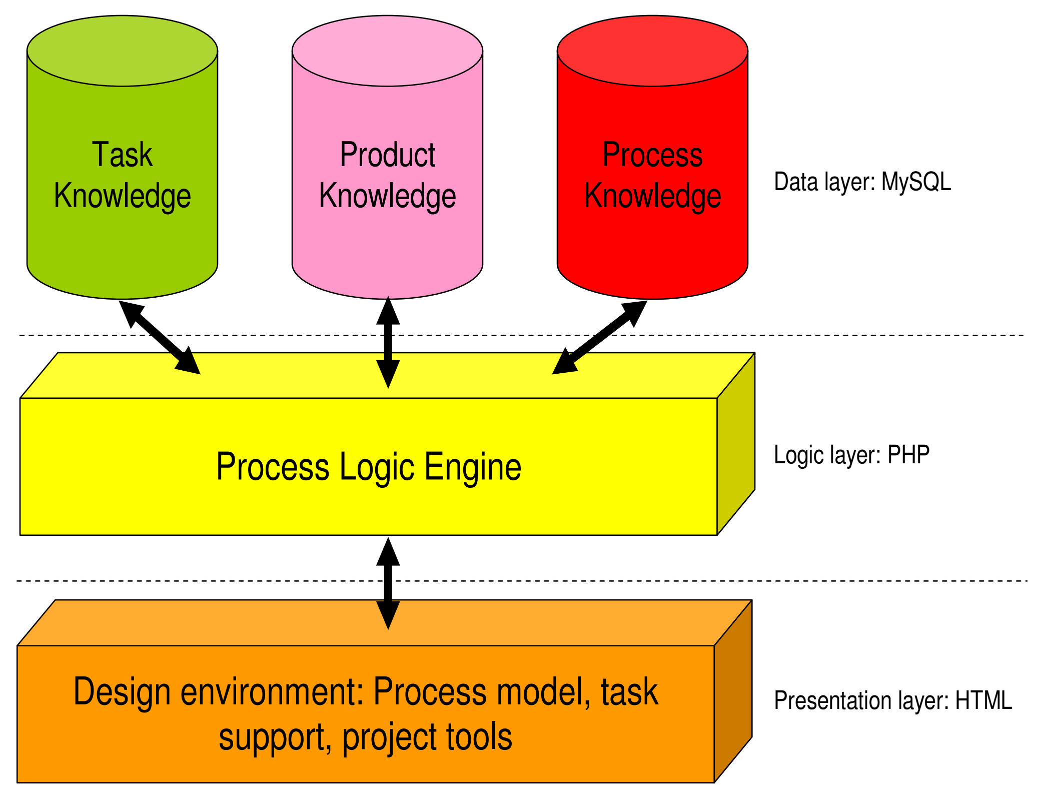


Figure 5.8-1: Proposed prototype 2 (web) system architecture

The system architecture applies a 3-tier model. The intention of this type of model is to separate the data, logic and presentation layers in order that changes can be made to one or more of the layers without requiring a fundamental change to the program. It is a standard model for database supported Web based systems. What the diagram shows is a set of three databases forming the data layer: task knowledge, product knowledge and process knowledge. The task knowledge database will include the 'how-to' textual descriptions, context descriptions and so on. The product knowledge database will be created based on the product ontology. This database will store all product data created during the project. The process knowledge database will store a representation of the design process, including tasks and their links. The logic layer performs all data operations required by the system, including retrieval of data from each database, storage of new data, and any calculations or operations required by the system. PHP provides the server interaction – performing the operations defined by the logic layer and sending the result to the presentation layer. The presentation layer provides a template for displaying the data, and provides the interface for the user. Web pages will be used for the presentation layer, combining HTML with PHP. HTML provides graphical markup of the system content.

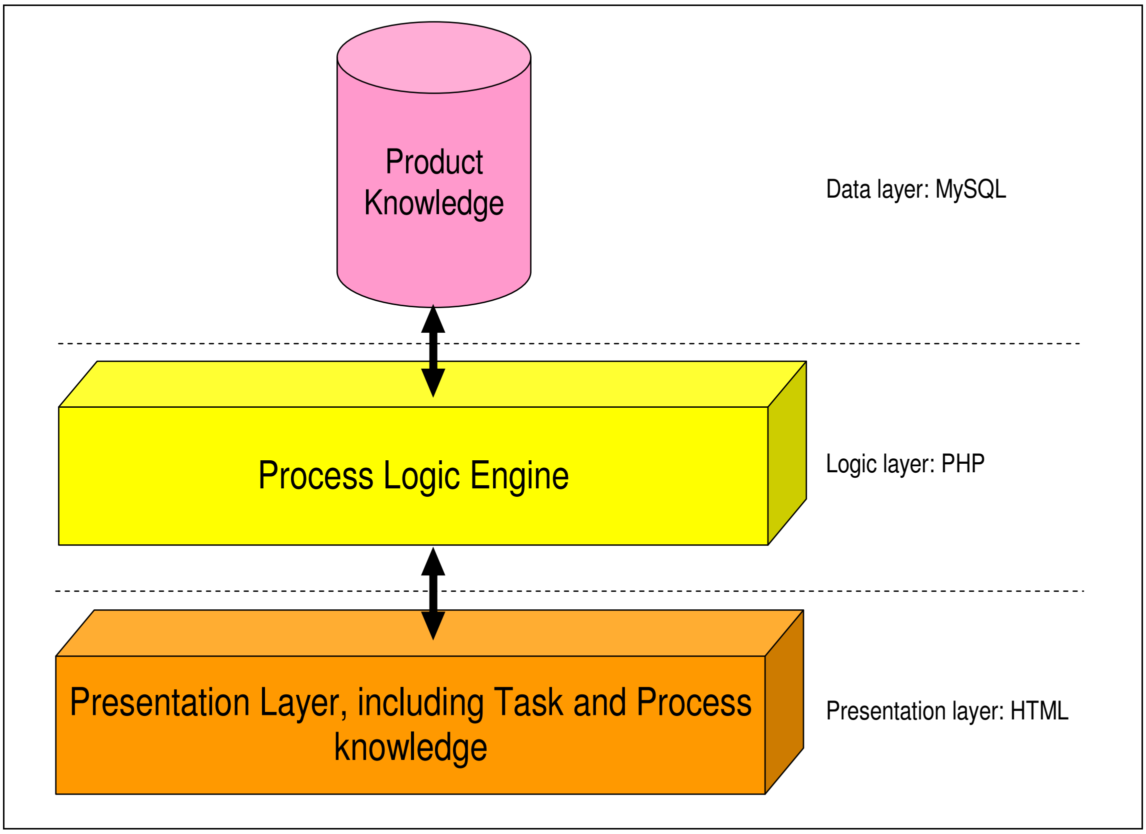


Figure 5.8-2: Implemented prototype 2 system architecture

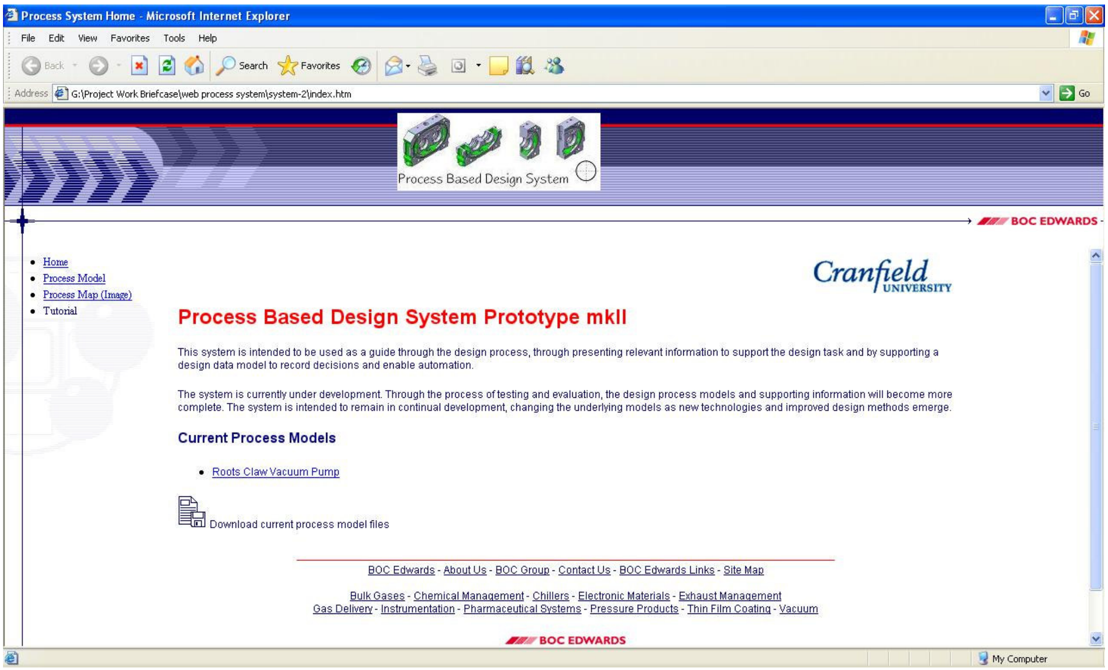
In order to reduce development effort, the implementation of the prototype will not be carried out according to the architecture shown in Figure 5.8-1. Neither process nor task knowledge will be stored in a separate database. Instead, they will be embedded in the presentation layer. The architecture as implemented is shown in Figure 5.8-2. For this small scale implementation, the aim was to reduce development effort. This would not be a suitable approach for a large scale implementation. The development scale system also makes it possible to maintain static task and process descriptions through creating individual web pages for each task. A full scale system implementation would store task descriptions and process sequence data in the database to enable a simple data entry and updating process. When using the system in an organisation, the effort required to add and update data would be significant due to the high volumes of data. The prototype system is not expected to require significant changes and updates, and the volume of data will be relatively low. As such, the ‘implemented architecture’ will be used as it requires less development effort.

For the Web prototype implementation, process knowledge is embedded in the system, through task pages which correspond to the tasks in the design process. The best practice task sequence, including precedence and iteration, is enabled by navigating through the system. The task pages also provide task knowledge. The task pages include a description of how the task should be carried out, and also provides access to related documents through the Web interface. Product knowledge is retrieved from the product database, and is provided on the task pages as data input. Data output is achieved through forms embedded in the task pages. These operations are supported by the system architecture in Figure 5.8-2. The 3-tier architecture shown in Figure 5.8-1 would be better suited to a large scale implementation. Since this prototype system will be limited to a relatively small number of tasks, embedding the task data and process data in the web pages (presentation layer) requires less development effort. For a larger scale implementation, a dynamic 3-tier method would be the better option, since time spent in development would be saved in updating and maintenance tasks.

5.8.2. Web enabled task page template

In order to provide a familiar user interface, the Web page layout that company A use for their Internet and Intranet pages was used for the design.

Figure 5.8-3 shows the homepage for the prototype system. The Web prototype system adopts the company Web page as a template. This was selected in order to provide a greater sense of familiarity with the page appearance and layout. The homepage is organised as a series of frames – the top frame shows a title bar, the left frame provides links to the home page and process model. The main frame provides links to the design knowledge reuse methods, organised by product type. In this case, there is one product type option, a roots-claw vacuum pump.



Process Based Design System Prototype mkII

This system is intended to be used as a guide through the design process, through presenting relevant information to support the design task and by supporting a design data model to record decisions and enable automation.

The system is currently under development. Through the process of testing and evaluation, the design process models and supporting information will become more complete. The system is intended to remain in continual development, changing the underlying models as new technologies and improved design methods emerge.

Current Process Models

- Roots Claw Vacuum Pump

Download current process model files

Figure 5.8-3: Web prototype system homepage

Other than the home page, the content of the remaining pages is defined according to a task page template. The top and left hand frames remain the same. The main frame contains the task page content. The general format of the template is as shown in Figure 5.8-4.

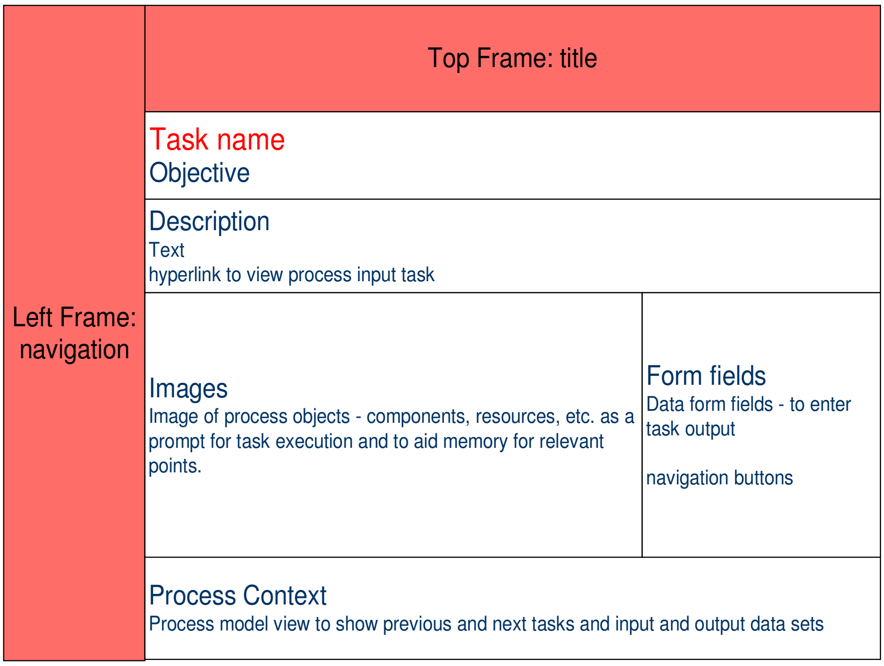


Figure 5.8-4: Web page template

The Web page template shown in Figure 5.8-4 is used for the layout of the Web pages. It also supports knowledge capture by showing the information and knowledge types required for each task. The top frame displays the title. The left frame is the navigation frame, providing links to the homepage and main process model. The central frame (the white area) is divided into several sections. Task name and objective are recorded on the top row. The task objective was identified during the knowledge capture phase as a question that is useful in understanding the tasks. A description of the task, including how to and any relevant context information, is recorded in the ‘description’ row. This section includes the ‘how-to’ description of the task. It is the intention to include a short description of around 4 lines and provide a link to the full text. This provides two functions. First, it forces the contributor to create a succinct description of how to carry out a task, which itself requires careful thought and analysis of the task. Second, the requirement for a short description limits the space requirement on the task page. Since this is a Web page, hyperlinks can be applied where necessary. This is especially useful for creating links to external documents, web pages or files that support the description of the task.

The ‘Images’ area is for any images relating to the process, which may be products, components, or resources. This serves to support the task description, as a prompt for task execution and to aid the memory. This element was added during the development of the Web based prototype system as a means to make the system look more professional, and to make the screen views interesting. It turned out that the addition of images was much more valuable than anticipated. An image of a previously used component shown to an engineer brings a whole range of discussion regarding the function, revisions, testing, materials, and relative success of the component and its features. As such, it serves to create an analytical mindset through prompting the user to recall key aspects of the component. The validation section will further discuss the comments made by the participants.

The right hand section ‘Form Fields’ is for the form in which data created by the task is entered. In the case of embedded methods, data applied by the method would be entered in this section. This cell also includes any navigation buttons to support the form (‘submit’ and ‘clear’).

The bottom row is for an image of the process model context, to show the previous task and next task in the sequence, as well as the data sets created and used by those tasks. The process objects in this area include hyperlinks to navigate directly to those tasks.

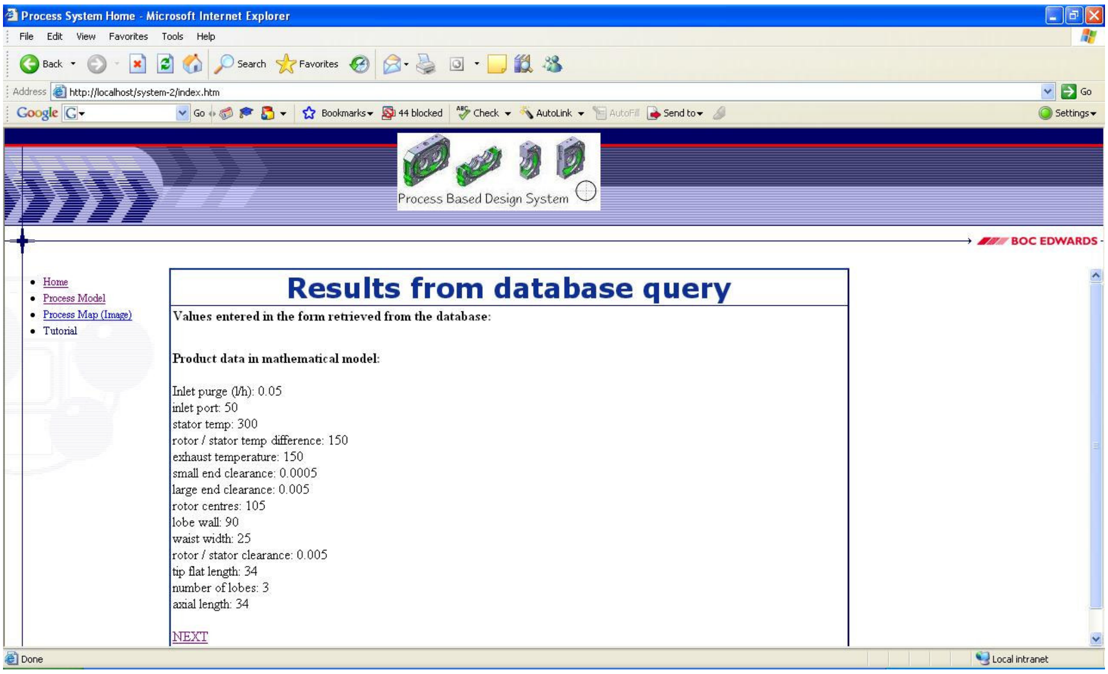
One missing element in this template compared to the Excel system is the data inputs. This was partly a technical limitation, and partly a space requirement. The user has access to a screen showing the data inputs, however for the prototype system the data inputs are not shown on the task page.

5.8.3. Web prototype database operations

The database system selected to store the product data was MySQL. The interface selected to access MySQL is PHP. The Apache Web server is also required. The EasyPHP application bundle combines MySQL server and apache Web server and provides a simple installation. DevPHP was used to write the PHP code. PHP is embedded in the Web pages, and provides and interface between the Web pages and the database, enabling dynamic Web pages. The database architecture as implemented is shown in Figure 5.8-2.

Each task has a data input. The MySQL database was created, using the product ontology as a guide. A table was created for each task page, and data fields were created for each data element. Within the Web page, the PhP script forms part of the html. Where html is essentially a layout formalism, PhP provides the capability to carry out database operations as part of the Web page loading procedure. This enables data to be retrieved from a database and displayed on the Web page.

When the user enters the data and clicks the ‘submit’ button, the system saves the data to the MySQL database. The next page is loaded, which contains PhP script (hypertext pre processor) specifying the retrieval of the data just stored and its display on the new page. For the mathematical modelling task, shown in Figure 8.3-2, the resulting data is shown in Figure 5.8-5. Initially, the page format was developed as a means to validate that the PhP and database operations were working, with a view to integrating the result into the task page. Space restrictions in the task page and a time restriction in the project led to the decision to keep the test page as the source of input data for the tasks. When a task page is displayed, the input data fields can be displayed by clicking the ‘view process input’ button.



Results from database query

Values entered in the form retrieved from the database:

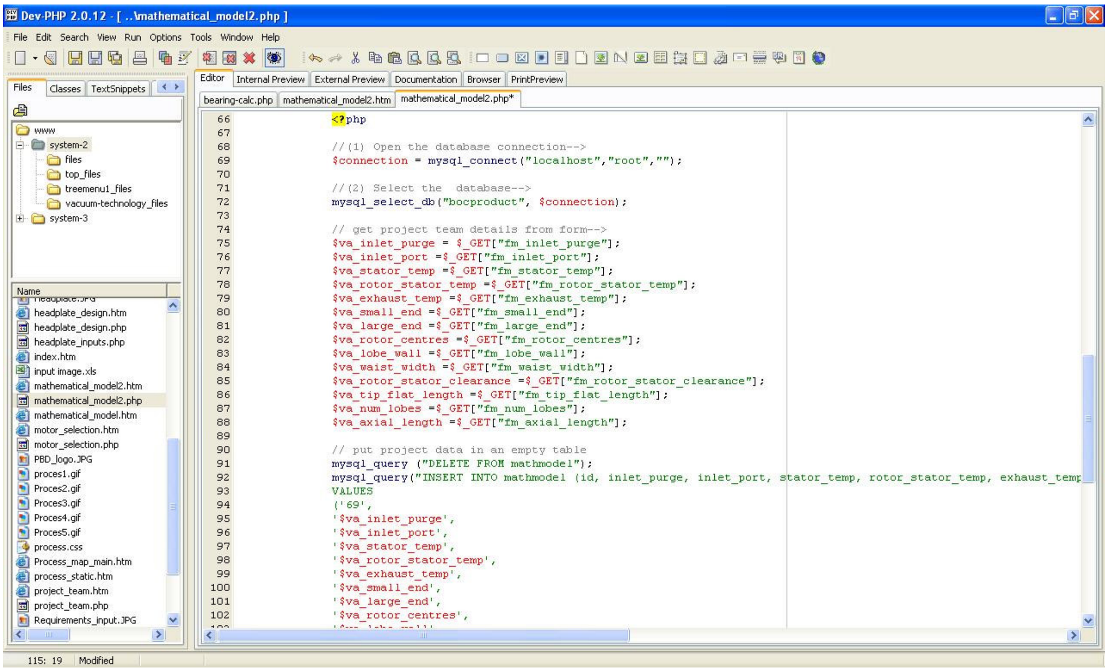
Product data in mathematical model:

Inlet purge (l/h): 0.05
inlet port: 50
stator temp: 300
rotor / stator temp difference: 150
exhaust temperature: 150
small end clearance: 0.0005
large end clearance: 0.005
rotor centres: 105
lobe wall: 90
waist width: 25
rotor / stator clearance: 0.005
tip flat length: 34
number of lobes: 3
axial length: 34

NEXT

Figure 5.8-5: Web prototype mathematical model task database query page

A screenshot from the application used to develop the PhP code for the database query page in Figure 5.8-5 is shown below in Figure 5.8-6.



```
<?php

//(1) Open the database connection-->
$connection = mysql_connect("localhost","root","");

//(2) Select the  database-->
mysql_select_db("bocproduct", $connection);

// get project team details from form-->
$va_inlet_purge = $_GET["fm_inlet_purge"];
$va_inlet_port =$_GET["fm_inlet_port"];
$va_stator_temp =$_GET["fm_stator_temp"];
$va_rotor_stator_temp =$_GET["fm_rotor_stator_temp"];
$va_exhaust_temp =$_GET["fm_exhaust_temp"];
$va_small_end =$_GET["fm_small_end"];
$va_large_end =$_GET["fm_large_end"];
$va_rotor_centres =$_GET["fm_rotor_centres"];
$va_lobe_wall =$_GET["fm_lobe_wall"];
$va_waist_width =$_GET["fm_waist_width"];
$va_rotor_stator_clearance =$_GET["fm_rotor_stator_clearance"];
$va_tip_flat_length =$_GET["fm_tip_flat_length"];
$va_num_lobes =$_GET["fm_num_lobes"];
$va_axial_length =$_GET["fm_axial_length"];

// put project data in an empty table
mysql_query ("DELETE FROM mathmodel");
mysql_query("INSERT INTO mathmodel (id, inlet_purge, inlet_port, stator_temp, rotor_stator_temp, exhaust_temp
VALUES
('69',
'$va_inlet_purge',
'$va_inlet_port',
'$va_stator_temp',
'$va_rotor_stator_temp',
'$va_exhaust_temp',
'$va_small_end',
'$va_large_end',
'$va_rotor_centres',
```

Figure 5.8-6: screenshot from Dev-PHP mathematic model database query task

The screenshot in Figure 5.8-6 shows the application used to develop the PhP script that stores and retrieves the product data in the MySQL database. The PhP script for that page is shown below (the complete PhP script is shown in the appendix):

```
<?php
//(1) Open the database connection-->
$connection = mysql_connect("localhost","root","");
//(2) Select the  database-->
mysql_select_db("bocproduct", $connection);

// get project team details from form-->
$va_inlet_purge = $_GET["fm_inlet_purge"];
$va_inlet_port =$_GET["fm_inlet_port"];
$va_stator_temp =$_GET["fm_stator_temp"];
$va_rotor_stator_temp =$_GET["fm_rotor_stator_temp"];
$va_exhaust_temp =$_GET["fm_exhaust_temp"];
$va_small_end =$_GET["fm_small_end"];
$va_large_end =$_GET["fm_large_end"];
$va_rotor_centres =$_GET["fm_rotor_centres"];
$va_lobe_wall =$_GET["fm_lobe_wall"];
$va_waist_width =$_GET["fm_waist_width"];
$va_rotor_stator_clearance =$_GET["fm_rotor_stator_clearance"];
$va_tip_flat_length =$_GET["fm_tip_flat_length"];
$va_num_lobes =$_GET["fm_num_lobes"];
$va_axial_length =$_GET["fm_axial_length"];

// put project data in an empty table
mysql_query ("DELETE FROM mathmodel");
mysql_query("INSERT INTO mathmodel
(id, inlet_purge, inlet_port, stator_temp, rotor_stator_temp,
exhaust_temp, small_end, large_end, rotor_centres, lobe_wall,
waist_width, rotor_stator_clearance, tip_flat_length,
num_lobes, axial_length)

VALUES
```

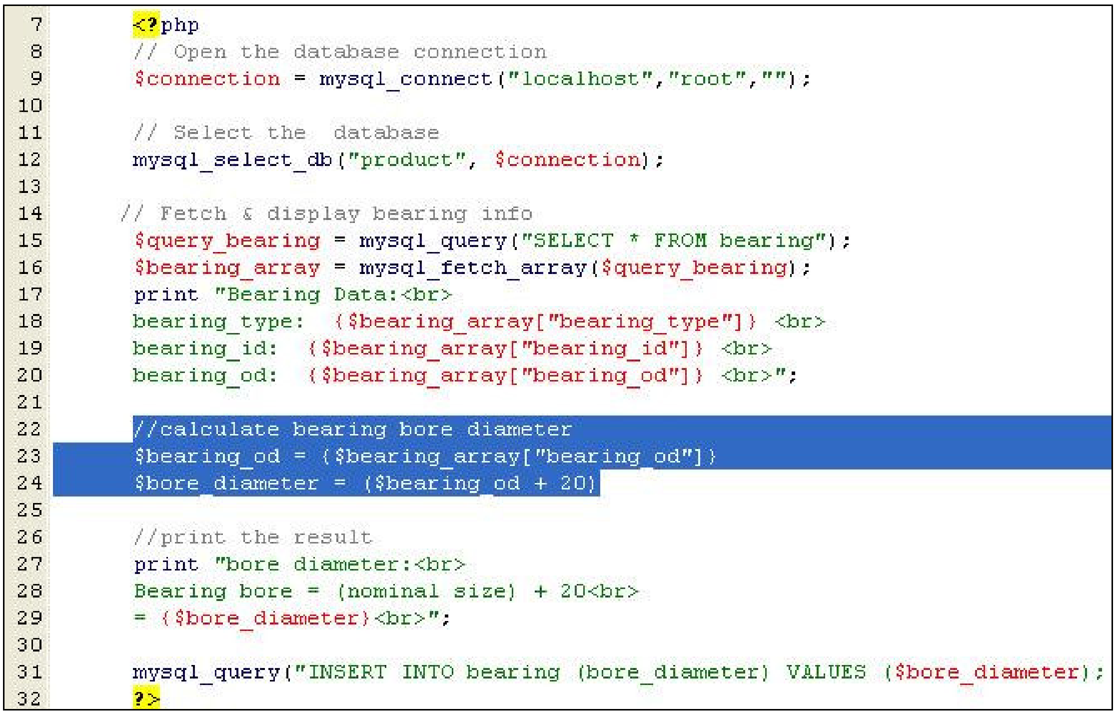
```
('69',
'$va_inlet_purge',
'$va_inlet_port',
'$va_stator_temp',
'$va_rotor_stator_temp',
'$va_small_end',
'$va_large_end',
'$va_rotor_centres',
'$va_lobe_wall',
'$va_waist_width',
'$va_rotor_stator_clearance',
'$va_tip_flat_length',
'$va_num_lobes',
'$va_axial_length')");

// print the result from the database
$query_math = mysql_query("SELECT * FROM mathmodel");
$math_array = mysql_fetch_array($query_math);

print "<b>Product data in mathematical model: </b><br><br>
Inlet purge (l/h):  {$math_array["inlet_purge"]} <br>
inlet port: {$math_array["inlet_port"]} <br>
stator temp: {$math_array["stator_temp"]} <br>
rotor / stator temp difference: {$math_array["rotor_stator_temp"]} <br>
exhaust temperature: {$math_array["exhaust_temp"]}<br>
small end clearance: {$math_array["small_end"]}<br>
large end clearance: {$math_array["large_end"]}<br>
rotor centres: {$math_array["rotor_centres"]}<br>
lobe wall: {$math_array["lobe_wall"]}<br>
waist width: {$math_array["waist_width"]}<br>
rotor / stator clearance: {$math_array["rotor_stator_clearance"]}<br>
tip flat length: {$math_array["tip_flat_length"]}<br>
number of lobes: {$math_array["num_lobes"]}<br>
axial length: {$math_array["axial_length"]}<br><br>" ;
?>
```

5.8.4. Support for automation and KBE

The system can support design automation and KBE methods through embedding the required logic in the system. A simple example will be shown to demonstrate that the proposed method has the capability to support more advanced calculations and analysis with further development effort. A product parameter (bearing OD) entered on the bearing design task (shown in Figure 8.3-11) has been retrieved from the database. The calculation assumes that the bearing bore should be 20 microns larger than the bearing OD. The highlighted text in Figure 5.8-7 makes this calculation ($bearing_od + 20) then saves the result in the database. More complex calculations can be made using the same method.



```
 <?php
 // Open the database connection
 $connection = mysql_connect("localhost","root","");

 // Select the  database
 mysql_select_db("product", $connection);

// Fetch & display bearing info
 $query_bearing = mysql_query("SELECT * FROM bearing");
 $bearing_array = mysql_fetch_array($query_bearing);
 print "Bearing Data:<br>
 bearing_type:  {$bearing_array["bearing_type"]} <br>
 bearing_id:  {$bearing_array["bearing_id"]} <br>
 bearing_od:  {$bearing_array["bearing_od"]} <br>";

 //calculate bearing bore diameter
 $bearing_od = {$bearing_array["bearing_od"]}
 $bore_diameter = ($bearing_od + 20)

 //print the result
 print "bore diameter:<br>
 Bearing bore = (nominal size) + 20<br>
 = {$bore_diameter}<br>";

 mysql_query("INSERT INTO bearing (bore_diameter) VALUES ($bore_diameter);
 ?>
```

Figure 5.8-7: php code representing product data calculations

The effort required to embed knowledge based support and automation is high. The degree of effort required for capture does not always correspond to the value of that knowledge. The value of the knowledge is also difficult to define. As such, the conflict between need and difficulty in justifying the effort in commercial terms may result in knowledge based support efforts being abandoned.

5.9. Novel principles embodied in the developed system

The developed system aims to meet the research gaps identified as well as the industrial gaps.

Design reuse for the whole product life cycle was identified as a research gap. The method supports design reuse for the whole product life cycle through enabling design reuse at the conceptual level: a design task can be described at any level, relating to a rage of product parameters that is not limited to a geometrical description of a product. For example, the description of a task to produce a functional specification would be possible using the proposed method. Since the method also supports geometrical design parameters, it is also suitable for supporting design analysis and detailed design.

Integrated product and process models were found to be lacking in the literature. The proposed method supports a process representation that is integrated with product data.

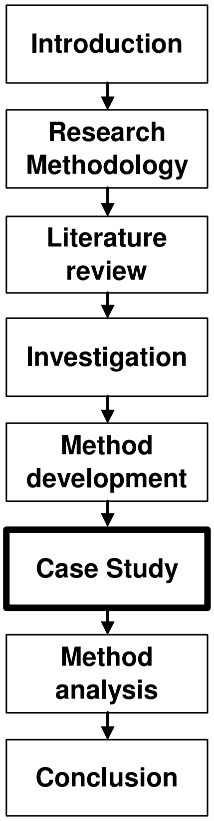
Finally, a ‘how-to’ element was found to be lacking in design process support methods. The proposed method supports task execution with a description and images. The task description also supports links to additional knowledge sources and links to relevant personnel.

In terms of addressing the industrial needs, there were three key areas: reuse context, the relationship between design reuse and the development process, and the integration of engineering and business objectives. First, the description of a design process specific to the company enables knowledge provision to be given when the task is being carried out. This ensures that design knowledge is provided in the right context. This same feature of the method identifies and supports the relationship between design reuse and the design process by showing when knowledge should be reused. Engineering objectives are often given priority. This proposed system, by supporting parameters outside of geometry, can integrate commercially driven design output requirements with engineering driven parameters. In addition, the application of ontology in product modelling promotes shared understanding of the design models and concepts.

5.10. Summary

This chapter has described the requirements for and proposed a solution to a design reuse system. A combination of process, task and product knowledge is captured and represented in a system, using the design process as a central element. Process knowledge describes the sequence of tasks. Task knowledge describes how to do each task. Product knowledge describes the inputs to the tasks: requirements, specifications, and existing layout. Product knowledge also defines the task output – the element of the product that is being created or updated by the task; the resulting data. This engineering layer built into the process model enables a data driven process. ‘Data driven’ refers to the task being carried out with the relevant product data: the data forms and integral part of the task and process. This integrated approach will support design knowledge reuse.

Chapter 6: Case study



This chapter will describe a case study in which the design knowledge reuse methodology is tested. Two prototype systems will be tested: first, a system based on Microsoft Excel, as described in the previous chapter. Second, a Web based system with database support. An analysis of the *system* is carried out. The following chapter describes the validation of the underlying *method*.

6.1. Case study development

The purpose of the case study is to carry out a test of the process based design knowledge reuse framework in order that it may be evaluated. This will be achieved by capturing knowledge from the case study company and representing that knowledge within the pilot system. An evaluation of the pilot system will then be carried out to assess the process based design knowledge reuse framework.

The case study will be carried out within the product development department of company A at their technical site. The products developed at that site are vacuum pumps for the semiconductor market.

The subject for knowledge capture is a component of the vacuum pump: the headplate. This was decided upon in a group discussion with representatives from the company. The headplate was selected as it is sufficiently complex to warrant an investigation, and it is critical to several of the product functions. It is also, as a single component, of sufficiently narrow scope to enable a detailed investigation within the time constraints of the project.

Key stakeholders for the design knowledge capture include engineers, technical specialists, and designers. These are the roles responsible for defining the headplate within a product development project.

6.2. Case study research methods

The case study approach will apply interviews and observation as primary data collection methods, with company documents as secondary sources.

Following the assumptions of critical theory, it is assumed that *objective* observation is not possible due to observer bias. Knowledge is created in an active sense, whilst being embedded in a rich context. Understanding of experience is derived from interpretation. Meaning is negotiated, and embedded assumptions are crucial in this process.

The research approach is qualitative and flexible. Threats to validity are to be mitigated through triangulation, audit and member checking. Initial interviews will guide the selection of subsequent research activities. This results in a model that, generally speaking, follows an iterative format: interview → checking → development → interview and so on.

A series of knowledge capture sessions will take place. The introductory sessions will be approximately 2 hours long. The purpose of these interviews is to better understand the design of the selected component. Discussion will be based around a process model, developed during the earlier research phases.

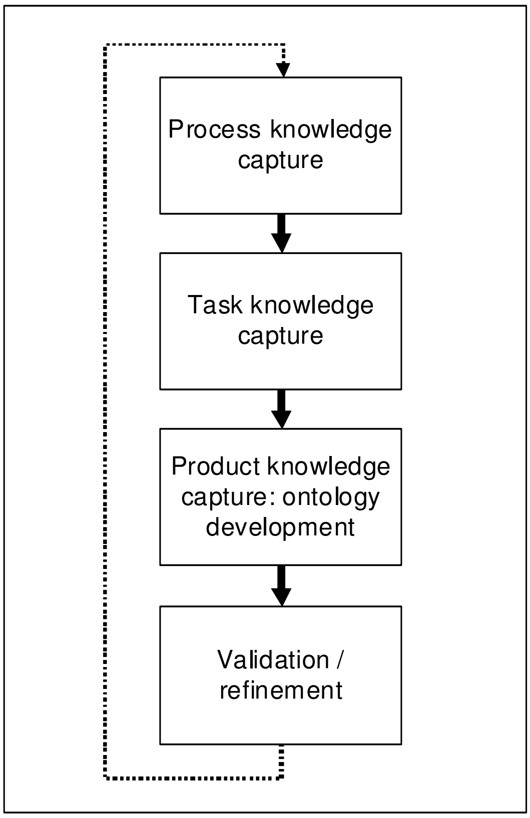


Figure 6.2-1: Design knowledge capture process

Subsequent sessions will be planned based on the identified need. It is expected that the create / validate / update cycle will take place several times. The general outline is shown in Figure 6.2-1. Once the process model has been captured, task knowledge will be added. For capturing task knowledge, the process model will form the basis of the interviews, and the participants will be asked to describe the tasks in a 'how-to' sense. Additional information sources to support the task will also be captured at this time. The product model will then be created in the same create / validate / update fashion. Terms will initially be applied from the other knowledge capture stages, and used to create a draft product model. This model will then be validated and updated through interviews. Notes will be taken during the knowledge capture sessions, including comments made by participants, process diagrams, and observations. In some cases, printed versions of process models, task models or product models will be annotated or edited during the session.

Once a complete version of the prototype system has been built, a workshop will be held to validate the combined content and also to comment on the prototype system. Changes will be made to the prototype system based on the result of the workshop. The final sessions will then be validation sessions: judging the perceived value of the process based design knowledge reuse framework based on the partially populated prototype system.

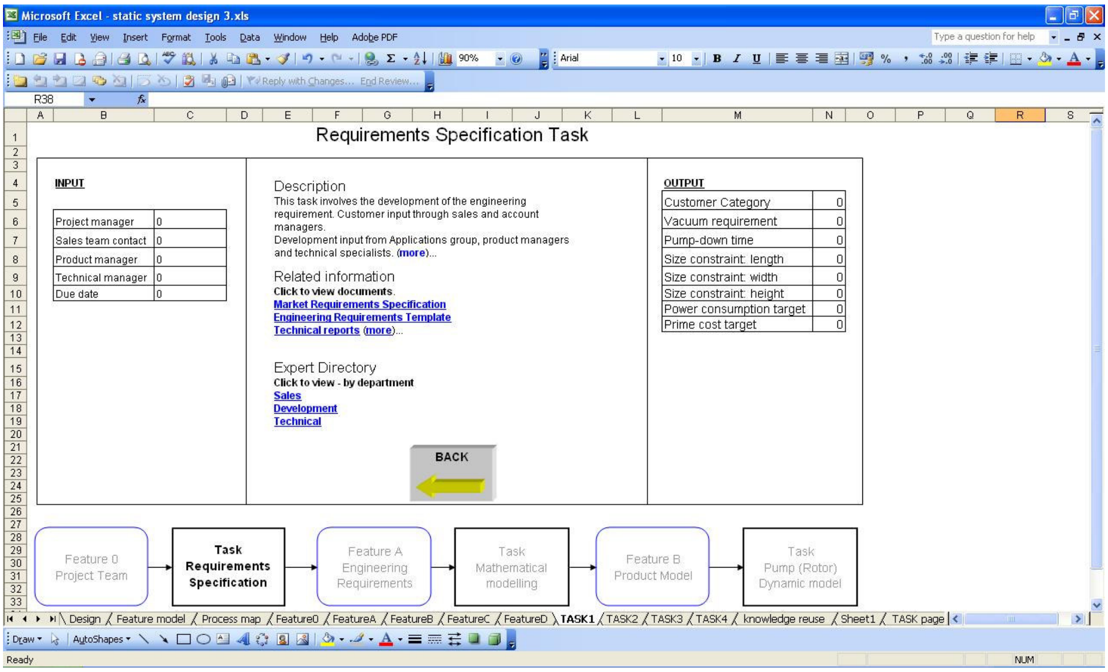
A key element of design process knowledge capture is model building. Design processes will be described using models. The models will be a key element of the communication and validation process.

6.3. Stage 1 prototype system: content and walkthrough

This section will show the content of the Excel prototype system developed in stage 1. The main process model has been shown in Figure 5.7-3, and the screenshot of the process page as implemented in the system is shown in Figure 5.7-2. The first four task pages will now be shown. The task pages include the data inputs and outputs, so the product model is effectively shown alongside the task pages.

The task pages show the data input and output fields. In the screenshots no data has been entered so each data field reads ‘0’.

The first page the user is shown is the process model, as shown in Figure 5.7-2. Assuming no tasks have been carried out previously, the first task to be performed is the requirements specification task, as shown in Figure 6.3-1. In advance of this task, the key members of the project team must be defined, including the project manager. The output from this task is a specification of the engineering requirement for the vacuum pump, including the major functional parameters as well as a cost target. The supporting documentation is critical to this task, particularly the marketing requirements specification. This defines the general customer requirement, potential market, and key product characteristics. Once the task has been completed and the requirements data has been entered in the form, the user navigates back to the main page by clicking the ‘back’ button, or they may navigate directly to the next task through the process objects on the bottom of the page.



Requirements Specification Task

INPUT

Project manager	0
Sales team contact	0
Product manager	0
Technical manager	0
Due date	0

Description

This task involves the development of the engineering requirement. Customer input through sales and account managers.

Development input from Applications group, product managers and technical specialists. (**more**)...

Related information

Click to view documents.

Market Requirements Specification

Engineering Requirements Template

Technical reports (**more**)...

Expert Directory

Click to view - by department

Sales

Development

Technical

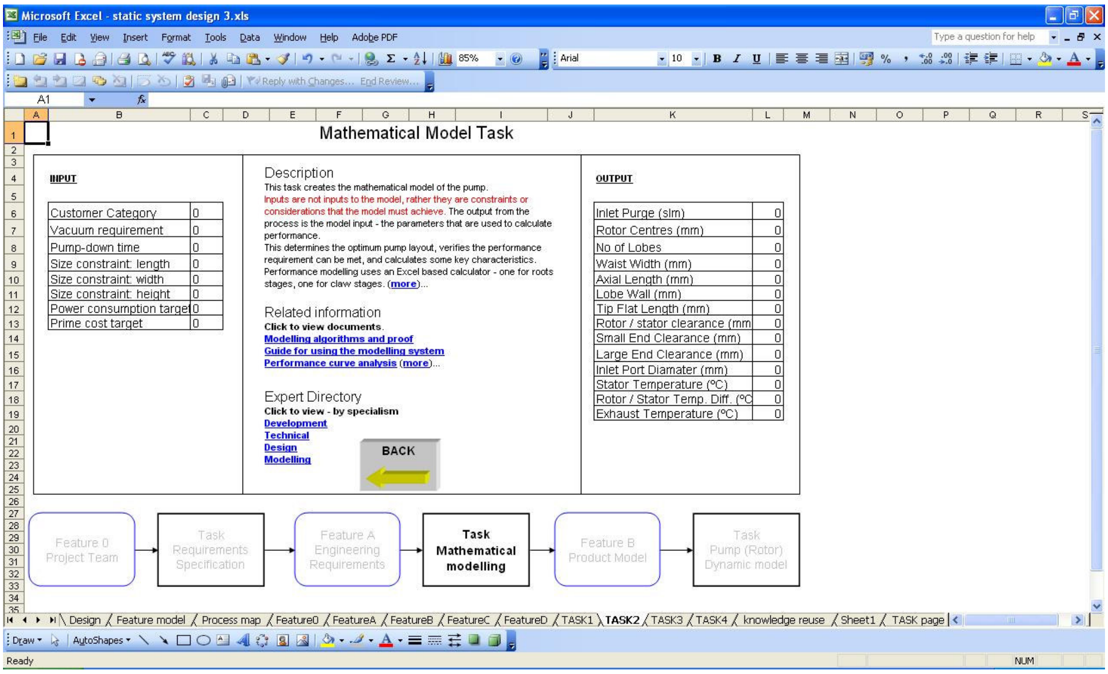
OUTPUT

Customer Category	0
Vacuum requirement	0
Pump-down time	0
Size constraint: length	0
Size constraint: width	0
Size constraint: height	0
Power consumption target	0
Prime cost target	0

Figure 6.3-1: screenshot of requirements specification task in Excel prototype

The second task, mathematical modelling, is shown in Figure 6.3-2. This task sets the principal performance related parameters of the vacuum pump, including stator dimensions and rotor / stator clearances. A working knowledge of the modelling system is necessary, alongside a range of additional inputs, including manufacturing capability data. The performance modelling task uses an Excel based calculator, which could in principle be linked to the design knowledge reuse system. The high sensitivity of the data in the performance modelling system prevented this from taking place. When the mathematical modelling task has been carried out, the user navigates to the next task.

The dynamic modelling task (Figure 6.3-3) takes the inputs from the previous tasks that define the key dimensions of the rotating parts of the pump in order to calculate the resonant frequency. The result must not be an exact multiple of the target running speed. This task brings together the engineering specification and performance model to verify that the proposed model does not operate at resonant frequency and vibrate excessively. How-to information and links to additional sources are available to the user. The user inputs the result and navigates to the next task. This is a good example of a task in which iteration is likely to take place. If the resulting dynamic resonance is an exact multiple of running speed, then some component of the pump design must change. In carrying out the tasks from specification to mathematical modelling to dynamic modelling, the results of this loop would be valuable in assessing the design history to better understand the relationships between the variables. This is a limitation of this prototype system: design history is not automatically saved.



Mathematical Model Task

INPUT

Customer Category	0
Vacuum requirement	0
Pump-down time	0
Size constraint: length	0
Size constraint: width	0
Size constraint: height	0
Power consumption target	0
Prime cost target	0

Description

This task creates the mathematical model of the pump.
Inputs are not inputs to the model, rather they are constraints or considerations that the model must achieve. The output from the process is the model input - the parameters that are used to calculate performance.
This determines the optimum pump layout, verifies the performance requirement can be met, and calculates some key characteristics.
Performance modelling uses an Excel based calculator - one for roots stages, one for claw stages. (more)...

Related information

Click to view documents.
Modelling algorithms and proof
Guide for using the modelling system
Performance curve analysis (more)...

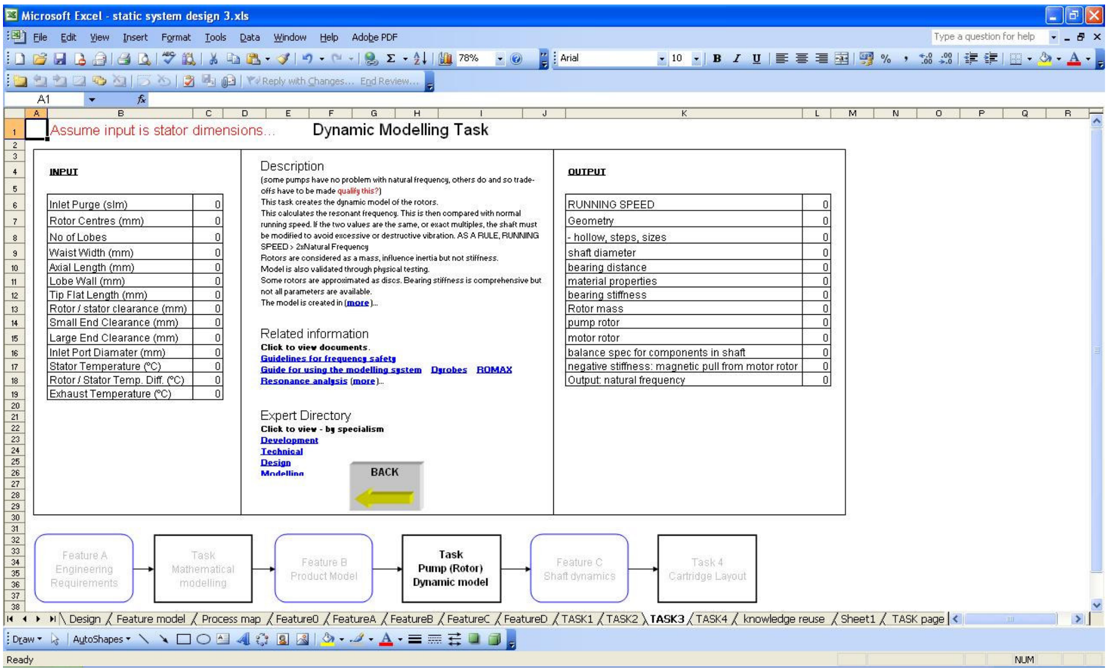
Expert Directory

Click to view - by specialism
Development
Technical
Design
Modelling

OUTPUT

Inlet Purge (slm)	0
Rotor Centres (mm)	0
No of Lobes	0
Waist Width (mm)	0
Axial Length (mm)	0
Lobe Wall (mm)	0
Tip Flat Length (mm)	0
Rotor / stator clearance (mm	0
Small End Clearance (mm)	0
Large End Clearance (mm)	0
Inlet Port Diamater (mm)	0
Stator Temperature (ºC)	0
Rotor / Stator Temp. Diff. (ºC	0
Exhaust Temperature (ºC)	0

Figure 6.3-2: screenshot of mathematical modelling task in Excel prototype



Assume input is stator dimensions...

Dynamic Modelling Task

INPUT

Inlet Purge (slm)	0
Rotor Centres (mm)	0
No of Lobes	0
Waist Width (mm)	0
Axial Length (mm)	0
Lobe Wall (mm)	0
Tip Flat Length (mm)	0
Rotor / stator clearance (mm)	0
Small End Clearance (mm)	0
Large End Clearance (mm)	0
Inlet Port Diamater (mm)	0
Stator Temperature (ºC)	0
Rotor / Stator Temp. Diff. (ºC)	0
Exhaust Temperature (ºC)	0

Description

(some pumps have no problem with natural frequency, others do and so trade-offs have to be made qualify this?)
This task creates the dynamic model of the rotors.
This calculates the resonant frequency. This is then compared with normal running speed. If the two values are the same, or exact multiples, the shaft must be modified to avoid excessive or destructive vibration. AS A RULE, RUNNING SPEED > 2xNatural Frequency
Rotors are considered as a mass, influence inertia but not stiffness.
Model is also validated through physical testing.
Some rotors are approximated as discs. Bearing stiffness is comprehensive but not all parameters are available.
The model is created in (more)...

Related information

Click to view documents.
Guidelines for frequency safety
Guide for using the modelling system Dyrobes ROMAX
Resonance analysis (more)...

Expert Directory

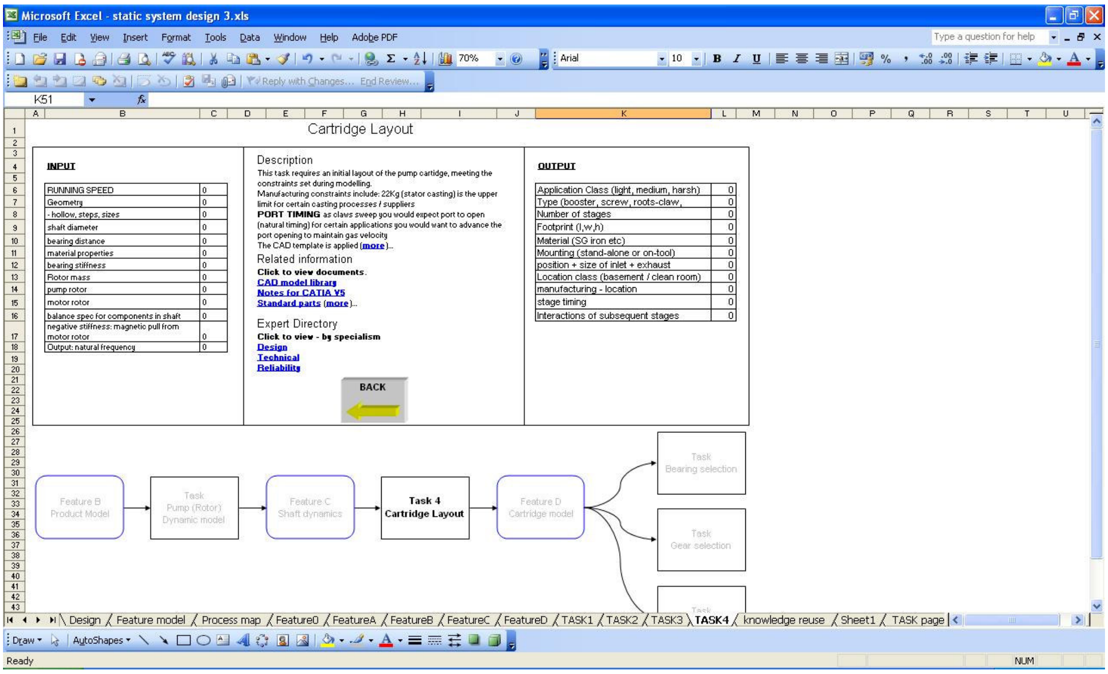
Click to view - by specialism
Development
Technical
Design
Modelling

OUTPUT

RUNNING SPEED	0
Geometry	0
- hollow, steps, sizes	0
shaft diameter	0
bearing distance	0
material properties	0
bearing stiffness	0
Rotor mass	0
pump rotor	0
motor rotor	0
balance spec for components in shaft	0
negative stiffness: magnetic pull from motor rotor	0
Output: natural frequency	0

Figure 6.3-3: screenshot of dynamic modelling task in Excel prototype

The next task, cartridge layout, is shown in Figure 6.3-4. This task specifies the major parameters of the pump cartridge, which is the mechanical system that produces the pumping performance. This task is essential to the development of the supporting systems of the product, including the casing, electronics, gas systems, exhaust and inlet manifolds, motor, power and cooling. The user enters the data and navigates to the next task. In this case, there are three tasks that can be carried out concurrently: bearing, gear and motor specification. These tasks will be described in the Web prototype section.



Cartridge Layout

INPUT

RUNNING SPEED	0
Geometry	0
- hollow, steps, sizes	0
shaft diameter	0
bearing distance	0
material properties	0
bearing stiffness	0
Rotor mass	0
pump rotor	0
motor rotor	0
balance spec for components in shaft	0
negative stiffness: magnetic pull from motor rotor	0
Output: natural frequency	0

Description

This task requires an initial layout of the pump cartidge, meeting the constraints set during modelling.
Manufacturing constraints include: 22Kg (stator casting) is the upper limit for certain casting processes / suppliers
PORT TIMING as claws sweep you would expect port to open (natural timing) for certain applications you would want to advance the port opening to maintain gas velocity
The CAD template is applied (**more**)...

Related information

Click to view documents.
CAD model library
Notes for CATIA V5
Standard parts (**more**)...

Expert Directory

Click to view - by specialism
Design
Technical
Reliability

BACK

OUTPUT

Application Class (light, medium, harsh)	0
Type (booster, screw, roots-claw,	0
Number of stages	0
Footprint (l,w,h)	0
Material (SG iron etc)	0
Mounting (stand-alone or on-tool)	0
position + size of inlet + exhaust	0
Location class (basement / clean room)	0
manufacturing - location	0
stage timing	0
Interactions of subsequent stages	0

Figure 6.3-4: screenshot of cartridge layout task in Excel prototype

6.3.1. Analysis of the stage 1 system

In this section the first prototype of the process based design knowledge reuse system has been described. The design process has been represented using a modelling formalism adapted from the Design Roadmap method (Park & Cutkosky 1999). A product data model was applied to the process, based on a product ontology developed with the participating organisation. The prototype system aims to assist design collaboration through providing a common view of the design knowledge. The common view is achieved through the application of the design process in combination with a product ontology. The process model shows where and how each product data element is produced. Task knowledge capture and representation is supported by the development of a task template.

6.3.2. Assessment with designers

The method was assessed through interviews with designers. The interviews were unstructured, and involved a walkthrough of the system with discussion over each aspect. Notes were taken, and they are summarised here. The participants had been involved with the development of the process based design knowledge reuse system.

One concern was that the knowledge capture process would take a long time in order to develop a system with sufficient content to become useful. This is a major issue that will be addressed in more detail in the next chapter. Another concern was the validity of the data stored: who created it, and when. Another concern was that the system exists outside the normal working environment and tools of the design team. It is not integrated with a CAD system, and does not integrate with any of the existing knowledge based engineering methods.

Summary of concerns:

- Data validity: who created it;
- Population of the system – knowledge capture effort;
- System is outside the normal working environment of the design team;
- Not integrated with CAD system or KBE systems.

It is considered that developing a tool that exists outside of the normal working environment of the engineers is a necessity for a research project of this type with limited time available for application development.

6.3.3. Technical limitations

At this stage of development, there are a number of technical limitations that are apparent, i.e.

- Static nature of the system (it does not react to user input)
    - No customised features for different users;
    - No recognition of project state (what task to do now);

  - No notification of change effects (the data that this task relies upon has been changed).

- Limited, basic user interface;

- Access control very limited – limit access to all or none (whole system), not specific parts;

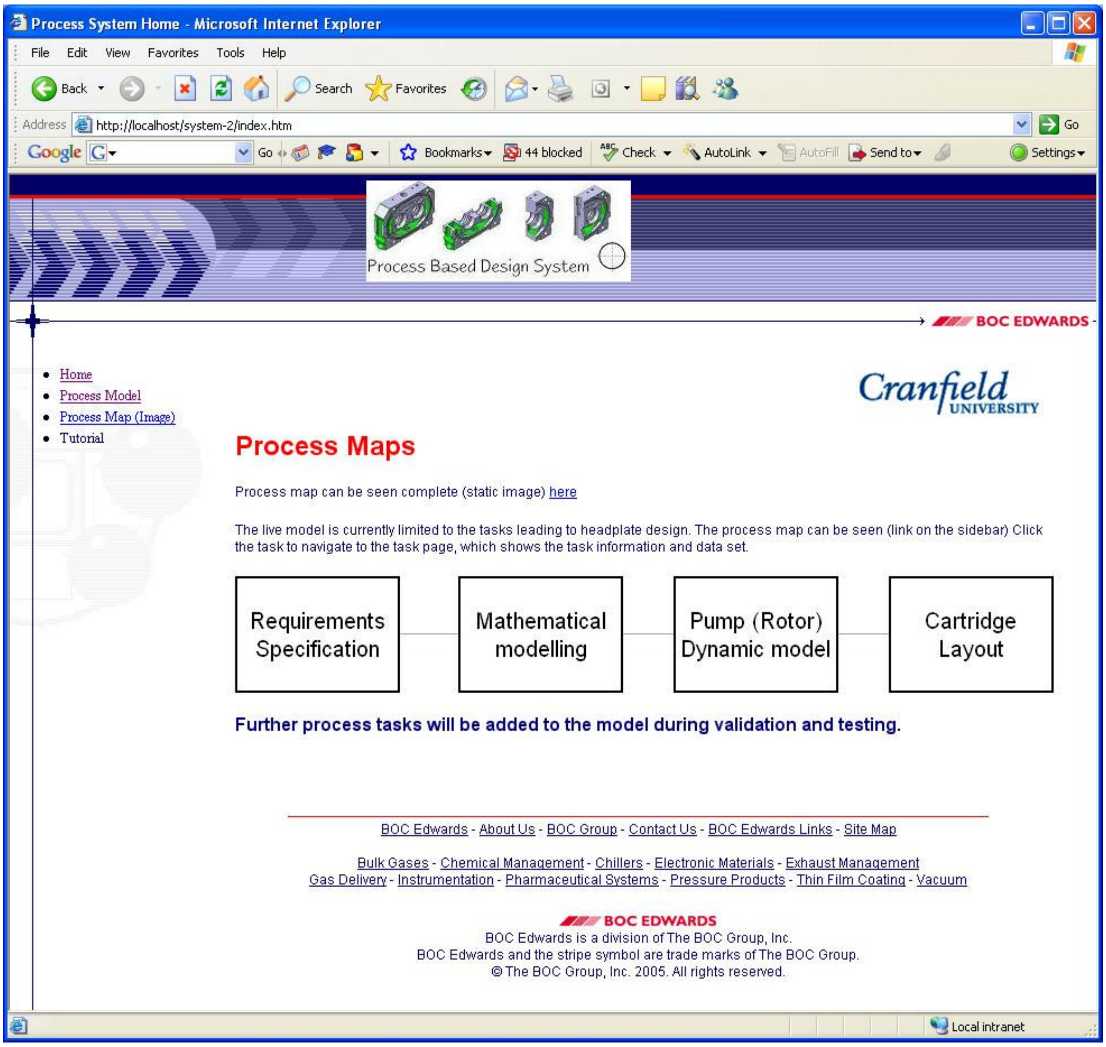
- Distributed collaboration is not supported – only one person can use the system at any time.

The second prototype will aim to demonstrate the potential for distributed collaboration, through access to the system and knowledge through the Internet. Access control methods are well understood in Web based applications. Web based methods also provide a range of capabilities to improve the user interface.

6.4. Stage 2: Web prototype system development

The Web prototype system is an implementation of the process based design knowledge reuse system developed using technology that enables it to be accessed through the Internet and displayed in a Web browser. The basic content of the Web based system is the same as the Excel system. Additional features provided by the Web based method includes a database to store and retrieve the product data, and an improved user interface.

The initial view of the Web prototype system is the homepage, shown in Figure 5.8-3. From the homepage, the user selects the process model, in this case ‘roots claw vacuum pump’. The process page is shown in Figure 6.4-1. From this page, the user may select the task they wish to navigate to. Let us assume they select the mathematical modelling task, as shown in Figure 8.3-2 (all figures with the prefix 8 are in Appendix 2:). The user is informed that the objective of the task is to ‘create a mathematical model to identify validate optimum design parameters’. The task pages in the Web based prototype tend to be larger than a single screen. Figure 8.3-3 shows the second part of the mathematical modelling task and Figure 8.3-4 shows the final part of the task page.



Process Maps

Process map can be seen complete (static image) here

The live model is currently limited to the tasks leading to headplate design. The process map can be seen (link on the sidebar) Click the task to navigate to the task page, which shows the task information and data set.

Further process tasks will be added to the model during validation and testing.

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Figure 6.4-1: Web prototype system page 1 - process model

Following the mathematical modelling task, the user navigates to the next page by clicking the ‘submit’ button. The process context shows that the task output is the data set ‘Feature B, product model’. The operations to store and display the product model data are is described in the next section.

Having navigated to the dynamic modelling task, the user is provided with the template data: task name, objective and so on. The first part of the task page is shown in Figure 8.3-5, and the second part in Figure 8.3-6. The supporting images show a basic model of the pump and the areas which the dynamic model applies as inputs. Guidelines for the analysis system are provided via hyperlinks, and a link is also provided to a description of resonance analysis principles. The link to the extended task description provides the potential to include previous results and graphs, and to describe instances of tests that had to be retried due to resonance, along with a description of the measures taken to change the natural frequency of the pump. It is in this extended task description that links could be provided to additional sources of knowledge, including previous project files.

The cartridge layout task is shown in Figure 8.3-7 and the lower part of the page in Figure 8.3-8. This task defines the overall dimensions of the cartridge, to enable the development of constituent and interfacing components. The task is apparently relatively simple, however the reliance of downstream design operations and the pressure to begin specifying and ordering components for a test product mean that the specification must be carefully considered and reviewed. A basic image was applied to the page for simplicity, however a CAD generated 3D image of a previous cartridge would be preferable to support the engineering thought process and prompt the user to investigate known issues in the new design.

The gear (Figure 8.3-9, Figure 8.3-10) and bearing (Figure 8.3-11, Figure 8.3-12) selection tasks apply the inputs from the cartridge layout task. Previous project data would support the selection of the gears and bearings, particularly reliability and service data. This can be provided alongside the task description. In some cases, the product strategy will support the selection of one type over another. For example, a low cost pump in a light duty environment is likely to specify standard bearing type, whereas a harsh duty pump may require a ceramic bearing to withstand the additional temperature load.

The specification of the motor (Figure 8.3-13, Figure 8.3-14) includes the motor rating and cooling method. A water cooled motor requires a water system, which has to be specified in a future design task. The motor power requirement is a result of a combination of system elements that are developed concurrently, so the task may be carried out a number of times in order to produce an optimum result.

The headplate design task is shown in Figure 8.3-15 and Figure 8.3-16. This is the component that was originally specified as the target for knowledge capture. The remainder of the process has been providing the inputs to support the design of the headplate.

This represents an interesting outcome of the headplate knowledge capture relating to the specification of the design task: most of the time spent modelling the process related to defining the inputs to the task rather than the task itself: the design task is defined in terms of its inputs. The engineering tasks (such as performance modelling) are much more systematically defined. Variables and their relationships are known and understood in order that they may be manipulated to produce a pump with the best set of performance parameters according to the specification. The design task appears to be less systematically defined. It includes the precise layout and specification of the product features and components such that they will produce the specified performance from a design that can be manufactured and assembled. The variables in this case are broader: the designer is working with bought-in components from suppliers that may change. There are often a number of trade-off decisions to make in each layout, where the relationships and variables are not precisely defined, or (in the case of new designs) known. Many of the design choices are known to work through experience of past designs. This type of knowledge can be recorded in the design knowledge reuse system. Some design choices must be verified by testing. Results of such tests can also be made available through the design knowledge reuse system.

6.4.1. User operation of the Web prototype system

After development and instantiation of the system content, including product ontology and data model, design process model, and task knowledge, the prototype implementation applied in a design situation is intended to operate as follows:

The flowchart shown in Figure 6.4-2 describes the system operation, from population through to completion of the product design process embedded in the system. The initial preparation ‘develop models, validate system’ is the knowledge capture, representation, process modelling and system development stage. This is followed by a validation process, to confirm that the system content is accurate and up to date. The operation of the system then proceeds as follows:

Step 1: the user accesses the system through the main page. This is a Web page, so will be accessed via an internet browser.

Step 2: the user navigates to the relevant process task, through accessing the process model and using the hyperlinks to access the task. Note that this feature could be automated with further development effort.

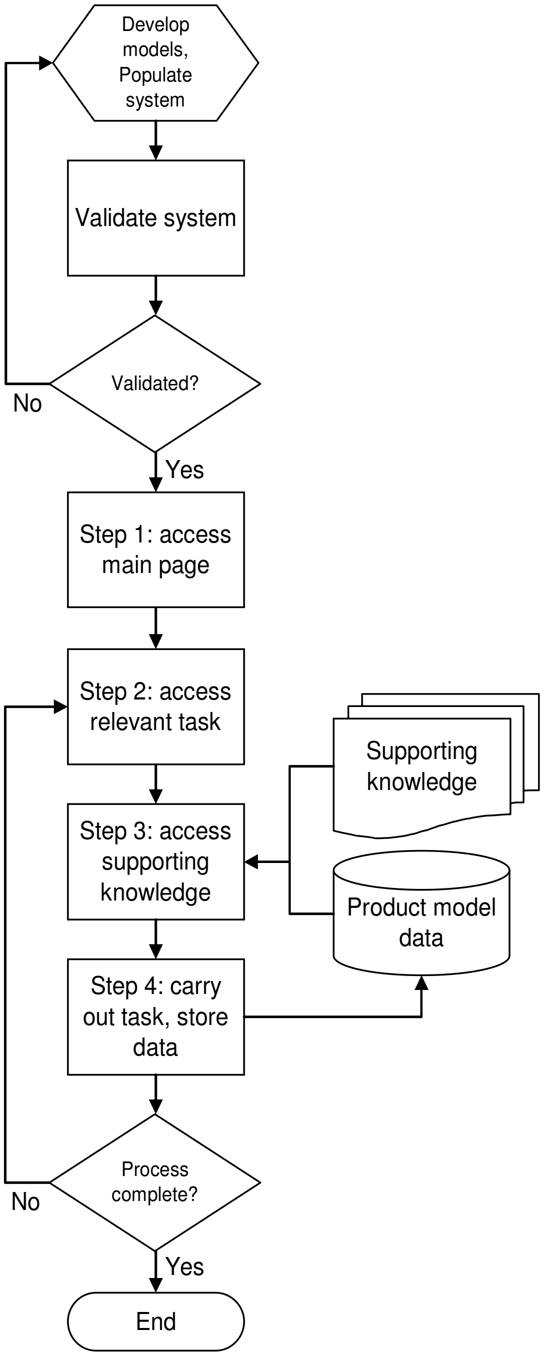


Figure 6.4-2: flowchart to show system operation

Step 3: the user refers to the task description on the task page. There is an option to access additional task knowledge through the task page interface. The user also refers to the data input and task images.

Step 4: the user carries out the required task and enters the data onto the task page. They then click to update the product data and the system takes them onto the next task.

At this point, if there are no more tasks to carry out, then the process ends. Otherwise, the user continues to the next task. The current implementation of the system directs the user to the next task automatically.

6.5. Analysis of stage 2 Web prototype system

In this section the second prototype of the process based design knowledge reuse system has been described. The design process has been represented using a modelling formalism adapted from the Design Roadmap method (Park & Cutkosky 1999). A product data model was applied to the process, based on a product ontology developed with the participating organisation. The prototype system aims to assist design collaboration through providing a common view of the design knowledge. The common view is achieved through the application of the design process in combination with a product ontology. The process model shows where and how each product data element is produced. Task knowledge capture and representation is supported by the development of a task template. The Web based prototype meets two key objectives identified from the first prototype: improved user interface and the potential for distributed collaboration through Web-based access.

The main purpose of this implementation is to create a prototype to describe to the user groups how such a system might work, or look, in practice. It differs from a commercial implementation in three key aspects: it does not include any developer interface, such as to create process models. Various features that were identified for the designer interface were not implemented, such as a data input display on the task page. Security features (access control, database protection) have not been implemented, although the technologies selected fully support these features. The prototype system proved useful in terms of validating the method and the represented knowledge. It prompted a variety of discussions and comments regarding the underlying method. These comments will be covered in more detail in the validation chapter. It also enabled users to critically assess the content of the process model, product knowledge and task knowledge.

The concerns noted in section 6.3.1 were not fully addressed by the second pilot implementation. The system remains static, to a large extent. Whilst an operation takes place to show that the database entries have been made, and the data is retrieved and shown on screen, the remaining content remains the same regardless of the user entries or project state. There are no prompts, alarms or changes in content based on user input. There are also no customised features for different users. Such features are possible with the Web based system; the barrier is now the development effort rather than the capability of the platform. The system does not provide notification of change effects: the data required to carry out the task is available, however changes that may have been made to data not directly applied by the task is not visible. Inconsistencies are therefore possible. The user interface is now much improved over the previous version, with a more familiar look and feel, images to support the tasks, and an improved data entry method. Access control remains very limited. Again, it is possible to implement security features in the Web-based system with additional development effort. Distributed collaboration is now supported in the prototype system. Advanced transactional features such as simultaneous data updates are not supported by the prototype system.

The product parameters also suffer from the static nature of the system: product parameters are structured in the system according to the data definition associated with the task model. The product ontology structure is therefore lost when the data model is applied to the system. A preferable method would be to maintain the product ontology structure and link particular data objects to the appropriate tasks. This would allow users to browse the product ontology structure, and provide the means to make links both from the product ontology to the task and from the task to the ontology.

6.5.1. How the system addresses the research gaps

The process based design knowledge reuse system addresses research gaps identified in section 3.5 in the following ways:

(1) Early design is supported by the model. Conceptual design, including engineering specification and product performance modelling, are supported. It would also be possible to extend the method to include the marketing requirements specification task by modelling the process and creating a data structure to support the tasks.

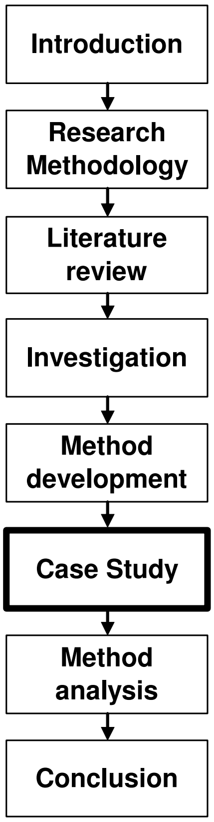
(2) The product and process model are applied in an integrated fashion through the application of a task template that includes both product data and task knowledge. The task uses product data as an input, and produces product data as an output, supported by the task knowledge.

(3) The ‘how-to’ element of the product design process has been addressed through the implementation of the task template. The template contains a task description (how to do it), related information (links to reference sources, previous project files, and other supporting documentation) and an expert directory. It is recognised that the phrase ‘expert’ should be applied carefully, and that in certain cases an alternative phrase should be applied.

6.6. Summary

The method for design knowledge reuse has been developed in a staged fashion. The first stage involved the capture and representation of the product knowledge, and the creation of a product ontology. The resulting ontology enabled a common product vocabulary, and supported product data modelling to enable product knowledge reuse in the developed method. The second stage was design process modelling. This took place using IDEFØ as a modelling formalism. The captured process enabled a shared view of the design process, and through iteration and validation of the model development, some process reengineering took place. The third stage was to apply a modelling approach that enabled the combination of product and process knowledge. The Design Roadmap (DR) method was selected, and the process converted from IDEFØ to the DR formalism. The product data was then combined with the process data, and again the process and product knowledge were tested, updated and validated. The fourth stage was to provide task knowledge: a ‘how-to’ element for the process tasks. This was carried out using a prototype developed using Microsoft Excel. The prototype enabled reuse of the combined product, process and task knowledge. The fifth and final stage in the method development was to provide distributed access to this knowledge in a more user friendly format. A web based implementation of the method was developed to demonstrate this capability for reusing product, process and task knowledge in a distributed environment.

Chapter 7: Analysis of the design knowledge reuse framework and prototype system



This chapter will describe the analysis of the pilot implementation of the design knowledge reuse system and the analysis of the underlying method. The analysis of the system took place in a workshop with the organisation supporting the major case study. The workshop content is described, followed by a summary of the comments made.

The analysis of the method seeks to assess how well the proposed method will support knowledge reuse, and to assess the limits of its applicability. A discussion on the application of the method suggests that the initial effort required to populate the system will be a major factor in an evaluation of the method. Two scenarios are therefore proposed for the assessment: the first time a design project applies the method, and a design project that applies the method when it is populated and the users have some experience. The method will be assessed in two industry case studies.

7.1. System analysis criteria

The requirements of the design knowledge reuse system are:

- To provide an integrated platform to enable the reuse of design knowledge, particularly early design, combining process and product knowledge with a data driven approach; and
- To represent the design process, including how-to descriptions, such that it can be usefully applied, therefore enabling knowledge reuse.

The analysis of the system will seek to identify:

- Whether a link between product, process and task knowledge is considered beneficial; and
- If the design process is adequately represented for design knowledge reuse

7.2. System analysis evaluation workshop

A workshop was held to evaluate the system. The proposed workshop structure intended to prompt focused discussion relating to the validity and perceived effectiveness of the design knowledge reuse system. It was also intended to allow sufficient freedom for the participants to provide an input based on their own perspectives.

The results of the workshop were analysed in a qualitative manner. Comments made during the workshop were grouped according to the questions posed. The comments are then discussed.

In advance of the workshop, the invited participants were given a document describing its aim and format, including the list of issues for discussion and comments. The document content is shown in Figure 7.2-1.

Evaluation workshop for design knowledge reuse system

You are invited to attend a workshop to evaluate the design knowledge reuse system that has been developed as part of a PhD research project. The system will be demonstrated, then evaluated. Participants are requested to comment on the following issues:

System aims:

- Reuse of task knowledge
- Structured information retrieval
- Central store and framework for project data

What the prototype should do:

- Demonstrate a process basis and relationships
- Show parts of a product data model
- Show that parameters from previous steps can be recalled / manipulated

Questions

- Does the system adequately represent the design process?
- Is having an explicit link with the design process a good thing?
- What else should it do?

Figure 7.2-1: Workshop Description and Questionnaire

The developed system was demonstrated to the workshop participants, by going through the design process as modelled in the system. This started with the system homepage, then onto the first task page. Data was entered, and then the next task page was shown. This approach continued, working through each task until the design process in the system was complete. Dummy data was entered into the system to demonstrate that the system stored data, showed the stored result, and (in some cases) made calculations based on previous entries.

7.3. Analysis of the workshop results

During the workshop, notes were taken. These notes were transcribed. Aside fro the notes taken in the specific question categories, comments made during the whole session were assessed and placed into a category. The three categories were defined according to the three questions.

Each of the three questions will now be addressed by listing, then discussing the comments made in the workshop that were categorised according to the questions.

The questions themselves are not simple, and they did not produce simple answers that can be readily applied, analysed or tabulated. Rather, they produced a complex set of answers which are not simple to understand or implement. The answers are embedded in a complex context. Through analysis of the answers was it possible to draw out some of the key themes relating to the analysis of the proposed system. These themes will be described in the following section.

7.3.1. Does the system adequately represent the design process?

Responses which relate to this question are as follows:

(1) "'Number of stages' is much a more complicated question that needs more inputs." One of the tasks has a data input for the number of stages in a vacuum pump. This is a complex question that needs to be addressed in a thorough manner, however the system showed it as a simple data input. Further work should be done to modify the description of the process.

(2) "The process is not automatic – several things are considered in your head at the same time, including past cases and manufacturing." The process by which designs are specified and solutions generated has been simplified and represented in the system. In current practice, experienced engineers consider several additional contextual elements that are not expressed in the system.

(3) "Inlet could be linked to pump requirements (throughput) e.g. a 1000 pump uses 100mm, 300 litre pump 63mm. There are a limited number of preferred sizes, relating to standard fittings." There were a number of additional process elements and product relationships that the analysis process highlighted. One such example is that a relationship exists between the diameter of the pump inlet and the pump throughput. This was not expressed in the system.

(4) "Headplate outputs – to drive the CAD system would be useful and save time (through developing a parametric model)." A benefit that the engineers identified was the development of a parametric model for the headplate and a link between the knowledge reuse system and the CAD system. at present, the system does not adequately represent the headplate to enable this.

(5) "Key parameters should be in it – not all of the data is needed in the process." A range of comments were made relating to the range of product data parameters available in the system. One such comment suggested that only a few key product parameters are necessary in the system. This is the approach which has been applied in the development of the method so far, so the comment justifies the selection of a limited parameter set.

(6) "Data elements & source should be available – to provide transparency" It was suggested that the source of product data should be shown. There were several comments relating to data source, data tracking, trust, and dependency. The comments suggest that some additional features are necessary to show data source and enable a backtracking feature.

(7) "It should be possible to look back at the data source (trace dependency)" This comment was addressed by the previous response.

(8) "Modules: some items will be designed to fit several units, so they are not optimised for a single product, but a product family." Product families were not addressed by the method since the focus of the development was limited to a single component. Product family design and multi product optimisation brings a high level of complexity that should be examined. For the purposes

of this research, this issue is beyond the scope. It should certainly be further investigated in future research.

7.3.2. Is having an explicit link with the design process a good thing?

The comments relating to this question will be each addressed:

(1) "Reuse of working methods **saves time**. This is the key measure." This is the most definitive response to the question regarding whether linking the design process to design knowledge is a good thing. It was considered by the participants in the workshop that reuse of working methods can save time in product development. The proposed design knowledge reuse framework enables reuse of working methods. Time is a key measure of product development performance, and is a focus for product development improvement. 'Meet engineering specification' is assumed to be the basic function of the design process. Additional performance measures include: time, commercial validity and product excellence. Time is a measure which is currently receiving a great deal of attention. Reduced development time means reduced development cost. It also means revenue can be generated earlier. Commercial validity could be considered as the most important measure of product development. A product with a clearly defined profitable strategy, with estimated costs and value that support a profitable model, will surely be pursued. A product whose unit cost become higher than market value may well be abandoned mid-project. Product excellence is a performance measure which is difficult to quantify, and has a variety of indicators from a range of perspectives.

(2) "With a systematised method you must be very careful (crap in crap out)." It has been emphasised throughout the development of this design knowledge reuse framework that validation has played a central role in developing product knowledge, product data and design process models. Even with the repeated validation, there were still elements of the data and knowledge in the system that were misleading or incomplete. This highlights the importance of multi-user validation, and the necessity of checking and rechecking content. It also highlights a fundamental dichotomy which must

be recognised when implementing knowledge based systems and methods. On one side of this issue, automated methods can save time and effort in product development. The other side is that automated methods can be misleading or wrong, or can create errors outside certain (invisible) limits. For example, a performance analysis calculation may produce an incorrect result if the pump throughput is below 100 litres per hour, yet not make this limit known to the user. The reason may be that at the time, it was assumed that such a low throughput would not be required, therefore the limit is self-imposed. Later, when a need is identified for that requirement, the original intent of the system is hidden behind an automated method. Even if the results of a systematised method are accurate and reliable they may still lead to problems. If the methods now embedded in a system are forgotten or unknown, then upgrades become problematic. It is also a major problem where these systems become unavailable due to system failures or resource shortages. This issue of taking care when systematising methods must not be overlooked. Three elements form the core of this issue: validated correct content, visible and known method and clearly defined limits.

(3) “Changes and evaluations are faster using Excel / VB than CAD systems.” Known analysis methods can provide superior local performance. Where an engineer is familiar with a particular method, such as Visual Basic and Excel, then applying that method will enable the engineer to produce an analysis result faster than with a CAD tool, or design knowledge reuse system. There are two options to consider here: should the method should be made available to the design team as-is, or should it be embedded in the system; integrated with the best practice design process.

The design knowledge reuse framework should take account of a range of methods and make them available to other users whatever the format. Whether or not to formalise a method and include it in the design process model must be addressed as part of the design knowledge reuse methodology. Providing one-off analysis methods which work within narrow limits only known to the engineer that developed it could cause some difficulty in transfer. Again, this issue must be considered as part of the design reuse methodology.

(4) "Most rules will be from manufacturing – constraints for milling tools etc." So far, few manufacturing methods, rules or knowledge have been included. It is the intention that future research will address the need for additional manufacturing knowledge in the design knowledge reuse system. This comment shows that there is a clear need to include manufacturing knowledge as a core element of a design knowledge reuse system. Many of the design decisions are made with direct reference to manufacturing methods or constraints. The importance of manufacturing method knowledge can not be overstated: a product is developed with a functional aim, and that function is achieved by a particular form with a given behaviour. This can be considered as a layered process (Ullman 2002). The form can not be developed in isolation from the manufacturing method, since specifics of the manufacturing method influence the product form. Manufacturing influencing the product form is true from early conceptual design, where functional analysis and material selection takes place. Material influences product function as well as the selection of manufacturing method. It has been suggested (Harding & Popplewell 1999) that product and process are so closely linked that they should be developed in parallel. For the development of a variant product, the manufacturing method may be defined in advance due to capital investment and existing expertise. In this case, manufacturing knowledge still forms a key part of product development knowledge.

(5) "Are the bearings direct in the headplate or are bearing carriers used? (A non-geometry problem.) What size is the crossover point: not on 'small' pumps, but how small?" These comments are examples of issues that are not directly related to product geometry, but are optimisation problems with multiple parameters. The example given was of bearing carriers, which are not used on small pumps. The issue must be addressed in an integrated fashion: what method is best suited to other members of the product family, what other products will share this component, what is the production volume, what is the manufacturing method of the component, what is the cost of each option in terms of production method plus bought-in components, what is the service (maintenance) implication, and so on. The design knowledge reuse framework should address such issues as this by storing the decision as well as the criteria and decision process, for future

reference. This can be related to the relevant component selection decision within the design process.

(6) “Modular construction: components will be designed to fit several units, so it is not optimised for one product, but a product family.” This relationship between component design and product families must be represented in the design knowledge reuse framework. The method must, therefore, be capable of representing multiple products. It should also be able to access data from multiple products in instances such as this.

(7) “A parametric input to define headplate features is possible – the thought process to develop the headplate is not so easy.” It is possible to create a basic parametric model that will generate a CAD model of the headplate, based on a set of inputs from the design process. Capturing the knowledge that would allow the parametric model to be built represents a significant challenge. The high number of design choices to be made, the close relationship with other design components and the high degree of complexity make the knowledge capture a difficult issue. The design knowledge reuse framework recognises that the (headplate) component design process is complex. Identifying the inputs and other important elements can support the thought process for creating a headplate. It is the high degree of complexity in the component design process that results in a problem so large it would be very difficult to model. As such, it is considered that the knowledge-support approach represents a more cost effective option.

(8) “Will parametric models be accurate and trusted? The programming (and error messages) in CATIA is hard, which causes problems.” Even simple parametric models are a difficult and time consuming problem in terms of development effort within the CAD system. Complex models are much more time consuming and difficult, and frequently error messages will be generated where the inputs or calculations cause certain limits to be breached. Even without the error messages, there is a trust issue inherent in automation, as discussed earlier.

(9) “Some things in the process model have project related needs, such as ‘component lead time of 10 weeks’.” The design process includes a lengthy

testing procedure, in which a prototype is built and tested in a variety of situations to prove the design is robust. This long test process puts additional pressure on the project manager to deliver a complete product within schedule. With schedule pressure, project management methods are required to ensure that activities can begin with all necessary inputs complete. One parameter that influences this scheduling problem is component lead time. Certain components take a long time to be delivered, and as a result they must be specified early enough by the design team that they can be ordered in time for the planned prototype build date. Such project-based considerations must be built into the design knowledge reuse system. This requires a specification of the design process that includes optimum scheduling for component ordering, supplier liaison activities, manufacturing process selection, and so on. These activities form part of the design process, since the prototype build and test is considered as a design activity: a physical sign-off process.

7.3.3. What else should it do?

A range of additional features were suggested. Since the system is in pilot phase, proposing additional features was one of the important elements of the workshop. Perhaps because of the nature of designers and engineers, this is the largest of the three response categories, and took up a lot of the discussion time in the workshop.

Some of the responses related specifically to the content of the system, including component parameters and required inputs for component specification. These comments will not be covered; only those comments relating to the features and operation of the design knowledge reuse framework will be discussed. They are not presented in order, and some comments have been combined where they had a common theme. The responses have been grouped into: parameters, tasks, platform design, rules / preferences and outputs.

Parameters

(1) **2 parameter sets**: one for the next task to progress, one for full specification of a given component

(2) Key parameters should be in it – not all of the data is needed in the process.

Both of these comments relate to the definition of multiple parameter sets. It is assumed that the product data are drawn from a finite set, and that there are subsets of those data which can be applied to particular tasks. A good example is early design: a set of requirements is provided, and a small set of data can be applied to the development of a product solution. In subsequent development of that product solution, additional data are required for more detailed analysis and specification of component geometry and manufacturing methods. The basic set of data remains constant (except where detailed analysis requires its values to change).

(3) Key parameters – those which influence a lot of other things – can the system show which ones these are?

A potentially useful feature is the identification of product parameters which influence a large number of subsequent parameters. If the system could identify these parameters, then the optimum design process may change to ensure that they are specified early and accurately.

(4) Drive parameters of component by changing earlier parameters, i.e. change centre distance and get headplate output.

Parametric capability could be included in the system: driving the creation of product parameters through knowledge based methods. This capability could be used to support product analysis and decision making as well as design automation: multiple product options could be created using the automated methods, and the results assessed.

(5) Data elements and source should be available – to provide transparency / trace dependency.

This was a recurring theme in the workshop and knowledge capture and validation exercises: the source of product data should be recorded. This relates to recording who defined certain product data. An additional element of data source is tracing dependency: what previous (and subsequent) data rely on this value, or are influenced by it changing? The prototype system did not provide support for dependency or transparency.

Tasks

(6) Can the system be narrowed down to important, time-consuming tasks? Those that cause grief – not necessarily difficult but that have a lot of constraints.

Support for highly constrained tasks was identified as an area in which the design knowledge reuse framework could provide a valuable contribution. Since the system shows data inputs and outputs, the relevant constraints can be imposed by the system. Those tasks with fewer constraints could still be represented in the system, however with less knowledge support to reduce development effort.

Platform design

(7) Platform design should be considered in the system – how to address the needs of the platform design process – as well as (local) optimisation.

The need to recognise modular design, and the capability of the system to access data from multiple products, has been recognised. An important element of this is the optimisation of the design process for a product family.

Rules and preferences

(8) Rules for the decision process – narrow band of parameter values in which rules remain applicable. Rule to apply this and tell you why.

(9) Simple rules e.g. bearing bore = nominal bearing size ±10µm + 20µm

(10) Preferred sized features / parts – catalogue (standard dowels, o-rings, bearings, seals)?

(11) Inlet could be linked to pump requirements (throughput) e.g. a 1000 pump uses 100mm, 300 litre pump 63mm. There are a limited number of preferred sizes (relating to standard fittings).

A variety of rules and preferences could be represented in the system. An important aspect of providing rules and automation in the system is in providing visibility of the method and explicit statements of the limits of those automated methods. It is also a viable option to include standard parts in the system, along with selection criteria within the design process. The standard parts could be recorded as part of the product knowledge, in a central repository.

<u>Outputs</u>

(12) Can you do it backwards? That is – see what input forced this dimension / parameter?

This capability was identified earlier, as 'show key parameters'. The capability to trace back through the system to show which parameters are parents of a given parameter is considered valuable. It would show influences for the purpose of assessing change decision – is the benefit of a given change worth the effort of implementing it, in terms of changing all of the parent characteristics? It could also assist in the development of knowledge based methods, by identifying relevant parameters and showing relationships.

(13) Headplate outputs – to drive the CAD system would be useful and save time (parametric CATIA model).

Producing an output that can be used by a parametric CAD model would reduce the design effort. It would require effort in developing those parametric models, so would need to be assessed on a case by case basis.

7.4. Summary of responses

The comments provided in the workshop have been discussed in three categories: "does the system adequately represent the design process"; "is having an explicit link with the design process a good thing"; and "what else should it do". The responses and the discussion around the responses will now be summarised for each of the three categories. The main intention is to provide some analysis regarding the usefulness and validity of the proposed design knowledge reuse framework. The analysis will also consider the current state of the system against the overall analysis of the method and the proposals for new features.

7.4.1. Does the system adequately represent the design process?

The design process model must be validated from multiple user perspectives. Sufficient detail for one user is not sufficient detail for another. The requirement for task precedence may also differ between users (where one does not have a preference and the other has a strict requirement).

In some cases, it is not possible to automate a task. In other cases, the effort required is too high to provide a benefit. Some means to assess tasks in this spectrum (cost vs. benefit of automation) would be beneficial. The value of additional product and task knowledge in such tasks becomes higher. Where a task is necessarily a tacit process, then care should be taken to provide the user with all relevant and necessary inputs, task knowledge and product knowledge.

The system is not currently capable of providing parametric CAD outputs or generating full geometry descriptions of the product. However, such capability is not necessarily required and should be considered in a cost-benefit exercise during system development.

There are a number of views on the range of product parameters that should be available during the design process. One view is that a limited range of product parameters should be available (as with the current approach).

Regarding product data, it was suggested that the source (task and person) should be provided.

Modular designs were not considered in the current system beyond describing that a particular component is common to a range of products. Product design strategy should be addressed by the design knowledge reuse framework, and this may include modularity.

7.4.2. Is having an explicit link with the design process a good thing?

Reuse of working methods saves time. However, the issue of whether the right method is being followed is not addressed by the system, but must be considered during its development. Other considerations include cost-benefit analysis of **detail** (product data extensiveness, accuracy and validity) and **automation** (embedded KBE type methods in the system).

The issue of effort saved by automation vs. effort cost in development was highlighted in the analysis. This is a similar issue to the level of detail provided in the system: the cost of eliciting and validating product data vs. the benefits of having a complete source of accurate and reliable data. Systematised methods must be carefully assessed in terms of the development effort, maintenance effort, project value and the associated effects (e.g. loss of working knowledge of the manual method, potential risks of errors).

A further issue to be addressed is that of local evaluations vs. system wide implemented methods. Should a quick analysis calculation produced and carried out in a spreadsheet be made available to other users, or should it be formalised and embedded into the design process as an automated procedure, or should the user be encouraged to maintain it separately?

A design process model is incomplete without a significant knowledge input from manufacturing, since knowledge relating to production of the product and its components is intimately linked with design and design decisions. The lack of manufacturing knowledge is a current limitation of the method. It is considered that the method could be extended to include manufacturing knowledge, however defining an appropriate method would require further research.

Several examples of complex design problems were provided in the workshop and throughout the knowledge capture process. The capability of the design knowledge reuse framework to support such complex decisions was considered critical. The degree of support was not fixed. Fully automated methods may be programmed in to the design knowledge reuse system. Alternatively, a range of additional supporting informal knowledge such as diagrams and text can support the decision by providing access to previous decisions. Previous descriptions of decisions may include the context, the decision criteria and the outcome.

Project related issues such as component lead times can be included in a process oriented method, as an element of product data and as part of the task knowledge. This type of knowledge is also embedded in the process model, since the best practice design process should take account of such factors. A knowledge reuse framework which is product- or component- centric would exclude such considerations.

7.4.3. What else should it do?

The view on product parameters was that a flexible approach is required. The product data should be displayed such that the minimum set is available, enabling the task to progress. It should also provide access to a complete data set that fully specifies a component or task. Conceptual design requires a parameter set that enables the design the team to quickly generate a solution for comparison with other options. Complexity and computational effort dictate that this parameter set should be as small as possible whilst providing an accurate enough result. Only the experience of the design team can say where this limit lies.

A second element relating to product parameters was a capability to identify important parameters: those with a large knock-on (or ripple) effect. Such capability may benefit a further proposed feature, which is to partially automate the system through knowledge based methods, enabling the effects of parameter change to be assessed. As well as identifying important parameters and tracing effects, the importance of data source was highlighted: who defined this product data, and on what basis? Elements of this are relatively simple to implement – recording additional parameters as part of the product model such as ‘date’, ‘time’, ‘person’ and so on to show who provided the data and when. Recording rationale could be achieved through providing an editable section for task knowledge. The more complex elements to implement are the ripple effect analysis and the knowledge based methods.

The view on support for design tasks was somewhat varied. It was proposed that reusing working methods saved time. However, there was clearly some reluctance towards a system which provided a detailed and structured method for every task. It was identified that support for highly constrained tasks would be valuable, through showing existing constraints and the current constraint data. To support this view of task differentiation, the methodology for developing the content of the system could support task analysis. Critical tasks, which are highly constrained, could then follow a different procedure than non-critical tasks with fewer constraints.

Modular design, or platform design, is not currently considered by the design knowledge reuse framework. An implementation of the method should consider the implications for platform design. This will not be fully addressed, due to time constraints. Modular design will be proposed as an issue for further research.

A variety of specific rules and preferences were proposed for the system, relating directly to the product data content. Since this was not a question topic asked of the participants, general themes for applying rules within the system were not addressed. Automation or KBE methods added to the design knowledge reuse framework would inevitably involve rules, in formal logic statements. It is important in these cases to provide informal statements describing the rules to the users, along with the intention and any known limitations or intended applications.

Outputs of the system proposed as additional features included CAD outputs, to generate a parametric model, and parameter analysis, as described earlier: to assess the ripple effect of a given parameter change. Providing outputs to generate CAD models should be considered as part of the development methodology. Due to the high effort involved with creating parametric CAD models, each case should be individually assessed. Each case should consider the such trade-offs of development effort vs. reward (such as time savings) for such additional features and automation.

7.5. System validation

A system to reuse working methods is valuable. The data quality is critical, and must be carefully validated. Inputs to a given parameter, and a view of the effects of changing a parameter, would be useful (impact analysis for parameter change). Non-product parameters can be usefully described in the system, such as expected lead time of parts. An additional element which could be included in the system is a description of preferred sizes for manufacturing features (for common tooling) and parts (for parts reduction and common stock keeping units).

According to the analysis of the comments made during the validation workshop, the design knowledge reuse framework would benefit the design process by saving time through the reuse of working methods. The other comments made in the workshop related to the implementation of the method. Three critical areas stand out, and they are: validation; automation issues (effort trade-off, care); and views.

Validation of the system content – both task knowledge and product knowledge – took place in advance of the workshop, through several iterations. Some engineers were present at the workshop who had not been involved with the system validation, and they highlighted several areas of product data that they felt should be changed in some way. This shows the importance of multi user validation. It also shows that even where a ‘complete’ validation exercise has taken place, errors will remain.

The validation issue is related to automation ‘care’. When automating a method, validation is even more important since a peer review process may assume that the method, once automated, is accurate and trusted. Where a method has been automated, additional safety features must be implemented. The method should be visible to the user, so they are able to assess whether it is appropriate in a new situation. This will also enable transfer of the method to a new application or system. The proposed application area and intended limits of applicability should be recorded and made available to the user.

Automation effort trade-off relates to the assessment of the effort required to automate a method, and a comparison of this result with an estimate of the potential reward, in terms of time saved either through a simple time per process or through time saved by error reduction. Automating complex methods is more costly in terms of development effort, however can save more time since the manual method is also complex.

‘Views’ relates to the identification and provision of product data that is relevant to a particular user in a particular task. The approach taken in the prototype system was a single view of product data for each task.

The criteria identified in section 5.2 were tested by the analysis, which sought to identify:

- If a link between product, process and task knowledge is considered beneficial

It was considered beneficial, as a principle with the potential to save time. This is a key measure of product development performance. In a variant or evolutionary design situation, the reuse of a relatively detailed design process model is possible. Product parameters and task knowledge can be associated with those tasks, enriching the knowledge reuse potential.

The analysis also asked:

- If the design process is adequately represented for design knowledge reuse

The design process should be represented in a more task specific format, enabling a clear distinction between a conceptual design process (whose aim may be to produce a set of product parameters for evaluation by a review panel) and an embodiment design process (whose aim is to produce a final engineering specification ready to be passed to the CAD specialists for detailed design). The use of different parameter sets and task descriptions may support this. Also, it is clear that validation is a crucial element of the process, and that where possible, the users should be given the opportunity to validate a process before it is implemented. Aside from these points for improvement, the design process is adequately represented for design knowledge reuse. The product, task and process parameters together support knowledge reuse.

7.6. Analysis of the underlying method

The remainder of this chapter will discuss the analysis of the underlying method.

The flowchart in Figure 6.4-2 describes the process for applying the design reuse methodology. The first stages of this process, representing the system setup operation, are shown in Figure 7.6-1. The first process, identified as a preparation task (denoted by the hexagonal box), requires the development of models and population of the system.

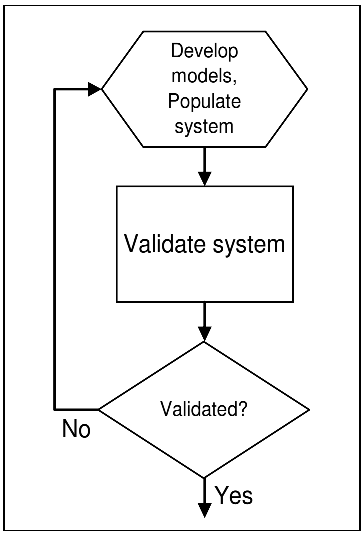


Figure 7.6-1: flowchart showing setup operation

This process would require many man months of effort if it were to be implemented in full for a complete design portfolio. Therefore, a likely scenario is to pilot the method using a subset of the design portfolio, in a similar manner to this research project. A key product structure, component, or assembly could be selected for such a pilot exercise. A proposed structure for a pilot exercise is shown in Figure 7.6-2. The flowchart describes setting up a pilot system, applying that within a project context and making an assessment of the value of the pilot implementation.

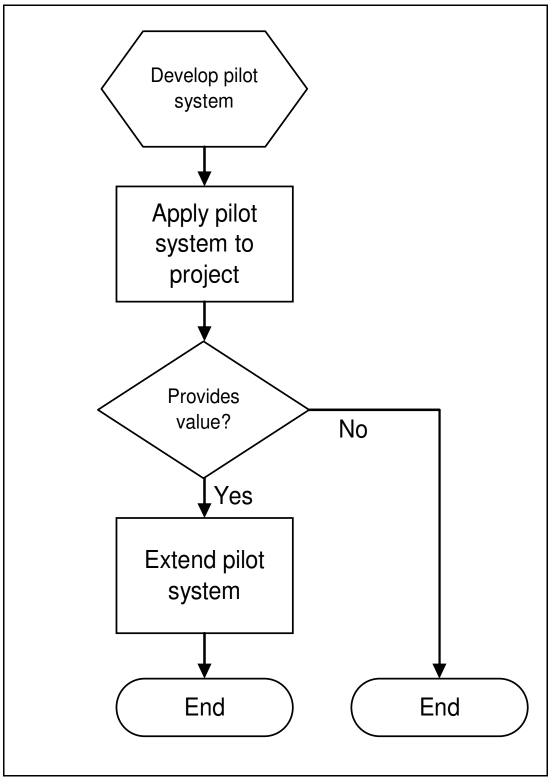


Figure 7.6-2: flowchart of pilot system development

If the method provides value relative to the development effort, then the method should be extended and a staged implementation process planned. If the method does not provide value, then the implementation should be abandoned. In both cases, the reasons should be assessed: why did the method provide benefit? What were the key aspects? This could be used to improve the future implementation. In the case that it did not provide benefit: why did the system not provide benefit? How could it have been improved? Were there limitations in the pilot example or project type? There is an important balance to be recognised in such a system in terms of effort vs. reward.

Initial feedback from the validation of the method suggests that it could potentially provide substantial benefit in terms of time reduction and quality improvement. The issue is with such high population effort, a pilot study may not show a benefit greater than the development effort. This relationship is described in Figure 7.6-3. Critically, the scale of the ‘time / cost’ and ‘scale of implementation’ axes are dependent upon the company implementing the method. The graph shows that effort is high at the beginning of the project, and that reward is zero. Effort falls as the system population reaches a critical stage, after which the system effort represents the maintenance requirement. Reward from application of the system begins at zero, and picks up once the system reaches a useable state. There are two crucial points: where effort and reward are equal (intersection at point B), and where total effort is equal to total reward (area under the graph).

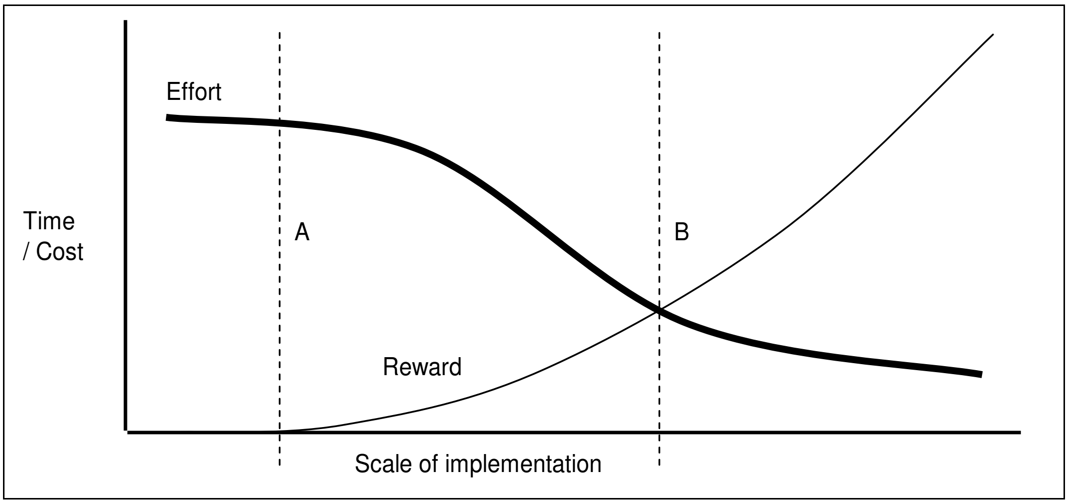


Figure 7.6-3: effort vs. reward for system implementation

Where this effort / reward discussion is relevant to a pilot implementation is in a complex environment. Here it is assumed that a complex environment extends the ‘scale’ axis, since there are a greater number of components, assemblies and relationships to include. As such, in a highly complex environment a pilot implementation may not achieve sufficient scale to demonstrate any reward (prior to point A). This increases the risk associated with the decision, since it is not known prior to point A whether the method will yield a significant reward. Between points A and B there the actual effort and rewards do not give a clear indication of the future trend. Aside from the difficulties in forecasting effort and reward, there is also substantial difficulty in measuring reward. Metrics must therefore be identified in advance of the project. (Design) Process time, product quality, rework time, and confidence levels are examples of metrics that could be applied to the reward measurement scenario. These metrics could be applied to a previous (similar) project to provide a qualitative basis for comparison.

In recognition of the high initial effort required of the method, it is proposed to assess the method from two theoretical standpoints. First, an assessment of the method as applied for the first time. Second, an analysis of the method after it has been used. The system is populated and users are familiar with its operation, then it is applied to a new project. The scenarios are outlined below:

(1) A design team applying the knowledge reuse methodology for the first time.

(2) Previous project used this methodology – how does the new project operate, and how does it benefit?

In each case it is the intention to evaluate the potential value through the reuse of design knowledge enabled by the method, along with the perceived difficulty level. A comparison should also be made with existing methods applied by each company taking part in the case study.

7.7. Design of the analysis questionnaire

The design of the analysis questionnaire is described in this section. A copy of the questionnaire was given to each participant at the end of each validation session. The participants were asked to tick the box that most closely matched their assessment of each scenario.

It has been identified that an analysis of the existing scenario would add value to the assessment of the pilot implementation. A similar approach will be take in the analysis of the design knowledge reuse framework proposal: the participants will first be asked to assess the existing situation, in terms of design effectiveness and design reuse.

The formatting was slightly different for the printed version: narrower margins were used, which allowed larger text areas for the ‘additional comments’ sections. The questionnaire is shown in Appendix 1:.

7.8. Analysis of process based design knowledge reuse framework: Case study 1

The format of the validation session was adjusted for company A, since knowledge capture had already taken place, and the results had been modelled. The first part was substituted with a demonstration / run-through of the process based knowledge reuse system Web-based prototype.

The session took place with a senior designer and an engineer. During the demonstration, comments were noted relating to the perceived utility and application of the method. At the end of the session, the participants filled in the questionnaires.

7.8.1. Comments made during the demonstration and discussion

It was considered that the methodology could provide significant benefit, with a number of provisions:

- Not as just another process to follow. The method needs to incorporate existing processes, reducing points of contact for reference material or NPI guidance.
- Provided people engage with it. There is currently an online design manual. Not everyone in the design team knows it is there or uses it.
- Ease of use is important – and users must be able to FIND the system in the first place.
- Software purchase decisions can be taken locally. A method with such broad scope must be driven from the top.
- Training would be required, particularly in the initial stages.
- Up to date lessons learned and guidelines would be required.

Additional features that could improve the implementation of the method were also proposed:

- The system could be implemented as a product knowledge framework, providing links to relevant product subsystems, functions or components.
- It is useful to have rationale for previous product features, as well as test results.

- Feedback from previous project, especially a record of ‘past disasters’, to prevent the next project tripping at the same hurdle.

There are also a number of potential limitations:

- The system could limit innovation if it prescribes in too much detail.

- It needs so much input to provide a useful example that this may limit buy-in (a useful demonstration of the system capability to users).

7.8.2. Questionnaire responses

Question 3 was changed to read ‘what amount of the design reuse capability are you applying’. Questions 6 and 9 were altered to read ‘using’ rather than ‘adopting’. Responses are recorded from the two participants in the same table, and an average of the two scores is shown for each question.

Current scenario: existing design process

		1 – Low	2	3	4	5 – High	
1. How effective is the current design process?	Late, quality problems, not to spec			✓	✓	(3.5)	On time, high quality, exceeding spec
2. What level of design reuse takes place?	No formal reuse				✓✓	(4)	Fully automated design
3. What amount of the design reuse capability are you applying?	Very little				✓✓	(4)	A great deal

‘First use’ scenario: new project; using knowledge reuse framework first time

		1 – Low	2	3	4	5 – High	
4. How would you judge the proposed method?	Limited practical value			✓✓	(3)		Useful method capable of significantly improving design
5. Would it provide a benefit over the current method?	Not at all				✓✓	(4)	Substantially
6. What degree of difficulty would you expect in using this method?	Low effort, cost and time				(5)	✓✓	High effort, cost and time

‘Experienced use’ scenario: new project; applying a refined version of proposed method

		1 – Low	2	3	4	5 – High	
7. How would you judge the proposed method?	Limited practical value				✓✓	(4)	Useful method capable of significantly improving design
8. Would it provide a benefit over the current method?	Not at all			(4.5)	✓	✓	Substantially
9. What degree of difficulty would you expect in using this method?	Low effort, cost and time		✓✓	(2)			High effort, cost and time

During the questionnaire, the questions and answers were discussed. In addressing ‘first use’ and ‘experienced use’ scenarios, additional comments were provided to support the answers:

<u>‘First use’ scenario:</u>

Team members influence what will happen in terms of design reuse, best practices, and so on: the application of design methods varies widely across projects.

Design reuse is improving, and has been applied a great deal in the current project, particularly through the use of predictive tools and knowledge based systems for conceptual modelling and analysis.

‘Experienced use’ scenario:

The result would depend on the project type. It would also be significantly influenced by the support and ownership of the method – good support would be essential to its success. In this scenario there is a good potential for benefit, with a high risk.

7.8.3. Summary of case study 1

The methodology could provide significant benefit, with a number of provisions. It should incorporate existing processes, reducing points of contact. Such a broad method must be driven from the top. Additional features that were proposed include a record of ‘past disasters’, product feature rationale, and a browseable product structure model. Potential limitations include hindering innovation and the high effort required in setup that may limit buy-in.

Currently, application of design reuse varies across projects. The affective application of any design tools and methods relies on the project manager and principal members.

For the ‘first use’ scenario, the method was judged as moderately useful (3 out of 5). The assessment showed that the method could provide significant benefit over the existing design method (4 out of 5). However, the difficulty level in adopting the method was judged to be very high (5 out of 5).

For the ‘experienced use’ scenario, the method was judged as potentially very useful (4 out of 5), with the potential to provide significant benefit over existing methods (4.5 out of 5). The difficult in using the method was judged to be moderately low (2 out of 5).

7.9. Analysis of process based design knowledge reuse framework: Case study 2

The second validation case study was carried out with a company that had not previously taken part in this research project. company D are a manufacturer of home heating appliances. Their design and manufacturing operations take place across

Europe. The UK site carries out the integration design, case manufacturing and final assembly. The other European sites design the various product modules. The focus of the case study is the integration design task carried out at the UK site. The case study consisted of a workshop in which the company product and design process were modelled. The process based design knowledge reuse framework was described in terms of how it might be applied to their product and process. The participants then assessed the value, suitability and effort required to implement the method.

7.9.1. Product modelling

The assembly design problem requires the integration of the three main product modules: thermal, hydraulics and electronics. A basic structure of the product, as created during the workshop, is shown in Figure 7.9-1.

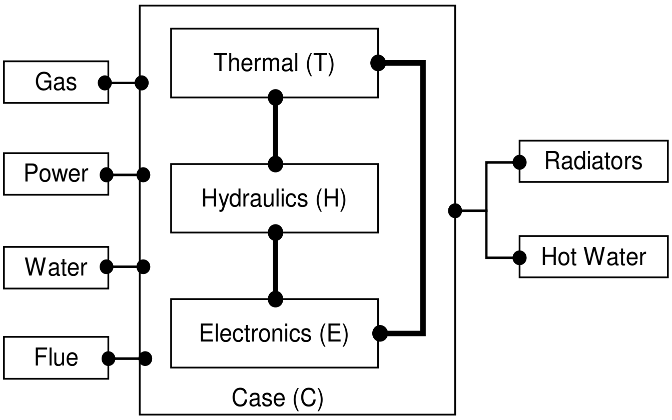


Figure 7.9-1: basic product structure

The product structure represents the three constituent product modules and shows that they are all interconnected. The thermal module is linked to the hydraulics module: pipes from the hydraulic module feed water into a heat exchanger (part of the thermal module). This heated water is then directed back to the hydraulics module, where it is directed out of the unit to provide heating to the environment, either as hot water or to radiators. The electronics module controls both the thermal and hydraulics modules. Each of the three modules are designed by a specialist design group separate to the integration group. Each module is designed for a specific product, however the specialist design centres also carry out research and development outside the scope of a specific project. The integration group is responsible for 3D layout of the component modules, as well as defining the various physical connections.

Parameters relating to the integration task from a connections perspective include internal and external fittings – as well as the three modules, there are four principle connections with the installation environment: Gas, Power, Water and Flue. There are also external connections to the hot water and radiators (depending on the product type: some products carry out only one of these functions). Connection parameters between these various modules include, amongst others:

T:H (pipes and fittings)

W:T (pipes and fittings)

W:H (pipes and fittings)

E:H (wiring and connectors)

E:T (wire length)

E:P (electrical connectors)

As such, it is possible to define a set of connections for a given product in terms of a standard connection set. This set needs to be extended to reflect the whole parameter set. It also needs to be extended to reflect the multiple connections (in / out, hot / cold, etc.) within a given interface.

7.9.2. Process modelling

The company has recently adopted a new product introduction process that describes the whole project, from concept generation through to service handover (which takes place after product launch). The functional perspective of the process shows the documents, procedures and measures that each function must have in place before each stage gate. Because the company had such an extensive process model in place, it was not necessary to create a detailed design process model. As such, the resulting model shown in Figure 7.9-2 is incomplete since it was not necessary to create a duplicate process model.

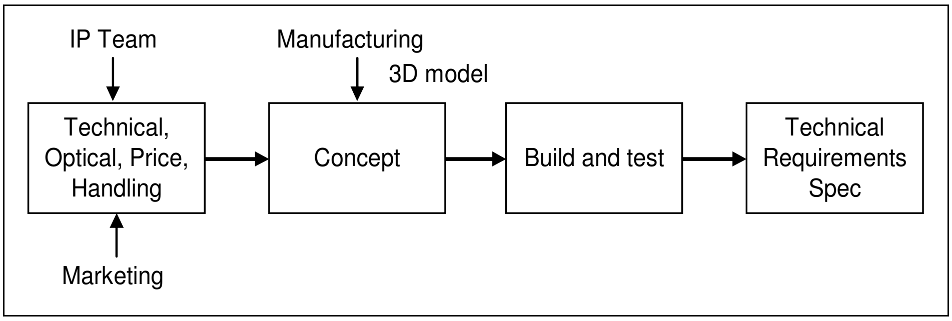


Figure 7.9-2: partial NPI process model

The process model shows that a marketing specification is fed into concept development stage. At this stage, a 3D model is created and a technical demonstrator produced. The build and test of the technical demonstrator is fed back to the concept stage, and results in the technical requirements specification. A distinction between the project focussed process model and an engineering focussed process model was made: the engineering function did not have product data level support from the detailed NPI process.

7.9.3. Interview / questionnaire

The results from the questionnaire are shown below. The responses from the two participants are shown on the same table.

Current scenario: existing design process

		1 – Low	2	3	4	5 – High	
1. How effective is the current design process?	Late, quality problems, not to spec				✓✓	(4)	On time, high quality, exceeding spec
2. What level of design reuse takes place?	No formal reuse			✓	✓	(3.5)	Fully automated design
3. What amount of the design reuse capability are you applying?	Very little				✓✓	(4)	A great deal

‘First use’ scenario: new project; using knowledge reuse framework first time

		1 – Low	2	3	4	5 – High	
4. How would you judge the proposed method?	Limited practical value		✓		(3.5)	✓	Useful method capable of significantly improving design
5. Would it provide a benefit over the current method?	Not at all		✓	✓	(2.5)		Substantially
6. What degree of difficulty would you expect in using this method?	Low effort, cost and time				✓✓	(4)	High effort, cost and time

‘Experienced use’ scenario: new project; applying a refined version of proposed method

		1 – Low	2	3	4	5 – High	
7. How would you judge the proposed method?	Limited practical value		✓		(3.5)	✓	Useful method capable of significantly improving design
8. Would it provide a benefit over the current method?	Not at all			✓✓	(3)		Substantially
9. What degree of difficulty would you expect in using this method?	Low effort, cost and time			✓	✓	(3.5)	High effort, cost and time

The participants completed the questionnaires, and wrote comments in the boxes provided, which were as follows:

Current scenario:

There is a project currently looking at design knowledge and component reuse. This should help future projects.

Because of the group structure, group knowledge and components are shared. Design knowledge and historical knowledge could be improved.

'First use' scenario:

Design reuse methodology has a limited fit to the current design process. Main areas would be in standard parts. The method would require significant effort and resource.

I have no doubt that it would improve design; implementation and buy-in would be the problem.

'Experienced use' scenario:

I believe we are currently trying to utilise our own version of knowledge reuse, but we need to improve buy-in from other departments.

7.9.4. Summary of case study 2

There were significant differences in the responses given to the questionnaire by the two participants. One participant was a project manager, who had recently completed a project using the detailed NPI process. It was suggested that this process was "invaluable to a project manager". This corresponds to the positive responses on the questionnaire.

The case study set out to model the company product and design process in order to provide a context within which to assess the proposed method. The nature of the company and their design problem is quite different to that of the first case study.

The current stage gate process applied by the company supports the commercial elements of the project, alongside product risk management and specification assurance. The current design method was judged by the participants to be very good. The proposed method could provide some benefit to the company Dy supporting the engineering process. Specifically, design knowledge reuse and component reuse could be applied. The application of standard parts is also a feature identified as offering potential value.

In the 'first use' scenario, the method was judged to offer moderate value (3.5 out of 5). It was not considered that it would provide substantial benefit over the current method (2.5 out of 5). The expected difficulty in adopting the method was judged as high (4 out of 5).

In the 'experienced use' scenario, the method was again judged to offer moderate value (3.5 out of 5). It was considered that it would provide a neutral benefit over the current method (3 out of 5). The expected difficulty in adopting the method was judged as moderately high (3.5 out of 5).

7.10. Comparison between the two case studies

The two companies taking part in the case studies to assess the process based design knowledge reuse framework have various similarities and differences. These will be summarised in this section, starting with the comparison metrics considered in the preliminary investigation in chapter 4. The comparison is shown in Table 7.10-1.

	company A	**company D**
Design complexity	Medium	Low
Design technology	Medium	Low / medium
Design process detail	Medium	Medium / high
Knowledge management maturity	Medium	Medium
Specification source	Application driven	Market driven
Product family	Range of variants	Range of variants
Regulation	Medium	Medium
Production volume	Medium	High
Production investment	Medium	Medium
Relative customer power	High	Medium
Development time	3 years	1 year

Table 7.10-1: Comparison between case study companies

A key difference between the two companies is the specification source. Company A supplies the semiconductor industry, which is an industrial market. Their product (vacuum pump) forms part of a manufacturing process. The specification for the manufacturing system provides a relatively firm basis for specification of the product. There are two major customers: the end user (semiconductor manufacturer) and the semiconductor manufacturing equipment producer, referred to within the firm as the OEM. In both cases, the product forms part of a complex system with specific requirements for gas displacement and chemical handling.

Company D supplies the domestic heating market. Their product forms an integral part of the home. The specification for a home heating system is simple, in a relative sense. It must connect to the radiators and hot water systems and provide a given heat output and flow rate. They have two main customers: installers and construction companies.

7.11. Generic knowledge support requirements for design support tools

The following description of knowledge support requirements is applicable to a wide range of design projects. The insight gained across the two case studies, combined with the findings from the initial investigation, shows a number of essential elements for design support tools in practical situations. The preliminary investigation highlighted some practical requirements for design support tools: to combine an engineering view with a commercial view; to promote shared understanding of the knowledge content; to improve design knowledge access and retrieval; and to support knowledge reuse for the whole product life cycle, particularly early design. These attributes relate to the knowledge *content*. The case study investigation has shown several other factors that relate to the emphasis of design support tools in terms of the specific product development focus. These attributes relate to the knowledge *context*. The contextual knowledge support categories are:

- Requirements definition
- Product function structure development and sharing
- Performance analysis data
- Common parts
- Product structure and layout

- Regulatory guidelines

An analysis of the relative importance of these categories can guide the knowledge support strategy, and highlight those areas which require greatest effort and focus.

7.11.1. Case specific contextual knowledge support

The contextual factors have a major bearing on the knowledge support requirements. Some of the key external factors that play a role are: markets, product specification, and product complexity. These external factors result in a different emphasis for the various contextual knowledge support factors. This section will describe the requirements in each case, and then discuss commonality and differences.

A detailed product requirement definition is crucial in developing a product for company A. The requirement definition includes details of the process that the pump will support, required vacuum performance, environment category (e.g. clean room), customer type, interface data (power, network connection etc), and key product characteristics. For company D, the definition of the product is also crucial from a marketing perspective, however from a technical perspective there are fewer variables that are less demanding.

The product function structure enables both companies to define performance parameters in a modular sense. Company D divides their design effort into distinct modules, whereas company A designs each of the modules in their modular product range in the same group. Modular definition of product function is therefore important to both groups, more so company D.

Performance analysis data is applied by both companies in modelling product function in the early stages of development. Company A design vacuum pumps in which manufacturing tolerances are crucial to achieving product function. Company D manufacturing is generally less sensitive to production tolerances. As such, the definition and sharing of data relevant to product performance is of greater importance to company A. There is also a distinction between market types: company A is more sensitive to engineering requirements as they produce a range of products with quite different requirements. Company D has a more stable requirement across their product range. The product performance therefore differs considerably.

Common parts and features data is of greater importance to company D, since they operate in a high volume production environment, whereas company A operate medium volume production. Clearly, benefits can be gained in both areas by specifying common parts and features. It is of greater importance to company D to ensure that common parts data are effectively shared in the NPI process. The relative importance of each of knowledge types (requirements, function, performance data, common parts, regulatory guidelines and layout data) is displayed in a radar diagram in Figure 7.11-1.

The critical element of product knowledge representation for company A is the definition and sharing of engineering requirements in order to create and assess a product that performs to that specification. The critical element of product knowledge representation for company D is the definition and sharing of a standard component library within a modular design domain. Regulatory guidelines are also a major focus for company D.

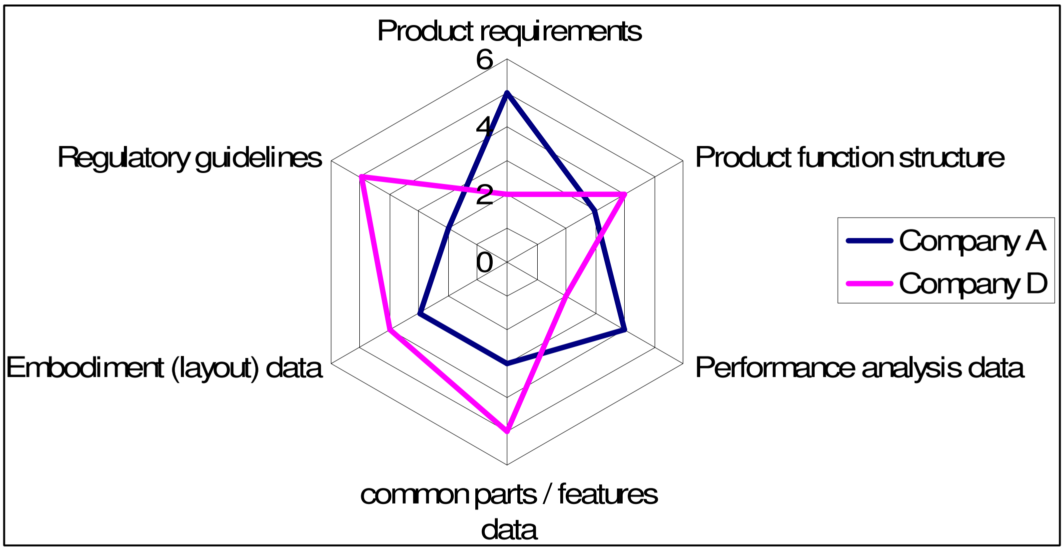


Figure 7.11-1: radar diagram showing relative importance of knowledge types

7.12. Summary of chapter 7

This specification complexity represents a key difference between the two companies in terms of its implications for product modelling. Company A requires a detailed engineering specification that leads to a product function structure with associated knowledge based engineering tasks applied to that structure to specify the details of the product structure. Company D requires a product specification to support project planning and design integration, however the engineering detail required is lower. The scope of the conceptual design stages in company A is broader. There are more variables to consider, a wider range of product options to suit the requirement, and a greater degree of engineering complexity.

This early design stage is the main focus of the process based design knowledge reuse system, and in company D the scope of that stage is limited. As such, the applicability of the method is limited.

Currently, both companies apply the stage gate method for the NPI process. Neither company has in place a data driven (engineering focused) NPI knowledge support method. It has been shown that the needs of each company are different. A design knowledge reuse framework that supports product, process and task knowledge has been evaluated in two case studies. It has been shown to support the needs of a company whose primary knowledge support need is the definition and sharing of engineering requirements (along with the methods to address those requirements) as a means to develop an effective product. It requires further work if it is to fully support the second company whose primary product knowledge support need is the definition and sharing of a standard component library to support the integration design task and minimise manufacturing costs.

An additional method to describe a generic product structure could be developed as an additional feature of the product knowledge model. This would entail an extension of the design ontology to include standard parts definitions.

Chapter 8: Conclusions and further work

8.1. Overall conclusion of the research project

The epistemological stance adopted for this research project is critical theory. This assumes that causal laws can be identified through interpretive understanding; interpretive since knowledge is created through interpretation. Embedded meanings and context have significant influence on interpretation.

The research aim is to provide a method for reusing engineering design knowledge. This aim relates to making proposals for new methods within well understood domains, rather than generating theory in a new domain. The research strategy adopted was therefore case study.

An preliminary investigation sought to characterise design knowledge reuse in practice. Three companies took part in the initial stages. Each one designed mechanical systems, with varying complexity. The relative design complexity correlated to the use of advanced design tools and the degree of maturity in the understanding and adopting knowledge management strategy and methods. The preliminary investigation showed that design knowledge reuse in practice is lacking, and that there are several limitations to adopting design reuse. There was not a clear design reuse strategy in any of the organisations. Design reuse practices that were in use were not part of a wider coherent structure, and this limited the potential to share good practice.

The main source of knowledge reuse was designer personal notebooks, shared documents and intranet. Each one has problems associated: personal notebooks are not shared, so can only be reused by the original author. Intranet use presented a similar challenge, largely due to the user driven content: whilst the notes are available, they are not easy to find and they are not presented in a way that makes them easy to reuse. Shared documents provided a level of design reuse in one company, however the value of the document seemed to diminish as its size increased. These knowledge reuse methods, where they are available for reuse, lack context.

Where design knowledge capture takes place locally, for instance in Excel models, there is a significant challenge in terms of reuse by a novice. Since these models tend to be created as a ‘quick calculation’, the limits of applicability are not defined, and the main assumptions are not documented. Reuse of such models can therefore provide unworkable solutions, which novices are not able to identify.

In the product development processes, there seemed to be an engineering bias. Whilst there is a business process structure in place in each case, the apparent focus of the design team is on the achievement of the engineering goals. Since engineering goals can be met better with a new solution (rather than an existing solution), this tends to be what happens. The engineering focused applied practice was not in line with the commercially focused prescribed practice. There is an apparent gap between the two.

In summary, the industrial challenges in adopting design knowledge reuse are:

- Access to relevant and contextualised captured design knowledge. Storage methods do not support reuse in context: centralised and unstructured vs. locally held and unavailable.
- Developing a relationship between design reuse and the product development process.
- Integrating engineering and business objectives.

A second major contributor to the proposal for a design knowledge reuse framework was a literature review. The review had two major outcomes: first, it provided the researcher with an understanding of the domain, including terminology, concepts and models that have been proposed and applied. Second, the literature review provided a contextual framework within which to position the research. This contextual framework supports the location of the research proposal within the existing body of academic literature as well as identifying gaps in that literature that the proposals may contribute to.

The literature review identified three key domains: knowledge management, design reuse and design process support. Knowledge management was important since the aim relates to design knowledge reuse, which broadly speaking fits within the domain of knowledge management. Knowledge management literature also provided definitions of knowledge and knowledge management. Design reuse is the subject of the research. The review suggested that the design reuse approach must consider design methodology, since design methodology and design knowledge reuse are reliant on one another; each influences the other. Conceptual design, and the view of design as a development of a theory of an artefact, is an important element of design knowledge reuse. Design reuse relates to design modelling, which links to strategic information and knowledge requirements. Formal guidelines for design knowledge reuse are currently lacking. Design process support was identified as a category after the review of knowledge management and design reuse literature suggested that the design process was an integral element of design reuse. This new category became the focal domain within which to locate the research. Within the design process support category, three sub-categories were defined: Methodology based design, Business process modelling for design, and Design process integration.

The following research gaps were identified:

- Design reuse for the whole product life cycle;
- Integrated product and process models;
- A ‘how-to’ element of the product design process;

The combination of literature findings, particularly the gaps identified, and the industrial challenges led to the proposal for a process based design knowledge reuse framework. The components of the method are: process, product and task modelling. Here, the method will be summarised along with a description of how the research gaps and industrial challenges are addressed. Formally representing the design process enables the structured application of design methodology, best practices and design reuse. This supports two of the industrial challenges: the process provides an element of context, plus it shows a relationship between the design knowledge reuse framework and the design process. Product modelling has been identified as an important element of design knowledge reuse, since a conceptual model of the product enables a focused, modular approach to design reuse. It also enables the design organisation to consider engineering and business objectives as contributing elements in a coherent strategy. The application of ontology in product modelling promotes shared understanding of the design models and concepts during the development process. Task modelling enables the provision of a ‘how-to’ approach to the design process, and supports the sharing of additional design knowledge through direct links to other sources and through links to relevant people. The integration of the product and process models enables a data driven approach to engineering design: providing product data as a task input, performing calculations (where appropriate) and capturing product data generated by design tasks. Conceptual level product modelling ensures that early design can be supported.

The method was implemented in a Web based prototype system. In developing the system, there were a number of interesting findings. Images are a powerful tool in design process support, and should be included where possible. A task template supports structured knowledge capture as well as reuse. The knowledge capture process is itself a knowledge management exercise, since the act of formalising and validating the design process is itself a reengineering exercise that requires a systematic view of current design methods. Process modelling that sets out to be 'as-is' tends to show 'should-be' even before validation and analysis.

The analysis of the prototype system suggested that the combination of process, product and task knowledge could support the reuse of working methods, which saves time. It also showed that process validation is a key part of the method development, and that user groups should validate the process before it is implemented.

The subsequent exercise sought to validate the method through further case studies. Two companies were compared. It was identified that the specification complexity represented a key difference between the two companies. Specification has important implications for product modelling. In one case, a detailed engineering specification was required. In the other, the required engineering detail was lower. The support for early design and a data driven engineering view of the process emphasise conceptual modelling. Conceptual modelling is critical in early stages, and the degree of that modelling relates to the specification complexity. The method was shown to be suited to design environments with complex specifications, leading to a high potential value for conceptual product modelling.

Design process support is an integral part of design knowledge reuse. The proposed method met the research gaps, identified as: knowledge reuse for the whole product life cycle (particularly early design), integrated product and process models, how-to element of product design process, and an engineering design process layer (data-driven design process) through the integration of process, product and task models. It also addressed the industrial challenges, identified as: access to relevant and contextualised knowledge; developing a relationship between design reuse and the design process; integrating engineering and business objectives. The method was implemented in a prototype system and evaluated through case studies. The scope of the method is limited to mature engineering domains in which a complex product specification is applied.

8.2. Summary of main achievements:

The main achievements in this project are:

- Proposed an appropriate research methodology for an applied research project
- Identified industrial challenges and requirements for design knowledge reuse
- Identified research gaps through an extensive literature review
- Proposed a process based design knowledge reuse framework
- Developed a prototype system to implement the framework
- Captured process, task and product knowledge and populated the system
- Assessed the system and method through company case studies
- Concluded that the proposed framework would improve design reuse

8.3. Further work

During the research project, there were several areas of work that were identified as interesting, but that did not contribute directly to the aim and objectives. There are also avenues for future research within the design knowledge reuse domain that will be described here.

8.3.1. Manufacturability analysis

Combining the design knowledge reuse framework with a manufacturability analysis method that can take account of nominal, actual and future capability would provide significant value, particularly in high tolerance machining. Manufacturing knowledge could be readily integrated with a process based knowledge reuse framework.

8.3.2. Service knowledge integration

Manufacturing businesses are recognising the increasing importance of service to revenue growth and customer retention. The particular needs of service in a design context need to be further investigated in order that appropriate support can be provided. Service design, integrated product and service offerings and service supply chain development are some of the factors that need to be considered.

8.3.3. Change effects

The proposed method would benefit from a method to provide details of the impact of changes to previous product model data, and to track those changes and their effects. Some work exists relating to associative design, however data integration at the task level has not been considered. A detailed investigation would be required in order to support such a feature, since change effects are potentially complex and can be far reaching. A method to show which parameters must be re-checked when a given change is made would add value to the user – particularly where this feature is related at the task level and shows how the parameter can be re-checked. This could form part of a sensitivity analysis in deciding whether or not the benefits of making a given change outweigh the costs of making it, in terms of added product development time and associated project slippage. Identifying parameter dependency chains would itself be a valuable exercise to support the development of an optimal design process. For example, in the development of the vacuum pump, the centre distance between the shafts supporting the rotors is known to be a critical parameter, and a great deal of the further development work is dependent on that parameter. Changing it may be proposed in order to change various performance or product size factors. Knowledge of the detailed effects of that change, including the dependent parameters and the sequence of re-design, would be valuable. This parameter dependency feature could be used to plan and track design changes and iterations throughout the development cycle.

8.3.4. Process templates

Further work is required to develop process templates to support company or industry best practice and design methodology specific processes, such as TRIZ, axiomatic design and systematic design. Additional templates, including FMEA and QFD, could be added to the template library. A key aspect of this work would relate to the implementation of a process template to an existing design process: integrating generic problem solving methods in a specific design environment.

8.3.5. Implementation guidance

Whilst an implementation plan has been proposed, a more detailed plan would be required for supporting a commercial implementation.

8.3.6. System features

Further work is also required to improve the proposed system, in order to make it suitable for commercial adoption. Briefly, this includes: security features, transaction features to prevent concurrent and conflicting data updates, and user personalisation including permissions (access to read, write or delete data entries).

A process writing feature is required to support process development in the system. The process writing feature would enable graphical ‘drag and drop’ type process development, including a range of templates.

8.3.7. Low overhead product data management

A key limitation of product data management technology is the effort involved with implementing product data. A low user overhead version that is able to maintain the same degree of data integrity could be combined with a process based design knowledge reuse system to provide an enterprise level system that can be used in an active sense in product development for all aspects of product development, rather than simply inheriting CAD data structures: a support tool for design that is underway rather than a record of what took place.

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Appendices

Appendix 1: Questionnaire

Proposal for PhD validation:

Reusing Design Knowledge through integrating Process, Product and Task knowledge

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Scenario analysis

Scenario 1: existing design method

Make an assessment of the categories below based on current practice. How effective is the design process? What level of design reuse takes place? What level of design reuse is possible?

Scenario 2: new project, first use of proposed design knowledge reuse framework

Make an assessment of how you think the proposed method would influence a project the first time it is used.

Scenario 3: new project, applying a refined version of proposed design knowledge reuse framework

Make an assessment of how you think the proposed method would influence a project as a mature and up to date system.

Scenario 1: current design process

		1 – Low	2	3	4	5 – High	
1. How effective is the current design process?	Late, quality problems, not to spec						On time, high quality, exceeding spec
2. What level of design reuse takes place?	No formal reuse						Fully automated design
3. What level of design reuse is possible?	Very little						A great deal

Any further comments on this scenario?

Scenario 2: new project; using knowledge reuse framework first time

		1 – Low	2	3	4	5 – High	
4. How would you judge the proposed method?	Limited practical value						Useful method capable of significantly improving design
5. Would it provide a benefit over the current method?	Not at all						Substantially
6. What degree of difficulty would you expect in adopting this method?	Low effort, cost and time						High effort, cost and time

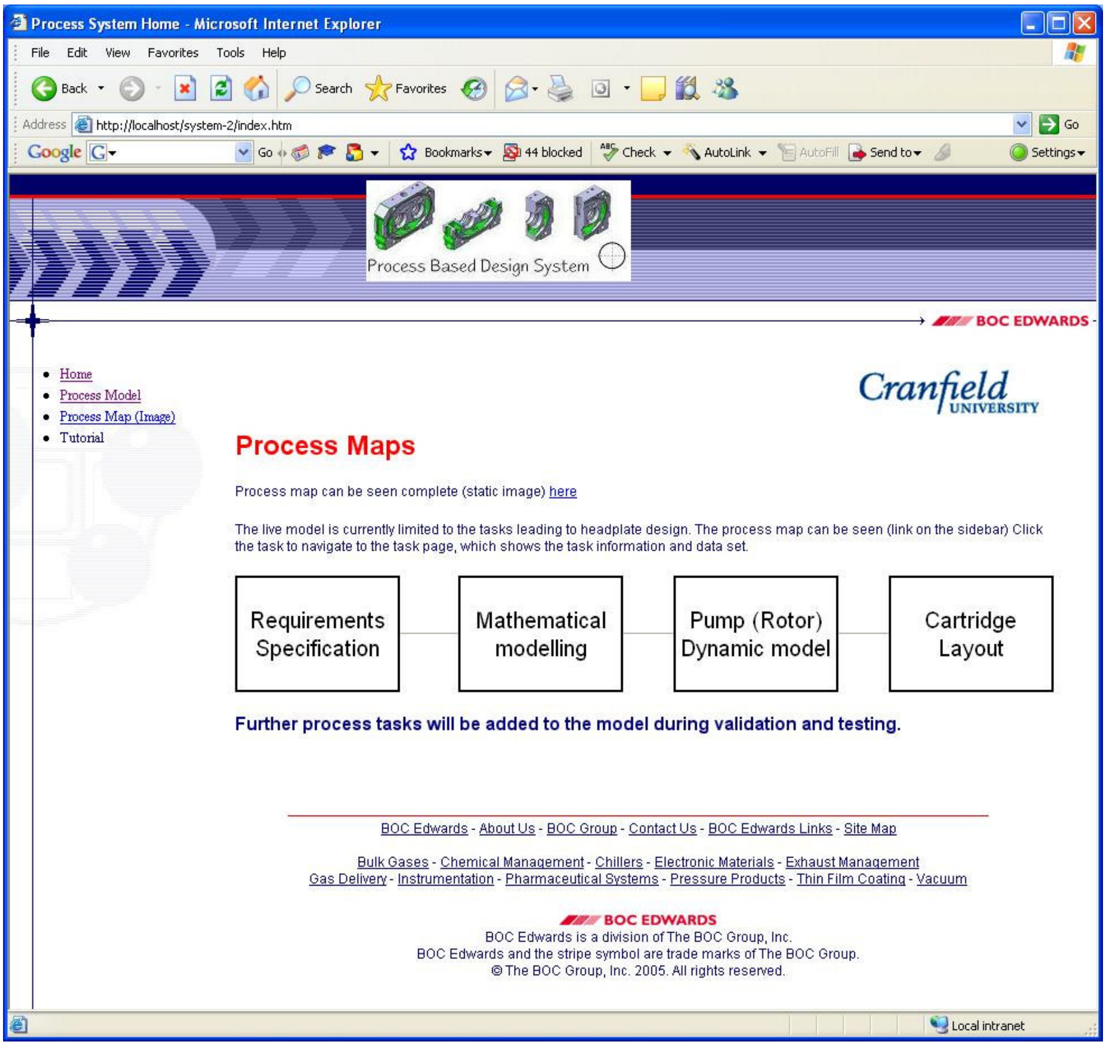
Any further comments on this scenario?

Scenario 3: new project; applying a refined version of proposed method

		1 – Low	2	3	4	5 – High	
7. How would you judge the proposed method?	Limited practical value						Useful method capable of significantly improving design
8. Would it provide a benefit over the current method?	Not at all						Substantially
9. What degree of difficulty would you expect in adopting this method?	Low effort, cost and time						High effort, cost and time

Any further comments on this scenario?

Appendix 2: Screenshots showing Web prototype System



- Home
- Process Model
- Process Map (Image)
- Tutorial

Process Maps

Process map can be seen complete (static image) here

The live model is currently limited to the tasks leading to headplate design. The process map can be seen (link on the sidebar) Click the task to navigate to the task page, which shows the task information and data set.

Requirements Specification – Mathematical modelling – Pump (Rotor) Dynamic model – Cartridge Layout

Further process tasks will be added to the model during validation and testing.

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Gas Delivery - Instrumentation - Pharmaceutical Systems - Pressure Products - Thin Film Coating - Vacuum

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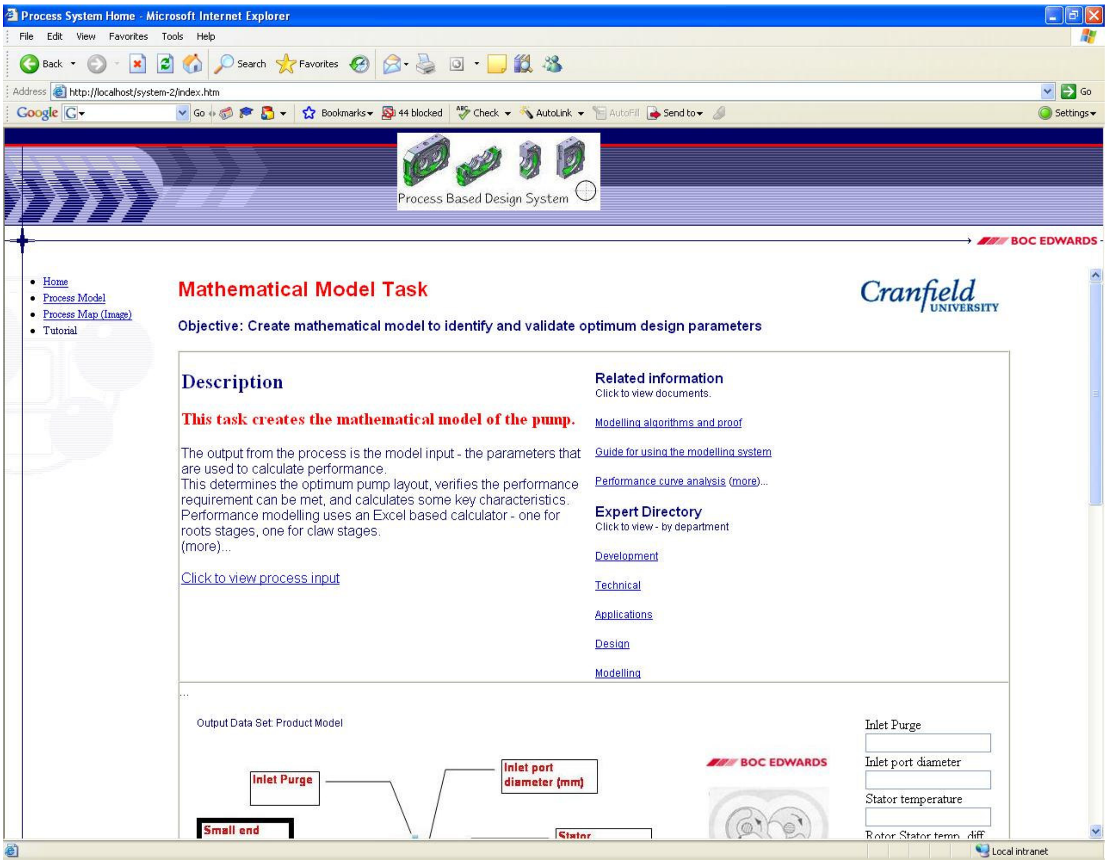
Figure 8.3-1: Web prototype system page 1 - process model



Mathematical Model Task

Objective: Create mathematical model to identify and validate optimum design parameters

Description

This task creates the mathematical model of the pump.

The output from the process is the model input - the parameters that are used to calculate performance.
This determines the optimum pump layout, verifies the performance requirement can be met, and calculates some key characteristics.
Performance modelling uses an Excel based calculator - one for roots stages, one for claw stages.
(more)...

Click to view process input

Related information
Click to view documents.

Modelling algorithms and proof

Guide for using the modelling system

Performance curve analysis (more)...

Expert Directory
Click to view - by department

Development

Technical

Applications

Design

Modelling

...

Output Data Set: Product Model

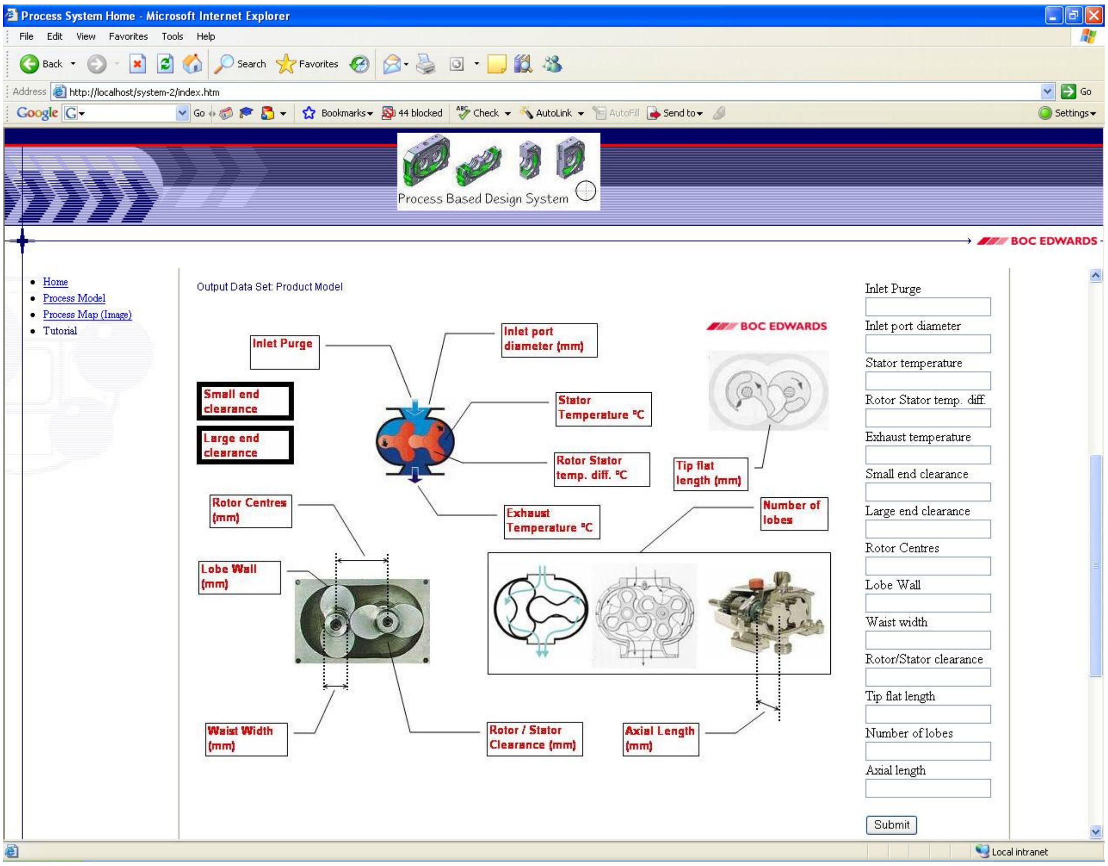
Inlet Purge

Inlet port diameter

Stator temperature

Rotor Stator temp. diff.

Figure 8.3-2: Web prototype system mathematical model task 1



Output Data Set: Product Model

Inlet Purge

Inlet port diameter

Stator temperature

Rotor Stator temp. diff.

Exhaust temperature

Small end clearance

Large end clearance

Rotor Centres

Lobe Wall

Waist width

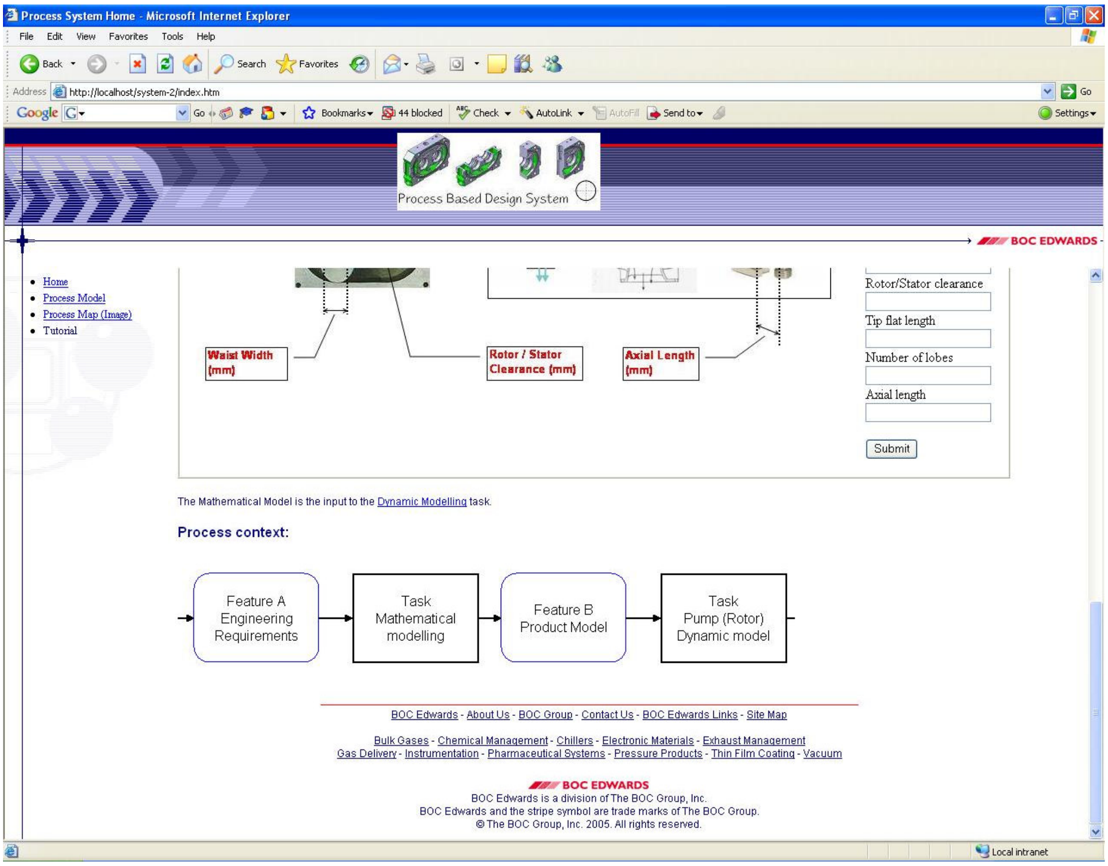
Rotor/Stator clearance

Tip flat length

Number of lobes

Axial length

Figure 8.3-3: Web prototype system mathematical model task 2



Rotor/Stator clearance
Tip flat length
Number of lobes
Axial length

The Mathematical Model is the input to the Dynamic Modelling task.

Process context:

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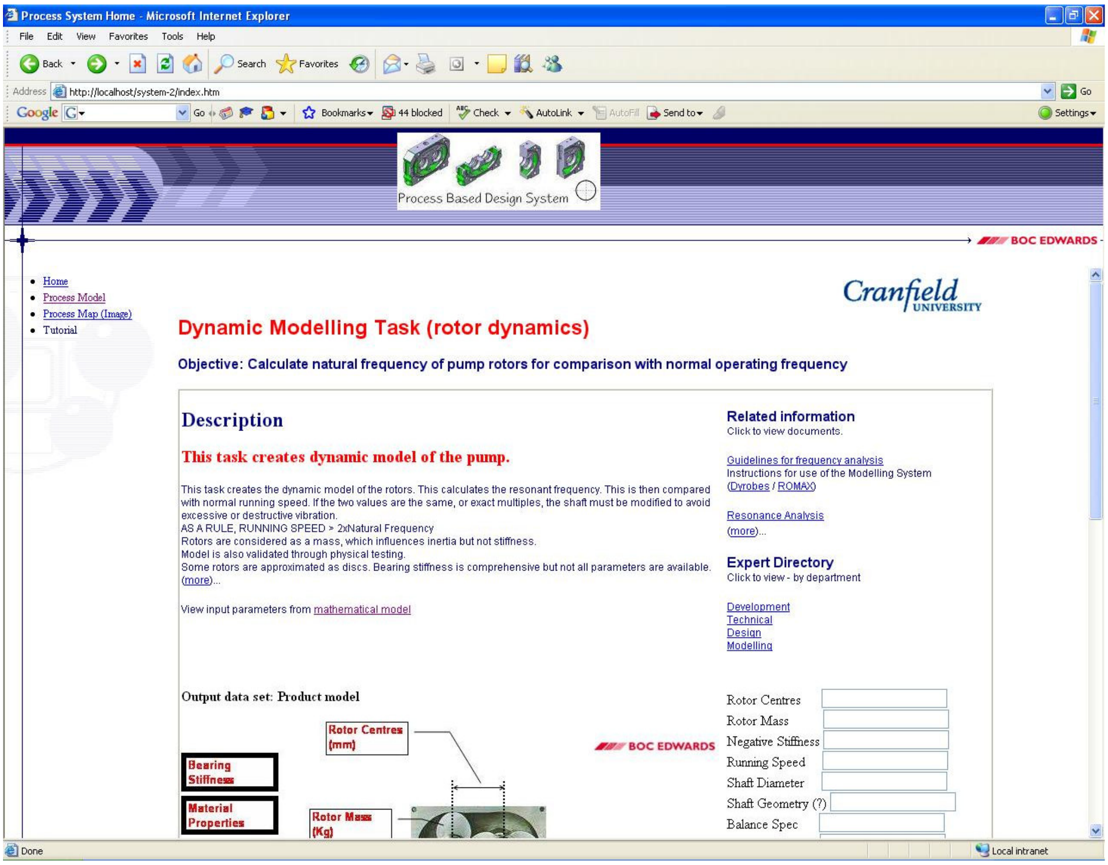
Figure 8.3-4: Web prototype system mathematical model task 3



Dynamic Modelling Task (rotor dynamics)

Objective: Calculate natural frequency of pump rotors for comparison with normal operating frequency

Description

This task creates dynamic model of the pump.

This task creates the dynamic model of the rotors. This calculates the resonant frequency. This is then compared with normal running speed. If the two values are the same, or exact multiples, the shaft must be modified to avoid excessive or destructive vibration.
AS A RULE, RUNNING SPEED > 2xNatural Frequency
Rotors are considered as a mass, which influences inertia but not stiffness.
Model is also validated through physical testing.
Some rotors are approximated as discs. Bearing stiffness is comprehensive but not all parameters are available.
(more)...

View input parameters from mathematical model

Related information
Click to view documents.

Guidelines for frequency analysis
Instructions for use of the Modelling System
(Dyrobes / ROMAX)

Resonance Analysis
(more)...

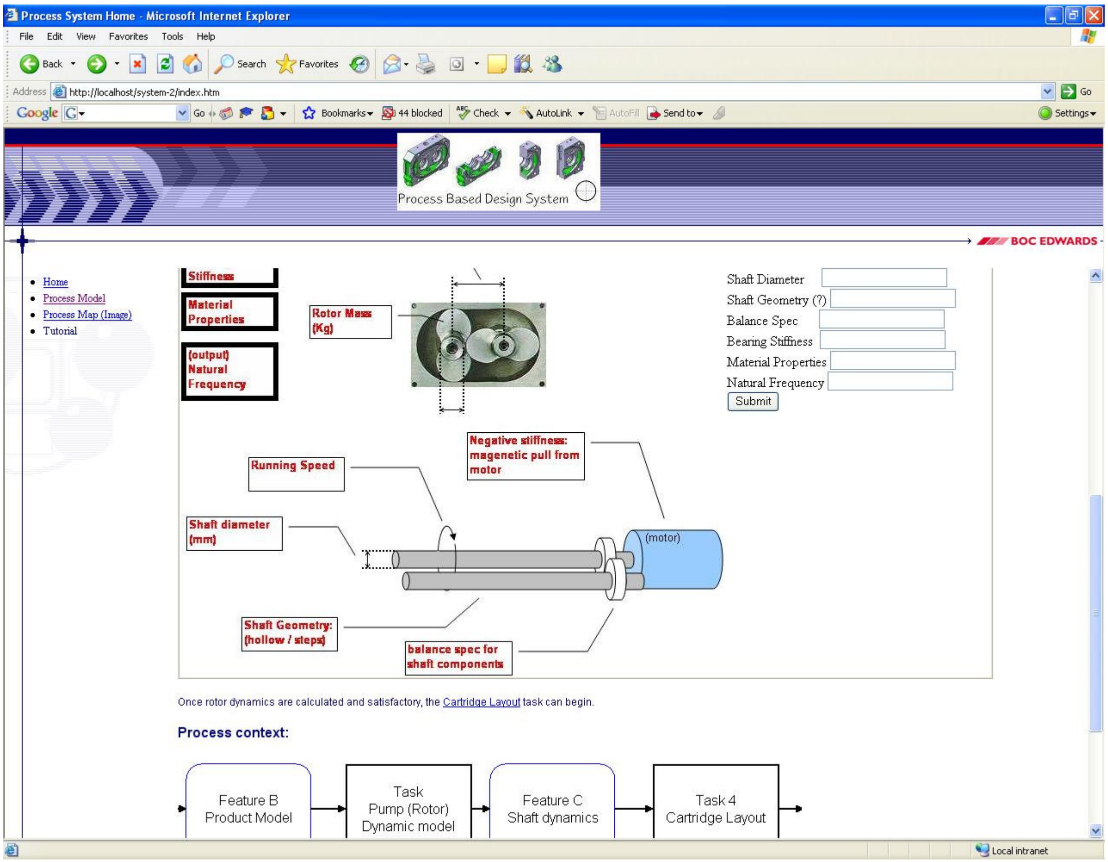
Expert Directory
Click to view - by department

Development
Technical
Design
Modelling

Output data set: Product model

Rotor Centres
Rotor Mass
Negative Stiffness
Running Speed
Shaft Diameter
Shaft Geometry (?)
Balance Spec

Figure 8.3-5: Web prototype system dynamic modelling task 1



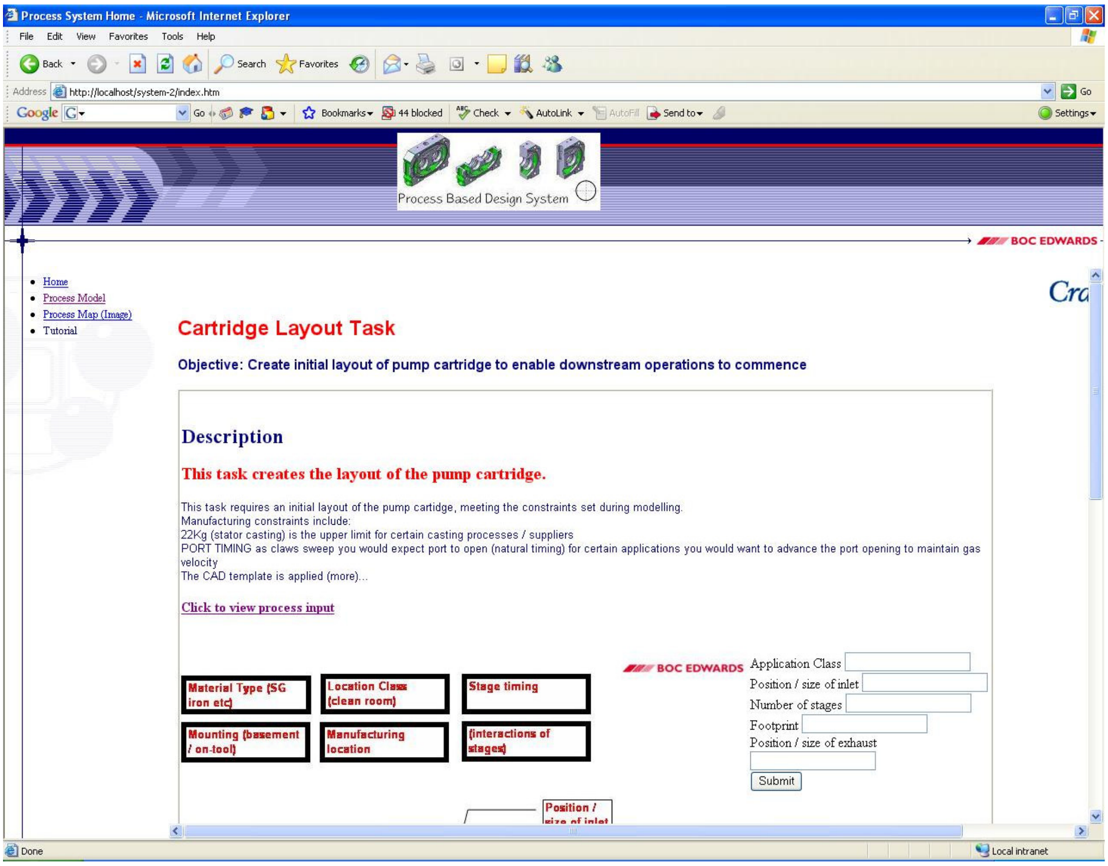
http://localhost/system-2/index.htm

Shaft Diameter
Shaft Geometry (?)
Balance Spec
Bearing Stiffness
Material Properties
Natural Frequency

Once rotor dynamics are calculated and satisfactory, the Cartridge Layout task can begin.

Process context:

Figure 8.3-6: Web prototype system dynamic modelling task 2



http://localhost/system-2/index.htm

Cartridge Layout Task

Objective: Create initial layout of pump cartridge to enable downstream operations to commence

Description

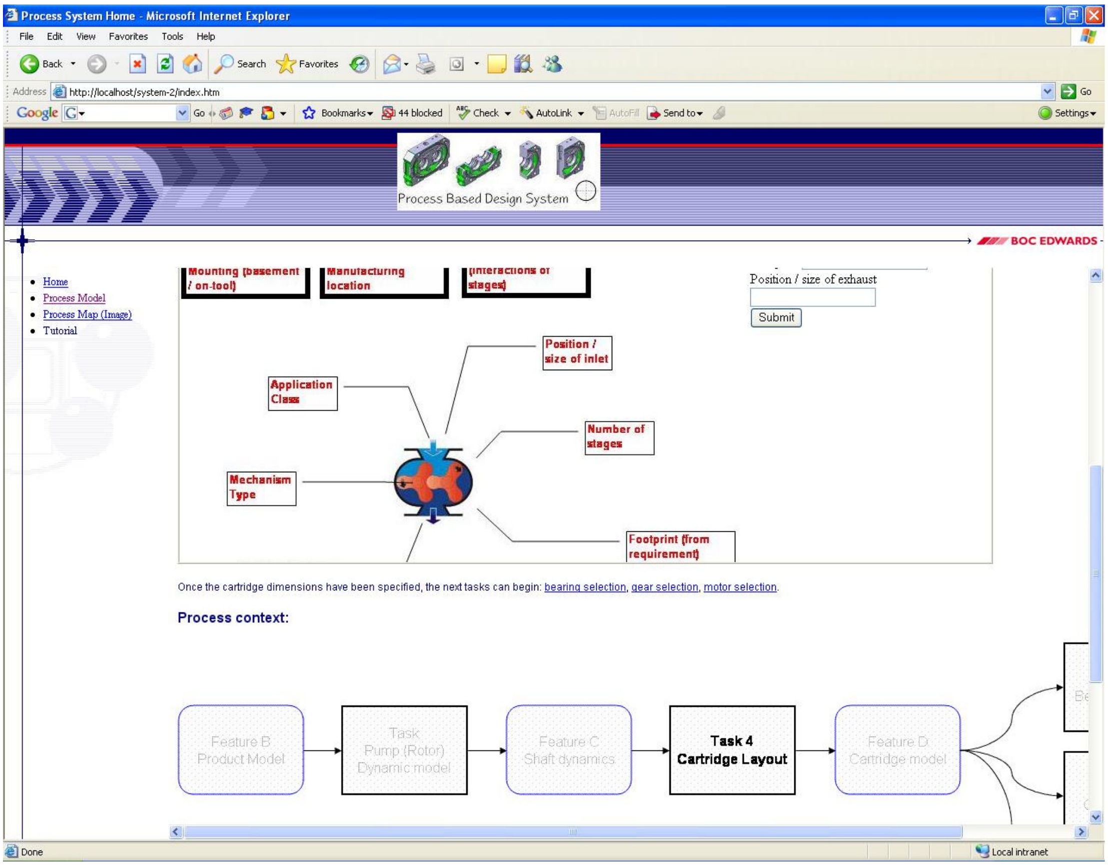
This task creates the layout of the pump cartridge.

This task requires an initial layout of the pump cartidge, meeting the constraints set during modelling.
Manufacturing constraints include:
22Kg (stator casting) is the upper limit for certain casting processes / suppliers
PORT TIMING as claws sweep you would expect port to open (natural timing) for certain applications you would want to advance the port opening to maintain gas velocity
The CAD template is applied (more)...

Click to view process input

Application Class
Position / size of inlet
Number of stages
Footprint
Position / size of exhaust

Figure 8.3-7: Web prototype system cartridge task 1



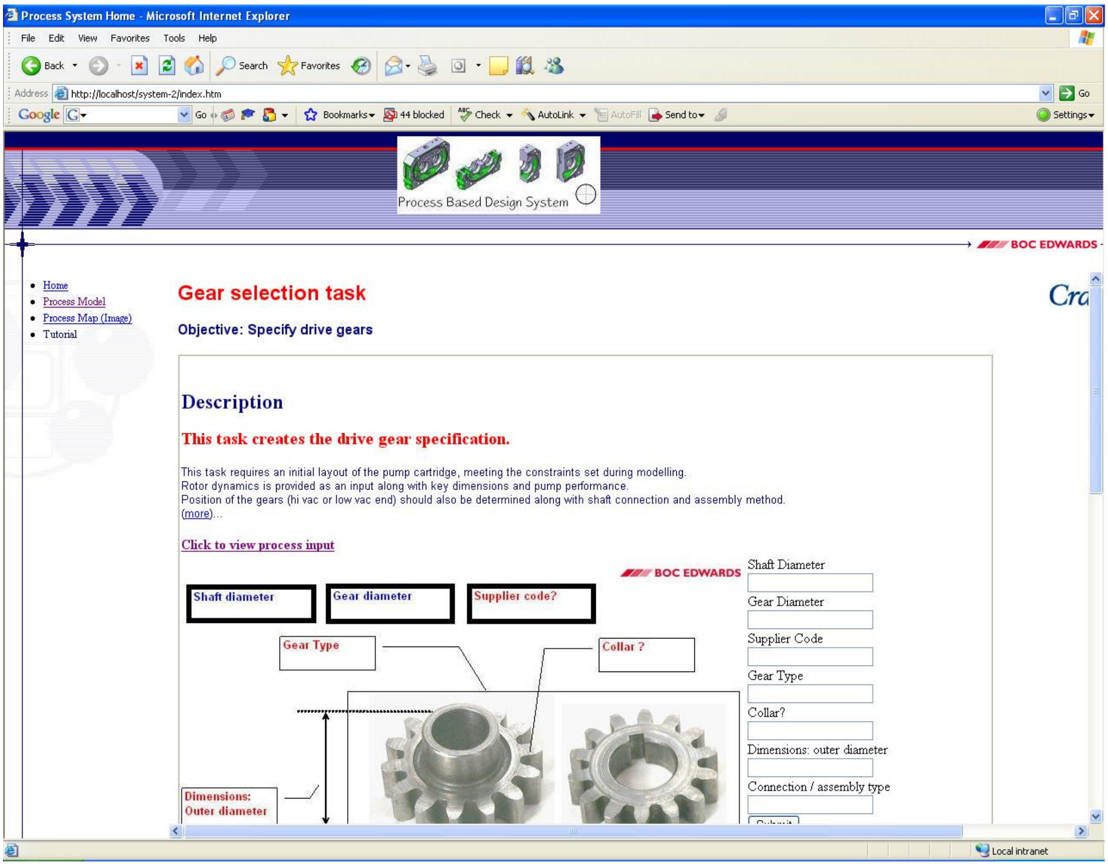
Position / size of exhaust

Submit

Once the cartridge dimensions have been specified, the next tasks can begin: bearing selection, gear selection, motor selection.

Process context:

Figure 8.3-8: Web prototype system cartridge task 2



Gear selection task

Objective: Specify drive gears

Description

This task creates the drive gear specification.

This task requires an initial layout of the pump cartridge, meeting the constraints set during modelling.
Rotor dynamics is provided as an input along with key dimensions and pump performance.
Position of the gears (hi vac or low vac end) should also be determined along with shaft connection and assembly method.
(more)...

Click to view process input

Shaft Diameter

Gear Diameter

Supplier Code

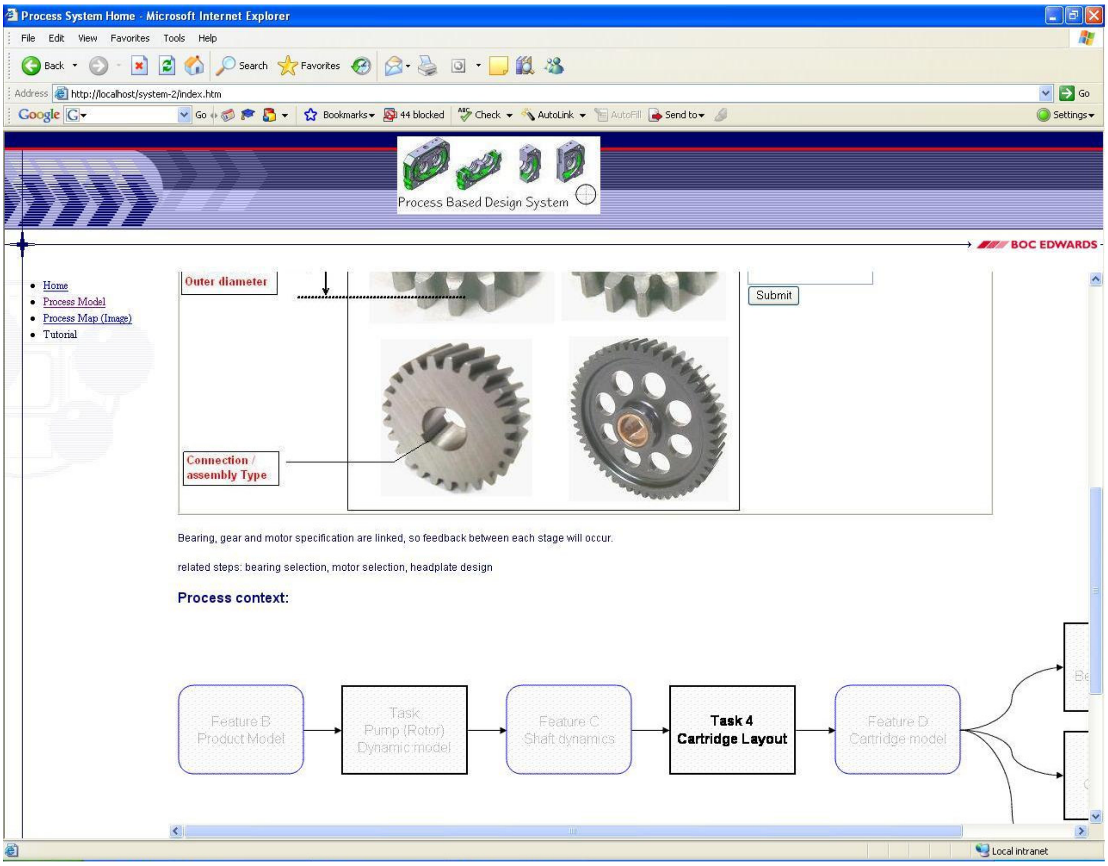
Gear Type

Collar?

Dimensions: outer diameter

Connection / assembly type

Figure 8.3-9: Web prototype system gear selection task 1

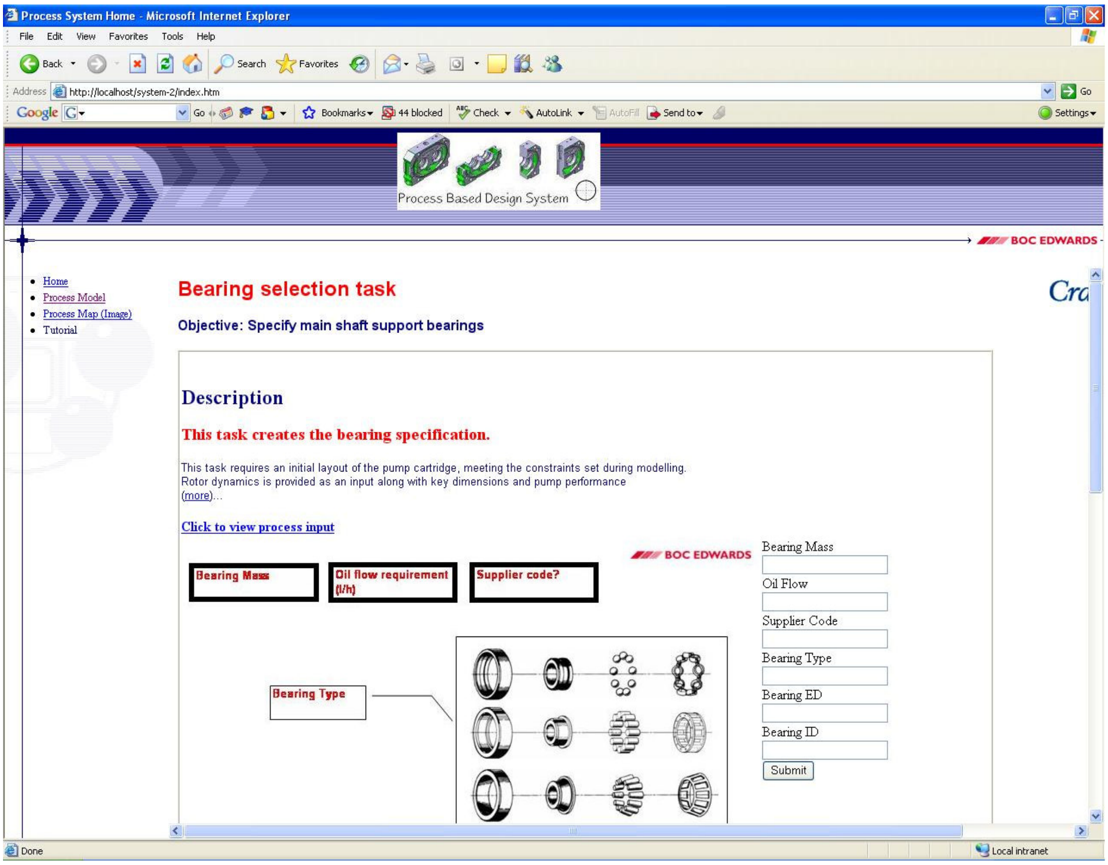


Bearing, gear and motor specification are linked, so feedback between each stage will occur.

related steps: bearing selection, motor selection, headplate design

Process context:

Figure 8.3-10: Web prototype system gear selection task 2



Bearing selection task

Objective: Specify main shaft support bearings

Description

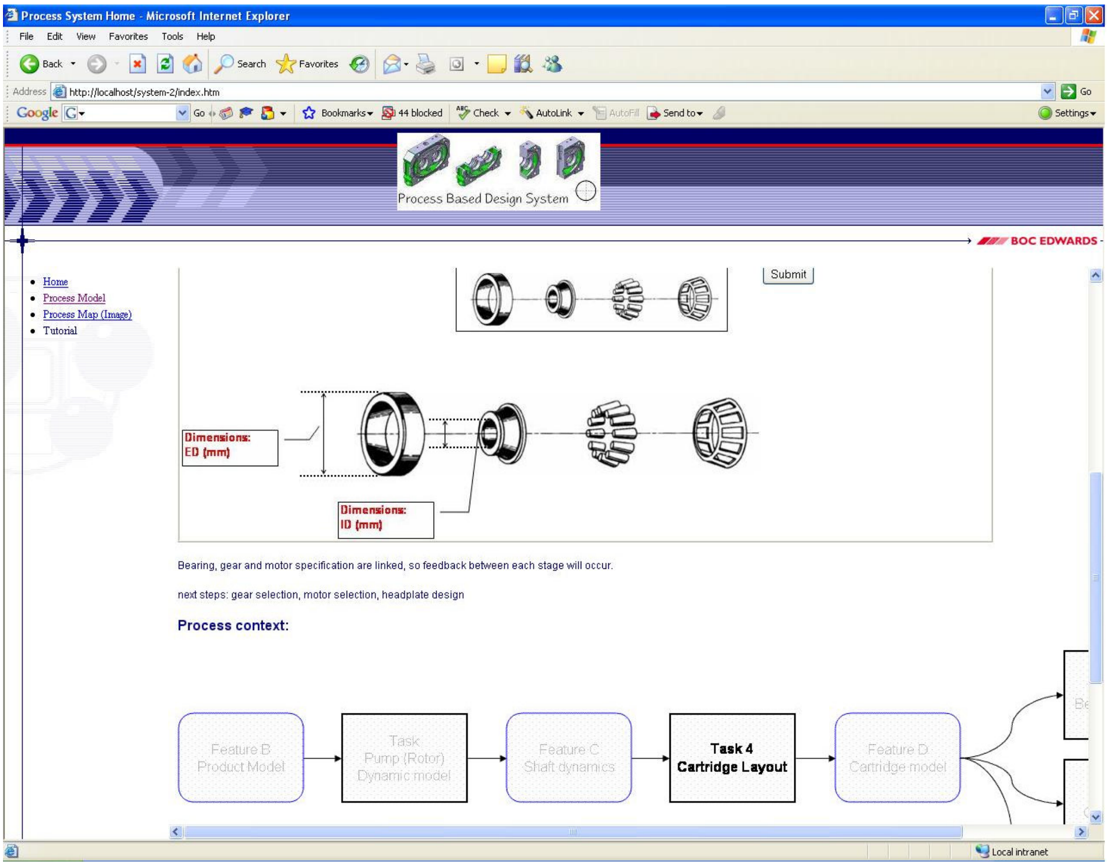
This task creates the bearing specification.

This task requires an initial layout of the pump cartridge, meeting the constraints set during modelling.
Rotor dynamics is provided as an input along with key dimensions and pump performance
(more)...

Click to view process input

Bearing Mass
Oil Flow
Supplier Code
Bearing Type
Bearing ED
Bearing ID

Figure 8.3-11: Web prototype system bearing definition task 1

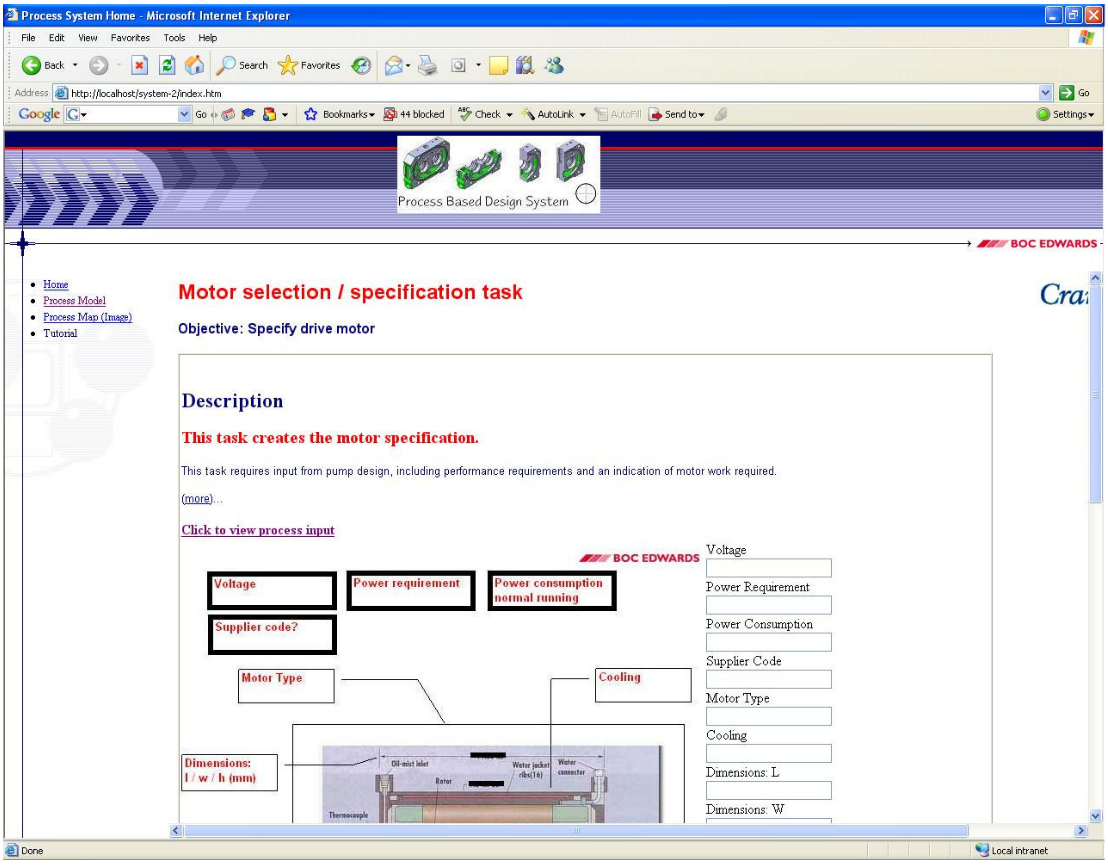


Bearing, gear and motor specification are linked, so feedback between each stage will occur.

next steps: gear selection, motor selection, headplate design

Process context:

Figure 8.3-12: Web prototype system bearing definition task 2



Motor selection / specification task

Objective: Specify drive motor

Description

This task creates the motor specification.

This task requires input from pump design, including performance requirements and an indication of motor work required.

(more)...

Click to view process input

Voltage

Power Requirement

Power Consumption

Supplier Code

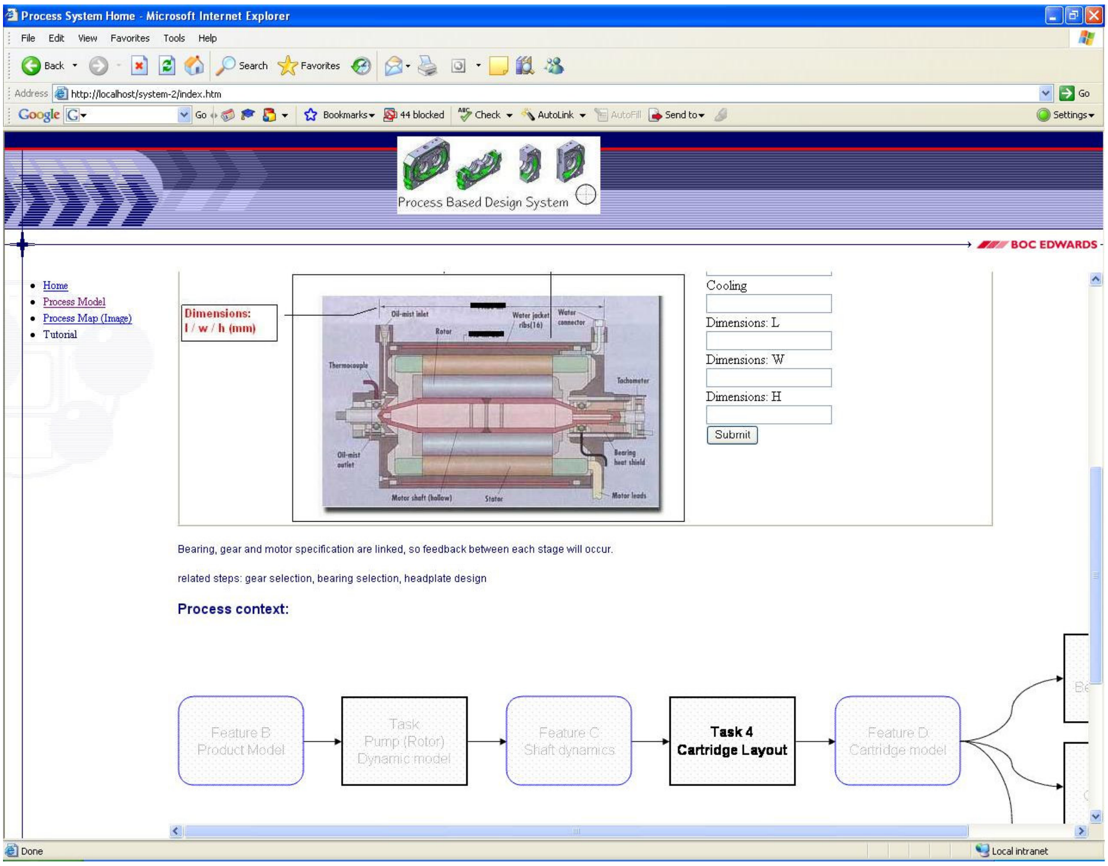
Motor Type

Cooling

Dimensions: L

Dimensions: W

Figure 8.3-13: Web prototype system motor definition task 1



Cooling

Dimensions: L

Dimensions: W

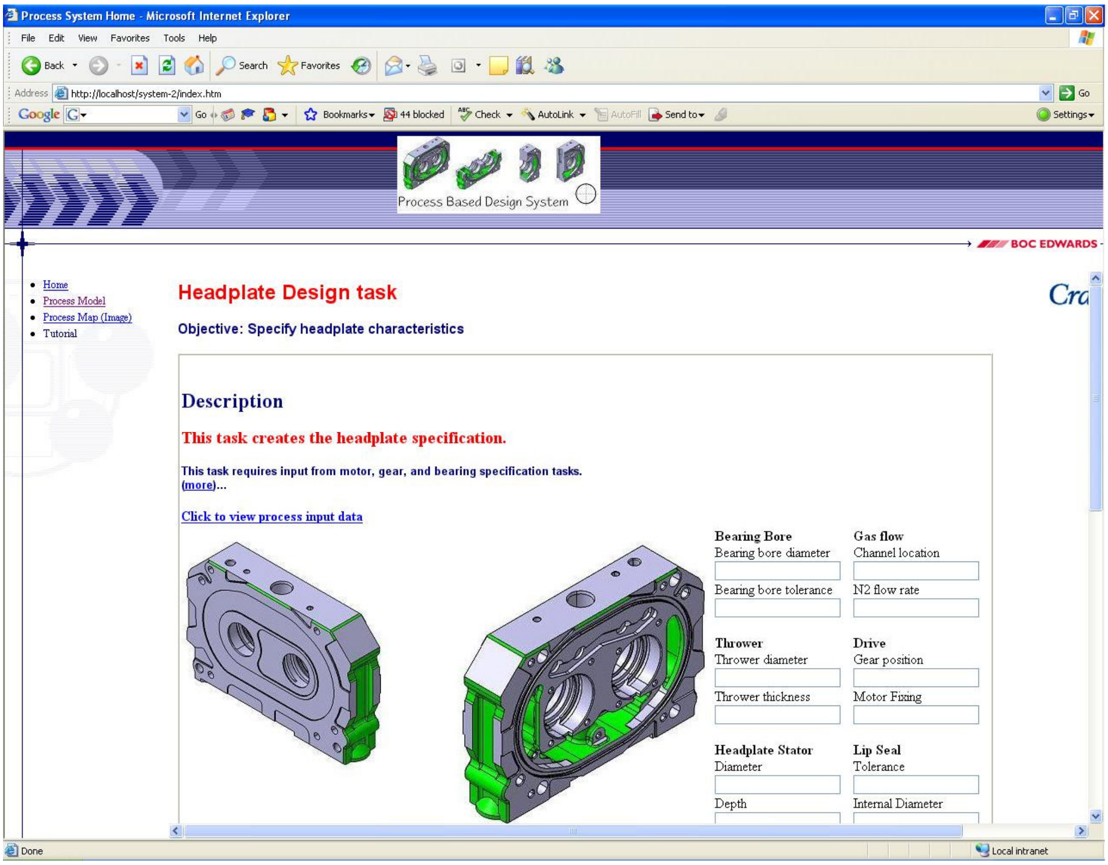
Dimensions: H

Bearing, gear and motor specification are linked, so feedback between each stage will occur.

related steps: gear selection, bearing selection, headplate design

Process context:

Figure 8.3-14: Web prototype system motor definition task 2



Headplate Design task

Objective: Specify headplate characteristics

Description

This task creates the headplate specification.

This task requires input from motor, gear, and bearing specification tasks.
(more)...

Click to view process input data

Bearing Bore
Bearing bore diameter
Bearing bore tolerance

Gas flow
Channel location
N2 flow rate

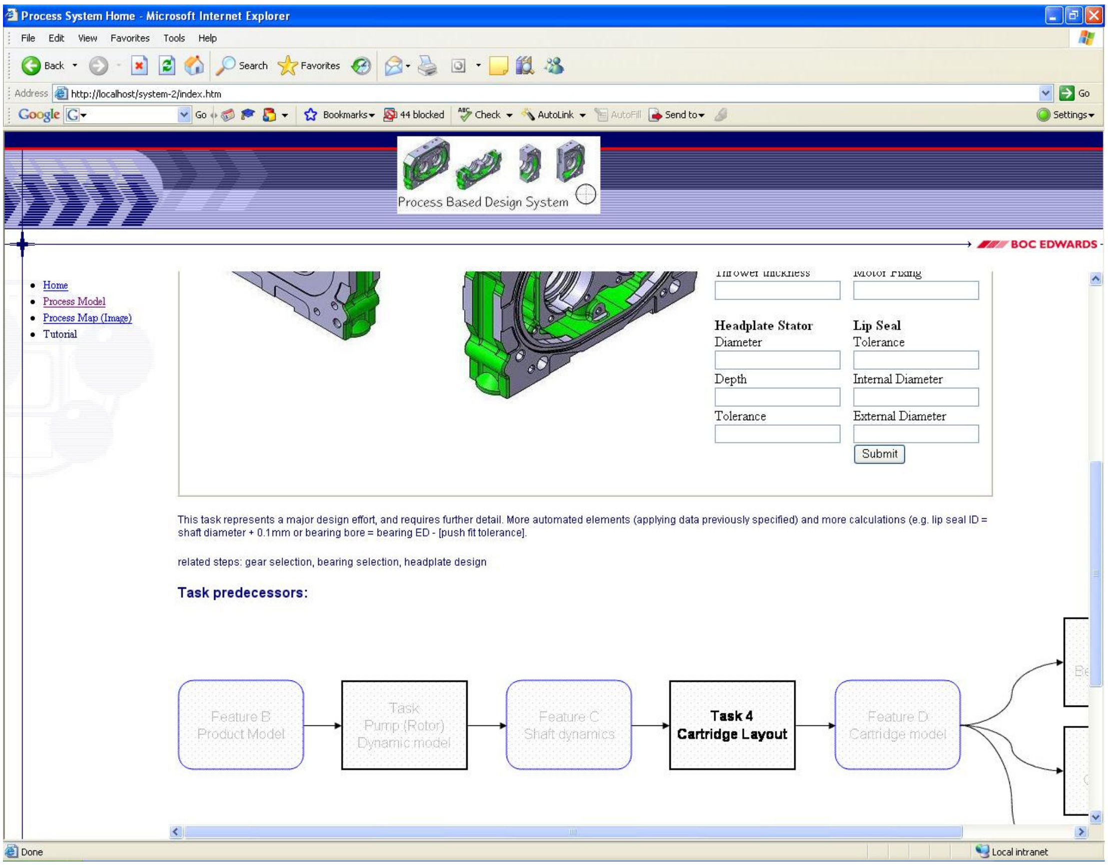
Thrower
Thrower diameter
Thrower thickness

Drive
Gear position
Motor Fixing

Headplate Stator
Diameter
Depth

Lip Seal
Tolerance
Internal Diameter

Figure 8.3-15: Web prototype system headplate design task 1



Thrower thickness

Motor Fixing

Headplate Stator
Diameter
Depth
Tolerance

Lip Seal
Tolerance
Internal Diameter
External Diameter

Submit

This task represents a major design effort, and requires further detail. More automated elements (applying data previously specified) and more calculations (e.g. lip seal ID = shaft diameter + 0.1mm or bearing bore = bearing ED - [push fit tolerance].

related steps: gear selection, bearing selection, headplate design

Task predecessors:

Figure 8.3-16: Web prototype system headplate design task 2