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An Engineering Design Knowledge Reuse Methodology Using Process Modelling

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Abstract

This paper describes an approach for reusing engineering design knowledge. Many previous design knowledge reuse systems focus exclusively on geometrical data, which is often not applicable in early design stages. The proposed methodology provides an integrated design knowledge reuse framework, bringing together elements of best practice reuse, design rationale capture and knowledge based support in a single coherent framework. Best practices are reused through the process model. rationale is supported by product information, which is retrieved through links to design process tasks. Knowledge based methods are supported by a common design data model, which serves as a single source of design data to support the design process. By using the design process as the basis for knowledge structuring and retrieval, it serves the dual purpose of design process capture and knowledge reuse: capturing and formalising the rationale that underpins the design process, and providing a framework through which design knowledge can be stored, retrieved and applied. The methodology has been tested with an industrial sponsor producing high vacuum pumps for the semiconductor industry.

Keywords: Design knowledge reuse, new product introduction, knowledge management, product lifecycle management

1 Introduction

Engineering design in mature domains is increasingly competitive in today's globalised manufacturing environment. One approach to assist in this competitive cycle is to reuse previous knowledge, and the main aim of this project is to provide an engineering knowledge management methodology to enable the creation of robust designs in less time, with lower production costs.

Although the design process output, or solutions can be directly reused, they can not be expected to function in the same way if they are directly scaled or if elements of them are reused in different systems. Knowledge relating to geometry can otherwise be reused through the formalisation of associations between product parameters. This enables optimisation of functionality where products are scaled up or down within certain limits. Parametric associations that are embedded in CAD models help to speed up product development, reducing the time required to reproduce well known components. Many Knowledge Based Engineering (KBE) tools provide the above functionality which provide solutions that interact with product data, particularly geometry. However, there is a wealth of non-geometric knowledge elements that could be reused but is missing from KBE systems. These include: project constraint reasoning, problem resolution methods, solution generation strategies, design intent, and supply chain knowledge.

A significant body of research work has addressed the subject of what knowledge is, how tacit and explicit knowledge differ and evolve (Nonaka 1994) (Saviotti 1998), that tacit knowledge is best dealt with by social methods and not IT systems (Lubit 2001) or that tacit knowledge *can not* be represented in an IT system (Johannessen et al., 2001) (Walsham 2001). The classic data, information and knowledge hierarchy has been questioned (Tuomi 1999). Many papers with 'knowledge' in the title (particularly within engineering) do not attempt to address the issue of what knowledge is, they simply provide methods and tools for the business of managing it. In the context of this paper, knowledge will be considered as '**actionable information**'. It is further assumed that knowledge can be stored in computer based systems, and in a variety of forms: documents (text), images, diagrams, embedded algorithms, formulae and rules. The important factor is that the 'knowledge object' infers knowledge to the user and that the object is in a format that enables *appropriate* application. Since it has previously been applied and stored, this application is reuse, and thus, *knowledge reuse*.

2 Review of Design Reuse

A selection of existing reuse methods will be described, relating to methodology, CAD / CAE, function, meaning (ontology) and matching (case-based reasoning). Reuse relating more specifically to the design process will be described in the following section.

Some approaches to design reuse base the system on a design methodology (Shahin et al., 1999) (Blessing 1995), structuring the elements of the system around the conceptual framework given by the design methodology (typically systematic design). General design methodology can form a core element of a design reuse method, or could itself be regarded as a design reuse method, in which fundamental principles are reused rather than specific design instances. Axiomatic design (Suh 1990) is an approach to systematise the design effort. Based on a formulation of the design requirement (which is cited as the most important and difficult task in engineering) alternative solutions can be tested against the principles, or design axioms. The core assumption supporting the axiomatic approach is that there is a fundamental set of principles that determine good design practice.

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.

Knowledge Based Engineering (KBE) is generally regarded as an umbrella term describing the application of knowledge to automate or assist in the engineering task. 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 knowledge representation method (Sainter et al., 2000).

Design reuse approaches that apply function (Rodgers et al., 2001) (Rodgers et al., 1999) base the knowledge structure on a functional decomposition, which is a similar approach to QFD. In the CADET system, a flexible rule base is applied to describe the domain knowledge – i.e. relating product attributes such as wheel size to requirement attributes such as ‘easy to push’. Another example is the Product Range Model (Costa and Young, R I M 2001) which is intended to support variant design activities through the representation of product functions, relevant design solutions and ‘knowledge links’ between these attributes.

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 (and manufacturing, service, etc.) concepts, data elements, and relationships between concepts (Kerr et al., 2004).

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 and Agogino 1996).

2.1 Design reuse issues

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., 2004a). 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).

Some important factors to enable reuse include a method to first make design reusable, then to store the reusable elements so that they can be found. Even if knowledge stored in computer based systems is accessed, if it is to be reused, several additional factors must be met: reusability, availability, and relevance. Efficient exploitation of past designs has been prohibited by the lack of a methodology to structure past designs and information (Shahin et al., 1999). With a well structured library of reusable past designs, and a method to make new design reusable, the issue of design reuse is greatly simplified.

Busby provided a detailed study into problems with 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 were knowledge loss through inappropriate replication, and error where existing designs were reapplied to new purposes.

A review of design reuse was carried out (Sivaloganathan and Shahin 1999). Several areas of future work are proposed, including: compatibility of knowledge models and design reuse models; integrating reuse tools with other systems; recording bad designs.

Design reuse remains a developing area, and many approaches have been developed. Further effort is required to understand the needs of knowledge users and producers in order that appropriate methods can be applied (Markus 2001) (Busby 1999) (Finger 1998).

2.2 Process-based design reuse methods

It has been suggested that the design process is a driver of design reuse for decision making at all stages of product development (Inns and Neville 1998). Design reuse tools should support the project (or design process) as a means to reuse knowledge, 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 and Gao 2004) (Baxter and Gao 2005). The following table represents an attempt to categorise existing work in which the design process has a relationship to design knowledge management or design reuse.

- **Design process as KM core**: the design process forms a central element of the knowledge management method, either through process templates, product model integration, or knowledge-based process support. (Blessing 1995), (Backer et al., 1995), (Park and Cutosky 1999), (Clarkson and Hamilton 2000)
- **Integrating design rationale process:** achieved either through annotation of a process model or by describing dependencies as part of the process. (BURGE and BROWN 2002), (Ramesh and Tiwana 1999)
- **Socio-technical system:** describing the design process as a socio-technical system has implications for representation, management and computation. (Lu et al., 2000), (Ramesh and Tiwana 1999), (Tucker and Hackney 2000)
- **Business process model:** describing design in terms of task dependencies, inputs, outputs, constraints and so on. This type of research provides a means to represent and manage design through the application of a logical structure. (Shooter et al., 2000), (Hayashi and Herman 2002), (Tate and Nordlund 1996), (Yassine and Falkenburg 1999), (Gorti et al., 1998), (Kalpic and Bernus 2002), (Pakovich and Marjanovich 2001), (Huang and Gu 2006), (Park and Cutosky 1999), (Concheri and Milanese 2000), (Clarkson and Hamilton 2000), (Sim and Duffy 2003), (Pavkovic and Marjanovic 2000)
- **Business process framework**: as with the business process model category, the process is described as a logical mechanism. The research categorised as ‘framework’ rather than ‘process’ describe the business model in a broader sense, as a collaborative exercise between business or product entities. (Salminen et al., 2000), (Blessing 1995), (Backer et al., 1995), (Huang and Gu 2006), (Classen and Lopez 1998), (Paashuis and Boer 1997)

- **Decision support through designer monitoring:** the designer interactions with a workstation (direct interaction) or PLM system (database changes) are monitored and responded to: active and dynamic design process support. (Leake and Wilson 2001), (Li et al., 2004), (Harding et al., 2003)
- **Design methodology as process description or management method**: a general design methodology forms a key element of the process representation approach, or is applied as a process management method – i.e. the design process describes how to follow the steps prescribed by the methodology. (Tate and Nordlund 1996), (Shahin et al., 1999), (Hicks et al., 2002), (Blessing 1995), (Salminen et al., 2000), (Backer et al., 1995), (Gardam and Burge 1997), (Pakovich and Marjanovich 2001), (Li et al., 2004), (Xu et al., 2002), (Paashuis and Boer 1997), (Clarkson and Hamilton 2000), (Hansen and Andreasen 2002), (Schofield and Gregory 2002), (Knott et al., 2003), (Li et al., 2004)
- **Design article representation**: a relationship between the product and the design process: as a product of the process, a means to monitor the process, or as integration of knowledge types through mapping relationships between process and product. (Shahin et al., 1999), (Hansen and Andreasen 2002), (Li et al., 2004), (Concheri and Milanese 2000), (Xu et al., 2002)
- **Design information capture and representation**: a method embedded in the design process to promote and enable reuse across projects, products, processes or decisions. (Hicks et al., 2002), (Matsumoto et al., 2005), (Concheri and Milanese 2000), (Zdrahal et al., 2000), (Ramesh and Tiwana 1999), (Knott et al., 2003), (Balasubramanian et al., 1999)

This analysis highlights 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 also 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 method for engineering design, in which a process model and product model are provided in a single framework.

One project which addresses some of these issues is the FIPER (Federated Intelligent Product EnviRonment) project. This 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.

Other notable process based methods include Signposting and the Design Roadmap. Signposting (Clarkson and Hamilton 2000) is a parameter driven task-based model of the design process. The task model does not have strong precedence links; instead the method uses the level of confidence in key design and performance parameters as the basis for identifying, or signposting, the next design task. The Signposting method is well suited to the development of new technologies in well understood application areas. The Design Roadmap (DR) method provides a novel formal method to represent the design process (Park and Cutosky 1999). The method enables the representation of feedback and feedforward processes, which are common in design yet uncommon in other representations. The process data model enables a variety of graphical representations, or views. Graph, matrix, tree and list views are supported. Additional functions, including resource management, document attachment and notification functions were added to the DR framework. The method mainly addresses project management issues, which implicitly applies product knowledge.

2.3 Next step of design reuse research

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. Further research is needed to explore the potential of an integrated process and product modelling approach. This should include non-geometric knowledge such as problem solving methods, solution generation strategies, design intent and project knowledge. These knowledge types are associated with the variety of tasks in today’s dynamic design process. The method proposed in this project complements the existing approaches by enabling product data to be linked to the non geometrical information through the process model. The CAD based methods will remain highly valuable in supporting detailed design, while these other elements can support early stages of product development.

3 Overview of the proposed approach

The underlying principle of the proposed approach is based on the interaction between a design process model and a product data model through a set of *parameters* to meet the particular needs of the application area: mature engineering design. In the early stage of new or developing designs, a great deal of details underlie (and can be extracted from) a description of a product that includes only a small number of parameters. These parameters may relate to size, performance, or other technical characteristics. Technical product types often include or refer to these parameters in the product name (e.g. iH 600, an ‘intelligent harsh $600m^3h^{-1}$ pump). The parameterised model of the product is then extended to include parameters that are calculated, or inferred, from the original specification. These parameters form a key element in the creation of a product development process describing the best approach to the design of that product within the organisation concerned.

Assuming that the organisation has developed similar products in the past, a large amount of product knowledge can be applied to the creation of the design process. During enactment of the design process, the parameter based product model is applied. As the process model is carried out, the product model is populated. Computational methods are applied through the creation of relationships between the process task model and the parameterised product model. This architecture enables a variety of analysis methods to use the same data set. The resulted product and process model together can be regarded as a *project model* or *project template*, and can be extended for specific product instantiations. The project model is created in such a way that the data sets are populated at the most appropriate time – and so any product analysis is scheduled to take place when the data is available.

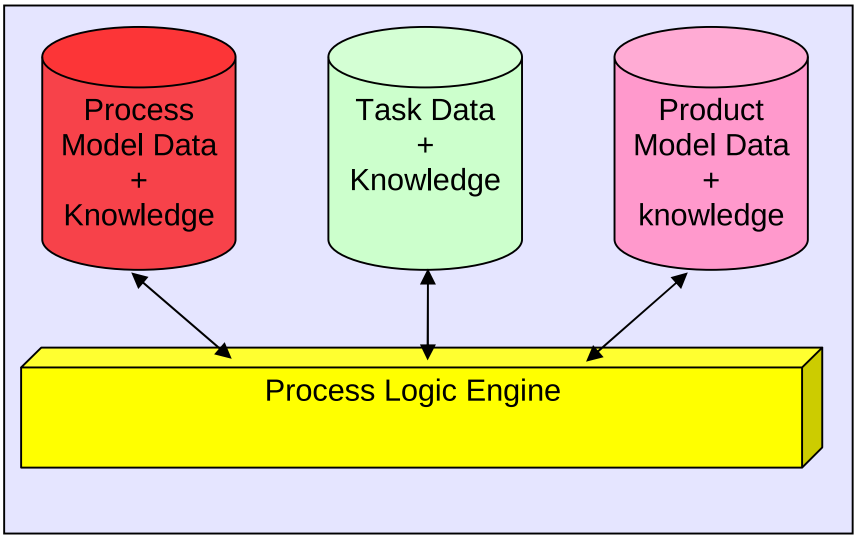


Figure 1: System architecture

The proposed design knowledge reuse system therefore has two key elements (see Figure 1): a *Process Model* and a *Product Model*. The Process Model itself provides a detailed structure that can be applied to the index and retrieval of additional information. The Product Model is a combination of product data and ontology. The product ontology in this case is a formal vocabulary defining the product objects. The product data can be directly manipulated within the system or externally. The product ontology enables reasoning relating to product concepts, and retrieval of similar concepts. The *Process Logic Engine* is the interface with the Process Model, which manages the assignment and updating of tasks. The Process Logic Engine also interacts with the Product Model, through the assignment of product data in the form of features. The Process Logic Engine serves as a trigger for the *Library of Analysis Methods*. These methods use the product data as input, carry out their function, and store the result in the product model database. There is also a link between the Process Model and the Library of Analysis Method to allow dynamic management of the process itself.

A major contribution of the method is derived from creating it. The method requires an investigation to capture the design process, followed by in-depth analysis to create the project model (template). This exercise will allow the organisation to formalise and improve their methods in advance of applying the tool, which itself will provide benefits.

As the limited scope of this project, the product model will be created to satisfy a minimum requirement, i.e., to allow the applicability and usefulness of the method to be evaluated during design process execution. The emphasis is its flexibility and extensibility (not its completeness), i.e., when the product model is created, the product parameter exists as an open data field that can be set to a variety of standards (real, integer, string). With the process model established, links can be created that point to additional data, enabling a focused retrieval method for information associated with a given task or task set.

4 Case Study

The industrial partners supporting the research project that this paper is reporting on are involved in mature engineering domains. A detailed design process model has been developed, and the supporting knowledge has been captured and added to the model. The following section describes the approach in more detail, with a description of the example.

4.1 The Selected component

The component selected for the knowledge capture exercise is the Head-plate, shown in Figure 2. The Head-plate serves several critical functions for the operation of the vacuum pump: seal, support, and lubrication. Internal, or shaft, seals prevent oil from crossing from the bearing cavity to the process chamber. External seals prevent transfer of atmospheric gas. Bearings support the shaft under load. They are lubricated with a single charge of oil for the service life of the pump.

The Head-plate is designed as a common item for a range of pump types. View (a) is the Head-plate stator side. The stator face is a key element of its functionality. Part of the functionality. Critical elements include stator tolerances, shaft seal and atmosphere seal. View (b) shows the bearing bores, critical elements include bearing bore geometrical and positional tolerances. The dynamic seal system, including gas flow channels for purge and pressure balancing, plays a major role in pump reliability. One gas flow channel can be seen in view (c).

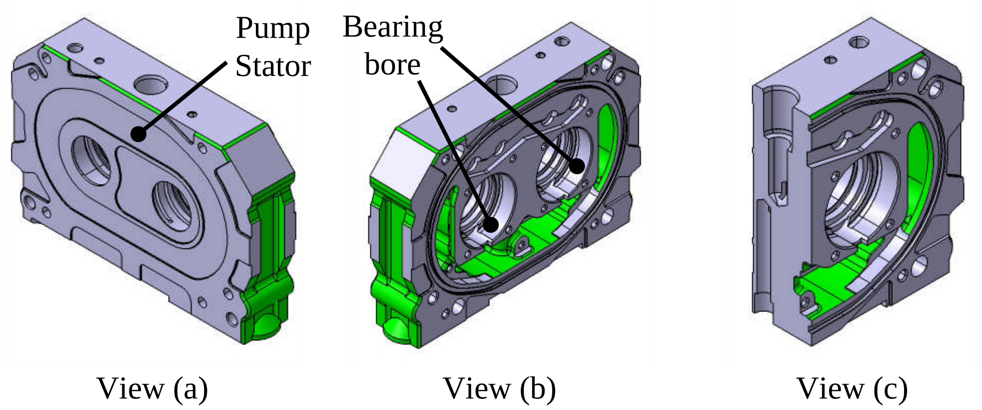


Figure 2: Images of the Head-plate Showing Different Functional Features

4.2 Process capture and representation

The design process for the Head-plate component was captured, and first represented using Integration Definition for Function Modeling (IDEFØ) (Technology 1993). IDEFØ includes activity boxes, with arrows representing inputs, outputs, controls and mechanisms. A single activity represents the high level purpose. Each activity can be broken down and shown in more detail in a child diagram.

The process capture was extended to show the source of the inputs to the design of the Head-plate. The IDEFØ representation requires several interrelated diagrams. The resulting process, at the top level of abstraction, included 8 tasks. The IDEFØ formalism specifies 6 activities per page, which means that the diagram is not able to show the whole process. It was also considered that this prevented the representation of both context and detail in a single representation. The IDEFØ series enabled an observer to gain an understanding of what is happening during the process. This would be adequate if the system analysis task was required for that purpose (as it is in a system design project). The requirement of the process representation method in this scenario is that it will enable the process to be reapplied, and knowledge about it to be reused. For this purpose the context is important, and so combination of the 6-node limit along with the complex array of link types shown in an IDEFØ diagram prompted the search for an alternative. It should be emphasised that is not a lacking in the process logic that prompted the selection of an alternative process modelling method. The change was driven by the need to understand, at a glance, an overview of the process and its context. This requirement is in support of system usability.

The headplate design process was later modelled using the Design Roadmap (DR) Framework (Park and Cutosky 1999). The DR representation consists of two node types, task (the task itself to be enacted) and feature (which is a task data set). Link types include precedence, abstraction and constraints. Precedence shows order of task execution, and likely iteration. Abstraction relates to the capability for a sequence of elements to be represented by a single element. Constraint links connect feature nodes, and show that a constraint exists. Note that the term ‘feature’ is the name given to the data objects included in the process model. It bears no relation to other uses of the term ‘feature’ in the engineering domain.

Figure 3 shows a view of Head-plate Design *Tasks*, modelled using DR Framework, with some of the *Features* and their attribute slots visible. Iterations, feedback and side-effects have been removed for simplicity. Within the Head-plate design task, both sequential and concurrent activities take place. Data that is required by later tasks is recorded in the features. For example, the Bearing Bore Feature contains data (size and tolerance) that will be used in the lubrication system design Task (see top of Figure 3). This same data set could also be used as an input to a manufacturability analysis Task, i.e., data sets can be called by any Task object. The main objective of the Features shown in this diagram is to provide data required by subsequent tasks. It is the Feature that triggers the Task. If a data set is required but not complete, the task will not be initiated.

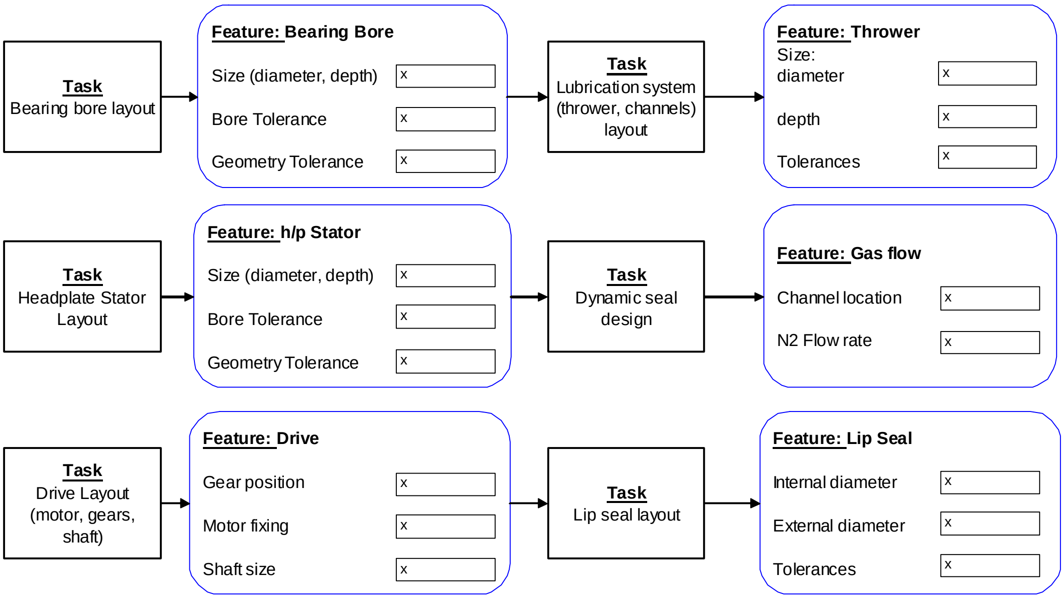


Figure 3: The Head-plate Design Tasks Modelled Using Design Roadmap Framework

4.3 Parameterised product model

The process representation method allows data to be carried through the process using the *Feature* nodes. Within this application, the data that is represented in the Feature nodes is both created and used by the *Tasks*. For example, the Requirements Specification Task produces a fully populated engineering requirements data set. Other Tasks use this Feature data as an input. It is possible to have a Task creating multiple Features, and for a subsequent Task to use multiple input Features.

The data handling provided by the process model enables the *Parameters* of the product to be created through the enactment of the design process. An implicit method for the handling of the data set is embedded in the design process, i.e., what the parameters are, where they are created, and where they are used. The explicit methods applied to the storage and manipulation of the data set are not made clear, so must be defined.

A full implementation of this method may involve several thousand Parameters. Grouping the parameters into *Sets* (*Objects*) could ease the retrieval and reuse process. Rather than call an individual Parameter, an Object could be called. These Objects are called by the Features in the Process Model. Using an inheritance model, it will be possible to treat the Parameter Set as a hierarchy of Objects. The attributes of the objects are populated through the product design process.

4.4 Spreadsheet-based test system

This section describes how Microsoft Excel is used to implement the design knowledge reuse methodology. The Excel implementation applies a process model as the central element. The process model is shown in figure 6. The prototype system architecture is described in figure 4. This prototype system differs from the system architecture described in figure 1. In the prototype system the process model itself is the central element, with links to task data and product model data. The task model has a user interface providing access to product model data.

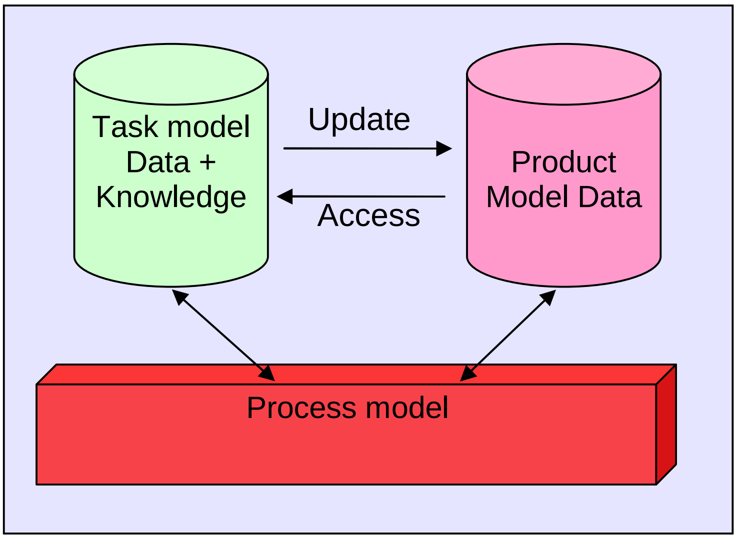


Figure 4. Prototype System Architecture

The process model contains links to the feature (data set) and task interface. In the Excel system, each feature and task object has its own worksheet. An example of the links between the worksheets is shown in figure 5: the ‘engineering requirements’ data set and the ‘mathematical model’ task are accessed is via the corresponding process object.

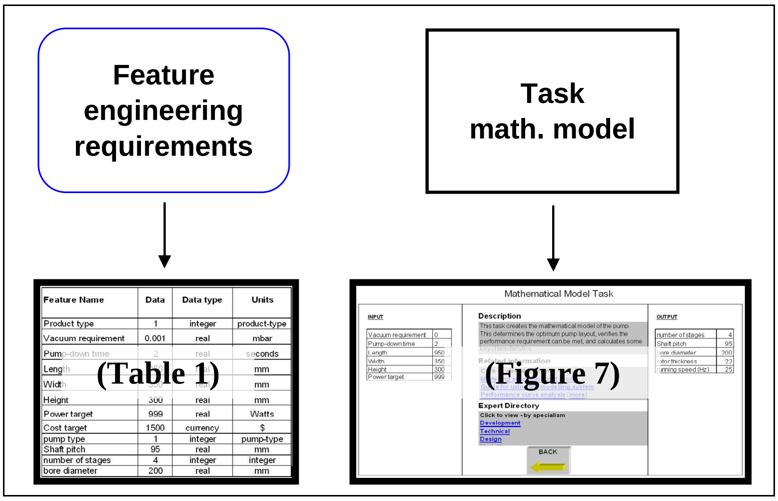


Figure 5. Process object links

The ‘feature’ link opens a worksheet containing a read-only view of the relevant product parameters. Changes are made to the product master model via the task pages. Each task page, such as the mathematical model task in figure 8, includes ‘output’ cells, which are the data input cells. Changes to these cells are reflected in the product master model, which is a separate worksheet.

Once a task is completed and the data is entered into the output cells, the user will click the ‘back’ button (bottom-centre of figure 7), which links back to the process model, as shown in figure 6. From the process model the user has the option to click on another task to complete or to click on a feature to view the data set contents. Future implementations should provide a dynamic mechanism to guide the user to the next task. This prototype system requires the user to select the appropriate task.

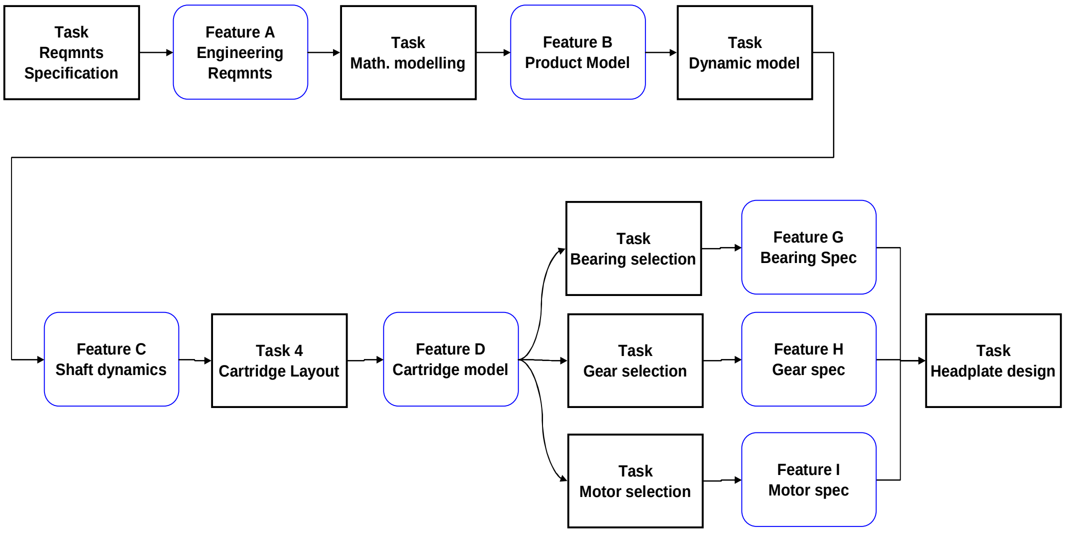
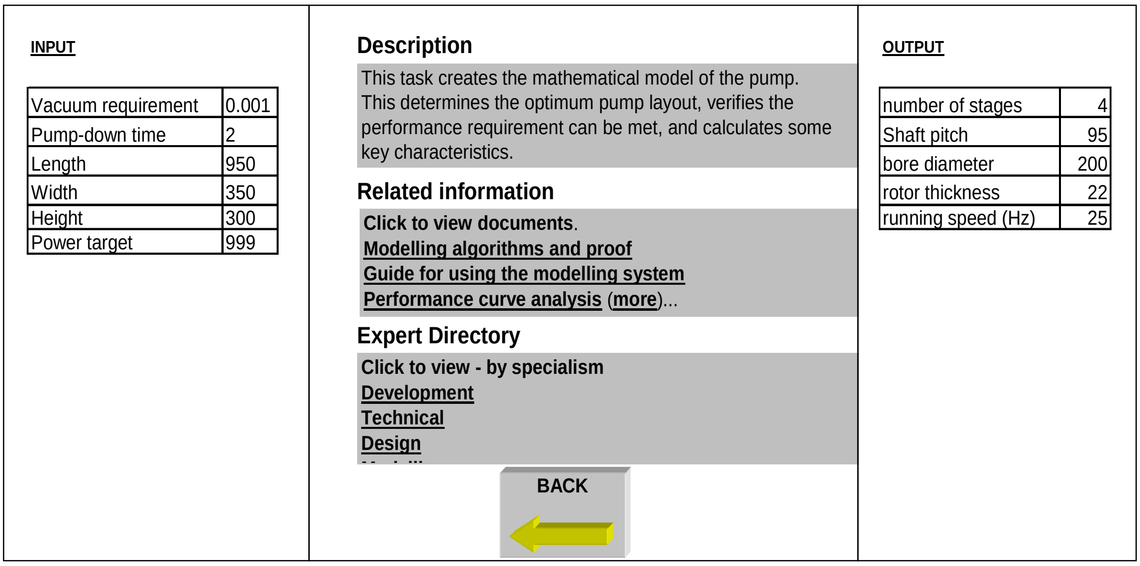


Figure 6: Design Task Overview Showing Precedence Relationships

In addition to the read-only data input and the editable data output fields, each task page contains: task description, related information and an expert directory. These fields can be seen in Figure 7. In order to reduce the information content of the task page, much of this information is stored elsewhere and accessed via hyperlinks. These links may refer to internal sources in other worksheets, or external sources on networked drives or the Internet.



INPUT

Vacuum requirement	0.001
Pump-down time	2
Length	950
Width	350
Height	300
Power target	999

Description

This task creates the mathematical model of the pump. This determines the optimum pump layout, verifies the performance requirement can be met, and calculates some key characteristics.

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

OUTPUT

number of stages	4
Shaft pitch	95
bore diameter	200
rotor thickness	22
running speed (Hz)	25

Figure 7: Mathematical Model Task Page

It can be seen that the *Description* header shows the synopsis of a more detailed Task Description document. The *Related Information* section contains links to other documents, images, or files. The *Expert Directory* section is arranged by specialism, in which each link goes to another page containing information about individuals, their experience, and their contact details.

Feature Name	Data	Data type	Units
Product type	1	integer	product-type
Vacuum requirement	0.001	real	mbar
Pump-down time	2	real	seconds
Length	950	real	mm
Width	350	real	mm
Height	300	real	mm
Power target	999	real	Watts
Cost target	1500	currency	$
pump type	1	integer	pump-type
Shaft pitch	95	real	mm
number of stages	4	integer	integer
bore diameter	200	real	mm

Table 1: Engineering Requirements Feature data

Parameters contained in the Feature objects are shown on the Task page. One such feature, ‘engineering requirements’ is shown in Table 1. The Parameters in each feature refer to data stored in the Master Product Model. In the Excel model this is contained in a separate worksheet. This method enables a single parameter to be accessed by multiple features. The Product Data includes *Feature name, Data, Data Type* and *Units* parameters. Only the name and data are displayed in the task pages. The data type and units fields are for error checking and consistency: calculations on product parameters should not be allowed where the units are not compatible.

Within the Master Product Model there is scope for a Standard Parameter Set, relating to standard components such as standard dowels, along with the associated product features – in this case tolerances for the associated press fit and clearance fit holes, along with other product features. The Product Model also contains any necessary universal data, such as density of iron, to enable calculations – in this case the mass of components.

4.5 System Knowledge

Three knowledge elements are included in the proposed knowledge reuse system: best practices knowledge (embedded in the process), task knowledge (supporting information and algorithms, or knowledge-based methods), and product knowledge (a product parameter template).

4.5.1 Process knowledge

The product model and process model together enable effective distributed collaboration on the product design. The process model itself represents knowledge relating to the process (best practices knowledge). A deep knowledge of the product and experience of carrying out the design process in the context of the organisation are required to specify the ‘best’ design process model. The sequence of activities to produce the required product function in the most effective way includes knowledge of relationships between product components, parameters, and materials. Process decisions such as likely or necessary iterations and task dependencies all contribute to the development of the process model. Additional project related (i.e. non-engineering) factors such as component lead time, product test times and organisational factors such as the availability of expertise and systems also contribute to the process model. As such, the process model represents one of the knowledge elements embedded within the proposed method.

4.5.2 Task knowledge

The second knowledge element is task knowledge. This includes information and automation. Supporting information is available to support the designer in completing the task. It includes general notes, formal design documentation, images, tables, and catalogues. Informal notes and annotation, or rationale, may be added during the process. The combination of these elements is intended to be brought together and edited for reuse in the next generation product template to support design decisions. Automation, in this context, is the application of knowledge based methods or algorithms to manipulate the product data. These algorithms take parameters from the product model as inputs, make calculations on them, and store them as new or updated parameters.

4.5.3 Product knowledge

The third knowledge element is referred to as product knowledge. In this implementation of the system, the product knowledge is represented by the parameter set. This enables the application of a product template to the development of a new product variant. The template can be applied at a variety of levels. The first is 'data labels only', to develop a whole new product of the same type (such as the next generation product in the range). The second level can be applied on a broad spectrum depending on the constraints: using a partial data model to develop a new product family member (such as a different pumping speed or application variant). Clearly the application of the partial data model exists within certain limits, which must be defined for each product type.

One aim is to extend the product knowledge element to include a product ontology to represent a collectively defined lexicon of terms, agreed parameter ranges and relationships between terms. This should improve the understanding of the design process, and also extend the capability for managing the design process in a distributed manner.

4.5.4 Relationship with KBE

This system is not itself a KBE system; however it does have the capability to include KBE methods. The main contribution in terms of KBE is a system to provide the capability to define multiple input and output data sets for analysis by multiple KBE systems. The definition of the product model will be shaped by the organisational requirements at the early design stages. Product model parameters and structure (content of individual data sets) will be defined according to the needs of the process, including KBE systems. The process model supports KBE by including the required tasks. Task knowledge includes KBE methods, or in the case of external systems, support for carrying out the task. Automation of the task, including data input / output, represents system task knowledge.

4.6 Application and extension of the DR method

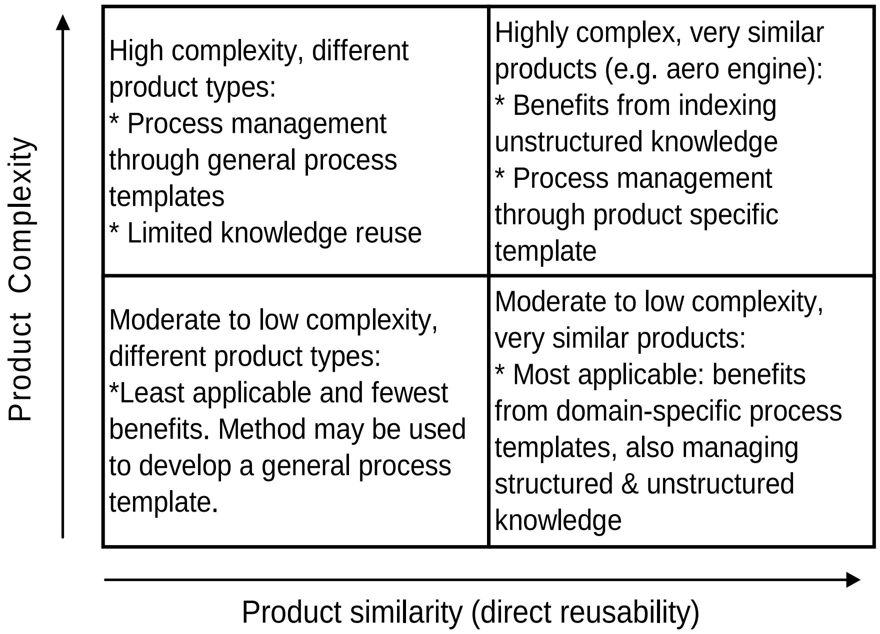
The process representation method is based on the DR (Design Roadmap) method. It should be noted that the implementation applies only a part of the DR framework. The basic process logic was applied: a data object precedes (and is consumed by) a task object. Precedence and abstraction links were the only types applied to the example. The other DR link types (feedback, feedforward and constraint relationships) would add value to an extended process model. The DR process logic was also not rigorously defined in this test system; the main objective being the process representation. It is therefore not possible to show alternate views of the process (design structure matrix representation is an option in the DR system).

One limitation of the DR method is that there is no method to link task knowledge, including supporting information and computational methods, to the process model. The approach described in this paper provides a method to link task knowledge to the process model. Supporting information is stored and indexed with relation to tasks. Through interaction with a product model, computational methods can also be applied to task support. The product model concept further extends the DR method, by suggesting that product and process data are stored separately.

5 Evaluation of the proposed methodology and its potential applications

Within variant design domains, where similar products are designed for several generations, this approach can provide significant benefit. The application of process templates along with the capability to store and apply additional information and data will significantly enhance the reuse of product knowledge, and so improve the product development effort. If the product in question is highly complex, and also highly similar to the last generation, the organisation will gain most benefit from the application of KBE technologies that aid the synthesis and analysis of the next generation product. The method proposed here, in that case, could be applied to the management of design and project knowledge, especially unstructured knowledge that supports product development. The calculations (KBE driven analysis) will be carried out using the proprietary KBE systems. So this method will be of use to the product development team, but more benefits will be gained from the application of KBE systems. The management of structured knowledge provided by this approach will allow the product development team to keep a central data store that tracks the product development, enabling better coordination of distributed teams. The process management methods and the methods to store and retrieve unstructured information will also serve a useful purpose. The significance of KBE and geometry based methods is due to the high relative importance of geometry in later stages of the design process [8], and the scale of the detailed design effort when compared to conceptual design, particularly with highly complex products.

The (project) model context relates directly to the product. A process map template is created for a specific product type, just as the product model template. If the type of product differs widely from one generation to the next, then the amount of detail relevant to the next product will be greatly reduced. There comes a point at which the benefits to be gained from applying such a context specific knowledge reuse tool are overtaken by the costs, when compared with following a general design process. In such cases, the method can be used to implement a general design (or innovation) methodology. It can also be used to store and manage design data through the process. This relationship is described in the matrix in figure 8.



High complexity, different product types: * Process management through general process templates * Limited knowledge reuse	Highly complex, very similar products (e.g. aero engine): * Benefits from indexing unstructured knowledge * Process management through product specific template
Moderate to low complexity, different product types: *Least applicable and fewest benefits. Method may be used to develop a general process template.	Moderate to low complexity, very similar products: * Most applicable: benefits from domain-specific process templates, also managing structured & unstructured knowledge

Figure 8: Assessment of the Potential Application and Benefits of the Proposed Methodology with respect to Different Product Types

These relationships must be tested in an industrial scenario in order to gauge the degree to which a particular approach is suitable, and to show what circumstances lead to a successful application of the method. Where vacuum pump is shown on the matrix to have moderate complexity, this is in comparison to an aero engine.

6 Conclusion

The method described in this paper addresses the need to reuse engineering design knowledge. Three knowledge types are supported: process knowledge, product knowledge, and task knowledge. The underlying principle of the methodology is the interaction between a product model and a process model through a set of parameters to meet the particular needs of an application domain. The proposed system provides project guidance and monitoring, a framework to organise information and knowledge retrieval, and a central repository of product data. These elements can be brought together through the use of a combined method to represent the design process, provide data support, and to form relationships between the process model and product concepts. The system has been tested with an industrial sponsor on a major component. The next challenge is to build additional product components into the model, with the longer term aim being to capture and represent knowledge for an entire product family.

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