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KNOWLEDGE REPRESENTATION AND RE-USE IN FMEA

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The research described in this paper addresses the ability rapidly and easily to create product variants through the capture and re-use of design and manufacturing knowledge. New methodologies are envisaged that enable companies to anticipate problems before they occur, thus transferring them from 'reactive' to 'predictive'. The implementation of predictive design represents the crucial move from standard parts to standard knowledge constructs. Standard parts can be used in any application that requires a defined function where the shape and properties do not need to be altered. However, standard knowledge constructs can provide parts that can be used wherever the function is required. Examples of the technique are presented from recently completed research concerning FMEA applied to electronic products.

1. INTRODUCTION

Manufacturing industry continues to face rapid changes in business environments and the impact of e-commerce, with the most noticeable trends being that Original Equipment Manufacturers (OEMs) are outsourcing more component manufacture and services to their supply chains; each supplier provides components or services to a number of OEMs or other suppliers; customers, suppliers, business partners, subsidiaries and the different departments of an enterprise will be more globalised; and the increased demand for expertise has resulted in faster flow of personnel between companies with a consequent potential loss of informal knowledge and experience.

Suppliers therefore have to have the ability rapidly and easily to create product variants that meet the same basic functional requirements but might be supplied to the different customers. The second requirement is for management structures to support the design effort across the extended enterprise to enable project management, resource allocation and communication among team members via a common platform.

The research described here addresses key issues in collaborative design using Predictive Engineering Technology, i.e., techniques that enable customers to anticipate problems before they occur, thus transferring them from 'reactive' to 'predictive', and emphasises the capture and re-use of corporate knowledge. The work focuses on a subset of predictive engineering, by capturing and representing design and manufacturing methods and costing knowledge such that it can be re-used.

Design is an iterative process which involves suppliers, customers and other departments within an enterprise. Most new products are new variants of existing ones, and most companies employ a large amount of predictive design, as even products perceived as 'cutting edge' are only in part innovative.

Substantial world-wide research effort has been expended on the use of IT for design and manufacturing, and has involved both computer scientists and engineering developers. The former group has been developing advanced tools such as object-oriented programming and database/knowledge base management systems, and more recently Internet/Web-based enterprise development toolkits. The latter group has been working on the application of the advanced IT tools for design and manufacturing applications, and has been mainly devoted to the automation of the decision making process and the integration of such systems through data transfer from one to another. Researchers have been also trying to parameterise product models and to associate design and manufacturing knowledge with geometric information. Commercial systems based on these technologies have played significant roles in manufacturing industry.

Problems with current engineering systems are becoming apparent. They have been developed and used for specific applications without considering the potential re-use of their individual methods in new or different applications. Knowledge and information is represented in data structures of a type which are no longer suitable for distributed and dynamic environments. There is no process/workflow control mechanism to ensure that the design process complies with enterprise objectives and best business practice. Manufacturing decision systems are rarely used for early design evaluation and cost estimation in bidding for contracts. Knowledge gained in previous designs or projects is rarely used for new designs/variants or projects due to a lack of knowledge standardisation. This research aims to make important contributions to the solutions of the above problems through the creation of new methodologies and the use of enterprise development tools.

2. LITERATURE SURVEY

In the US, the National Science Foundation (NSF) has a number of relevant on-going projects, such as the design re-use and design process assessment project which focuses on the development of an infrastructure for the re-use of design process and design information (Grafton, 1996). The rapid assessment of early designs project uses set-based representation of early design descriptions permitting approximate assessment using imprecise, partially complete design information (Hazelrigg, 1998a). The generic designer assistance tools project combines graph-based function models with geometric models so that a design solution can be achieved by optimisation algorithms (Hazelrigg, 1998b). The US National Institute of Standards and Technologies (NIST) has a number of major projects in the integration of design and manufacturing (NIST, 2003). Some US researchers are developing Internet/Web-based collaborative design/life-cycle support systems such as the enterprise-web portal developed by Rezayat (2000) and the collaborative product conceptualization tool developed by Roy and Kodkani (2000) using web technology. The above projects are not focused on knowledge representation and re-use but on design processes and integration through IT/Web technology.

In the knowledge management/engineering area, most work has been done in the computer science discipline, and the research is mainly devoted to generic methodologies which are applicable to a wide range of business sectors such as finance, administration, medical and general engineering. A typical example is the knowledge management technology tool kit – CommonKADS (Schreiber et al, 2000). Other well-known knowledge management systems are reported by Angele et al (1998) and Brazier et al (1996). These systems are not specifically aimed at design and manufacturing applications, and therefore are not integrated into the design environment.

Some work has also been done in Engineering Design Centres in the UK. For example, the Schemebuilder design environment developed by Lancaster University (Chaplin et al, 1994) provides a tool to assist multi-disciplinary system design from concept to embodiment stages with problem analysis and alternative evaluation functions, using Bond Graphs to represent a product scheme. The Schemebuilder and the Bond Graph representation are rigid and aim at finding a design solution through scientific methodologies.

3. AIMS AND OBJECTIVES OF THE RESEARCH

The research is developing a predictive design environment using component-based development tools, in which design knowledge can be standardised and represented. Predictive design particularly helps companies in well-established industries to maintain a competitive position. The reasons are severalfold.

- Because they are well established, they are more successful in setting up predictive design engines – they know a lot about their product and how to design it.
- Competitive advantage is particularly difficult to achieve in mature markets where low levels of innovation are possible.
- The use of predictive design frees time for the generation of innovative ideas. The costing information from a predictive design system considerably lowers the risk involved in aggressive pricing policies.
- The use of formal methodologies will significantly reduce new product development time and enhance integration of business processes.

Specific objectives of the research are:

- To capture design knowledge and develop methodologies for the standardisation and representation of the captured knowledge so that it can be re-used for new products or variants;
- To develop a design environment for collaborative product development in a distributed and controlled manner across an extended enterprise;

- To capture manufacturing and costing knowledge and develop methodologies so that such knowledge can be used for design of new products or variants;
- To develop a predictive design engine consisting of a set of independent methods which can be adapted and re-used for similar products or services; and
- To test and evaluate the developed methodologies with collaborating companies.

4. METHODOLOGY

The research is acquiring and classifying knowledge needed by the design team. The following categories of knowledge have been identified:

- Experienced designers/managers have *customer requirements and anticipation knowledge* based on previous products and/or services. In new product development this knowledge can be crucial to the correct interpretation of the customer requirements thus maintaining high quality;
- The design team's *project management knowledge*, such as best practice procedures, methodologies and business processes used in previous projects, is currently not systematically maintained. A formal methodology to represent and re-use such knowledge is being developed;
- *Product knowledge* is regarded as the knowledge about previous (similar) products and contains a product model together with knowledge about how the final product is determined and what assessment/evaluation methods are used.
- *Manufacturing methods knowledge* (including assembly) about previous products should include how the methods are selected and evaluated for previous products.
- *Costing knowledge* includes costs of parts (made in house or by suppliers) and assembly of products or modules, and product development costs;
- *Test and failure mode knowledge* becomes more important to designers to predict the quality of produced products and to determine tolerances and thus will be addressed by this project.

The process planning knowledge capturing methodology developed and used in previous research (Gao et al, 2000, Tang, 2000) is being improved and used for the capture of the design knowledge. The methodology has been successfully tested with industrial applications and the process planning system developed has been used by industry. Industrial collaborators' products and design process will be used as case studies to evaluate the methodologies being developed. One company designs door latches for major car manufacturers, and most of their components are sheet metal parts from suppliers and the process is the assembly of the final products. However the manufacturing knowledge with their suppliers is very important for their product development, especially for the early design stage. If their designers have the manufacturability and costing knowledge to evaluate their concepts of new products, they will be able to negotiate with their suppliers to cut the costs of parts and will reduce the time of product development. The design and costing knowledge are being captured from our collaborator and the manufacturabilty knowledge from its suppliers. Another collaborating company design and manufacture high vacuum pumps for the semiconductor and chemical industry. Although their design and manufacturing knowledge is available in house, it is not formally captured and represented for use in the design process. This second company is an OEM and manufactures the key parts, whilst the first is a supplier company and outsources all its parts to second-tier suppliers. By comparing the different types of business of the two collaborators and their different types of products, a generic methodology can be proposed which will be suitable for or easily adapted to a wide range of manufacturing business.

The captured knowledge will be analysed and as much as possible standardised based on the types and functions of products and problems to be solved. Standard *knowledge constructs* can then be developed using the Web-based programming tools. The knowledge constructs can be used to form the decision logic of a *solution* which is the backbone of the knowledge engine, which can make use of any design knowledge as required. Unlike many knowledge management systems, this prototype system is being developed within the PDM/CAD design environment as it is the preferred environment for product development teams. The Knowledge Constructs are *basic methods* implemented and stored in a library and are developed as the result of the knowledge capture described earlier. The knowledge constructs and methods in the Knowledge Engine are being developed in a way that they can be re-used in their entirety or as part of *new methods* for future designs or projects. Information and data in different formats (e.g., spreadsheets, files, CAD data, Word documents, etc) can be accessed by the methods in the solutions of the knowledge engine. PDM control functions can be used to manage the information/data, the design process, and the procedure for using the methods to form further methods to find solutions. It also manages the different variants of product structures and associated design knowledge and manufacturing cost information.

5. FAILURE MODE AND EFFECT ANALYSIS (FMEA)

Failure Mode and Effect Analysis (FMEA) is a widely used concurrent engineering tool for quality improvement and risk assessment and completed research work is described here as an example of the knowledge capture and re-use methods discussed above. A specific objective of the research was to investigate the implementation of FMEA in conceptual design with the focus of the work on the information modelling of FMEA knowledge, and an emphasis on knowledge re-use. A relational data model has been created to support the automatic generation of the FMEA, and replaces the traditional brainstorming process for FMEA report creation. Inputs of failure reports from the factory floor are used but as an alternative approach, designers can provide the characteristics of the components of their design to generate the FMEA. Prototype software has been created to demonstrate the above capabilities. The data model is also intended to support the viewpoints of multiple users, namely, the product designer, the field engineer, the process engineer and the maintenance engineer.

BS 5760 Part 5 (1991) states that “FMEA is a method of reliability analysis intended to identify failures, which have consequences affecting the functioning of a system within the limits of a given application, thus enabling priorities for action to be set.” Basically, FMEA can be classified into Design FMEA and Process FMEA. Design FMEA deals with design activities, such as the design of products, machines and tooling, whereas process FMEA is concerned with manufacturing processes.

Traditionally, FMEA is used in hard copy or spreadsheet format to capture the potential problems of a design or process. The implementation of a highly manual FMEA is a difficult task, and FMEA is often found to be not user friendly, hard to understand and insufficiently flexible. There is also often duplication of information in other documents in the factory. For these reasons many companies use FMEA merely to satisfy the contractual requirements of their customers (Dale, 1996). Users may find FMEA a "tedious and time-consuming activity" (Price et al, 1995). This is especially true when FMEA is used in complex systems with multiple functions (BSI, 1991). FMEA is often conducted late in the design cycle after prototyping (Price et al, 1995). Changes made at later stages may be very costly, and a poor design concept cannot be compensated for at later design stages (Hsu and Woon, 1998).

According to Wirth et al (1996), the method has two fundamental weaknesses. Firstly, there are no guidelines on how to conduct an FMEA. Secondly, all FMEA-related information is recorded in natural language, with team members using their own vocabulary. Lee (1999) believed the difficulties are due to the unstructured knowledge representation and limited reasoning support. Hence, it is clear that one of the effective ways to overcome the current shortcomings is to formalise and automate FMEA generation. Many manufacturing companies have their own method of recording previous product or process failures, and this information may be sufficient to generate important elements within a comprehensive FMEA. However, in addition to this knowledge, relevant modelling and reasoning techniques are required to support the automatic FMEA generation method.

6. FMEA MODELLING AND REASONING

The knowledge in the FMEA needs to be modelled and codified to support the automation process. Knowledge of both structure and the function of the system under consideration are needed for FMEA automation (Hunt at al, 1995, Eubanks et al, 1997). Hence, functional modelling and structural modelling are often associated with FMEA research. A functional model describes the intended function or the purpose of a system, and consists of two main components: function and behaviour. The function of a system provides the design intent, whereas the behavior describes how the structure of an artifact achieves its function (Gero et al, 1991, Russomanno et al, 1993). A structural model is defined as "the components that make up an artifact and their relationships" (Gero et al, 1991). It refers to the configuration of the product or system, and contains information on all the components, entities, sub-processes or sub-systems, together with the interactions among them. A structural model may typically refer to the physical assembly of a mechanical or electrical product (e.g. a car or an electrical circuit), or to software configuration.

In FMEA automation, brainstorming is replaced by computer reasoning to generate the cause to effect. There are two types of reasoning, i.e. quantitative reasoning often based on physical laws and numerical data and qualitative reasoning which is more descriptive than measurable. Qualitative reasoning is used here as being similar to the human thought processes used in the early stages of design.

A knowledge-based system can be built based on shallow knowledge that uses heuristic rules to establish empirical relationships between conditions and conclusions (Atkinson et al, 1992) or deep knowledge which simulates the actual behaviour of a system based on scientific principles. Deep knowledge is generic and shallow knowledge is difficult to maintain, but for FMEA automation shallow knowledge is chosen for its higher level of abstraction that is considered appropriate to concept design.

7. THE FMEA MODEL

An object-oriented approach is used for FMEA modelling. The model consists of basic classes, such as [Part], [Generic Function], [Function Unit], [Model] and others. A [Part] is characterized by its [Property]s and [State]s. A [Generic Function] can have many [Behaviour] objects associated with it. A [Function Unit] is created based on a [Part] which forms the operator to a [Function], another [Part] which is the operand of the [Function] and a [Generic Function] which describes the [Function] itself.

A series of [Function Unit]s make up a higher level [Function Unit], which is known as the assembly of those units. The operator of the higher level [Function Unit] is the [Model] that go to make up its assembled components, i.e. the operators from the lower level [Function Unit]s. The relationships among the objects can be represented by figure 1.

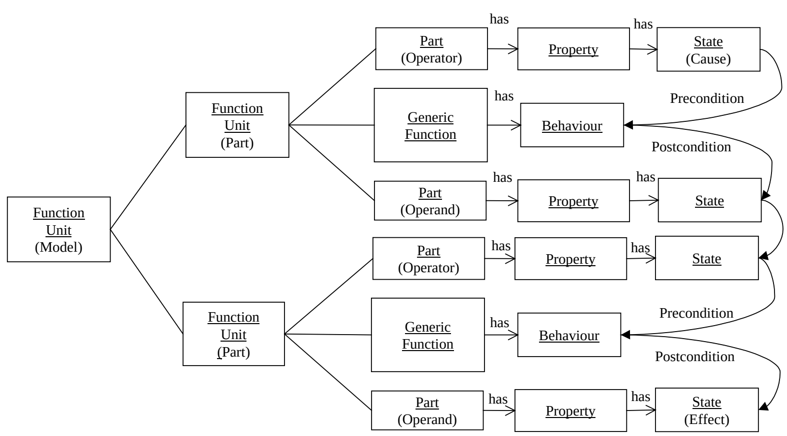


Figure 1. An Example of an Object Layout and their Relationships

The state of the operator will determine the [Behaviour] of the [Generic Function] within a [Function Unit]. This is the precondition relationship. The [Behaviour] will in turn decide the state of the operand within the [Function Unit]. This is termed the post-condition relationship. The interaction between [Function Unit]s within an assembly is carried out through the [Part] itself. This is because in most cases, an operand of a [Function Unit] is an operator of the next [Function Unit]. Hence, if a state change occurs, the changes will be propagated until the last operand in the system, i.e. the operand that is not used as an operator for the next [Function Unit]. Figure 1 (above) shows as example of effect propagation. The information about various states of a part, and the behaviours corresponding to specific states are stored in the database. If a [Function Unit] is created, the operator, operand and the [Generic Function] involved will be used as the keys to search for the matching [State]s and [Behaviour]s. The selected [State] from the operator is the cause of this [Function Unit], and the effect is defined by the [State] of the operand. Hence, a [Part] is able to act or respond to the system through its distinctive "memory". A relational database is used to store the information of the objects as well as the heuristic rules governing the object. This overcomes the difficulty suggested by Atkinson et al (1992) that maintainability is a problem if the software is directly related to the engineering system. With rules residing in the database, independent of the software, an engineering change will only affect the information in the database, not the software itself. Furthermore, a database is capable of storing as many rules as needed, resolving the concern on the quantity of rules.

8. APPLICATION IN AUTOMATIC FMEA GENERATION

FMEA generation requires that characteristics of parts be combined with behaviour information. This will involve several steps including the establishment of the design concept (an example is shown in figure 2), the selection or creation of parts, the creation of part properties and states, the selection or creation of functions and their behaviours, the creation of function units and the creation of assemblies.

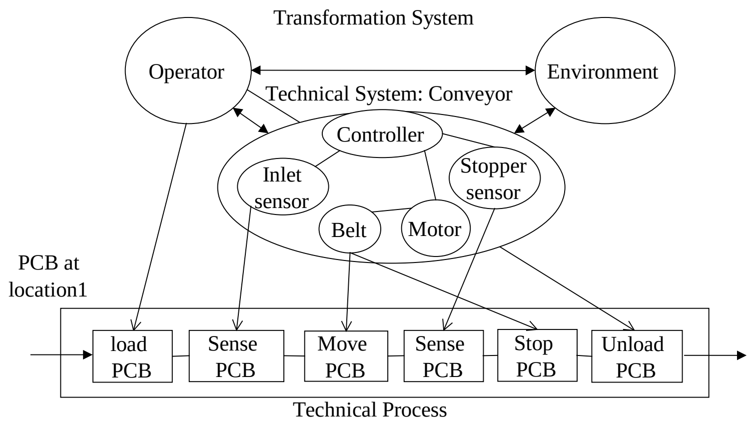


Figure 2. Transformation Model for Conveyor

An important activity is the establishment of pre- and post-condition relationships between part states and behaviours which are defined by the user from prior knowledge or from failure reports. Normally, a failure report will provide information about the failure (behaviour), the cause of failure and its source (operator state) and the effect of failure (operand state). Hence, with continuous data input from failure reports, the system can 'learn' from previous failures. There appear to be many steps involved in the generation of an FMEA, but knowledge re-use within the database is a central feature of the approach.

In the traditional FMEA method, the knowledge of an FMEA is limited by the case being recorded by the user. Using this new FMEA model, the knowledge resides in the part, not in the cases. Hence, the system is able to respond to new cases not previously captured by the user. For example in PCB assembly, failure cases may have been recorded for 'motor moves belt' and 'belt moves PCB'. Hence, should the motor fail, then the belt will not move, and consequently the PCB fails to move.

Hence, the information captured in the database would be:

Function Unit 1:	motor moves belt	Function Unit 2:	belt moves PCB
Operator:	motor	Operator:	belt
Generic Function:	move	Generic Function:	move
Operand:	belt	Operand:	PCB
Precondition:	State: motor failure Behaviour: not moving	Precondition:	State: belt not moving Behaviour: not moving
Postcondition:	Behaviour: not moving State: belt not moving	Postcondition:	Behaviour: not moving State: PCB not moving

If another user created a design with the function unit: "motor moves PCB", which has never been captured from a failure report, a search will be made for the operator "motor" with function "move" and the likely precondition retrieved (State: motor failure – Behaviour: not moving). The same process is carried out on operand with the name "PCB" and function "move". In this case, it retrieves the likely postcondtion (Behaviour: not moving - State: PCB not moving). The combination of this information will result in a new case: "motor fails, PCB not moving" – an effective re-use of knowledge.

9. CASE STUDY

Failure reports are used as the source for cause and effect chain building which eventually leads to the generation of an FMEA. The failure records of a conveyor and a chip-mounting machine have been used for the case study, courtesy of Motorola Technology Malaysia PLC. A sample extracted from the failure report for a chip-mounting machine is shown below:

ITEM_ID	DATE_ATND	NICKNAME	DATE_RQS	PROBLEM	CAUSE	SOLUTION	DATE_CLOSE
A24517	3/27/02 7:46	SIE-S20-13	3/27/02 7:21	incorrect nozzle length	nozzle worn out	replace	3/27/02 8:00
A24531	3/27/02 8:04	SIE-S20-10	3/27/02 8:03	unable to pick-up	nozzle clogged	replc. new nozz	2/27/02 8:06
A24535	3/27/02 8:09	SIE-S20-10	3/27/02 8:09	intermittent comms.	loose connection	fixed properly	3/27/02 8:17
A24539	3/27/02 8:19	SIE-S20-10	3/27/02 8:19	comp fly/overturn	shutter jam/bent	change	2/27/02 8:51

All related parts for the conveyor are modelled and captured by the system. The full FMEA generation as created as shown in figure 3.

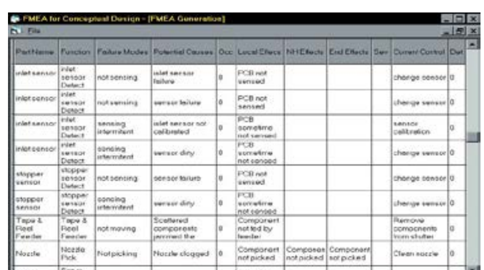
In the case of the chip-mounting machine, not all parts are modelled, i.e. not all parts are provided with the properties, states and behaviours that are required for the FMEA generation. The chip-mounting machine has a conveyor which is similar to a conveyor used in a previous case. Hence, the data can be reused without creating additional parts for its conveyor. The result is as shown in figure 4. Even if the machine is not fully modelled, it is capable of providing a generated result based on the historical data and user input from the limited failure reports. The user can then complete the FMEA manually.

The result of the FMEA generation depends very much on the data input from the user. An inaccurate input may cause the system to provide a false result. A precautionary step is taken so that the user has the final decision on whether to accept the result of an FMEA generation, and save it into the FMEA file. The user can always go to the software to rectify the input later.

FMEA for Conceptual Design - [FMEA Generation]

PartName	Function	Failure Modes	Potential Causes	Occ	Local Efects	NH Effects	End Effects	Sev	Current Control	Det
inlet sensor	inlet sensor Detect	not sensing	inlet sensor failure	0	PCB not sensed	PCB not sensed	PCB not sensed		change sensor	0
inlet sensor	inlet sensor Detect	not sensing	sensor failure	0	PCB not sensed	PCB not sensed	PCB not sensed		change sensor	0
inlet sensor	inlet sensor Detect	sensing intermitent	inlet sensor not calibrated	0	PCB sometime not sensed	PCB sometime not sensed	PCB sometime not sensed		sensor calibration	0
inlet sensor	inlet sensor Detect	sensing intermitent	sensor dirty	0	PCB sometime not sensed	PCB sometime not sensed	PCB sometime not sensed		change sensor	0
inlet sensor	inlet sensor Signal	no signal	inlet sensor failure	0	controller not active	motor not running	PCB not moving		change sensor	0
inlet sensor	inlet sensor Signal	sometime no signal	inlet sensor not calibrated	0	controller sometime not activated	motor sometime not running	PCB sometime not moving		sensor calibration	0
Motor	Motor Move Belt	not moving	Motor coil burnt	0	belt not moving	PCB not moving	PCB not moving		change motor	0
Belt	Belt Move PCB	not moving	belt broken	0	PCB not moving	PCB not moving	PCB not moving		change belt	0
	Belt				Component	Composer	Component			

Figure 3. Generated FMEA for Conveyor



FMEA for Conceptual Design - [FMEA Generation]

PartName	Function	Failure Modes	Potential Causes	Occ	Local Effects	NH Effects	End Effects	Sev	Current Control	Det
inlet sensor	inlet sensor Detect	not sensing	inlet sensor failure	0	PCB not sensed				change sensor	0
inlet sensor	inlet sensor Detect	not sensing	sensor failure	0	PCB not sensed				change sensor	0
inlet sensor	inlet sensor Detect	sensing intermitent	inlet sensor not calibrated	0	PCB sometime not sensed				sensor calibration	0
inlet sensor	inlet sensor Detect	sensing intermitent	sensor dirty	0	PCB sometime not sensed				change sensor	0
stopper sensor	stopper sensor Detect	not sensing	sensor failure	0	PCB not sensed				change sensor	0
stopper sensor	stopper sensor Detect	sensing intermitent	sensor dirty	0	PCB sometime not sensed				change sensor	0
Tape & Reel Feeder	Tape & Reel Feeder	not moving	Scattered components jammed the	0	Component not fed by feeder				Remove components from shutter	0
Nozzle	Nozzle Pick	Not picking	Nozzle clogged	0	Component not picked	Composer not picked	Component not picked		Clean nozzle	0
	Servo									

Figure 4. FMEA for Chip-Mounting

10. CONCLUSIONS

This paper has described ongoing research in the capture and re-use of knowledge in design and manufacture in a predictive design environment. The focus has been on application in the field of Failure Mode and Effect Analysis (FMEA). The current shortcomings of FMEA have been identified, and a way proposed for semi-automatic FMEA generation to overcome those difficulties. The proposed model is based on the study of various methods applied in FMEA research and is strongly based in knowledge re-use methods. The model is intended to be generic so that it can be applied to many design cases including product and process design. The system successfully demonstrates FMEA generation based on user input, and the reuse of existing knowledge. Only two manufacturing process cases have been investigated so far. The ongoing developments include

- Extending the cases study to include more cases including design cases for verification
- Enabling a part to inherit the characteristics of another part which is considered as its "parent" in the parts library
- Application to multiple users.

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