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IMPROVED PRODUCT, PROCESS AND RATIONALE REPRESENTATION AND INFORMATION ORGANISATION TO SUPPORT DESIGN LEARNING

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ABSTRACT

Many companies are moving from a product provision business model to a product-service model, where the producing company retains ownership of the product and supports it through life. In such a scenario it becomes possible to obtain a greater richness of information relating to product performance. However, in order for this information to be usefully deployed in improving design and manufacturing practices it is necessary to reconsider the means by which the design record is represented and organised such that linkages between the design record and the emergent outcomes as seen in service are explicit. In this manner, design episodes which continually lead to suboptimal or undesirable performance in service may be identified and remedial action taken.

Current representation practices focus upon a generally topological or geometric depiction of product, structured according to the Bill of Materials, which is supported by primarily textual depictions of the process followed and rationale employed. Although an engineer may be able to retrieve and assimilate information contained within these representations, it is difficult to provide a unified view of a specific episode as distinct elements within these representations are not computer-interpretable and dependencies across the representations are not explicit. This paper proposes a method by which decomposed elements of the representations of product, process and rationale can be computationally identified and linked, thus providing a mechanism to accumulate evidence of outcomes in use regarding aspects of the design for prospective improved design learning,

Keywords: Design representation, information management, learning from use

1 INTRODUCTION

The ability to learn from one's experience is key to improving subsequent performance, be that at an individual, team or corporate level. Under a product provision business model, feedback from service is funnelled through third parties such as the customer or agent of the customer, which necessarily impairs the quality of such feedback and the ability to learn from it. The shift to a product-service business model, in which the company that provides a product retains ownership and supports, maintains and as appropriate improves the product though its life provides an ideal opportunity for companies to obtain detailed information regarding the performance of a product in service, information that can usefully be deployed in improving design and manufacturing processes. To this end, personalization approaches to knowledge management, which promote the development and retention of knowledge by individuals and communities, are a key mechanism that enable this but may be informal and ad hoc. Though effective in some situations, codification strategies, which embed knowledge in formal information resources, are increasingly needed because of much longer product lifecycles and geographically distributed teams and the need to capitalise on the maturity of IT tools. Some examples of codification approaches include online customer and service reporting systems, maintenance and service records and reports etc. In addition, some 'valuable' learning episodes may also be recorded in best practice and lessons learned databases for future reference.

If experiences and observations from service are to be used as a means of learning in order to improve the design process, it is essential to be able to identify which aspects of the design process led to specific outcomes. The design process is taken to be a series of activities which generate a representation of the desired product, and which are guided both by information resources (such as materials properties databases and company guidelines) and by rationale employed by the engineer.

By identifying the aspects of process and rationale (including the information resources consulted) which were enacted during a specific design episode, and assessing the in-service performance of the aspect of product addressed during that design episode, it becomes possible to deduce the suitability or accuracy of the process and rationale utilised in that episode. In service, it is possible to accumulate feedback such that aspects which continually lead to suboptimal outcomes may be identified and addressed.

If this is to be achieved, however, it is essential that the aspects of product, process and rationale are identifiable within the design record. Linkages between these aspects must be made explicit such that the process which led to the evolution of a feature of the product is identifiable, as are the rationale and information resources which guided that process. Further to this, it is argued that explicitly linking elements of product, process and rationale will allow for an interested party to retrieve more extensive information relating to a design activity in a more appropriate context as opposed to piecemeal retrieval of isolated and text-based information which must then be assimilated by the engineer.

We argue below that, currently, the process undertaken and rationale employed in a design episode are largely documented in text records such as reports and meeting minutes. As such, it may be difficult to deduce, for example, which design episode led to which product feature or the reasoning behind a choice of analysis parameters without recourse to manual retrieval and assimilation of various different documents, within which the elements of interest may not be readily identifiable. If the design is to be reused, it is essential that the design record allows distinct elements to be located and also that the record indicates how these disparate representations interact. This paper considers improved representations with this purpose in mind.

In many branches of engineering the product representation centres around a geometric depiction of the product, with further supporting information, encompassing process and rationale, in pictorial or textual representations. Efforts to model process through graph methods, such as through the use of IDEF [1], Petri nets [2] and related research, have to some extent addressed these concerns by identifying elements which are logically related. Similar notions have been applied to the capture of rationale, for example IBIS-based approaches such as DRed [3]. The product representation, however continues to be represented geometrically or topologically, and whilst recent research into annotation [4] allows for differing elements to be identified it does not provide a complete semantic description of the product.

This paper proposes an improved means of product representation within which specific elements are made computationally identifiable. This paves the way for linking together the associated elements of product, process and rationale. Topic Maps have been identified as an appropriate way of browsing such elements once they are interlinked. Topic Maps are a means of indicating how concepts within a domain are related, and where those concepts reside within a document corpus. The key to the application of Topic Maps is the idea of merging, where different maps may be combined around common topics and associations, thus natively providing for integration of information resources. In the case described in this paper, Topic Maps may be applied to the linking of product, process and rationale representations. With such linking, it is envisaged that emergent outcomes of design activities may be traced to the constituent aspects of a design episode, thus providing some indication as to the veracity of these aspects.

1.2 Structure of Paper

This paper addresses three different issues: the representation of product, process and rationale; information organisation and learning from use. These will be described in the following three main sections respectively. The paper will conclude with some brief discussion and an outline of planned future work.

2 PRODUCT, PROCESS AND RATIONALE REPRESENTATIONS

Structured representations are used to a varying extent in engineering design. Formal, computational approaches to product modelling have been used for many years, and are now firmly centred on solid models for product geometry, combined with bills of materials (BoMs) for product structure. Computational representations of process and or rationale have been available for some time, based largely on graph representations, but for the most part description of the process undertaken and the rationale employed in design is achieved via unstructured or semi-structured text documents – e.g. reports, minutes of meetings and correspondence. We argue that by describing the product and the process and rationale employed in its design in semi-structured or structured computer-based representations, and then by linking these representations together, a much richer and more exploitable model of the outcome of the design process is achievable.

Integrated models for design have been reported elsewhere in the engineering design literature. The IPPOP (Integration of Product – Process – Organisation for engineering Performance improvement) project [5] reports the integration of a process model with a product model by the use of versioned product data, and with an organisation model by reference to resources, constraints, goals, etc. The NIST information modelling framework [6] was proposed to capture information about products, assembles, tolerances and the evolution of products and product families. It consists of four major components: a Core Product Model (CPM) with the capability of capturing and sharing the full engineering context in product development; the Open Assembly Model (OAM) for assembly and system-level tolerance information; the Design-Analysis Integration model (DAIM) as a basis for integrating design and analysis; and the Product Family Evolution Model (PFEM) for the evolution of product families and of the rationale of the changes involved. The formal model developed by the MOKA (Methodology and tools Oriented to Knowledge-Based engineering Applications) project [7] represents product meta-classes and views (i.e., function, structure, behaviour, representation, and technology), and relations between them.

Each of these reported approaches has considerable merits, but also some limitations. The simple connection of process model and product model is not enough, and more detailed and closer connections are needed, such as the linkage of an activity with specific parameters/functions/features of the product. More specifically, in IPPOP, the product model links product structure with product functions, but information on design rationale and product history is lacking. The NIST CPM framework succeeds in capturing assembly, subassembly, part and tolerance information, but loses information such as design history and conceptual solutions. Furthermore, while it is closely related to analysis and the evolution of product families, it does not provide a mechanism for recording the whole design process and the rationale employed. The MOKA approach improves capture, analysis and structuring of the knowledge required for Knowledge-Based Engineering (KBE) applications, but is not a good solution for recording rationale and the relationships between product features and the processes and rationale used in their creation and evaluation.

2.1 Scopes of Design Representation

We propose that in design it is important to provide a framework for the documentation of design activities using diverse information entities to represent different views on the product and the design process, but also to allow a computer interpretable audit trail to be built of the way in which these information entities are used. This audit trail will record how the design develops through the design process, how information is used (e.g. which information is used for each decision; which information results from each evaluation activity etc.), and what is the rationale used by the design team in making their design choices.

An integrated product, process and rationale (IPPR) modelling approach is currently being developed by the partners in the Knowledge and Information Management Through Life (KIM) project[1], of which the research reported here is a constituent part. In this approach the design team may generate, during the design process, structured or semi-structured models of the following:

- The physical product or service that is being designed, the former in the form of conventional computer-aided design models supplemented by annotation.
- Design and design evaluation processes, described in terms of activities that involve manipulation of information entities to generate new information.
- Rationale employed in the course of design exploration and decision-making, in the form of issues, questions and answers relating to the design.
- Information entities used in design evaluation (e.g. finite element and computational fluid dynamics models)
- Miscellaneous information entities recording design knowledge – for example recording the results of information search; meetings with suppliers etc.

The first three types of model (along with references to pre-existing information entities within and external to the designing organisation) form what may be considered to be the basis of the

[1] https://www-edc.eng.cam.ac.uk/kim/

transactional design record – the product, process and rationale. The fourth type are essentially auxiliary or intermediary models, which are generally derivatives of design models used in order to make assessments of the design. The fifth type are generally learning documents, indicating the means by which necessary *understanding* of the design domain, means of analysis, properties of available resources etc. were developed when evolving the design.

We argue that by themselves these models are useful, but their full value is only obtained when they are interlinked to allow dependencies to be revealed. In the following sub-sections, we comment on each of the different modelling approaches, and how these need to be adapted to allow their integration in a IPPR framework.

2.2 Product Models

Over the last four decades, various approaches to product modelling have been proposed by academia and industry [8]. Techniques have included early approaches such as wire frame and surface modelling and constructive solid geometry (CSG) and boundary representation (B-rep) solid modelling, and more recently feature-based and parametric modelling methods. Currently, most commercial Computer-Aided Design (CAD) systems adopt a hybrid representation, such as the application in Pro-Engineer [9] of a feature-based approach with associative parametric solid modelling based on B-rep and surface model. Along with developments in modelling approaches have been improvements in user interfaces and in design flexibility. However, the focus has largely remained on providing geometric and topological depictions of the product, and descriptions of the high-level design and engineering context and semantics have been limited.

Most efforts at providing linkages to product models focus on linkage between parts in assemblies, or linkage from external models to high level representations, such as of assemblies and parts. However, high level connections cannot make good sense for users in most situations as activities and rationale are often related to specific design elements, such as part parameters, features and tolerances, not to the whole product or part. Therefore, the product model needs to be decomposed to different levels of detail, from assembly and parts to further details, such as features, surfaces, parameters and tolerances. In addition, there may be several design iterations during a design process. To reflect iterative development, the product model not only should include the final design, but also should record the conceptual designs considered, alternative design solutions and the development of the chosen solution – in other words the temporal development of the design should be recorded.

In the IPPR approach we are exploring various mechanisms for providing linkages to product models. A particularly promising approach is the use of annotation of the product model to provide for external links from the model and to semantically identify parts of the model. For example a process activity that refers to the loading of a face of a part can make explicit reference to annotation on a boundary representation CAD model of the part. We initially embedded the markup in the CAD model data structure [10]. Our current work is exploring the use of external XML annotation linked to the product model through unique identifiers for each model element. We are also exploring the embedding of annotation in other graphical models used in the design process – sketches, diagrams etc (for example using the SVG language) and the use of lightweight, portable representations such as PLM XML, created and supported by UGS [11] which supports the recording of non-geometric product model information.

2.3 Process Models

Process models of interrelated or sequential activities can be constructed to study and understand complex systems and to facilitate the visualisation of information flow in the systems. Various modelling approaches have been applied extensively in modelling such domains as business systems and manufacturing systems. The modelling of activities and information flows in engineering design processes has also been done widely through various process modelling techniques [12]. These techniques range from high level approaches (e.g. Decision Structure Matrix (DSM) [13], Gantt charts etc.) to low level (e.g. $IDEF_0$ [1], Petri Nets [2], Signposting [14] etc.). Recent developments include new tools for the representation of processes in a work flow modelling context, such as the XML Process Definition Language (XPDL), and the Business Process Modelling Notation (BPMN) of the Business Process Management Initiative (BPMI). The BPMN specification provides a graphical notation for expressing business processes in a Business Process Diagram (BPD) [15].

We suggest that high level models are satisfactory for partitioning of the design process, and allow precedence relationships between tasks to be identified, but they generally do not allow information dependencies to be closely modelled, for which we require low-level models. In this regard we are working using an XML representation of $IDEF_0$ nodes to model elementary activities (although in principle other representations would be suitable). $IDEF_0$, one of the most commonly used of the IDEF family of languages, is a functional model derived from the Structured Analysis and Design Technique (SADT). An $IDEF_0$ model is composed of a set of hierarchically linked diagrams with supporting text that display increasing levels of detail describing functions and their interfaces within the context of a system. A node of an $IDEF_0$ diagram represents an activity and its inputs and outputs (typically information entities), the mechanisms used to carry it out (e.g. staff, machines, software) and the controls on the activity (e.g. specifications, standard procedures, guidelines etc.). In the IPPR framework, the $IDEF_0$ based XML documents are particularly appropriate in describing **transaction** activities, in which some standard procedure is carried out in the design process – for example for design analysis or evaluation. Of course in many cases an activity may be decomposed into further activities at a greater level of detail. In addition to the basic $IDEF_0$ node, we therefore consider also a node which aggregates a series of nodes at a lower level. Transaction activities are normally repeatable, and in such activities it is most important to record the information dependencies and the procedures applied in order to achieve the audit trail.

An alternative to a transaction activity is one that is aimed at **learning**. In such cases diverse information sources may be used – documents, colleagues, suppliers etc – in order to identify the most appropriate approach to some design issue. In such cases the outcome of the activity is more likely to be a narrative, and therefore the structure of the record of the activity is less important. Conversely, a learning activity may generally be built upon as more information becomes available, and therefore it may be important that the documentary record is extendible. We propose that in these cases conventional documents or WiKi documents [such as discussed in 16] are the most appropriate record.

2.4 Rationale Models

Design rationale is typically recorded today in the form of unstructured text – for example in design or design analysis reports, letters and emails and records of meetings. Such records are often time consuming to generate and edit, and furthermore the lack of structure in such representations makes it difficult and time-consuming to trace. Approaches for improving rationale capture have been studied for many years but have not been popular in practice due to inherent subjectivity. One of the earlier systems for recording and structuring issues during decision-making processes was called Issues Based Information System (IBIS) [17]. It is a directed graph with nodes representing issues that are linked to nodes representing alternative solutions by arcs. The solution nodes can then be linked similarly by arcs to nodes representing arguments for or against them. Tools building on an IBIS-type approach to design rationale capture include Compendium [18], which is based on graphical hypertext and the Design Rationale Editor (DRed) [19], which is based on a general purpose interactive graph editor. IDEF has also developed IDEF6 – IDEF Design Rationale Capture for the same purpose [20]. In short, rationale capture methods seek to identify design issues and questions/responses and then define the relationships between them by directed arcs. In the early stages of the design process many of the questions will be unresolved. Activities will be carried out in order to generate information to allow them to be resolved. By formally linking the issues/questions with the activities required for their resolution, again an audit trail can be built of the development of the design.

3 THE ORGANISATION OF IPPR MODELS

The decomposition of product, process and rationale supports the computational interpretability of information elements within each representation, thus allowing computational approaches to be utilised in retrieving such information for use by an engineer. A complete depiction of a design episode may be achieved by considering elements across the different representations concurrently, where the element of interest of the product may be considered together with the activities involved in its creation or evaluation and the rationale employed. As such, it is important that the logical links between elements across the three representations be expressly indicated, such that an engineer may locate and assimilate this information.

Such integration may be addressed via the use of Topic Maps. Topic Maps are a means of expressing how different concepts or topics within a domain are related and where occurrences of such topics may be found within an underlying document corpus. The Topic Map overlays the corpus, and occurrences of a given topic with the corpus are indicated by Uniform Resource Indictors (URIs, a means of resource identification which provide either unique names or paths to resources), meaning that a Topic Map can be generated (by identifying relevant topics, how they are associated and where they occur), modified and shared with no modification to the document corpus itself. The structure and physical organisation (in terms of relative locations on network drives or within Product Data Management systems) are hence irrelevant, assuming they are visible to the Topic Map. As discussed previously, the elements within the IPPR representations are computer interpretable, hence it becomes possible to link directly to a given element as opposed to a complete document, refining the identification of information of interest to the engineer.

Topic Maps have a further benefit in that they were originally designed to assist in the merging of indexes of electronic documentation [21], as Garshol and Bogachev state, they are '..ideal for information integration, because of the clear conceptual model and built-in support for merging' [22], and hence they are well-suited to unifying both distinct elements within representations and of unifying across representations.

3.1 Topic Maps

A Topic Map comprises a number of topics which are nodes representing a concept occurring within the domain of interest. Linkages between these topics are indicated and defined by associations, where each topic in that binary association is assigned a role to indicate the nature of the relationship. For example, the topics 'analysis_x' and 'feature_a' could be linked by the relationship 'definition', where the topic 'analysis_x' would have the role of 'defines' and 'feature_x' the role of 'defined_by'.

It is possible, of course, to have more than one relationship between two topics, both because of different inherent types of relationship (for example, it is equally valid to assign the association of 'utilises' to the pair of topics identified previously) and because of viewpoint-dependency (for example, 'output' would be an association similar to 'definition' but focusing more upon information flow). It is possible to impose some class structure upon the map, by introducing topic and association *type*, such that permissible roles are indicated by the different types of topic involved in each type of association.

The freedom in the identification of associations is arguably one of the strengths of Topic Maps, as the ability to assign a number of associations according to differing viewpoints allows different users to share a common structure without enforcing a shared (and arguably suboptimal) viewpoint upon the domain.

Although not intrinsically visual, Topic Maps lend themselves to visual display and browsing as the topics and associations form directed graph structures which may be traversed from topic to topic by following associations of interest. This assists in the comprehension and retrieval of information described by a Topic Map, as although providing a computer-interpretable structure in which to indicate associations between elements of a document corpus, they may be considered "intelligent support for human browsing, not unlike a flexible index or map which can take on different shapes for different users" [23]. Such browsing may be assisted by the use of *scope*, which pares the Topic Map down to indicate only the associations and occurrences of interest within a specific viewpoint or scope. It is therefore possible to restrict the displayed associations and occurrences to only those corresponding to a particular interest, for example when examining the check stresses of an aircraft strut it is possible to view associations indicating which information entities such as materials data and load cases were used in the analyses.

The use of scope allows for related items of interest to be found given an initial item. They do not directly facilitate retrieval of this initial given item. In the case described here, it is possible to identify the element of interest by browsing the representations which the Topic Map describes, however it may be the case that a relevant element can only be identified in the content of associated elements (for example a specific process may only be of interest if it is seen to act upon a general product part). A query language, TMQL, has been developed that allows a Topic Map to be interrogated in order to retrieve elements of the map that correspond to certain specified conditions. As Topic Maps cater for classes, in the form of types, it is possible to query at a more abstract level than simply requesting certain topics or associations to be listed.

A draft proposal for such a standard was issued in 2003 [24] and a further refined draft followed in 2005 [25]. Efforts are underway to release a formal standard for TMQL under standard number

ISO/IEC CD 18048 [26]. The committee responsible for TMQL highlight that a query language is useful for visualising Topic Maps [27]. The use of scope allows for entities that are not of interest in a given viewpoint to be omitted, but the use of a query language further refines the ability to restrict the display of non-relevant entities.

3.1.1 Expression of Topic Maps

While there are a number of standards for Topic Maps, there are two key standards (which define syntax) that are of greatest interest. The earliest is ISO 13250 [28], which is expressed as an application of SGML and uses the HyTM syntax. This was the first standard for Topic Maps, being adopted as an ISO work item in 1996 and published as a standard in 2000. A second standard, XTM [29], sought to develop or otherwise adapt the ISO standard to improve performance on the Internet. The consortium responsible for this standard identified XML as a key technology that will shape the future of the Internet, and hence XTM is a grammar for XML. This standard, XTM 1.0, was released in December 2000. As XML is rapidly becoming the 'lingua franca of information exchange' [22], this standard has been identified as suitable for application in this work.

3.2 Proposed Application of Topic Maps to the Unification of IPPR

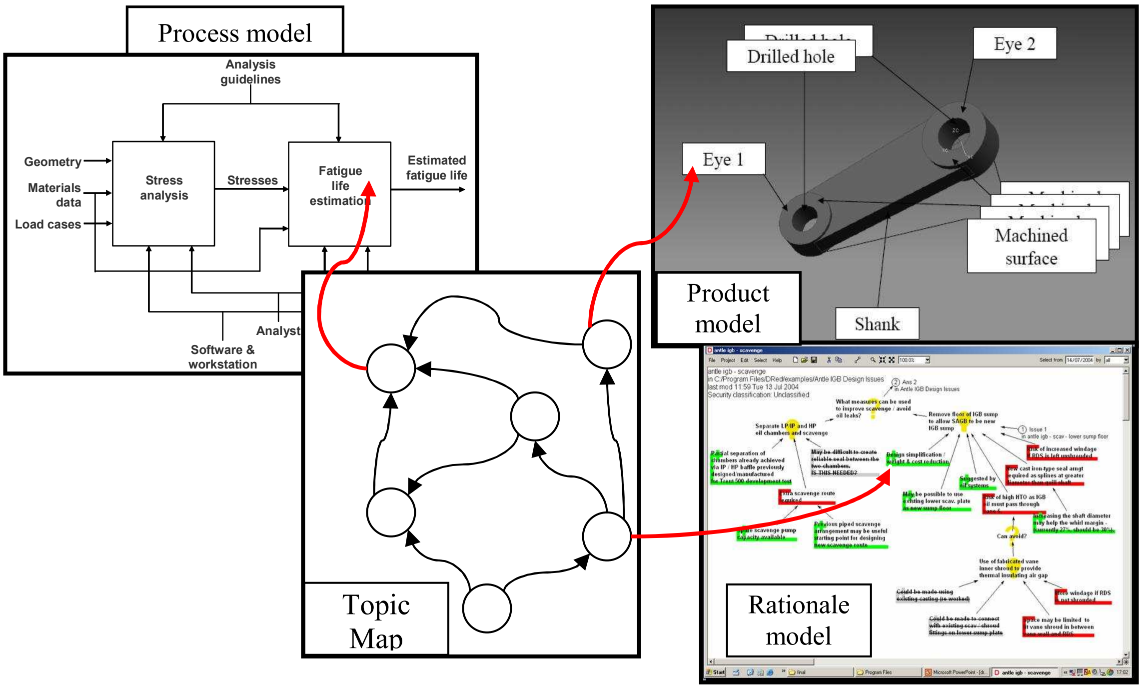

Figure 1 Topic Map Linking Elements of IPPR

Figure 1 indicates how the Topic Map may unify the differing representations of IPPR. The Topic Map acts as an intermediary, indicating the linkages between the disparate representations but not fundamentally altering them. This allows the engineer to interrogate or act upon the information contained within the differing representations, but at any point to traverse across to distinguish associated elements in different representations. As such, it is possible to identify a feature of interest and then to locate the process and rationale documentation that will indicate how this feature came into being. As the rationale, process and BoM representations are directed-graph structures, it is possible to subsume the intra-representation linkages into the Topic Map, such that browsing may take place entirely within the Topic Map. This logical linking also presents an opportunity for linking the elements of IPPR to emergent outcomes, where the performance of a particular part in service can be linked through the Topic Map to the specific part of the design process in which it was designed and to the rationale employed during this process. In this manner it is possible to deduce those processes and items of rationale which are suboptimal, allowing the engineer to 'learn' which aspects of the design episode may be usefully reused and which must be reconsidered. This form of learning from use will be described in the following section.

4 LEARNING FROM USE THROUGH FEEDBACK OF OBSERVATION

4.1 Current approaches

In order to enable learning-from-use for continuous improvement, many paradigms in the literature emphasize the importance of feedback loops and mechanisms. In Total Quality Management (TQM), for example, continuous improvement is a phrase suggesting that a process or product should always get better as knowledge about it and experience with it accumulates over time. In TQM, Deming pioneered the use statistical analysis in manufacturing and use the resulting data to control quality during manufacturing. In Business Performance Management (BPM), Key Performance Indicators (KPI) are measurable quantities used to monitor performance against business or operational targets to assess performances. BPM typically employs a number of quantitative techniques to organise, monitor and analyse business performance, as well as enhance processes by creating better feedback loops.

To this end, a number of feedback mechanisms are employed in engineering companies to gather and learn from service and operations. Strategies in knowledge management can be broadly categorised into those of personalization and codification. Personalization approaches emphasize human resources and communication, whereas codification approaches emphasize the collection and organization of knowledge [30]. In supporting learning-from-use, knowledge gained through the operation of a product can be fed back through a personalisation or a codification approach. In practice, a combination of these two approaches is usually adopted.

In the context of product-service systems with much longer lifecycles, involving more dynamic and geographically distributed teams, personalization approaches may not be sufficient. The drawbacks of these approaches are that they rely greatly on memory and on informal social networks. Furthermore, service personnel are often geographically remote from design and manufacturing sites. It is arguable that personalization approaches alone may not result in the level of learning required for companies competing on knowledge economy. In order to capitalise on the maturity of IT tools, increasing efforts are now placed into the development of systems and tools to enable codification and sharing of experience. For instance, it is now common for non-trivial experience to be codified and recorded in databases for future reference. For example, NASA has a publicly accessible database of lessons-learned in the space program [31].

In the context of engineering design, feedback from service represents a significant resource for learning. For instance, the knowledge gained about the functional or operational performance of the product through its use can provide a basis for assessing and updating design knowledge. At present, service observation is fed back through records mainly in text-based documents. Some online reporting systems are also commonly used as a means to collect feedback information from service and from customers. Typically the documentation may be based on structured forms and templates, and may be customised according to company and domain-specific requirements. The feedback process is sometimes included in a standard work flow procedure. These approaches sometimes lead to issues associated with subjectivity and incentivisation due to extra work loads etc. Due to the open-ended structure and free-style writing, these records usually present some challenges to retrieval and do not lend themselves to structured knowledge discovery techniques. To improve reuse, the documentation may be indexed or organised according some classification scheme.

4.2 Potential benefits

In discussing organizational learning, Argyris [32] suggests two levels of learning, i.e. single-loop and double-loop learning. In single-loop learning, individuals, groups or organizations modify their actions according to the difference between expected and obtained outcomes. In double-loop learning, the entities (individuals, groups or organization) question the values, assumptions and policies that led to the actions in the first place; if they are able to view and modify those, then second-order or double-loop learning has taken place. Single-loop learning defines behaviour that is reactionary in nature. Double-loop learning, on the other hand, would examine the situation and develop new ways to address it.

Automatic data logging and monitoring technology are used to capture operational data continuously. These systems usually results in large volumes of data, therefore, robust strategies are required prior to deployment. This may include embedding intelligent systems e.g. decision-support and data mining algorithms [33, 34]. An example is for the purpose of predictive maintenance. Online health monitoring and fault diagnostic systems are used for maintenance of aircraft engines embedding state-of-the-art technologies such as Case Based Reasoning for decision-support. The Distributed Aircraft Maintenance Environment (DAME) is an e-Science project demonstrating the use of GRID infrastructure to implement for deployment such systems in distributed environments.

However, information from service has often not been reused to modify a product's design to reflect Argyris' definition of a double-loop learning. So far, development of intelligent decision-support applications largely focus on facilitating single-loop learning, i.e. for better reactive actions based on information collected from service and operations. On the other hand, Stone et. al. [35] demonstrates the benefits of relating observation of failures in service to the functionality of products despite a retrospective and manual approach.

As mentioned earlier, the move to product-service business model means there are greater opportunities to capture and reuse information and knowledge in the design process, because the designing company is also in control of the through-life service element. It is envisaged that by unifying the IPPR representation and linking to observation of the design outcome in Topic Maps, a key contribution in automating the identification of the relationship between aspects of the design and observation can be made. The hypothesis in this paper is that the improved mechanism for learning from experience may be achieved through the identification and linking of operational observations to the IPPR representation. The proposed improved IPPR may allow for such observations to be established automatically because the elements in the representation are computer-interpretable. If we are able to assess the performance of a design episode more objectively, the structured and consistent representation allows the relationships between elements in the IPPR to be traced, revisited and reused in a later stage.

By objectively building up a body of evidence that is linked to the IPPR representation created in upstream design activities, the framework may allow inference of the performance of elements or a cluster of elements, or the associations between them and a certain phenomenon. For example, by associating occurrences of certain type of premature failure to manufacturing tolerance or design rationale, process sequence etc. may inform subsequent changes to a design procedure. The evidence may come from in-service product behaviour, function, failure trends and can provide a basis for engineers to draw deeper insights and conclusions from. Further work in this respect includes developing a representation for observations that is consistent with the IPPR representation and is amenable to knowledge discovery approaches to allow for the inference to be made automatic.

5 DISCUSSION AND CHALLENGES IN FUTURE WORK

This paper has proposed a means by which the semantic content of the design record may be made more computer-interpretable, and further proposed a method of organising the documents that comprise these records into structures that will allow for easier retrieval and assimilation on the part of the engineer. Alongside presenting opportunities for design reuse, as the processes and supporting rationale utilised in the design of a component are clearly expressed, this also allows for evidence of product performance in service to be associated to these processes and rationale, in doing so providing a means of validation for these processes. This is argued to be of increasing importance when considering the progression many companies are making in moving towards product-service business models in place of product provision [36] and the necessary impact this has on the ability both to retrieve information of previous design activities and of improving these processes in the light of observations from service.

The proposed approach describes a starting point from which a number of challenges have been identified which present interesting avenues for further work. A key consideration is in the aggregation of each representation within the Topic Map. The product representation is, to a greater or lesser extent, hierarchical along the axes of process-activity and of product decomposition, and it is important that these axes may be used as navigation within the Topic Map. A design episode is iterative in nature, due to both planned refinement and rework, and this must also be indicated within the structure of the map. It is also important to allow an engineer to browse at differing levels of detail: under certain situations the engineer may wish to retrieve information at a fine level of detail, for example indicating how a specific calculation was performed, whereas other situations may require higher-level perspectives, for example in identifying resources used within a certain period of the design episode. Hence, not only does the iteration have to be adequately integrated within the map, it has to be integrated at differing levels of abstraction.

A further challenge is in the identification of suitable means of representing observations from service. Alongside issues of manifestation, where observed defects may be caused by suboptimal performance of a different part of the product, it is also important that observations are captured in a uniform manner such that they may be attributed to the correct aspect of product within the design record. As the product is decomposed, it is essential that this attribution occurs at the correct level of decomposition.

6 CONCLUSIONS

This paper has presented a means by which service observations may be linked to design records for purposes of increasing understanding of the design process in question. A necessary part of this approach requires the decomposition of the design record into distinct elements, to which observations from service may be linked to provide a clear path from design process to design outcome, and a method of linking the disparate aspects of the design record. Topic Maps are seen as a suitable mechanism for this approach. A number of open questions are posed, which form the basis of future work.

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REFERENCES

[1] IDEF0. Announcing the Standard for Integration Definition For Function Modelling (IDEF0). *Draft Federal Information Processing Standards Publication 183* (National Institute of Standards and Technology, 1993).

[2] Murata, T. Petri nets: Properties, analysis and applications. *Proceedings of the IEEE*, 1989, 77(4), 541-580.

[3] Bracewell, R.H. DRed and design folders, a way of capturing, storing and passing on, knowledge generated during design projects. In *ASME DETC/CIE 2004.* Salt Lake City, USA. 235-246

[4] McMahon, C.A. and Davies, D. The use of markup in documents and in computer aided design: a comparison. In *International Workshop on Annotation for Collaboration Methods Tools and Practices.* November 23rd-24th.

[5] IPPOP. Integration of Product – Process – Organisation for engineering Performance improvement [online]. 2003. Available from: http://projects.opencascade.org/IPPOP/Introduction/index.htm [Accessed 1 January 2007]

[6] Brix, T., Doring, U. and Reeßing, M. Multistage modelling in early design phases. In *ICED03.* Stockholm, Sweden, 19-23 August 2003.

[7] MOKA Consortium. MOKA: A Framework for structuring and representing engineering knowledge [online]. 2003. Available from: http://web1.eng.coventry.ac.uk/moka/informal.htm [Accessed 1 January 2007]

[8] Bojcetic, N., Pavkovic, N. and Pavlic, D. Extended CAD Model. In *ICED05.* Melbourne, Australia, 15-18 August 2005.

[9] PTC. *Pro/ENGINEER Modelling Users Guide*. (Parametric Technology Corporation, Waltham, Maryland, USA, 2006).

[10] McMahon, C., Davis, D. The Use of Mark-up in Computer-Aided Design and Lessons for Text Documents. In *International Workshop on Annotation for Collaboration.* Paris, France, Nov 24-25, 2005.

[11] UGS. Open product lifecycle data sharing using XML: White Paper. (UGS, Plano, Texas, 2005).

[12] Pavkovic, N., Marjanovic, D., and Dekovic, D. Object-oriented modelling of the design process. *Proceedings of ICED'01*Glasgow, 2001).

[13] Steward, D.V. The design structure system - A method for managing the design of complex systems. *IEEE Transactions on Engineering Management*, 1981, EM-28, 71-74.

[14] Clarkson, P.J. and Hamilton, J.R. 'Signposting', A Parameter-driven Task-based Model of the Design Process. *Research in Engineering Design*, 2000, 12, 18-38.

[15] White, S.A. Business Process Modelling Notation. (Business Process Modelling Initiative, 2002).
[16] Wodehouse, A.J., Grierson, H., Ion, W.J., Juster, N.P. and McGill, L. Enhancing Design Learning Using A Digital Repository. In *ICED05.* Melbourne, Australia, 15-18 August 2005.
[17] Kunz, W., and Rittel, H.W.J. Issues as elements of Information Systems. (Center for Planning and Development Research, Berkeley, USA, 1970).
[18] Conklin, J., Selvin, A., buckingham Shum, S., and Sierhuis, M. Facilitated Hypertext for Collective Sensemaking: 15 years on from gIBIS. *Proc. 12th ACM Conference on Hypertext and Hypermedia*Arhus, Denmark, 2001).
[19] Bracewell, R.H., and Wallace, K.M. A tool for capturing design rationale. *International Conference on Engineering Design (ICED'03)*Stockholm, Sweden, 2003).
[20] Mayer, R.J., Crump, J. W., Fernandes, R., Keen, A., Painter, M. K. Information Integration For Concurrent Engineering (IICE) *Compendium of Methods Report* (KBSI, 1995).
[21] Pepper, S. The TAO of Topic Maps [online]. Ontopia. 2002. Available from: http://www.ontopia.net/topicmaps/materials/tao.html [Accessed 1 August 2006]
[22] Garshol, L.M. and Bogachev, D. TM/XML - Topic Map Fragments in XML. In *TRMA 2005.* Leipzig, Germany, October 2005. 210-230 (Springer-Verlag Berlin Heidelberg)
[23] Kemeny, Z., Erdos, G. and Vancza, J. Representation and Navigation Techniques for Semi-Structured Knowledge in Collaborating Communities. In Bernard, A., ed. *Chapter for forthcoming VRL-KCiP Knowledge Management book* 2007.
[24] Garshol, L.M. and Barta, R. Information Technology — Document Description and Processing Languages: TMQL requirements. (ISO/IEC JTC 1/SC34, 2003).
[25] Garshol, L.M. and Barta, R. Information Technology — Document Description and Processing Languages: Topic Maps Query Language. (ISO/IEC JTC1/SC34, 2005).
[26] ISO/IEC CD 18048, *Information technology -- SGML Applications -- Topic Map Query Language (TMQL)*, 2006 (ISO)
[27] Garshol, L.M. and Barta, R. Information Technology -- Document Description and Processing Languages: Topic Map Query Language, Use Cases. (ISO/IEC JTC 1/SC34, 2003).
[28] BS ISO/IEC 13250:2000, *Information technology - SGML applications - topic maps*, 2000 (British Standards)
[29] TopicMaps.Org. XML Topic Maps (XTM) 1.0 [online]. TopicMaps.Org. 2001. Available from: http://www.topicmaps.org/xtm/ [Accessed 1 April 2006]
[30] McMahon, C., Lowe, A., Culley, S., Corderoy, M., Crossland, R., Shah, T. and Stewart, D. Waypoint: An Integrated Search and Retrieval System for Engineering Documents. *Journal of Computing and Information Science in Engineering*, 2004, 4(4), 329-338.
[31] Network, N.E. Engineering Experiences and Lessons System (EELS). 2006).
[32] Argyris, C. *On Organizational Learning*. (Blackkwell, Oxford, 1999).
[33] Yu, R., Iung, B., Panetto, H. A Multi-Agents based e-Maintenance System with Case-Based Reasoning Decision Support. *Engineering Applications of Artificial Intelligence*, 2003, 16, 321-333.
[34] Kiritsis, D., Bufardi, A., Xirouchakis, P. Research Issues on Product Lifecycle Management and Information Tracking Using Smart Embedded Systems. *Advanced Engineering Informatics*, 2003, 17, 189-202.
[35] Stone, R.B., Tumer, I. Y., Stock, M. E. Linking Product Functionality to Historic Failures to Improve Failure Analysis in Design. *Research in Engineering Design*, 2005, 16(1-2), 96-108.
[36] Alonso-Rasgado, T., Thompson, G. and Elfstrom, B.-O. The design of functional (total care) products. *Journal of Engineering Design*, 2004, 15(6), 515-540.

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