Knowledge Management In The Engineering Design Environment

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The Aerospace and Defense industry is experiencing an increasing loss of knowledge through workforce reductions associated with business consolidation and retirement of senior personnel. Significant effort is being placed on process definition as part of ISO certification and, more recently, CMMI certification. The process knowledge in these efforts represents the simplest of engineering knowledge and many organizations are trying to get senior engineers to write more significant guidelines, best practices and design manuals.

A new generation of design software, known as Product Lifecycle Management systems, has many mechanisms for capturing and deploying a wider variety of engineering knowledge than simple process definitions. These hold the promise of significant improvements through reuse of prior designs, codification of practices in workflows, and placement of detailed how-tos at the point of application.

I. Introduction

Enterprise Knowledge Management (KM) projects are a common way for many organizations to deal with pressures from regulations such as Sarbanes-Oxley, loss of employee experience through retirement of the Baby Boomers and quality improvement and certification processes. Very little attention has been paid to the possibility of capturing domain specific knowledge, such as product development and fabrication knowledge, in the new breed of software known as Product Lifecycle Management (PLM) systems. These are complex software systems that typically have a very structured database surrounded by a wide variety of design and manufacturing applications.

The results here are from a brief study conducted in response to management questions about the knowledge management capabilities of the design tools in use at the California Institute of Technology, Jet Propulsion Laboratory (JPL). It provides a first look at knowledge capture, management and reuse using the Teamcenter PLM system from UGS. Similar capabilities exist in competing systems such as the PLM software from Dassault Systemes and the Enterprise Resource Planning (ERP) software from SAP and Oracle. A structure for knowledge management in engineering software systems is established and illustrated with examples from the UGS Teamcenter Enterprise (TC Ent) and Teamcenter Engineering (TC Eng) software. This scope of this initial investigation was limited and no endorsement of UGS products is intended.

Knowledge Management Systems (KMS) have been defined as a line of systems which target professional and managerial activities by focusing on creating, gathering, organizing and disseminating an organization's "knowledge" as opposed to "information" or "data."[2] Most organizations pursue KM through a blend of approaches, with designated roles and departments implementing KM.[6]

Knowledge Management literature casts a firm's knowledge assets as its structure, culture, processes, employees and physical artifacts, with an emphasis on employee knowledge. Amaravadi sees considerable value in the firm's operating procedures and provides seven dimensions to view processes.[1] Garvin broadly classified processes into work processes, behavioral processes, change processes and managerial processes.[5] In work processes and managerial processes are the operational processes of engineering/design, manufacturing/service and financial/accounting processes. The explicit knowledge in processes differs from the tacit knowledge held by employees in that it is generated as a result of conscious management and monitoring of processes.

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II. Enterprise Knowledge Management

KM has progressed to become an enterprise activity known at the executive level.[6] It is postured as a business critical information activity. Its business case is based on effective practices for "knowledge workers," aimed at minimizing information recovery and rediscovery and effective collaboration for team members.[4] A second motivation is to enable the enterprise to more effectively handle the transition of the work force. Two transitions at the forefront of the argument are 1) the retirement of the "baby boomers" and 2) the increasingly migratory situation for noncraft employment.

The Information Technology (IT) literature pushes implementations that support this approach,[12] although most traditional information systems are not designed to support organizational learning.[13] Effective solutions try to capture desk top communications as they occur to minimize the effort required to establish the knowledge cache.[7] A basic architecture element is the shredding of the document content, but in generalized domain independent structures. These might be keyword based, but the structure is typically independent of the domain. This front side work uses minimal manual involvement and aims to maximize subsequent search and recovery.

Most IT implementations provide integrative services via corporate portals.[3] These provide a single entry point to access databases and applications for knowledge embedded in processes and libraries. These provide easy access to goals, procedures, and rules, but they do not aid organizations in capturing and documenting their learning.[13]

PLM systems fit the description of "enterprise workplace" for the domain of product development, where users can focus on getting work done with the help of specialized IT resources.[8] By aggregating common functions, PLM systems can break the "condition of disconnectedness" that plagues current IT users. Users' desires to use a knowledge system are strengthened when use increases their relationship capital. Relationship capital, that level of trust, respect, and closeness of working relationships a user has with the rest of a peer user group, is a valuable resource because it gives individuals access to new information, knowledge, ideas, and opportunities embedded in the network but that would be invisible to outsiders.[11] To be an effective IT system for a learning organization, the organization might also need to reengineer its business processes.[13]

A. Enterprise Infrastructure Applications

Typical implementations capture work activity communications such as email,[9,10] electronic memoranda and business documents such as orders, proposals, position papers, etc. Content Management (CM) is defined as software that builds, organizes, manages, and stores collections of digital works in any medium or format.[14] Many implementations try to mimic and seek to replace existing storage services for these expressions, such as the PC hard drive, the department file server and the email server. To maximize adoption and minimize manual front side effort, these implementations want to be drop in replacements. More complex systems integrate with the authoring environment to extract metadata from documents and classify them as they are processed.[14]

For example, Oracle Collaboration Suite uses the Oracle Database as the server-side implementation for email and for file storage. Oracle Files mimics the file services of PCs but invisibly shreds the files so that the internal elements are known to the database.[15] The implementation uses the file type deduced from the file name extension to select a template that has captured not only the internal structure of the file but also the basic information structure. For example, the template for a Microsoft Word document is based on the internal binary structure of .doc files, identifies paragraphs and headings, and understands the mark up intent of the heading hierarchy (H1, H2, …).

Domain specific knowledge about the structure of normal business documents can be added to the shredding process.[14] Oracle Files can use work process based templates and standardized office work templates which, for example in Microsoft Word, can include fields and key words. These template fields and key words reflect the domain vocabulary and information structure while the specific document carries the instance values. Microsoft Office 2003 uses XML form templates where the forms are standardized and each document carries the data in an XML payload. On the server side, Microsoft Internet Information Server (IIS) and SQL Server know how to parse and store the XML-structured information. The effort to set up the template structure can be significant and works best for highly structured work flows and task specific documents. Good examples include claims processing, travel expense reporting, equipment inventory assessment or field observation records.[14]

Even though the notion of relating document management with work flow has been prevalent for many years,[14] design engineering and product development activities have not been studied widely for relevant structure. A few work flows already exist. Inspection reports and certain other repetitive quality assurance activities are in place as manual paper flows or electrified in computer services. Most manufacturing organizations already capture and digest these artifacts as part of their quality improvement practices. There are fewer examples on the design side. Drawing release is probably the best know work flow for aerospace design. This activity routes the drawing, and perhaps its related electronic models, through a list of approvers that represent the necessary disciplines. At the successful conclusion of the flow, the drawing is vaulted, marked as released and made generally available.

Another approach is to cull structured data from unstructured text in a process called information extaction.[23] Much of the available information is in documents written in natural language and with little apparent structure in Web pages, memos, news articles, e-mail and historical documents. McCullum describes the stages of information extraction which leave structured data in a database for subsequent data mining and use as actionable knowledge. *Segmentation* finds the starting and ending boundaries for a field. *Classification* determines the correct database field for the text snippet. *Association* determines which fields belong together in the same database record. *Normalization* puts information, such as dates, in a standard format. Finally, *deduplication* collapses redundant information, eliminating duplicate database records. This is automated in practice through rules, although effective rules bases can contain thousands of rules that are intricate and difficult to maintain. Commercial and open-source programs are available.

Combining attributes from different business processes is the basis for providing different views of the integrated information.[14]

B. Document Standardization Activities

There are several efforts underway to develop a mark up taxonomy for general documents, especially using XML as the mark up language. For example, the Dublin Core is a set of XML elements that capture metadata about documents.[16] A number of groups, such as museums, libraries, government agencies and commercial organizations, have formal oversight committees to standardize the community-specific application of the Dublin Core in their domain. The Dublin Core metadata elements are a set of 15 descriptors that resulted from interdisciplinary and international consensus building. Example elements include Title, Creator, Subject, Date, and Description. The standard recommends that fields such as Subject be expressed as keywords, key phrases, or classification codes that are selected from a controlled vocabulary or formal classification scheme.[16]

A number of vertical industries have developed standards for information exchange. These standards typically define the content of process documents such as purchase orders or inventory reports. For example, the American Petroleum Institute hosts the Petroleum Industry Data Exchange (PIDX) Committee.[17] PIDX standard documents include Purchase Order, Purchase Order Acknowledgement, Purchase Order Change, Inventory Inquiry Advice, and Invoice. Human Resource organizations have adopted standard forms for Resume, Time Card, and Job Descriptions.[18] As a final example, RosettaNet is a non-profit consortium that has developed common, standardized processes and forms for sharing electronic business information.[19,20] RosettaNet participants are developing data exchange standards for transfer of design information to manufacturing; release, management and the exchange of factory production information; and distribution of manufacturing information to support product improvements, downstream manufacturing, quality and warrantee entitlement.

These are examples of standardized schema and business processes that are required in order to recognize and leverage information stored in enterprise systems.[14] Process work flows and document templates then provide reference models and package them as reusable knowledge assets.[14]

III. Structure for Knowledge Management

The broader notion of "knowledge management" is greater than simply taking care of knowledge that exists, or transforming from one form, such as the implicit, or tacit, knowledge of experienced personnel, to another form, such as the explicit knowledge in guidelines and manuals.

Knowledge Management can be broken into four stages that require different activities.

Knowledge Capture is the identification of structure and the collection of data into that structure. This might occur in special activities aimed at developing structure or organizing data, or it might happen implicitly during the accomplishment of an activity. The result is a data store with an organization that is of greater value than the isolated facts.

Knowledge Management, as a subtask, is the maintenance, indexing, cleaning, preserving and persisting of the knowledge store. In itself, the activity doesn't add more knowledge, but the maintenance processes might make the existing knowledge more valuable or more usable. The construction of indices to assist in searches is an example of adding value.

Knowledge Access is the set of methods for inquiring of or investigating the knowledge store. The knowledge store organization can be complex and finding information, drawing conclusions or identifying patterns requires mechanisms for finding, collecting, aggregating and displaying desired information.

Knowledge Application is the end act of using the knowledge found in the store in a current activity. This is the purpose of Knowledge Management and the reason for collecting the information, maintaining the store, and studying its contents.

IV. Design Principles for Knowledge Capture in Product Design

Following the prior, more general KM activities, a few guiding principles can be identified. These provide general approaches to building knowledge capture into the design process in ways that maximize its value downstream.

A. Identify design knowledge structure and embed it in tools

There are many opportunities to establish structure in the product life cycle. The product structure is generally known as the Bill of Materials (BOM) and consists of a hierarchy of assemblies and components. The Design BOM has an arrangement that aids the design activities while the Manufacturing BOM has an arrangement more suited to the build activities. There are organizational structures that reflect the Design Department and the Manufacturing Department. Of course, these exist in a variety of electronic forms and systems, but representing them in the PLM system lets users associate members with activities, components and documents. There are data structures, such as those in engineering analysis, which might provide a logical arrangement for idealized solid models, meshed models, loads, boundary conditions and results.

Structure can also be expressed through a wide variety of relationships. Following “where used” links lets a parent assembly be found.

1. Example: Product Structure

TC Eng has a very detailed schema tightly tuned to product design. The product component architecture is known as the Bill of Materials and TC Eng works with BOMs as a central information architecture. The Navigator application lets a user drill down from a particular hardware component to find the subcomponents and the Product Structure Editor is an application specialized in creating, editing and configuring product architecture via the BOM.

The Manufacturing BOM is constructed in Teamcenter Manufacturing (TC Mfg) from the Design BOM. The Manufacturing BOM is linked to a fabrication process, resources and facilities. The fabrication process is an ordered list of process steps and activities with durations.

2. Example: Activity Structure

TC Eng contains an organization model that is based on Projects, Groups and Roles. Users perform product development activities in the name of a particular Project, as a member of a particular Group and acting in a particular Role. Security, access, and permissions are based on the user’s current values and the security policies determine user freedom to move around in this organizational structure model as appropriate to perform an assigned task.

TC Eng uses this structure to associate hardware components depicted as Item records with Projects and Users. A component or assembly Item is owned by a User’s Group. The permission structure usually insures that only the owner has write permission to implement the typical work practice that component design is assigned to a single person. Other practices can be set up, such as everyone in a Design Group has write permission when the group works that way.

3. Example: Analysis Data Structure

Well established Aerospace and Defense design practices require that design analysis results be reviewed, approved and archived in the project files of record. The current state of practice is that the electronic reports, review material and critical data files are captured and stored in the project library. Using KM tools, these can be searched by keyword to recover prior work. In TC Eng, the new Computer Aided Engineering Manager shreds the loads, models and result cases into the design database. These are linked to the component and assembly Items and version controlled. This data structure is built into the NX analysis tools such that the database is automatically populated and updated whenever the analysis is saved.

B. Identify data about product elements and capture it in forms that are part of the product element data.

In addition to data derived from the product design, such as weight and materials used, the PLM system might capture the names of the design participants, such as the project engineer, the designer and the analyst. Geometric data, such as its bounding envelope, might help spatial search engines.

1. *Example: Custom Forms*

TC Eng allows each site to design custom forms for display and collection of metadata to augment the Out Of The Box (OOTB) schema. At JPL, fields were added for Designer, Engineer, and Manufacturing Engineer to the OOTB hardware Item. These are in addition to the OOTB owner, group and date fields.

2. *Example: Descriptions*

A Description field is common in the OOTB schema and its use is motivated by search examples of finding prior work parts. Descriptions on Items can provide intended use information to aid in reuse and Descriptions on Item Revisions can provide lifecycle markers to understand the design evolution in later inquiries. Most TC Eng entities have Description fields, including Datasets, Processes, and MSWord Documents.

3. *Example: Release*

The structure associated with the Drawing Release workflow consists of required roles and the names of the people who actually signed. It also consists of steps that might implement a pre-release check cycle and fail back paths when reviewers disapprove.

4. *Example: Change Approval*

Another mature Process workflow for Aerospace and Defense is Change Control. Released designs can only be changed in a structured process that captures information about the content of the change, its consequences and justification. Light weight implementations capture this information in form fields but more substantial changes might require attached documents. In the latter case, the search engine would need visibility into the attached documents.

C. Identify processes and capture them in tools

Work flow and process automation subsystems in PLM software are a well known way to automate accepted practices. The drawing release process and the configuration change process are probably the best well known, but wizards are another. These are guided, sequential dialogs that lead a user through a task such as fastener selection or analysis of hole edge margin.

1. *Example: Machining Parameters*

NX CAM contains CNC process steps that can be associated with features such pockets. Process parameters such as feeds and speeds, tool family, and wall offsets can be preset in the process step. The process steps can be stored, selected by the programmer and used, changing only those default parameters that are needed. Templates for the process steps can be set up by experienced machinists according to shop established practices and then uniformly deployed by all machinists.

2. *Example: Fastener Wizard*

Wizards are special process flows formatted to guide engineers through a particular design step. The Fastener Wizard guides the designer through identification, sizing and installation of fasteners, such as bolts, in a CAD assembly. Detailed knowledge about available fastener diameters, strength, grip length and hardware such as washers and nuts are captured and displayed in the Wizard steps.

3. *Example: Drawing Release*

Drawing release is a fundamental practice in every Aerospace and Defense organization. Release for manufacture or flight usually entails significant review and approval efforts. Both TC Ent and TC Eng have workflow systems with which the organization can capture its drawing release and approval process. Hardware items submitted to a Release Process are configuration managed from interim changes and electronically routed to identified personnel for approval. Electronic signatures are captured to establish required functional representation. Process automation steps, such as preparation of a PDF image of the drawing, can be included.

4. *Example: Change Control*

Both TC Ent and TC Eng have OOTB models of the industry standard CMII change control process.[21] These default flows capture a statement of the change request, an analysis of the impact and approvals. Local practices can be implemented, such as multiple stages of approval or the use of specific justification and analysis forms. The configuration of hardware items in the change flow is managed, associated with the change control documents and protected from interim changes.

5. *Example: Cabling Design & Routing*

NX has a cabling module that understands design entities such as signals, wires, and harnesses. It includes a work flow that follows best practice: 1) identify channels which are spatial zones to carry cabling early to reserve space for harnesses, 2) route signals using rules over the channels, & 3) form routed signals into harnesses and apply installation hardware and connectors.

6. Example: Process Studio

NX Simulation Process Studio lets expert analysts "encapsulate complex processes in a way that enables non-specialists to safely and effectively benefit from the same technology."[22] This is clearly a form of knowledge capture that is closely coupled to the analysis discipline work environment. The analyst can author a Wizard as a means to script manual tasks or develop standard practices for wider deployment. The resulting processes can be configuration managed and refer to other managed items such as the design drawing.

7. Example: Fabrication Processes

TC Mfg implements a Part, Process and Plant model for fabricating components and assemblies. The Part is represented by the Design BOM as morphed into the Manufacturing BOM, and the Plant is represented by the various factory assets such as CNC machines or inspection facilities. The Process is the sequence of build steps and operations required to fabricate the part. At JPL, the manufacturing engineer works with the hardware engineer to develop the fabrication steps such as rough machining, heat treat, finish machining and inspection which are captured in Oracle Manufacturing. In TC Mfg these are called a Bill of Process (BOP) and libraries of BOP templates can be built up. Standardized process templates can save time in developing individual part fabrication plans, but more to the point here, they capture best practices and required activities. For example, a process specification can be tied to a given step, or an inspection instruction worksheet can be tied to the template inspection step.

D. Provide Access/Search Capability

The promise of reuse is dependent upon finding prior components or work that is relevant to the design or fabrication task at hand. A strong search engine is essential, along with standardized stored queries. In less well structured searches, the user might interactively drill down through the structures and relationships looking for candidate items. This is largely a visual activity using tree or graph displays. In addition to looking for prior designs or searching libraries of standard parts, users might search for reports, processes (to find participant names or notes) or templates.

1. Example: Searching

Searches might be graphical and interactive or query-based. TC Eng has a relationship pane where a tree of "where used" or "references" relationships can be interactively followed. TC Ent's graphical pane supports a broader and more heterogeneous set of relationships. Queries can also be considered interactive as search criteria are iteratively refined to narrow the returned list of matches to likely candidates. Both products provide 3D viewing panes for Items collected while searching.

2. Example: Spatial Query

Spatial query takes place in the 3D context of an assembly. The result is a list of components that are within a surrounding area or within a given distance of a component or location. In TC Eng and TC Ent, the 3D models are shown in the visualizer and the user can continue the investigation by suppressing irrelevant components or looking into likely assemblies. Searching for parts within a given distance can find spatial collisions or violations of envelopes or stay-out zones that are not represented by graphical entities. Such searches are often used as initial steps in a task process to provide a working context.

3. Example: Regulatory Compliance

Tracking material usage can begin with a query on a "material" property of parts within a product BOM. Highlighting the matches in the BOM will result in the 3D component models being highlighted in the visualizer. The BOM revision rules can be used to compare prior revisions to current revisions and the BOM options can be used to compare product variations. In TC Eng, the Multi View Editor supports side-by-side views of both BOMS along with the 3D models of each to more clearly understand the query results.

V. Discussion

Custom forms in TC Eng associated with Item Masters and Item Revision can have fields for organization-specific roles such as Engineer and Designer. Our industry needs to identify a common set of roles, much like the Dublin Core developers did for their documents. These then need to be adopted into the OOTB schema.

A Description field is common and its use is motivated by search examples of finding prior work parts, but this isn't a particularly effective at getting the description filled in. Instead, the description field tends to become a free text field for encoding subsequent process or activity data once the form structure is set. For example, a structural analysis team wanted to identify the design review associated with a particular archival analysis report, but there were no life cycle stage fields on the form. They developed a set key words and values that would be entered by the analyst in the Item Revision Description. A two-tiered search query that found Item Revision Descriptions that contained their keyword along with a value of "CDR" would be used to retrieve the desired prior report.

The TC Eng Process workflow has a Description field but users don't understand its value. At JPL, the most commonly used Process is "Freeze" which locks up all the submitted Item Revisions by making them Read Only. This captures the state of the design at that time. The Description field might be used to document that this is the end-of-the-month baseline or that this is the Design Review baseline. A search that found this Process instance would lead to the top-level assembly for that baseline. Of course, Item Revisions have Descriptions and similar text would make the Item Revision an appropriately searchable entity.

Implementing the Release Process in a workflow is standard practice, but the data captured during the process could be much more valuable. The electronic process captures the user identification and date stamp for each reviewer. Most people do not supply any textual information if they approve, but they are expected to provide support for disapproval. Such entries are seen as memory joggers for use in subsequent in-depth reconciliation discussions that lead to a correction. This is sufficient for errors such as "The length dimension is 55.3 but should be 58.3" but isn't at all helpful for process improvement investigations in later review since it provides no clue about why it was 55.3 and not 58.3.

Basic infrastructure data can be captured automatically by the software such as user name, date and time, but these tend to be marginally useful. TC Eng maintains a Project, Group and Role for each user and these provide some information about the work context, but provide little semantic value. The "whys" need to be input by the user, perhaps in the Item Revision Description, or in the Freeze Process Description. It will probably be the "whys" more than the "whats" that provide the richness required to drive reuse.

This generation of Knowledge Management in PLM tools will greatly expand the value of the knowledge store. Search tools and interactive discovery techniques will let us find associated and related facts. Unless something else is added, the "whys" must be deduced and continually rediscovered.

VI. Conclusion

Deploying a PLM system is a large undertaking. Frequently, the organization must adopt new processes as manual activities get automated. Existing data and projects need to be migrated to the new system and the company personnel need training in the new software as well as the processes. The return on investment for these systems is often based on the time saved due to automation or the reduced risk of regulatory mistakes. It is clear now that PLM systems can also contribute significantly in other ways such as retention of the knowledge and best practices of retirees, enhancement of product and process reuse and quality improvements through standardization.

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