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IMPROVING THE QUALITY OF FLEET/FACILITY SUPPORT KNOWLEDGE

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ABSTRACT

Tenix Defence and Australian Navy developed an architecture for managing maintenance support knowledge for the ANZAC class of frigates that substantially improves the quality of that knowledge by incorporating a number of automated and web-based review and validation processes. The architecture also closes the knowledge cycle to feed back in-service experience to continuously improve the quality of the maintenance support knowledge.

INTRODUCTION

Large projects to produce fleets (i.e., ships, heavy vehicles, aircraft) or engineering facilities (mines, power plants, manufacturing plants) are knowledge intensive over very long life spans. For example, Tenix Defence signed a firm/fixed price contract in November 1989 (Tenix 2002) to deliver eight ANZAC Frigates to the Royal Australian Navy (RAN), two for the Royal New Zealand Navy (RNZN) and a complete integrated logistic support (ILS) package of operating and maintenance knowledge comprising documentation, training and spares. Development of support and operating documentation began soon after the contract was signed, and the knowledge embodied in the documents will have to be maintained until the last ship goes out of service some four decades later, in approximately 2033.

The Need for Explicit Knowledge for Support and Maintenance

Even with mundane maintenance procedures, the quality and correctness of the contained "knowledge" may be tested in life and death situations. If the knowledge doesn't exist, is incorrect, or isn't accessed or used when needed, systems may fail and people die. Engineering products can be particularly dangerous if necessary knowledge is not available, recognised and managed (Yates 1999, 2000).

- On 5 May 1988, an engine room fire on board the RAN supply ship Westralia killed four crew and hospitalised five. The Board of Inquiry concluded (CoA 1998):

> 16.1 The fire in HMAS WESTRALIA on 5 May 1998 was caused by diesel fuel from a burst flexible hose spraying onto a hot engine component and then igniting. ... In the Board's view, the hoses were not properly designed and were unfit for the intended purpose.
>
> 16.2 A change of this type should have been processed through the RAN configuration change process as well as being approved by the ship's classification society, Lloyds Register. Both processes were bypassed, largely as a result of ignorance and incompetence. Key personnel within the RAN, and more particularly ADI Limited, were not adequately trained or qualified for the responsibilities placed on them....

- Two workers died and eight were injured in the 25 September 1998 explosion and fire in Esso's Longford gas plant. Gas supplies to the state of Victoria were cut for two weeks, and millions of people lost wages, heating and hot water. Business lost around $A 1.3 billion (Clarke 2000; Dawson and Brooks 1999). The explosion resulted when a restored hot oil supply fractured a gas heat exchanger that had frozen because of an earlier failure of the hot oil supply (Longford 1999). As stated by DNV (2000), the Royal Commission found that "knowledge management at the 30-year-old plant was a key deficiency....'The lack of knowledge on part of both operators and supervisors was directly attributable to a deficiency in their initial or subsequent training. Not only was their training inadequate, but there were no current operating procedures to guide them in dealing with the problem which they encountered on 25 September 1998.'"

The Westralia tragedy began with the maintainers' sensible desire to expedite ponderous paper-based configuration change procedures to replace chronically leaky rigid fuel lines. To avoid bureaucratic delay, the change was requested via an inappropriate procedure. Had Naval and contractor staff followed applicable configuration change procedures and quality standards, safe hoses would have been selected and installed (CoA 1998: Section 10). Appropriate Navy procedural documents and Lloyd's standards probably existed several places on the base where the maintenance was performed. The Board of Inquiry did not ask if those who made the procedural errors knew where the relevant manuals and standards were held[1]. The evidence reported did not clearly establish whether the key people were truly 'ignorant and incompetent', or simply didn't have or take the necessary time to locate and go to where the appropriate procedural documentation was physically held to obtain or refresh knowledge of the policies and procedures.

For Longford, much of the engineering technical documentation relating to the gas plant was held in the metropolitan main office, not on site in Longford. No safety case documents highlighting the brittleness and danger that frozen vessels would fracture when heat was suddenly applied existed on site.

Both cases exemplify the need to have ready access to appropriate and high quality explicit knowledge, and the possible consequences from assuming that individuals will have the necessary knowledge in their personal memories when and where

[1] Key actors in the decision processes, Mr Morland and Mr Jones, were both excused from giving further evidence at different times in the proceedings on grounds of ill health.

needed to support decisions in unusual situations. Both tragedies were in some part due to the lack of high quality knowledge management systems able to deliver infrequently required knowledge to end users when and where it was really needed.

What is "Knowledge"?

This paper uses the term "knowledge" with a specific meaning that needs explanation. There is significant confusion over usage of the "knowledge" within the KM discipline[2]; to the extent that one reviewer of an earlier draft of this paper claimed it had little to do with "knowledge". Following Coombe (1994-1999), "data" refers to elemental units of information (in the broad sense). "Information" in the strict sense refers to data made understandable to people or usable by computers through syntax provided by text or database relationships. "Knowledge" refers to information given an overall contextual meaning through semantic connections with other information. Where semantic connections can be captured explicitly independent of human memory, then "knowledge" can also exist explicitly.

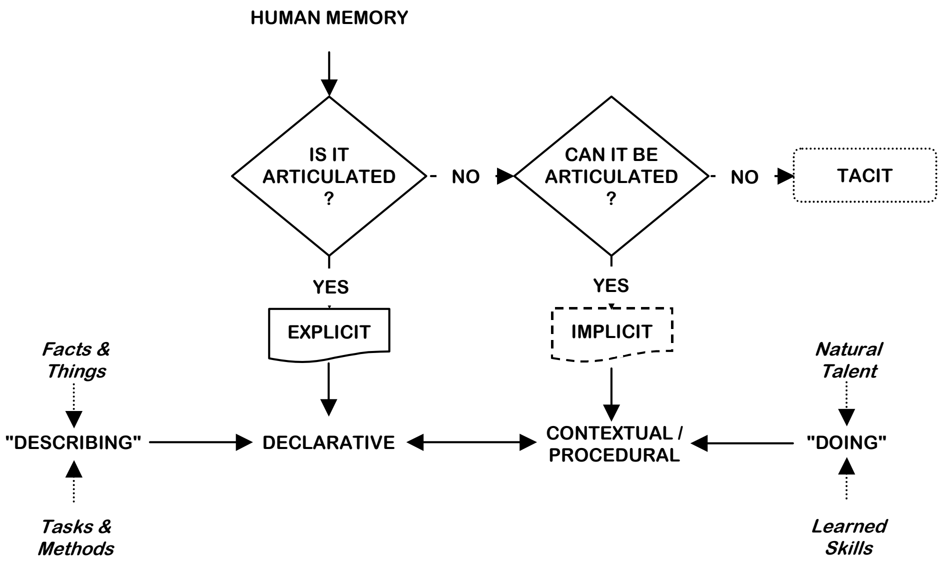

Figure 1. Explicit, implicit and tacit knowledge (after Nichols 2000).

The related terms "explicit", "implicit" and "tacit" also pose difficulties (Figure 1). Explicit knowledge is expressed outside personal memory (i.e., in text). A person can readily absorb the meaning and significance of explicit knowledge because the information is embedded with contextual clues that provide semantic structure. Authors writing paper documents distil some of their personal contextual knowledge into the explicit formal structure of their texts. However, with paper much of the authors' personal knowledge relating to the content cannot readily be expressed in the formal document structure, and thus remains implicit to authors and unavailable to others.

[2] Hall (in preparation) shows that there are two quite different paradigms in which the term "knowledge" is defined. This paper uses the less common paradigm.

Knowledge Management System Architecture

Tenix and the Client have developed a complete systems architecture (Figure 2) to assemble and manage knowledge to support the ANZAC frigates in service. The architecture to provides feedback to continuously improve the quality of fleet support knowledge embodied in the various support and documentation deliverables. Because of its complexity, the quality of the planned maintenance documentation for the ships has been the most problematic to manage.

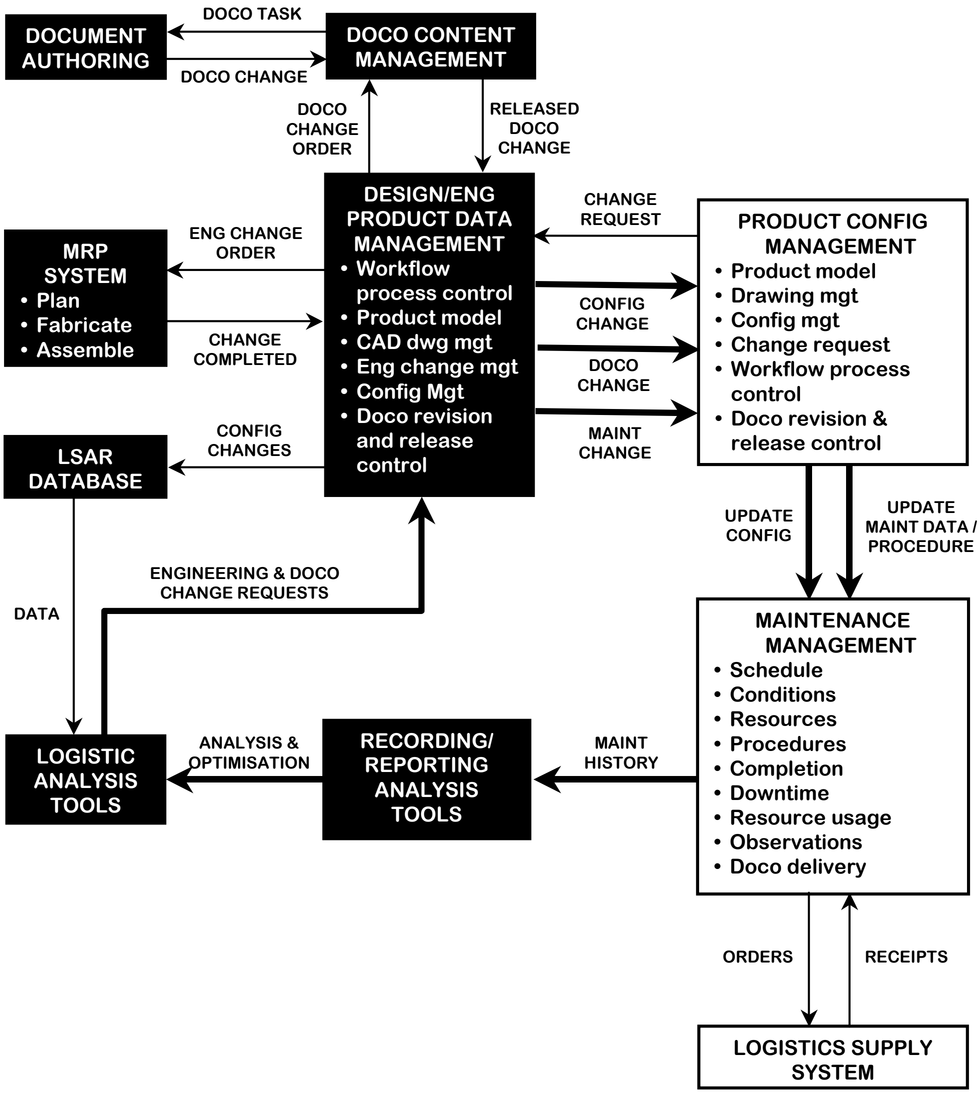

Figure 2. Complete systems architecture closing the circle for maintenance management knowledge. Tenix systems are shown in black, Client systems in white. For Tenix, document authoring is FrameMaker+SGML, document and content management is InQuirion's SIM/TeraText DCMS, design/engineering product data management is Sherpa Works and a variety of in-house developments, manufacturing resource planning (MRP) is a variety of in-house developments, logistic support analysis record database is the in-house ILSDB, logistic analysis tools are a variety of third party applications, recording reporting analysis tools is provided by Tenix's in-house development, CSARS. For the Client, product configuration management is currently provided by a Sherpa system, maintenance management by Eden Technology's AMPS system, and logistics supply system by the Standard Defence Supply System (SDSS)

This paper describes how some of these systems help to build quality into knowledge-based maintenance support deliverables and to continuously improve the knowledge in-service. The technology described here also helps people transform implicit contextual knowledge into explicit forms that can be preserved, managed and easily retrieved long after the knowledge creators have forgotten the contexts or have left the project. This also helps to assure the quality of explicit content in the documents. Although the ANZAC implementation focuses on a particular subset of maintenance knowledge, it demonstrates functionality we are working to apply more generally through the entire life cycle of large engineering projects.

FLOWING KNOWLEDGE INTO MAINTENANCE DOCUMENTS

Documentation Cycle for Major Engineering Projects

Figure 3 illustrates the overall context and generic flow of knowledge through any major engineering project into support documentation.

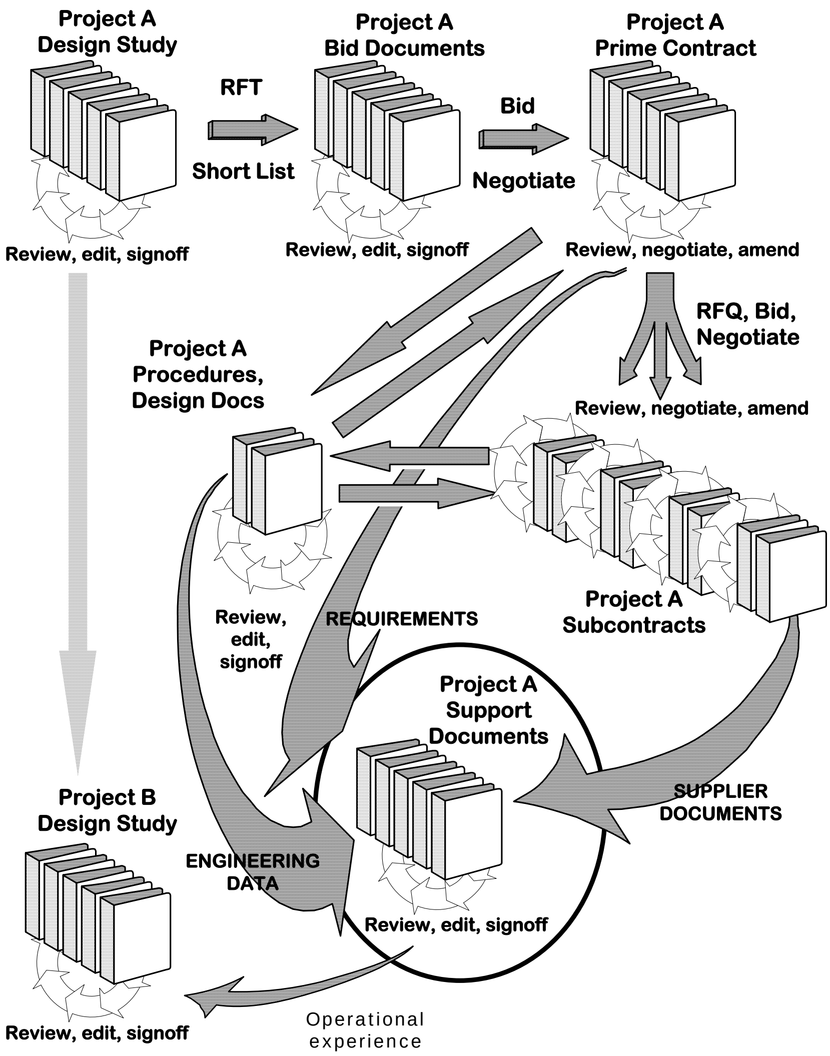

Figure 3. Prime contractor's view of the documentation cycle for a large defence or engineering project. Support documents include maintenance procedures and technical and operating manuals.

Once the prime and major subcontracts are in place, technical authors and/or experienced maintenance personnel assemble and distil a wide range of knowledge gained from source documents provided by suppliers and in-house engineers into maintenance processes and procedures.

Documentation in the ANZAC Ship Project, and in many other large projects is highly redundant (i.e., more than 50%). The same elements of knowledge are repeated across many different documents in a stage, and also flow down through several different stages in the life cycle. Managing redundancy is one way to improve quality.

Flow of Knowledge into Maintenance Procedures

Figure 4 shows in more detail how Tenix authors distil and combine content from several sources together with "engineering best judgement" to document how the ship's systems should be maintained. The deliverables are collectively referred to as planned maintenance documents.

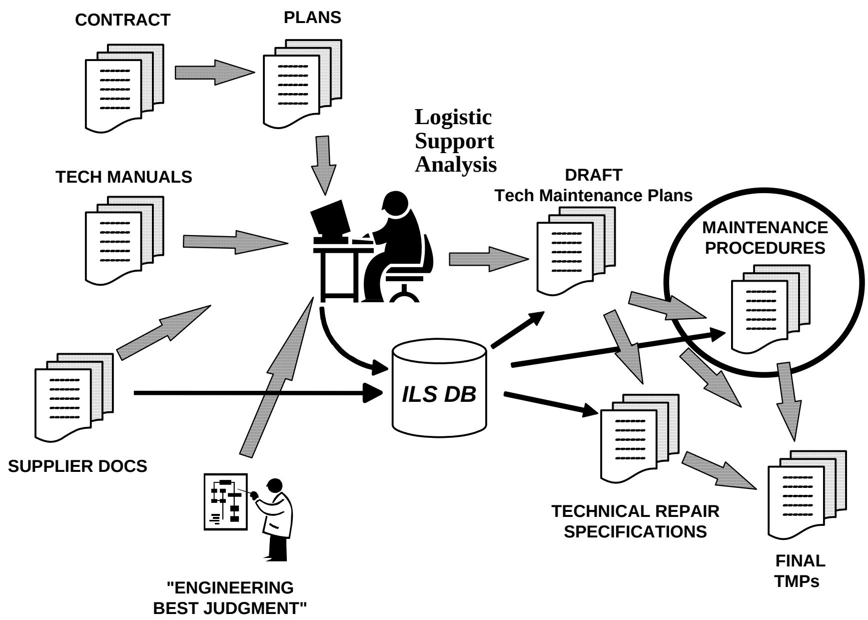

Figure 4. Knowledge flow in the production of planned maintenance documents.

Development of a fleet maintenance philosophy responds to contractually defined capability requirements. High-level plans written at a client/contractor management level define this philosophy. Guided by these plans, Tenix's logistic support analysts/authors use their tacit "engineering best judgement" to extract and filter information from supplier/Tenix technical manuals and other documentation, standards, etc., to draft technical maintenance plans (TMPs). A TMP for each ship system sets out the types of maintenance required, and the frequency and circumstances under which each type must be performed.

Besides assimilating maintenance knowledge into documents, logistics analysts load information about equipment, components and parts relevant to the maintenance activities into an ILS Database (ILSDB). Line items in this database are defined and placed in the overall systems hierarchy and engineering design for the ships. Items of information relating to configurations of specific ships included in the maintenance documents must be maintained against current ship configurations based on engineering and production master data.

Maintenance Requirement Cards (MRCs) document maintenance procedures to be done by naval staff on-board. Technical Repair Specifications (TRSs) describe in contractual scope of work terms overhaul and repair tasks to be performed by external agents.

TRSs relate to kinds of equipment that require overhaul. There are approximately 600 for the fleet as a whole. Once accepted by the Client, TRSs remain relatively static and are comparatively easy to manage because most engineering changes replace equipment (and the associated document) rather than modifying equipment in ways that impact content in the document. Also, equipment suppliers or authorised repair agents have the necessary expert knowledge to complete the work safely to their personnel and the equipment.

MRCs are more difficult and problematic, and are examined in more detail.

Each ship requires more than 2,000 separate maintenance activities. Otherwise identical documents for Australian and New Zealand ships reference different crewing regimes, different documents and different parts (paint colour was a significant "gotcha" - otherwise identical spare parts have different part numbers because they are painted a different colour of grey). Also, ships are upgraded in production or in service at different times with new components and systems. Even when new, no two ships are precisely identical and differences grow through time, which means that routines must be configuration managed for each ship individually.

Some maintenance routines are performed daily, where crew can learn and remember what is required. Other - often complex, critical and potentially dangerous routines - may be performed only annually or less frequently. Few personnel have prior experience with such infrequent activities.

The Client's Computerised Maintenance Management Environment

In-service maintenance activities performed on the ANZAC frigates are managed by Eden Technology's Asset Management & Planning System (AMPS)[3] relational database application. AMPS was implemented in 1992-1993 by the Client's ANZAC Project Authority in parallel with Tenix's development of an initial system for authoring MRCs. Maintenance knowledge is electronically transferred into AMPS via the Tenix authored MRCs. Configuration, scheduling and resource knowledge is transferred in an agreed comma delimited format. Knowledge required by maintainers is transferred in the form of HTML texts and graphics.

AMPS manages and delivers the knowledge on-screen to maintenance planners and as printed output to maintainers. Based on triggering circumstances (e.g., calendar periodicity, elapsed running hours, out of bounds measurements, etc.) encoded in each MRC, AMPS prompts ship maintenance planning officers to schedule maintenance activities and shows the resource requirements for each activity to assist planning.

[3] http://www.eden.com.au/product/amps.shtm. AMPS will be used by the RANs's entire surface fleet - Eden Technology 2001).

When maintainers are tasked to perform an activity, AMPS prints a maintenance instruction, including lists of resources required (as determined from MRC metadata) and the procedure text, safety warnings and cautions, and any graphics and tables provided in the MRC document. Instructions may also include requirements for maintainers to record measurements or other observations for entry back into the AMPS system.

Thus, AMPS delivers situationally relevant knowledge to maintainers where and when it is needed.

MRC Content Management Environment

Maintenance routines were initially authored in a WordPerfect macro-controlled merge table environment, which allowed more than 20 different deliverables and reports to be extracted from the MRC records (Hall 2001). The merge/macro system provided automatic validation for key data items against master data extracted from the ILSDB. However, as the number of ship-sets of documents increased, even with automated validation, key linking data used by AMPS could not be maintained absolutely consistently across the ever-increasing number of MRC documents holding the same information. By delivery of the fourth ship, more than 8,000 separate MRCs were under management, and single engineering changes to the ships might require several thousand files to be individually updated in the WordPerfect environment.

Following on from Westralia, under a documentation "quality" heading, the Client demanded all health and safety information across all MRCs to be reviewed and updated, which had to be incorporated in the ship five delivery. To facilitate crew training, the Client also wanted MRC texts to be completely standardised so task and step descriptions were described in the same words wherever the same actions were performed in different routines.

In 2000, after completing the fourth ship-set of MRC documents in WordPerfect, Tenix migrated four ship-sets of ship-specific routines (~8,000 documents) into a document and content management system (DCMS) based on RMIT University's Structured Information Manager[4] (Hall 2001). This technology, based on SGML (ISO 8879 - 1986), made it possible to collapse ship and navy specific information for each routine into "single source" master MRCs sufficing for all ships. In 3,000 hours labour, five authors condensed 8,000 ship-specific routines into approximately 2,000 equipment related routines sufficing for all ships using the particular equipment.

Test, Evaluation and Validation (TE&V)

Over the first 10 ship-years of in-service operational experience (the Test Evaluation & Validation - TE&V period), the ANZAC Ship contract required Tenix to prove that critical ship systems remained available for at least 90% of their total time in service, and that the overall combat capability provided by the ships remained available for at least 80% of the time. The intent of the TE&V period was to test whether the support

[4] Since Tenix's implementation of the DCMS, RMIT has spun off the SIM development organisation as InQuirion, and SIM technology is now being marketed under the tradename, TeraText (http://www.teratext.com.au/). Aspect Computing (http://www.aspect.com.au/) assisted in the design and implementation of the DCMS.

knowledge embodied in the logistics and documentation package sufficed to ensure that the ships met the Client's requirements for in service capabilities. If any specified availabilities failed to be achieved, Tenix was required to do whatever necessary *at its own cost* under fixed-price terms of the contract to correct and prove that it had corrected the situation.

Class System Availability Reporting Software (CSARS)

The contract also required Tenix to develop a system to collect the necessary information to prove that TE&V requirements were met. Onboard AMPS systems recorded downtimes, maintainer feedback on the maintenance instructions and other results associated with maintenance. This information was extracted electronically into Tenix's Operational Availability Recording and Reporting System (OARRS) that calculated ship and system availabilities via system availability hierarchies based on downtimes recorded for specific equipment (Shelley 1996).

TE&V data from the first 10 ship-years of operational experience was completed in October 2000 with the entire validation process successfully completed in December 2001. The Client considered the process to be successful enough that it contracted Tenix to extend and update OARRS to what is known as the Class Systems Analysis and Reporting Software (CSARS™). This was implemented in the third quarter of 2002. CSARS has been licensed for essentially the entire Australian Navy surface fleet to analyse reliability, [operational] availability, maintainability and sustainability (so-called RAMS analysis) to measure the actual capabilities of their ships in service.

IMPROVING QUALITY OF MAINTENANCE KNOWLEDGE

Tenix's DCMS includes an electronic workflow environment to control and track drafting, reviewing, editing and publishing MRCs (Figure 5). The process is basically the same as previously followed in the WordPerfect environment, when instructions and documents for review were physically circulated in paper folders. However, the speed, traceability and ready access to source knowledge provided in the electronic environment led to major improvements in quality along with order of magnitude reductions in labour and cycle times.

Structured Authoring and Automatic Validation in the DCMS Environment

There are major cognitive differences between the paper-based paradigm of a word-processed document and the content-based paradigm of an electronically managed structured document. Even though word-processed documents may be electronically managed and distributed in document management systems, documents are treated as discrete objects and cannot readily be parsed by computer systems to identify, manage and extract elements of knowledge.

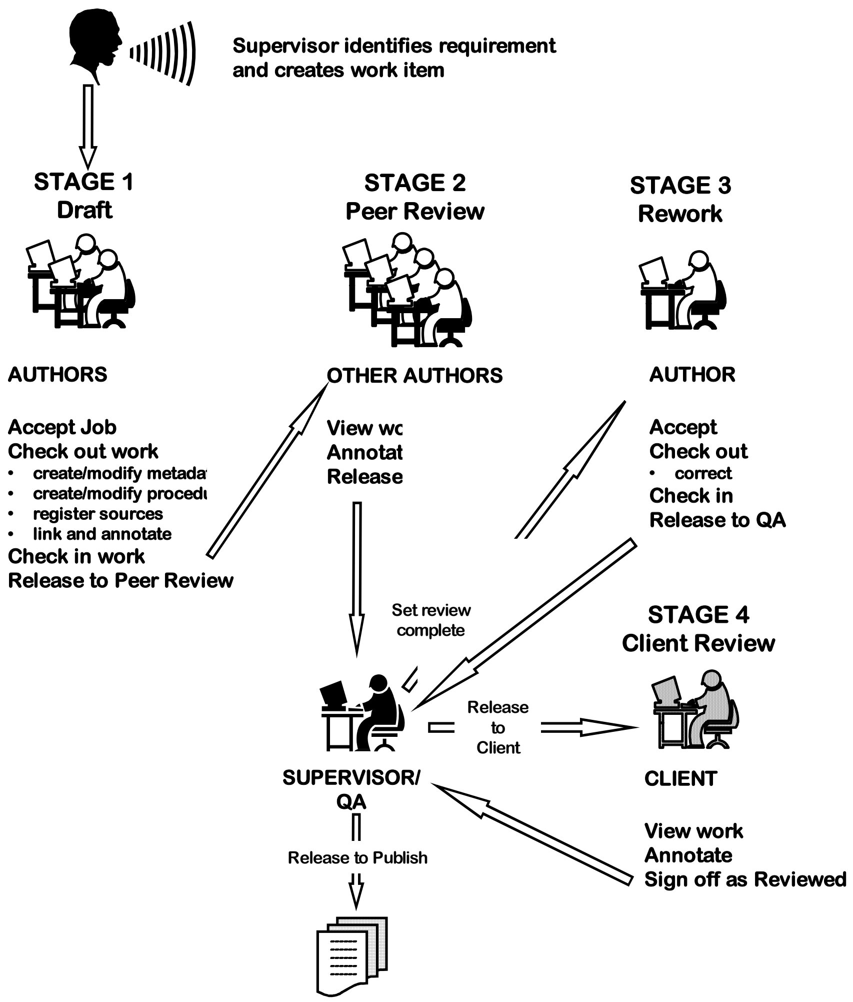

Figure 5. Workflow management of the process for authoring Maintenance Requirement Cards in the SIM/TeraText DCMS environment.

By contrast, DCMS recognises, manages and "intelligently" processes elements of content (i.e., knowledge) within the document. The logical structures of deliverable documents managed in DCMS must conform to the sequence and hierarchy rules established by the SGML DTD (document type description - Sperberg-McQueen & Burnard 1994)[5] that define the semantic structures of conforming documents. When prompted by the author, or as a document is checked in, DCMS automatically validates document structure against the logical rules of the DTD and all metadata against master data derived from a number of sources (e.g., AMPS codes provided by the Client, part numbers and configuration identifiers held in the ILSDB, etc.). Any mismatches are highlighted to authors so that they can be immediately corrected.

Query, Retrieval and Cloning

A major quality goal relating to training is to deliver the same knowledge consistently wherever it occurs in the documentation. DCMS's powerful indexing and query facilities allow the entire document set to be searched in seconds for similar

5 SGML is the ancestral technology to the better known HTML and XML that provide the basic standards that make today's World Wide Web possible.

documents or fragments of text. Depending on the nature of the authoring task, a whole document may be cloned and edited, or the appropriate block(s) of text can be cut and pasted to ensure consistency across the document set. This type of standardisation was one of many quality improvement tasks performed as routines were migrated from WordPerfect to the DCMS environment. For example, all health and safety warnings and cautions were reviewed and standardised across every single deliverable.

Electronic Review and Signoff

DCMS's electronic workflow helps deliver high quality documentation. Jobs progress instantly between authoring, review, and rework tasks. Even when authors and reviewers are not collocated, the entire editorial cycle can be completed in hours while all the required contextual knowledge to complete the work remains fresh in the author's memory. In a paper environment, review folders may be lost totally, or delayed for weeks or months before they are returned to authors for rework - by which time much of the immediate contextual knowledge has been forgotten.

Annotations, Hyperlinks and Source Registration

DCMS facilitates creating and managing two-way hyperlinks within and between documents[6]. DCMS also includes a powerful annotation architecture (Figure 6) that extends the concept of a hyperlink. This allows authors to preserve in retrievable explicit form significant components of the implicit knowledge available to them when documents are created or edited.

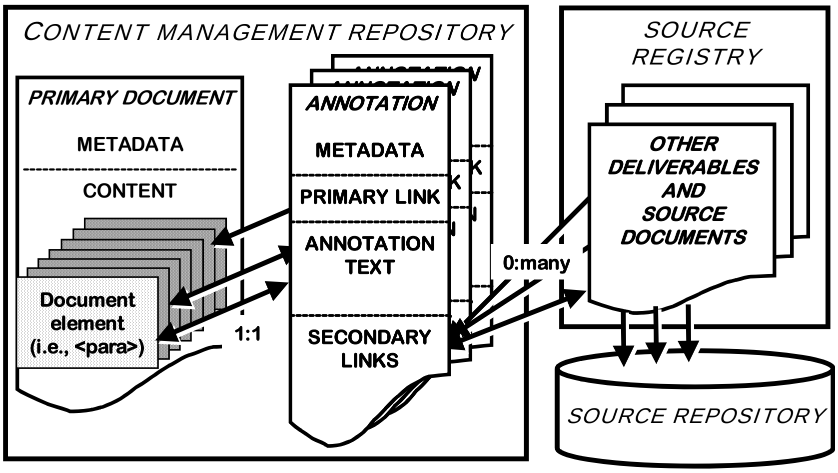

Figure 6. Annotation architecture in the SIM/TeraText DCMS environment.

DCMS manages two qualitatively different types of documents: those created in DCMS for delivery to the external Client (i.e., "deliverables"), and those received from external sources that are registered and archived for fiduciary purposes because they have been referenced in some way by deliverables (i.e., "sources"). Deliverable documents held in the Content Management Repository are structured, fully indexed

[6] Hyperlinks can be created in word processing environments, but once created, are not easily managed.

and fully managed in the workflow environment. Source documents are registered in the Source Registry to record version and publishing information to detect when new versions are received from the document publishers. When source documents are available electronically, binary files are preserved in the Source Repository in the form received. A hyperlink between the source registry entry and the source repository launches the file to an appropriate external viewer.

In deliverables managed in DCMS, all explicit references to sources are hyperlinked with two-way links to registration data for the source documents.

Annotations are special XML documents external to deliverable documents that link to specific content in deliverables, and can optionally link to other deliverables or to IDs of documents registered in the Source Registry. A primary 1:1 link connects the annotation and a specific content element in a deliverable. Metadata automatically records details of the annotation's author and date. An annotation may contain 0:many secondary links to documents registered in the Source Registry (establishing a 2-way link in DCMS - but not in the deliverable document itself, between the deliverable element and a source). Finally, the annotation provides the author with free text to record the reasons for establishing the annotation that normally will relate to contextual issues surrounding the document (i.e., implicit details relating to formally cited and uncited reference material, author's engineering best judgment, etc) that capture the circumstances of how the document was constructed, in ways that could never practically be managed with paper documents.

DCMS provides three types of annotations:

- *Author Annotations* record details of source materials referenced in creating or editing an element of text, e.g., a source registry item and descriptions of precisely what and why information in the item was referenced. DCMS preserves author annotations for the life of the deliverable elements to they are attached.

- *Internal Review Annotations* provide review feedback and other comments to document authors. These are archived, but are dropped from the deliverable document when the next major version is published.

- *External Review Annotations* record external review (i.e., Client) comments for attention of Quality Assurance and authors. Tenix staff can also create comments to be read by external reviewers. External Review annotations are archived and dropped from the deliverable as above.

Internal DCMS users can see all annotations. External reviewers can only see External Review Annotations.

Query and where-used functions allow easy retrieval of contextual knowledge preserved in annotations. Annotations and links into the deliverable content establish a searchable and processable semantic web (Berners-Lee et al. 2001) relating knowledge in the document to surrounding contexts. The W3C Organization (Koivunen 2002) and Weborganic Systems[7] have developed somewhat similar

[7] http://www.weborganic.com/.

annotation concepts. Annotations in DCMS explicitly capture contextual knowledge authors had when authoring deliverable documents. Such knowledge is lost from human memory through time over a multi-year documentation life span and as authors leave the organization.

Being able to retrieve this contextual information in DCMS greatly assists authors maintain long-lived documents. Should a referenced source document change, a 'where used' reporting function allows all deliverables referencing that source, and thus potentially impacted by the change, to be identified in a few seconds. Without such links, impact analyses depend heavily on author's inherently fallible implicit knowledge, and may take weeks without any assurance that all potentially affected documents have been identified.

Closing the Loop to Continuously Improve the Quality of Maintenance Knowledge

Learning from In Service Experience

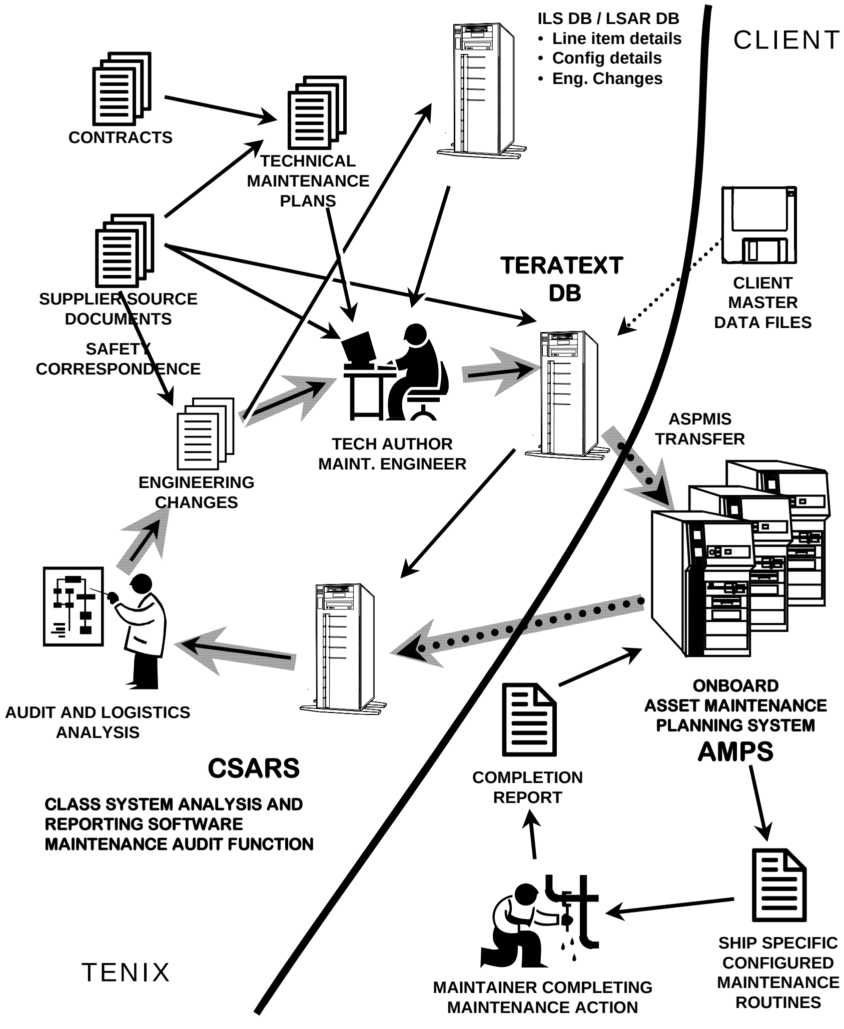

Figure 7. Closing the knowledge loop for ANZAC Frigate maintenance activities. Dotted arrows indicate batch data interchange interfaces.

As shown in Figure 7, along with DCMS, AMPS and various logistic analysis tools, the CSARS system completes an organisational "learning" loop to rapidly feed back results and lessons learned from operational experience into the logistic analysis and documentation process to correct and refine the knowledge embodied in the support documentation and data deliverables.

By continually observing and feeding back in-service results from using and applying support knowledge into the maintenance management knowledge, the quality of this knowledge as expressed in optimising life-cycle support costs and in-service availability is continuously improved. In a paper-based documentation environment the process would take years and be fraught with human errors. Tenix has anecdotal evidence from the Client that operational experience only rarely was applied back into the maintenance knowledge base.

However, the conjunction of a computerised maintenance management system (AMPS) and Tenix's tools for rapidly analysing and recycling operational experience and learning provides a platform that will enable the establishment of a safe, lean maintenance philosophy (Scire 2000; O'Hanlon 2002; Mather 2002, 2002a).

Conclusions

Measurable benefits from migrating content from the WordPerfect environment into the DCMS environment included:

- Routines delivered for Ship 5 were cut by 80%. Five ships would have required some 10,000 ship-specific maintenance routines. Structured authoring and content management cut the number required for the full class of 10 ships to around 2,000.

- Subsequent content deliveries were cut by 95%. Prior to implementing DCMS, to track configuration changes, Tenix delivered a full set of updated MRCs to each ship every year. With DCMS, net changes only are delivered as they become effective as part of the engineering change process.

- Keyboard time for one change cut more than 50%. Fewer documents are impacted by change (e.g., in one case 56 separate MRCs were condensed into one), and those documents are edited much faster since are no longer concerned with formatting issues that arose in the word processing environment.

- Change cycle time cut from 1 year to days. As proven in the conversion of documents from the WordPerfect environment to SGML in the DCMS environment, the rewrite, review, rework, signoff and release for publication took less than two hours of labour for the average MRC - where the process conspicuously improved the quality of the documentation in terms of structure, textual standardisation, conformance to health and safety standards, other measures of correctness and readability.

Based on DCMS's success with maintenance procedures, Tenix is now working to extend the technology to a wide range of document types across other projects.

Theoretical improvements in knowledge quality to be gained from better controlled authoring workflows and closing the circle from AMPS back into the authoring and maintenance of content are clearly evident, but are more difficult to measure and quantify in practice. Over the long term, quality improvements in operating and maintenance knowledge should be reflected in increased ship and system availabilities, reduced operating costs and reduced injury and accident rates in maintenance activities. However, fleet operators and managers are only now beginning to apply CSARS in practice.

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