Managing Lifecycles of Complex Projects

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Abstract

In this paper, Product Lifecycle Management ("PLM") refers to both the software application framework and discipline for electronically authoring and managing product related data, information and knowledge in large and complex engineering projects. Properly implemented, PLM revolutionizes the way projects are managed and can greatly reduce project costs by comparison to paper-based authoring and management systems. This paper summarizes some of the concepts developed over 17 years analyzing, controlling and designing systems to manage technical data, documentation and knowledge relating to various aspects of defense projects.

Introduction

PLM refers to the computer-aided management of the information life-cycles of complex and costly projects. Things requiring management include definitions of products, their structural subassemblies and components, plus associated technical data, drawings, computer-aided manufacturing (CAM) instructions and many different kinds of texts. These are generically called "documents" and collectively known as "content". In today's world, essentially all project content is produced and stored on computers in electronic formats. This paradigm is gradually replacing the classical engineering management paradigm based on the management of paper documents. When fully implemented and used effectively by the client and the project's supply chain, PLM technology arguably has the theoretical capacity to reduce project costs by 50% compared to paper-based documentation and management methods. This is achieved through better tracking and measurement of work, and by a greatly increased ability to reuse already validated content. The result reduces costs and schedule for engineering design and documentation, reduces engineering and production rework as sources for project delay, cost blowout and lost opportunity costs due to late delivery of capabilities, and produces additional savings through optimization of lifecycle support costs. On the other hand, there are few if any cases where these levels of savings have been achieved, probably because most project and engineering managers still think of documents as heavy piles of writing on paper, rather than as electronic content that can in many cases be effortlessly and instantaneously acted on and progressed at the speed of light.

Thomas Kuhn, in his famous 1962 book, "The Structure of Scientific Revolutions" established the idea of a paradigm, comprised of an unconsciously held world-view and associated ideas about the "way things are done". Kuhn argued that an existing paradigm could only be replaced by a revolutionary or transformational process leading to a whole new way of thinking (i.e., a new paradigm). Based on personal experience, in this paper I will try to explain what the PLM paradigm is and why managers of large projects and programs should try to incorporate it into their thinking.

In 1990 I joined the company that became Tenix two months after it signed what to now has been Australia’s largest and arguably most successful defense contract, worth $US 5 billion. Tenix engineered and built a fleet of 10 frigates, known as the ANZAC Ships. Eight ships were built for the Royal Australian Navy (RAN) and two for the Royal New Zealand Navy (RNZN). The contract terms, authored in the paper paradigm, were draconian – prices were stringently fixed except for currency fluctuation and inflation as calculated from independent indices. The fixed price covered the design and delivery of ships and support packages including operating and maintenance documentation, initial spares, crew training facilities and crew training. Warranty provisions with cost and liquidated damage penalties covered everything, and we were obliged to design a monitoring system to prove to the clients’ satisfaction that the ships and support package met contracted operational availability targets over 10 ship years of in-service operations. The Project was completed 1n 2006, 17 years after contract signature. Every ship was delivered on-time and on-budget to the respective clients, for the price negotiated in 1989 – one of the few large defense projects in Australia, if not the world, to do so.

Helped by the gradual shift to electronic documents while the ANZAC Ships were being completed and delivered, Tenix expanded through acquisition from a single project company to an extended enterprise including armored vehicle, aircraft systems integration, electronic systems development, infrastructure, government services and investment businesses. For the RNZN, Tenix is building seven more new vessels from a multi-function transport ship to patrol boats. For the RAN, Tenix has a continuing alliance with the combat systems supplier and the Navy’s System Program Office to provide engineering and support for their 8 ANZACs. We have also converted a new tanker to a fleet oiler, and have just achieved preferred contractor status in a $3 BN project to build two Landing Helicopter Dock amphibious ships.

During this period I have been involved in various roles involving documentation, content management and knowledge management ranging from controlling and amending contract and subcontract documents, to participating in the design and implementation of technical documentation management and PLM systems.

Here I try to summarize some of the reasons why I think PLM is so important for large programs and how it can be deployed to help manage the engineering and authoring activities conducted by defense and other complex engineering enterprises.

Goals for Project Management

The operating organization's (the "client") primary requirement is to have the capabilities of the engineered products available when needed. To meet this requirement, products must:

- *Do what they are supposed to do reliably*, i.e., not break down when performing critical roles.
- *Be available for service when needed*, i.e., not frequently out of service for maintenance or for long periods of "down-time".
- *Be readily maintainable*, such that the products' regular operators and maintainers can quickly fix problems when they arise.
- *Be supportable*, in that critical consumables and spares are available with minimal delays in the supply chain.
- *Be operable within limits of human knowledge & capacity considering health, safety and operational knowledge issues* — taking special cognizance that heavy/complex engineered products can kill!

Secondary considerations for the operator are to minimize product costs to free limited financial resources to procure additional capabilities. For long-lived products such as ships and armored vehicles, support and maintenance costs for the product's life are typically several times the original acquisition costs. Thus, giving due regard to meeting the required capabilities, the product should be designed not only to minimize acquisition costs, but also to minimize documentation, support & maintenance costs.

Adequate performance on all the above issues depends on the quality of authoring, management and transfer of technical knowledge from supplier to operators and maintainers by training and documentation. For the fleet operators, this technical knowledge must be:

- *Correct* in the sense that all knowledge deliverables have been subjected to stringent review and quality control to ensure their technical and operational accuracy in terms of the product's engineering and functional details.
- *Consistent* across the fleet to facilitate human training and computer systems interoperability
- "*Applicable*" to the configuration of the individual ship/vehicle
- "*Effective*" for the point in time re engineering changes, etc.
- *Available* to who needs it, when and where it is needed, and
- *Useable,* both in the sense that it is readily understandable by human operators and maintainers, and in the sense that it can be readily managed and processed in computer systems

To help minimize product costs, besides meeting the operators' requirements expressed above, the supplier has additional goals relating to assemble and produce the technical knowledge package for the product — bearing in mind the contradictions; e.g., to

- minimize production time (faster),
- deliver high quality (better), and
- complete the work for a low cost (cheaper).

The PLM paradigm has been designed to help stakeholders achieve all of these goals.

What is PLM?

PLM is an acronym for product or project lifecycle management and is an extension of product data management (PDM). The PLM paradigm establishes a product or project centric organizational framework for managing data, documentation and knowledge relating to complex products or projects. Although PLM principles can be practiced without using computer systems, the methodology is most often implemented in enterprise solutions targeting engineering and industrial manufacturing organizations producing complex, long-lived and costly products; and, increasingly, product end-users managing large and complex acquisition programs. PLM technology provides tools to facilitate collaboration among stakeholders and controls the progressive development and validation of information through product/project lifecycle stages (Figure 1).

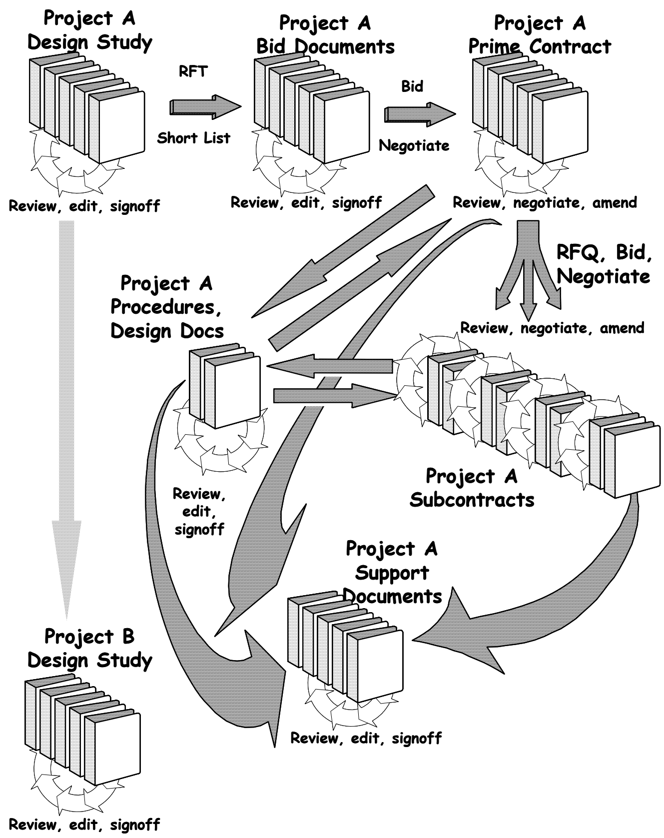

Figure 1. Documentation development and information "flow-downs" in a large engineering project. (Hall et al., 2002)

PLM systems track and control the life cycle of products/projects, ideally from the client's concept development, through bidding, contracting, design and production through to in-service support and even disposal. PLM techniques are most often applied in an engineering framework, although many of the management principles are broad enough to apply to all kinds of large and complex projects.

Such projects generally require great quantities of documentation to specify, represent and approve what is to be designed and then built; together with the need to deliver to the client all kinds of training, operating, and maintenance documentation to support the engineered product. This documentation represents a content base of technical data, information and documented knowledge relating to the project.

The PLM paradigm originated in the need for engineering projects to control product engineering changes and "configuration", so that all the component parts of the engineered product work together properly to meet the client's requirements as discussed above under Goals for Project Management. The design, properties or other details of individual components are often changed during the engineering and production processes. Configuration management and engineering change control processes are required to ensure that the effects of a change to one part are understood, reflected and compensated for with respect to all other parts of the product that interface with or are otherwise affected by the change to the first part. All these influences and changes must be accounted for to ensure that: (a) the effects of all changes are properly documented for engineers, production and end users, and (b) changes are authorized and managed so that the delivered product remains safe and meets client and all other requirements for the operational life of the product. Complex processes like this are fallible, and failures in the process can lead to costly rework in the production phase of the project, or even worse – to product failure in service with consequent economic loss, injury, and even death to product end users, as exemplified by the engineering management failures leading to the Challenger space shuttle disaster. It is far better and less costly to catch an error in documentation development rather than after the error has been cast in concrete or steel.

As implied in Figure 1, an essential factor in all large engineering projects is a very high level of duplication or redundancy of information across different components of the project – because identical or similar information has to be supplied for each system or module comprising the product); and down through the different project stages from concept development to disposal – as the information for each system or module is refined through contract negotiations and the various engineering processes. Also, to ensure quality of the engineering activities and the documentation relating to and deriving from these activities, each document will typically undergo several cycles of review and editing before it is signed off and released as being official.

A fully developed PLM paradigm closely links the all the activities of engineering change and changes to affected documents within a single engineering change process. Because of the very high degree of duplicated information (which would exceed 50% in many projects) great cost savings can be achieved through the automatic reuse of information rather than reauthoring it – if the necessary changes between documents and down through different stages of the project can be clearly identified and tracked for management. Reuse, rather than rewriting or manually transcribing data onto paper, has the added advantage that it avoids introducing authoring or transcription errors in information has already been validated as correct.

Aside from allowing proven information to be effortlessly reused, the other major area of saving the PLM paradigm offers is to greatly reduce the time required to complete a review, edit, approve and release cycle through the electronic management of documentation workflows. This can be particularly important to the contracting organizations in the concept development and bidding stages of a project, where time is of the essence in preparing winning bids (Figure 2).

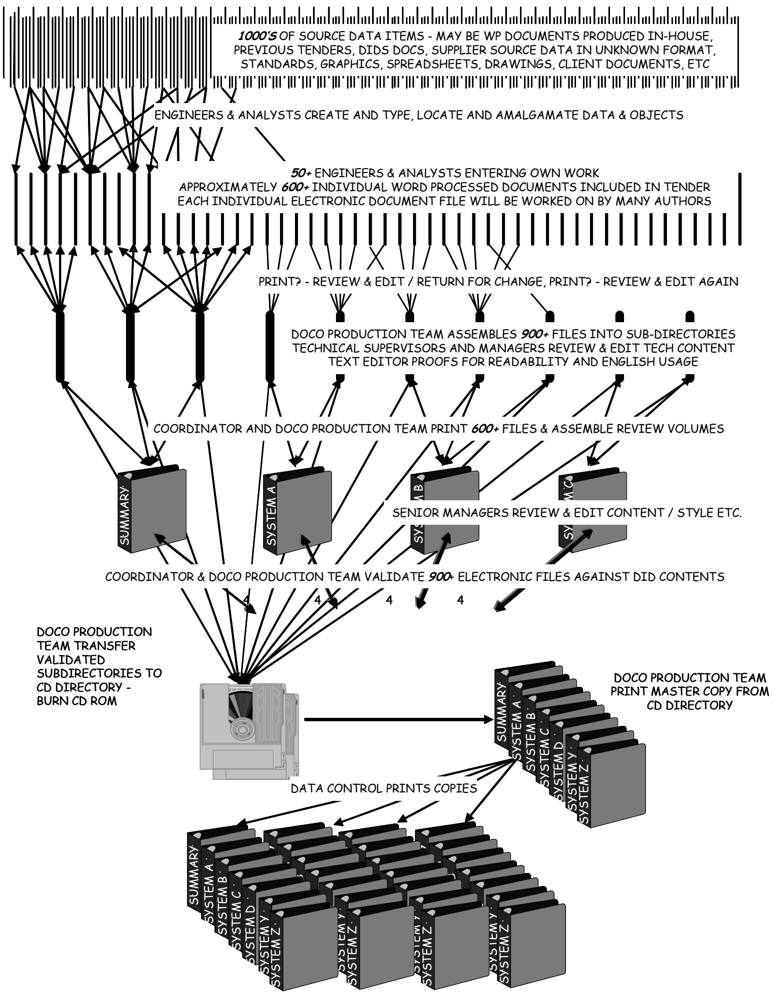

Figure 2. Information flow into a tender response in the world of the paper paradigm. Doco is an abbreviation for documentation. Multiple arrows connecting to a single binder indicates the reuse nformation.

By comparison to the days of the paper paradigm, when folders full of paper documents and drawings were physically transported to crowded in-trays for review, and often got lost in the process; in the PLM environment, when one person finishes a task, the document is instantaneously directed to the next person in the workflow. Key information can also be validated automatically. Workflow systems track the progress of all activities against the document in relation to critical paths in the project schedule. The location and responsibilities for delays can be immediately identified and resolved. When PLM is fully exploited by the client, contractors and subcontractors, it seems reasonable that the content reuse and schedule reductions should substantially reduce the overall project cost, both through reduced labor requirements for knowledge workers and general reductions in costs through substantial reductions in project durations (to say nothing of offsetting benefits to the client organization from introducing needed capabilities sooner).

How does PLM work?

Ideally the PLM application serves as an "umbrella" providing a single user interface and central workflow control over a variety of different software modules or applications (Figure 3). However, the PLM paradigm can also work for engineering enterprises that still have to perform the same functions using less well integrated systems.

PLM applications have their origins in computer aided design (CAD) – to represent the physical product; and electronic workflow systems – to manage the processes. In today's world, essentially all project documents are produced and stored on computers in electronic formats. In addition to controlling the engineering and related documentation processes, a fully implemented PLM system also maintains overall project schedule and provide cost and schedule control functions (CS^2) to give senior managers a high level overview of project progress and rising issues from cost or schedule deviations.

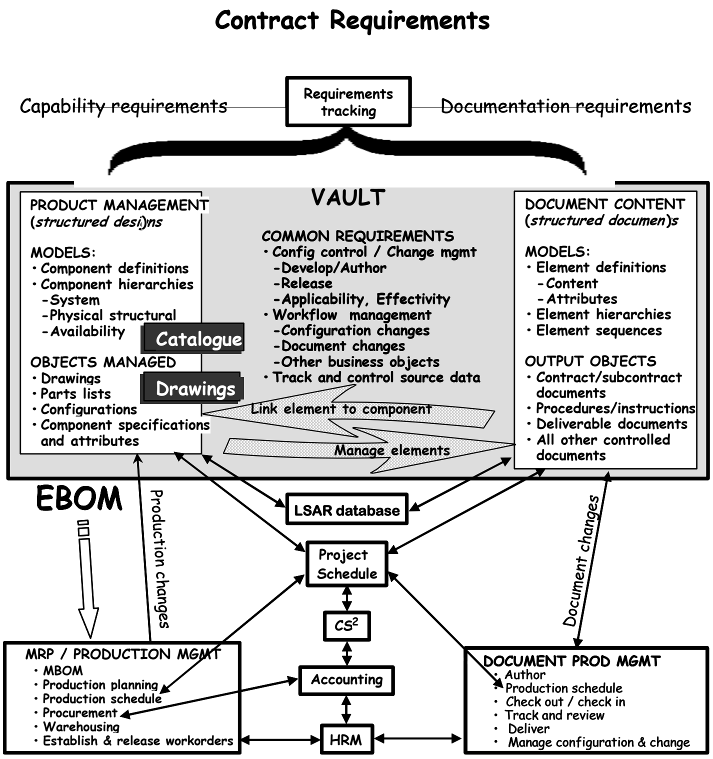

Figure 3. The PLM umbrella can be a common user interface covering the mechanics of defining a product in terms of its parts and in relationship to the contractual requirements it is supposed to meet, and should link to and manage equivalent components or modules of information in the drawings and variety of documents to components and parts. The “umbrella” also needs to exchange information with a variety of other, subsidiary applications. The "VAULT" is a controlled repository for all kinds of business objects managed by the PLM system. The Catalog is the master list of all parts and assemblies. EBOM is the engineering bill of materials. MBOM is the manufacturing bill of materials. LSAR refers to the logistic support analysis record, a standard database structure for support-engineering data. MRP refers to manufacturing resource planning.

As suggested by Figure 3, reuse and configuration change management are facilitated if the documents can be authored in a modular structure of hierarchical elements that relate directly to systems, subsystems, components and parts as appropriate in the hierarchical breakdown structure of the product. The XML-based S1000D standard for electronic technical documents[1] greatly assists this, by:

- establishing a common numbering scheme for engineered components and document modules relating to the components,
- defining the structures of a range of different module types relating to the components,
- establishing the concept of a common-source database to provide source information for compilation of the publications and for use in electronic logistics information systems to deliver modules of information direct to the user.

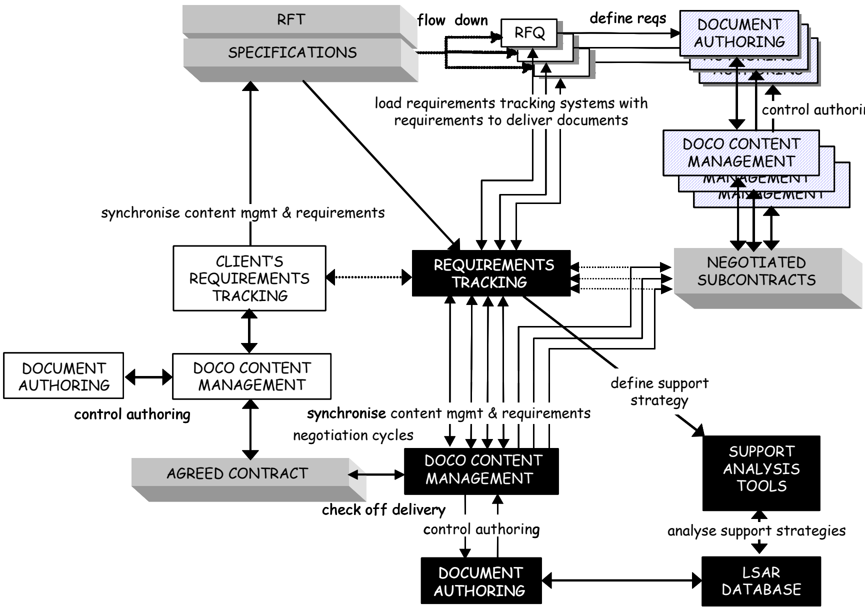

Figure 4. The prime contractor's PLM functions used in the stages of contract and subcontract negotiations for a large project. Prime contractor functions are shown with white text on black. Documentation deliverables are shown in grey. Subcontractor functions are shown as patterned boxes. Client functions are shown with black text on white backgrounds.

Ideally, the client, prime contractors and major subcontractors will all run PLM systems. Figure 4 is a substantially simplified view of the main PLM functions in this early stage of the project. In this case, the lifecycle of a product begins when the client establishes a concept of the product it desires in terms of a list of capabilities and requirements that it can express as a request for information (RFI) or request for proposal (RFP) that potential suppliers may respond to in terms of how their product would satisfy the requirements, or

[1] http://www.s1000d.org.

as a more concrete request for tender (RFT) that specifies fairly exactly what the client wants. The client can establish each requirement as an object within an overall hierarchical requirements breakdown structure in the PLM system, and begin attaching appropriate background documents relating to the overall project and what each requirement comprises. At this stage, nothing has been fabricated, and the entire project is expressed in its documentation.

Potential prime contractors respond by consulting with a variety of potential subcontractors to design a priced solution to the client's requirements to document a proposed or tendered solution. Through rounds of negotiations concerning specifications, prices and schedules, the documented proposal is refined into a prime contract. The prime contractor will then flow down and document appropriate requirements into RFQ's and leading to negotiated subcontracts with major suppliers.

At least in the Australian defense industry, requirements are increasingly being developed, managed and tracked using a tool known as DOORS[1] that works within the PLM paradigm. Doors organizes requirements in a structured framework that can be (but hasn't been) linked into the overall PLM system. Requirement statements can then be flowed down into RFI or RFT documents, and then into contracts and subcontracts. In many cases, the content of the requirement can be flowed directly into the subsidiary documents without reauthoring; and where reauthoring is required, there will be a clear and easily traced audit trail leading back to the original contractual terms.

Where content can be managed at the level of XML elements, the flowdown of information with appropriate review and signoff can be quickly and safely achieved. Unfortunately, we do not yet have agreed XML standards for constructing structured contracts that relate to the requirements-based view of the product, so the processes of tender response, contract negotiation, amendment and flow-down into subcontracts still remains very much in the more fallible paper paradigm. However, once contracts and subcontracts are in place, engineering design and the remainder of the project can all be carried out within the PLM paradigm.

As the project evolves to include production of physical product and these begin to be delivered into service, the scope of the PLM functions broadens significantly as illustrated in Figure 5. During manufacturing and service receipts from lower-tier suppliers are tracked against subcontract requirements, and physical deliveries entered and logged into the warehousing system as being available to be assembled into manufactured products. Engineering changes may occur at any time, e.g., as driven by the lower-tier suppliers' engineering changes, the prime contractor's test and trials results, or client requests for change. Deliveries of the physical products and associated technical data, documents and training packages are tracked against contractual requirements via the requirements management function by both the supplier and the client.

Document & content management provides a central repository (vault) for documents and should manage authoring of all new documents and changes to existing documents. Product data and configuration management, where all information is linked to particular products, product components and subassemblies, or parts, remains at the heart of the system.

When a product is delivered to the client, it is normally accompanied by a number of contractually specified documentation deliverables, including operators and maintenance manuals, technical data and a variety of other technical data the client needs to

[1] http://www.telelogic.com/products/doors/index.cfm

successfully operate and maintain the product. These processes are all managed and checked off in the requirements management/tracking system to ensure to ensure the terms of the contract are fulfilled.

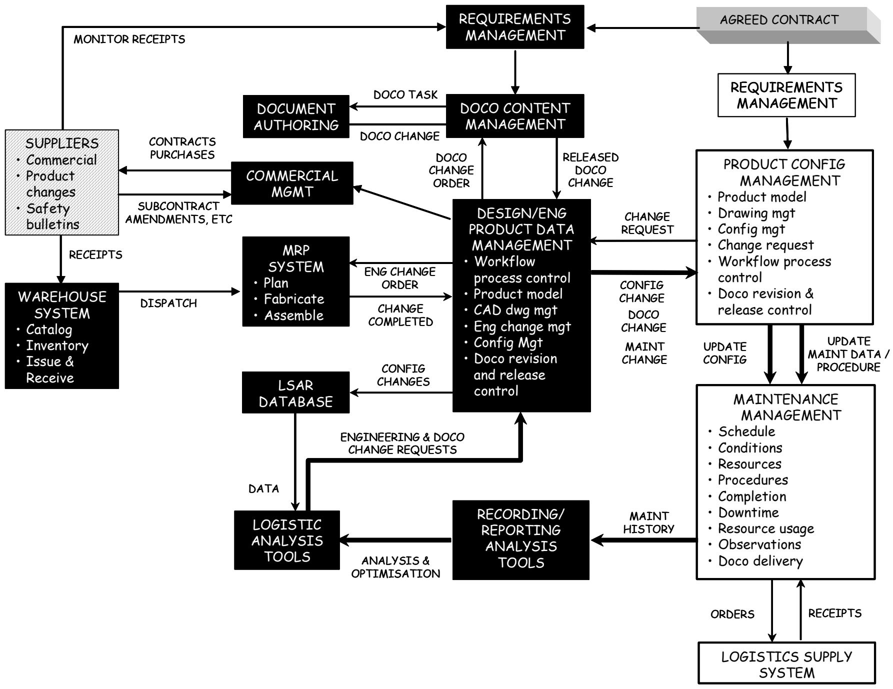

Figure 5. Functional components in the PLM paradigm for complex, costly and long-lived engineered product during the "in service support" phase of a project. The client's applications are represented in clear boxes. The prime contractor’s applications are shown in black boxes. Note, although they are shown in black here, depending on contractual arrangements, documentation management and logistic analysis for in-service support may be conducted by either the supplier or the client or both.

As products are maintained in service, defects, warranty and safety issues may be discovered, and/or operational experience may suggest the need to make engineering changes (large or small) or changes to the operating and maintenance documentation. Normally, these are passed back to the supplier as change requests which require management within the PDM system to ensure that appropriate actions are taken. Actions may range from simple documentation changes, to full-blown engineering changes involving new parts or in some cases even new systems. Where new parts or components are required, engineering details are passed to the manufacturing resource planning function to track and manage the fabrication process.

The fully developed PLM paradigm offers an interesting capability for continuous improvement to the product through its lifetime in service. Many in-service products are supported by computerized maintenance management systems that monitor many aspects of the product’s operational experience, including component failures and associated component, system or product downtimes, spares and consumables usages, maintenance costs, and a variety of ‘health’ parameters recorded by maintainers. These data are available to be extracted by monitoring systems such as the recording/reporting analysis tools illustrated in Figure 5, as operated by Tenix during the first 10 ship-years of ANZAC ship operational experience. Preliminary observations from the recording/reporting analysis tools then feed into the logistic support analysis record database to identify any components or systems contributing to excessive downtime or maintenance costs. These observations will then support the development of changes to maintenance procedures, spares allowances or engineering changes to reduce maintenance costs and improve the availability of the product.

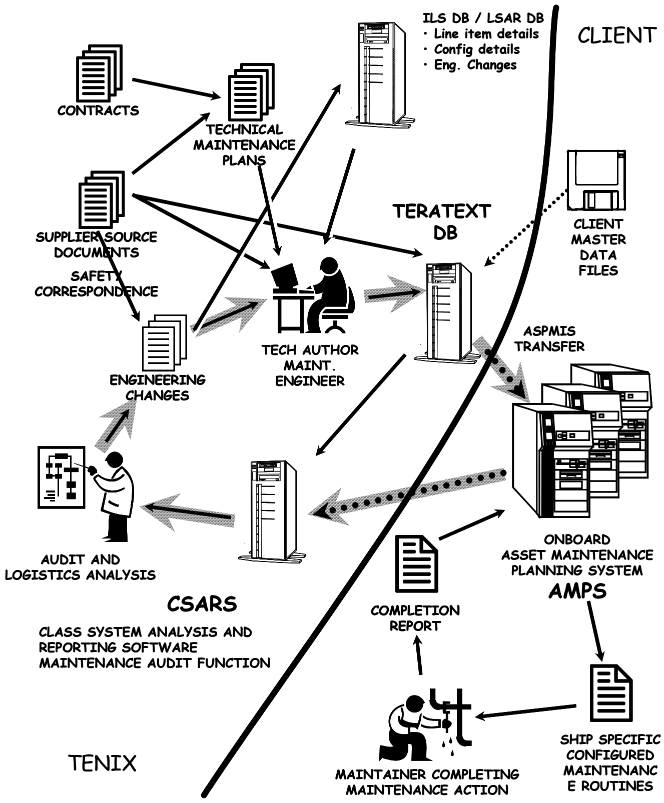

Figure 6. A simplified view of the PLM paradigm during the "in-service support" phase implemented in the early stages of the ANZAC Ship Project, when Tenix still had to prove that the ships met the operational availability requirements of the contract. TeraText manages maintenance routines and associated technical data. The ILS/LSAR database represents the part of the system responsible for engineering change and configuration control. This is validated against a separate product data management function not shown in this diagram. ASPMIS was a unique data transfer protocol for transferring structured maintenance documentation, associated metadata describing maintenance routines and other technical data to the client's computerized maintenance management environment, known as AMPS. CSARS provides the recording and reporting analysis tools.

Figure 6 illustrates the in-service phase of the PLM paradigm as practiced in the first 10 ship-years of operational experience with the ANZAC Ships, when they were still under the test, evaluation and validation period of the contract. During this period Tenix was responsible for monitoring operational availability of the ships and major systems, and making any changes required within the fixed contract price to ensure that the contractually specified availabilities were achieved. The level of system integration is now substantially greater, and an alliance between the client, combat systems supplier and Tenix as the platform systems supplier are responsible for the feedback loop analyzing operational data and feeding that back via logistic support analysis into engineering and documentation change as shown by the shaded lines in Figure 6.

The progressive application of aspects of the PLM paradigm at a comparatively early stage in production of the ANZAC Ships certainly helped Tenix with its successful and profitable completion of the ANZAC Ship project, “on budget, on time, every time”. However, because aspects of the paradigm were implemented piecemeal and many managers still think in terms of paper documentation, it is fair to say that the company has still not realized all the benefits that could be achieved from a full understanding of data, information and knowledge reuse and the possibilities to minimize review, edit, signoff and release cycle times to condense the entire project schedule.

Implementing PLM Systems

There are a variety of PLM systems available on the market. The top three in terms of world wide sales are:

- Dassault Systèmes (3DS) Enovia MatrixOne - http://www.3ds.com/products-solutions/plm-solutions/enovia-matrixone/overview/.
- Parametric Technologies Corporation (PTC) Windchill - http://www.ptc.com/appserver/mkt/products/home.jsp?k=37.
- Siemens (UGS) Teamcenter - http://www.ugs.com/products/teamcenter/.
- There are many other PLM suppliers as can be determined from the many free and priced reports produced by CIMdata - http://www.cimdata.com/index.html, who monitor the PLM industry and offer a variety of consultancy services.

Each of these PLM systems integrate a variety of different modules to achieve the overall project/product management capability. All have the ambition to cover the range of functions from authoring text and CAD documents to maintenance management and through-life support. Tenix has had some experience with versions of all of these products and has experience integrating functions provided by legacy systems and other suppliers (e.g., the TeraText content management system – http://www.teratext.com) to build PLM systems to meet company requirements.

Because they are designed to bring large and complex projects under control, all PLM systems are themselves comparatively costly and complicated to implement to meet the requirements of the particular organizations. Basically this involves picking and choosing from among the various modules and functions.

Appendix 1 provides generic specifications for a PLM system capable of managing a variety of large and complex projects.

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Appendix.
Functional specifications for a PLM System

1. *Product Structure Modeling and Management*: The PLM system should be able to assist users create and maintain hierarchically organized product breakdown structures for a variety of products.
   a. parts/components/software catalogue
   b. parts/component types
   c. parts/components have user-definable attributes/metadata
   d. links to variety of electronic file objects associated with part/component
   e. graphical user interface assists hierarchy building and viewing
   f. serialization (i.e., iteration of same part/component when used multiple times in the overall system)
   g. configuration status (e.g., review, authorize, release)
   h. track and audit changes to product models
   i. ability to assign same objects to different product model hierarchies
      i. parent product
      ii. bills of materials, as (designed, planned, built, maintained, user defined,
      iii. system design,
      iv. logistic support analysis record (LSAR) hierarchy,
      v. reliability hierarchy
   j. Establish, preserve & output baselines to appropriate standards
2. *Vault Management*: The PLM system should provide an access protected central repository for storing instances of all kinds of electronic files and objects associated with the engineering or project management processes.
   a. Document/object types
      i. CAD models
      ii. engineering drawings
      iii. data sets
      iv. Office documents
      v. PDF
      vi. email
      vii. scanned images
      viii. etc.
   b. document metadata
   c. manages links between vaulted items and product model objects, workflows, etc.
   d. offers standard search functions and searches relating to product model component links
   e. vault should include functions to allow/control access to all electronic file objects in conjunction with other components of the PLM system and to track and audit all changes to file objects. These should support the following capabilities
3. Access security model
   a. file locking (i.e., file may be checked out for viewing but locked against editing)

b. file status model (e.g., draft, under review, released controls access and locking)
c. file versioning (sub versions / released versions)
d. check-in to capture metadata re date, author, etc.
e. check-out to capture metadata
f. Note: Ideally the system should be able to recognize, control and version XML/SGML document fragments in association with content management functionality.

4. *Workflow/Process Management*: The PLM system should provide a generic workflow/process management capability able to electronically progress a variety of different processes.
   a. graphical process modeling
   b. able to link a variety of electronic objects held in the vault to the process, such that they are progressed through the process with appropriate access and status changes.
   c. Electronic distribution on signoff or passing particular status change
   d. Boolean branching
   e. audit trail
   f. process monitoring (i.e., due dates, late actions)
   g. in-box / email notification of new action requirements
   h. to-do list
5. *Document Management*: Documents include all kinds of file objects such as MS Office files, engineering drawings, CAD models, database reports, etc. other than dynamic objects such as active databases. Where possible the authoring platforms should be integrated within the PLM umbrella.
   a. "unstructured" documents managed at the file level
   b. "structured" documents (e.g., CAD designs, XML, SGML, etc.) with ability to check-out, edit, reuse, and version document components as well as whole documents.
   c. standard search and retrieval functions as well as via links to product model and workflow objects.
   d. file packages issued under PLM control to appropriate end-user application
   e. all document changes controlled & tracked via check-out/check-in via workflow/process management in association with appropriate authoring/editing tools,
   f. publication of "authorised/released" documents to appropriate library/portal systems for circulation and viewing.
6. *Change Management*: PLM system to track and audit all changes to managed objects in the system as per capabilities of the workflow management.
   a. engineering change workflow process
      i. applicability to configuration items/baselines
      ii. applicability to documents
   b. engineering change processes to meet requirements or relevant technical regulatory frameworks
   c. document edit workflow
   d. process change workflow

7. *Configuration Management*: A 'configuration' in PLM is a set of product-wide relationships between parts, assemblies and their associated documentation and data files. A configuration can be created at the initial design stage and used as a framework for development. It can be directly related to bills of materials for the manufacturing resource planning system. Configurations change throughout the product life and managing these changes is known as configuration management (CM). CM records all changes to the product and ensures these are appropriately authorized. The above capabilities shall provide the necessary tools for effective configuration management as per MIL-HDBK-61A or other standard as required, to include:
   a. configuration identification
   b. configuration control
   c. configuration status accounting
   d. configuration verification and audit
   e. data mangement
8. *Reporting and Publishing Functions*: The PLM system shall have the capabilities to provide required management status tracking and audit reports and to assist in the preparation of client required data and documentation deliverables.
   a. late actions
   b. b. baselines & bills of materials (engineering,, production, as-delivered)
   c. c. LSAR data/reports
   d. d. deliverable document packages
   e. e. etc.
9. *CITIS Functionality*: CITIS in defense contracting refers to a Contractor Integrated Technical Information System/Service. In association with appropriate firewalls, the PLM system should provide capabilities to allow client, partner and subcontractor appropriate facilities to add/edit/access data and documents held on system.