Product Life Cycle Data Management: A Cross-Sectoral Review

Gary Ford, Tom Bartley, Joel Igba, Alison Turner, Chris Mcmahon

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Faculty of Engineering, University of Bristol, UK

{cegnf, tom.bartley, ji0905, am0249, chris.mcmahon}@bristol.ac.uk

Abstract. The paper explores data management in the product life cycle of three engineering domains – civil/construction, marine and wind energy – each with distinct but potentially common issues. The approach has been to assess issues within each domain against the life cycle stages defined in ISO 15288 "Systems and software engineering - System life cycle processes", i.e., Concept, Development, Utilisation, Support and Retirement. These were then assimilated and comparisons drawn to identify common problems and areas that appear particular to the do-main. The paper presents a position statement, taken from the experience of practitioners in each of the relevant sectors; the purpose is to understand if there may be opportunities for cross-sectoral learning.

Keywords: Information management; Lifecycle; Civil; Marine; Wind

1 Introduction

The management of engineering data for the operation and maintenance of large complex artefacts such as ships, buildings and power generation systems is very challenging owing to the long life spans, multiplicity of stakeholders, diversity of data types and complexity of interactions in the artefacts and supporting systems. This paper explores these challenges and in particular makes a cross-sectoral analysis of issues across three distinct engineering domains: construction and civil engineering, marine (UK Defence) and renewable energy (offshore wind). Initial comparison of the domains would indicate a number of similarities, e.g., complexity, capital investment, but none-the-less significant differences exist, in business/engineering maturity and structure of the supporting industry, which have strong implications for data management approaches in each domain.

The purpose of the paper was to explore opportunities for engineering communities to share good practice with others and identify issues which are still to be resolved across all engineering sectors.

2 Background

The three sectors under study are construction/civil engineering, marine and wind energy. Each is characterised by large, long-lived artefacts and by distributed operations, but there are differences, especially in the nature of the industries.

Within civil engineering/construction, Egan's [1] 1998 report highlights the disjointed and adversarial nature of the industry. Designs are often created by multiple companies, and construction and operation may be performed by entirely different organisations with little input to upstream decision making. To counter this, in the UK the Government (along with major clients worldwide) has adopted a Building Information Modelling (BIM) strategy which mandates a life cycle approach to the production of project information on public projects by 2016 [2]. BIM is the construction industry's response to Product Lifecycle Management (PLM), in which a federated database is developed to serve an asset from "*cradle to cradle*" [3].

Marine engineering/construction within UK Defence currently constitutes 3 of the 4 major Ministry of Defence (MOD) projects, e.g. the Queen Elizabeth class aircraft carrier with capital expenditure in 2012/13 of £9.1 billion. However, the operation and maintenance cost of a warship will typically be twice the cost of acquisition [4]. Data management within the marine domain experiences issues similar to construction, e.g., ships designed and built by multiple companies and operationally maintained by another set of organisations, but national security, nuclear engineering and weapons systems are important additional factors, creating a complex data management environment.

The wind energy resources will have a large role to play in meeting renewable energy targets but to be competitive the Cost of Energy (COE) produced from them must be competitive. Hence there is need for innovation and improvements in the sector with reliability and COE as the major drivers. In wind power higher than expected costs of Operations & Maintenance (O&M) is a particular issue [5]. Reducing the cost of O&M triggers the need for a more comprehensive and integrated through-life service and maintenance management approach [6]. Data management is an important step towards optimising O&M activities and reducing COE [7].

As an example of the challenges involved in the operational support of very long-lived artefacts for which much information is pre-digital we have studied the Clifton Suspension Bridge (CSB) in Bristol which first opened in 1864. The bridge is managed by the Clifton Suspension Bridge Trust (CSBT) which finances all maintenance, conservation and operating costs through tolls. The Trust owns a range of information dating from the 1830's including the original bridge design in addition to operations, management and maintenance details for the bridge. There also exist many technical investigations, reports and general interest material that also form part of the CSBT's collection.

3 Systems Engineering Life Cycle

A number of standards exist that can be used to assist in managing the construction and operation of a system. The selection and adoption of a life cycle will be dependent upon a number of factors, e.g., definition of requirements, anticipated complexity, urgency, proof of concept, etc. Given the size, cost and complexity of a typical civil engineering project/maritime vessel the design and construction will normally adhere to a life cycle typical of ISO 15288 [8] which defines discrete stages to form a system life cycle, i.e., Concept, Development, Production, Utilisation/Support and Retirement. This review selected ISO 15288 as a current Systems Engineering standard recognised by The International Council on Systems Engineering for a structured comparison of the life cycle stages for each of the selected artefacts. Each ISO 15288 stage details a number of deliverables and purpose, e.g., Concept ~ "*develop preliminary system requirements and a feasible design solution*". The ISO standard, originally intended for Systems Engineering was modified in 2008 to include software engineering. Some major technical projects carried out to maintain or improve an asset may be viewed as having life cycles of their own embedded within the whole system life cycle.

The utilisation/support stage of the life cycle includes both operation and maintenance and these are the activities that typically cost an organisation most out of the entire life cycle. In some cases up to 70% of the total cost of ownership of an asset is consumed at this stage [9].

4 Data Management within Each Domain

Civil engineering/construction: BIM has become the accepted term for a new paradigm in the production and management of a built asset's information through design, construction and operations with a view to achieving transformational change [10]. Because the industry has traditionally been slow at adopting new technologies the adoption of BIM is mainly a client-led initiative. Whilst there is an established understanding of how BIM will be implemented there are many technical and cultural challenges to overcome and there are few examples of effective life cycle information management. The Institution of Civil Engineers has identified many case studies where BIM processes have been used effectively in distinct sectors or part of the construction life cycle [11].

An important factor for some clients in specifying the use of BIM is that it can enable better Facilities Management [12]. The Construction Operations Building Information Exchange (COBie), a subset of the Industry Foundation Classes (IFC) standard, has been developed to aid handover of as-built in-formation about an asset in human readable format (spreadsheets) [13]. COBie structures information hierarchically describing the facility's objects and systems and includes service schedules and maintenance requirements and can then be used to interface with Computer Aided Facilities Management applications and used throughout the life of the asset. There are issues in having too much data in that it becomes inaccessible and there is complexity in the number of soft-ware packages which need to interact [14].

There are many issues to be resolved before BIM is fully functional. The construction industry has large quantities of legacy data. Where data does exist it is often very difficult to find and likely to not to be in a digital format. Model interoperability also remains an issue [15]. The buildings sector is very mature at producing 3D models and the IFC standard is becoming mature enough for widespread use. However, as yet for the linear asset sectors (e.g. highways, railways) the standard is not yet comprehensive enough.

Marine: Warships are complex integrated systems, and may be viewed as systems of systems, e.g. a submarine contains in excess of 100 integrated systems which are linked structurally, mechanically, electrically, hydraulically and pneumatically. PLM of a warship/submarine thus requires a comprehensive systems approach from initial concept through to disposal necessitating the integration of numerous complex systems delivering a synergistic, flexible, maintainable, reliable and available cost effective weapon platform. To support such an approach the UK MOD has developed an Acquisitions Operating Framework [16] that decomposes the full acquisition life cycle into 6 distinct stages: Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal (CADMID). Assessment and Demonstration map onto the Development stage of the ISO 15288 life cycle and In-Service maps to Utilisation and Support.

The development of a warship/submarine entails a number of specific engineering tasks that correlate to and overlap with the CADMID life cycle, e.g. design survey, design synthesis, design assessment, system design, etc. [17]. Each stage within the life cycle specifies data or physical outputs, e.g. User Requirements Document and Through Life Management Plan (TLMP) for the Concept stage, System Requirements Document, refined TLMP and detailed plans for Assessment and combination of prototyping and engineering evaluation of the evolving design and its maturity for Demonstration stage.

To aid independent assessment of major defence programmes, a formal gate process is used to assess the maturity of the design. This includes definition of the Support Solution (for in-service) and its data requirements against the Support Solution Envelope and ISO 10303 for PLM. In addition, a warship may receive a number of upgrades to enhance its capability or extend its life. Each will constitute a discrete CADMID life cycle.

The complete lifespan of a naval vessel may be extremely long. The new Ford-class aircraft carriers of the USA are designed for a 50-year lifespan. The data associated with such a lifespan are considerable and issues include multiplicity of formats stored in multiple locations and hardware systems, owned by many organisations and with much of the data security classified in addition to being commercially sensitive. Records maintained by naval vessels are often more complex and onerous than commercial vessels, e.g., quality control: material certification, surveyed material condition, high value/sensitive equipment, and legislative requirements for operation (Lloyds Shipping, Nuclear Inspectorate). This is particularly relevant with respect to nuclear power plant.

The "*In-Service*" stage of the project will not only encompass capability enhancements of the artefact but also preventive and corrective maintenance. Royal Navy data indicating the "*material state*" of an artefact is stored in a considerable number of sources, including the Unit Maintenance Management System (a work management scheduling application utilising Reliability Centred Maintenance as the maintenance methodology), Operational Defects system (that records defects that degrade the operational capability of a vessel), engineering logs (paper-based logs detailing defects, fuel usage, engine hours run, equipment temperatures, fire main pressure,…), financial reports (planned and actual expenditure of maintenance undertaken), test/trials specifications and stores usage reports.

The data sources may be combined to formulate a material state assessment; however, the integrity and accuracy of the sources vary. They may exhibit fuzziness, incompleteness and randomness. For example, trials teams' reports lag the operational environment/system condition; financial reports may reflect the hours available rather than the actual work undertaken rather, test specifications reflect what has been achieved rather than a perspective of the system condition/performance. There is also an issue of trust in the data since the management of the data sources may vary between vessels and classes of vessel.

Wind energy: The first wind farms were built in the UK in the 1980's [18] with a typical design life of between 20 to 30 years [5] which suggests most early turbines are reaching the end of their design life. A number of wind turbines may suffer from early failure, however, this may still be considered acceptable within the overall design of the artefact. The life cycle stages of Concept, Design, Production, Utilisation, Support and Retirement apply equally in the wind energy industry, which has adopted and incorporated computer aided tools for design and data management from its infancy. As noted by Guo [19] and Hameed [20] the main life cycle stage where data management issues persist is during Utilisation/Support. This is because of the gaps that currently exist in the ability to capture, feedback and re-use in-service information of wind power plants.

5 Product Lifecycle Management Data Issues

Tables 1, 2 and 3 show data management issues at the different life cycle stages for civil/construction, marine and wind sectors respectively.

Table 1. Data Management Issues: Civil/Construction Sector

Life cycle stage	Issues (especially concerning long-lived assets)
Concept	With an ageing infrastructure, similar projects may have been undertaken previously; hence, a search of historical information is essential. For ageing assets search/retrieval of legacy data is often difficult and tacit knowledge is used.
Development	Development of design solutions relies on legacy data to understand what has been done in the past or to validate calculations or models. There are issues with finding relevant data and it is not always known whether it even exists. During the development stage much data can be generated, and in some cases almost all data is kept regardless of value. Data may not be in a digital format and it may be stored in locations that require special provisions. There are interoperability issues owing to data and organisational diversity. .
Production	Issues arise in capturing details of work undertaken and how. The "as-built" dataset is often incomplete or has errors, without checking every drawing and document this is difficult to manage. There is no formal process for storing configuration data or the required data format. This can result in data that is

	less useable in the future and may require time to convert or digitise.
Utilisation/ Support	Conversion and interpretation of original data is challenging for example because original drawings are in "imperial" units, modern materials are SI units. Inspections and regular risk assessment are part of ongoing asset management and may generate substantial quantities of data in various formats. Issues include data capture, format and storage and whether information can be found when needed. In some cases the data that is collected may never be used, conversely data that has not been recorded would be useful. Data quality is an issue; any data used must be checked first as errors have been found in calculations, drawings and surveys. Many different people may have worked on the asset over many years which raises issues with respect to retrieval, classification and terminology. Some data about the asset may be very old and need preservation. Digitisation may be needed to aid access and to prevent excessive handling of originals
Retirement	A long term storage policy is required for retired assets, especially for culturally significant artefacts. To enable the safe retirement of infrastructure, information relating to how it was built, the as-built structure and materials used may be required.

Table 2. Data Management Issues: Marine (Defence) Sector

Life cycle stage	Issues
Concept	Documenting and agreeing user requirements is challenging given the numerous operational, human factors, safety, environmental, security and other issues identified by stakeholders, e.g. operational capability/ restrictions, potential future changes, constraints on capability such as legislation, policy, timescale. The process of defining user and system requirements for complex naval systems has resulted in "the addition of costly, and often unneeded, requirements to the Department's most expensive platforms" [21].
Development	The engineering task, Contract Design is the process within this stage; the process will produce a number of detailed specifications the builder can utilise, e.g., Performance specification, System specification, Sub-system specifications, Equipment specifications, Material specifications, Standards, Acceptance criteria and methods, Costs, Build Programme, Delivery date.
Production	The construction of a naval vessel generates a very large volume of design and construction records including "as fitted" documentation of the artefact. It is not uncommon as a consequence of "supplier changes, changing needs and technologies and in-service engineering changes, [that] no two ships are identical when delivered or remain static after delivery." [22]. Configuration management is essential to maintaining a record of the artefact. Test specifications: a precise record of the design is essential when defining test specifications. They are maintained not only by the builder but also the operators, and there are quality issues in their collection
Utilisation/ Support	Configuration Management (CM) records may be incomplete/inaccurate and as a consequence effective operations and maintenance may be an issue. Failure to maintain satisfactory CM records has the potential for significant impact. Material state: data to ascertain the material state for maintenance is multifarious and requires fusing and analysis. Furthermore, the management/ administration of the numerous data sources is subject to variations with respect to

	operational commitment, on-board management and data configuration. Test specifications and results as a consequence of maintenance and upkeep are created and maintained to verify the installation and performance of the numerous onboard systems. Test specifications are maintained not only by the shipyard but also the operating navy.
Retirement	Configuration Management: records may be incomplete/inaccurate because of changes in legislative policy and/or hazards not envisaged at the time of construction raising potential issues regarding the disposal of controlled materials. Consultation documentation regarding the disposal of nuclear submarines [23] and the handling of radioactive waste is an issue. Sales literature: a vessel may be sold for further use as a warship, artificial reef, recycling, etc. hence a "detailed" sales brochure may be produced for prospective buyers, e.g., "Commercial sale of Type 22 frigates" [24]. Drawings, documentation, etc., associated with a "retired" vessel will be archived for reference in potential future designs, lessons learnt etc.

Table 3. Data Management Issues: Wind Energy Sector

Life cycle stage	Issues
Concept Development Production	There are institutional barriers that hinder communication during design of wind turbines [19] which lead to issues with data access and ownership. During product development, issues arise with respect to data transparency and availability, whereby components and subsystems are produced by multiple suppliers unwilling to share design information for confidentiality reasons [5]. There are also issues with ownership of key design information especially when several sub-suppliers are involved in designing and delivering parts of a system while trying to preserve their Intellectual Property. The use of legacy data for product development purposes may be problematic, because the wind sector is still relatively young with little historical data and because of poor data accumulation during the in-service stage of early turbines.
Utilisation/ Support	Data management issues during utilisation include data capture, access, technological level, data availability, data quality, database management etc. [20] discuss in detail the challenges in collecting reliability and maintainability data of offshore wind turbines, and assert the need for a common shared database such as the Offshore Reliability Database used in the oil and gas industry. Some researchers and laboratories have started to capture field data, but in-service data collection may be difficult owing to access issues especially in the case of offshore turbines and onshore turbines erected on harsh terrains. Technicians may not complete maintenance records within the turbine due to safety concerns, space limitations, etc. thus record keeping may comprise on-site photographs and off-site report completion. Consequently there may be a "time lag" between inspection and reporting, and data may lack definition and quality. Assessing availability/reliability data is often difficult, exacerbated by confidentiality, data collection methods, e.g., hand-written and computer-written report sheets raising issues with respect to inconsistency of data source format. Some failures of turbines have been gathered without details of the failure mode. There is inconsistency in file formats and problems with interoperability due to the use of both hand-written and computer based field data collection. Such issues make it difficult for data to be reused for new designs. .
Retirement	Although a number of wind turbines have been decommissioned as a conse-

	quence of catastrophic failure and early installed turbines are just reaching their end of life there is limited experience or evidence that would support any claims of data management issues during the retirement stage of wind turbines. .

6 Cross-Sectoral Comparison

Mapping the "information management" issues given in the previous section to these engineering processes the areas of potential concern identified in Table 4.

Table 4. Analysis of Information Management Issues. Note (1) Owing to limited maturity of wind technology, issues associated with "Retirement" are excluded.

Data operation	**ISO 15288 Stage**. Note C ~ Civil, M ~ Marine (Defence), W ~ Wind														
	Concept			**Development**			**Production**			**Utilisation/ Support**			**Retirement**		
	C	**M**	**W**	**C**	**M**	**W**	**C**	**M**	**W**	**C**	**M**	**W**	**C**	**M**	**W**[1]
Generate	x			x			x			x			x		
Collect	x		x	x		x	x	x	x	x	x	x	x		
Transform	x	x	x	x	x		x	x	x	x	x	x	x		
Retain										x	x	x			
Retrieve	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Disseminate	x	x	x		x	x		x	x		x	x		x	
Dispose	x			x			x			x			x		

The largest number of issues relate to "Civil", potentially as a consequence of the age of structures, construction techniques, material, legacy data and complexity of the support function. In all domains information management issues are related to the maturity of the technology and the availability, accuracy and volume of data. The Marine domain is assisted by a controlled and defined system engineering environment, and the considerable history and experience of ship design and maintenance, but data dissemination of sensitive data is an issue.

Collecting data is an issue for all domains. This may be due to the availability of data/stakeholders, and volume and accuracy of data. Issues may also arise as a consequence of the physical environment. Data retrieval although an issue in each domain exhibits differences in application, e.g., Civil ~ large volume of legacy data including historical paper records, Marine/Wind ~ numerous locations and data held by multifarious organisations. Utilisation/Support identifies the largest number of issues, i.e., collating, processing, retaining and retrieving data potentially as result of the volume of data, availability of data / stakeholder, time constraints.

7 Conclusion and Proposals for Future Work

Engineering domains have similar data management issues but it is important to consider the circumstances in each domain to understand the full range of issues that may apply. In particular, very long lived artefacts have special requirements especially artefact such as the CSB which has a distinctive requirement "*to pre-serve […] in perpetuity*", not simply as a monument but as a fully functioning bridge. The large volume of CSB data which includes historical records exacerbates the data management issues. Special issues may also arise, however, when issues of national security or commercial confidentiality are present, as shown by our study of the marine sector and wind energy respectively. For all of the sectors studied the greatest number of issues, and hence perhaps the greatest potential for improvement, arise in data management for the utilisation/support stage. Technology may ease the burden of data collection by means of remote sensing, hand held devices, etc. allowing data to be more readily transformed. Engineers and management may subsequently utilise/apply data mining techniques to retrieve, interpret and exploit data as a real resource/tool.

Future work should start by clarifying the issues highlighted into specific work-flow issues and expanding the study to encompass a larger number of case studies. The stages of the life cycle could be grouped into pre-utilisation (concept, development and production), utilisation/support and retirement. Grouping the stages may provide a clearer understanding of the cross-sectoral nature of issues but suffer from a loss of granularity as a consequence; finally, data/information transfer between stages may also be studied as a potential area of weakness.

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References

1. Egan, J.: Rethinking Construction: Report of Construction Task Force, London: HMSO. (1998)
2. Government Construction Strategy. www.gov.uk/government/publications/government-construction-strategy
3. Smith, M.: BIM in Construction - Building Information Modelling. www.thenbs.com/topics/bim/articles/bimInConstruction.asp (2011)
4. Harris, F.: Total Ownership Cost. American Society of Naval Engineers Day 2011, Arlington, Virginia, 10-11 February 2011, pp. 3 (2011)
5. Musial, W., Butterfield, S., McNiff, B.: Improving wind turbine gearbox reliability. In Proceedings of the European Wind Energy Conference. (2007)
6. Igba, J., Alemzadeh, K., Anyanwu-Ebo, I., Gibbons, P., Friis, J.: A Systems Approach Towards Reliability-Centred Maintenance of Wind Turbines. Procedia Computer Science, 16, pp. 814-823. (2013)
7. Fischer, K., Besnard, F., Bertling, L.: Reliability-centered maintenance for wind turbines based on statistical analysis and practical experience, IEEE Transactions on Energy Conversion, 27, no. 1 pp. 184-195. (2012)

8. Systems and Software Engineering - System Life Cycle Processes. International Organization for Standardization. www.iso.org/iso (2013)
9. Koronios, A., Nastasie, D., Chanana, V., Haider, A.: Integration Through Standards–An Overview Of International Standards For Engineering Asset Management. In Fourth International Conference on Condition Monitoring, Harrogate, United Kingdom (2007)
10. Venugopal, M., Eastman, C. M., Sacks, R., Teizer, J.: Semantics of model views for information exchanges using the industry foundation class schema. Advanced Engineering Informatics, 26(2), pp. 411–428. (2012)
11. BIM 2012. London. www.ice.org.uk/News-Public-Affairs/ICE-News/ICE-BIM-2012-report (2012)
12. Arayici, Y., Onyenobi, T., Egbu, C.: Building Information Modelling for Facilities Management (FM). International Journal of 3-D Information Modeling, 1(1), pp. 55–73. (2012)
13. Nisbet, N.: COBie-UK-2012. AEC3 UK Ltd. (2012)
14. Anderson, A., Masters, A., Dossick, C. S., Neff, G.: Construction to Operations Ex-change: Challenges of Implementing COBie and BIM in a Large Owner Organization. Con-struction Research Congress. ASCE. pp. 688–697 (2012)
15. Grilo, A., Jardim-Goncalves, R.: Value Proposition on Interoperability of BIM and Collaborative Working Environments. Automation in Construction, 19(5), pp. 522–530 (2010)
16. Acquisition Operating Framework. www.aof.mod.uk/index.htm
17. Warship Engineering Management Guide. Defence Equipment & Support, December 2007. (2007)
18. Tavner,P.J., Xiang,J., Spinato,F.: Reliability Analysis for Wind Turbines. Wind Energy, 10(1), pp. 1-18. (2007)
19. Guo, H., Watson, S., Tavner, P., Xiang, J.: Reliability Analysis for Wind Turbines with Incomplete Failure Data Collected from after the Date of Initial Installation. Reliability Engineering and System Safety 94, no. 6, pp. 1057-1063. (2009)
20. Hameed, Z., Vatn. J., Heggset. J.: Challenges In The Reliability And Maintainability Data Collection For Offshore Wind Turbines. Renewable Energy 36, no. 8, pp. 2154-2165, (2011)
21. National Defense Authorization Act Fiscal Year 2006. The Committee on Armed Services House of Representatives. www.gpo.gov/fdsys/pkg/CRPT-109hrpt89/html/CRPT-109hrpt89.htm (2006)
22. Hall, W.P., Richards, G., Sarelius, C., Kilpatrick, B.: Organizational Management of Project and Technical Knowledge over Fleet Lifecycles. Engineering Asset Management, pp. 767-778. (2006)
23. Submarine Dismantling Project. www.gov.uk/government/organisations/ministry-of-defence/series/submarine-dismantling-project
24. Commercial Sale of Type 22 Frigates. www.gov.uk/commercial-sale-of-type-22-frigates