PRODUCT LIFE-CYCLE MANAGEMENT IN SHIP DESIGN: FROM CONCEPT TO DECOMMISSION IN A VIRTUAL ENVIRONMENT

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ABSTRACT

This paper discusses how Product Life-cycle Management (PLM) tools can benefit the ship design process. Primarily, the concept of PLM applied to ship design will be decomposed in six key elements: database, modeling and simulation tools, value chain processes, product hierarchy management, product management and project management. Some of these elements rely heavily on the use Virtual Prototyping to be achieved. The next step applies these concepts to the ship value chain. This will be done through the development of a simplified scenario, where it is discussed how a vessel can be conceived and designed using an integrated design platform, applying PLM methods. Most of the information previous to product finalization is obtained through simulation of virtual models, using virtual prototype concepts. Our assumption is that combining PLM techniques with virtual prototype concepts enables a good control over the ship design project as a whole, through means of efficient modelling and simulation management. That way, the time and cost necessary for the product development can be reduced.

INTRODUCTION

Among the several perspectives that a *ship* can be observed it is, essentially, a very complex and specific product, with an equally complex value chain (VC) (Gaspar, *et al.*, 2012). The particularity of such product can be summarized in 7 characteristics (Erikstad, 1996): a ship is a self-contained structure operating in the boundary between two fluids; it consists of a multi-dimensional, partially non-monetary performance evaluation; high-cost of error if inefficient design; shallow knowledge structure between form and function; very traditional industry with preconceived standards; strict time and resource constraints; predominantly one of a kind and engineered to order solutions.
The amount of data involved in designing and constructing such complex product is huge. So it is the amount of working hours through different phases of the project. The number of variables involved makes the data handling and sharing between departments, phases and players challenging tasks.
Being able to deal with these tasks in an efficient way is essential to ensure the most rentable product. In other words, the *right vessel for the right mission* (Gaspar *et al.,* 2015).
Nowadays it is usual to have each process of the whole project treated independently by different groups, in a way that the information generated in each process is not efficiently related to others. This can increase the project total hours (and consequentially cost), as well as leaving room for communication issues.
PLM methods provide a way of dealing with huge amount of data in complex products life-cycle. This can be achieved through many techniques, such as efficient information indexing, database management, product decomposition and analysis and project management.
Many decisions during the ship design phases are based on key performance indicators (KPIs) tradeoffs, such as structural strength *vs* building cost *vs* cargo capacity, vessel speed *vs* fuel consumption, seakeeping *vs* seafaring. The cost and complexity of these decision making processes make virtual prototyping (VP) a very handy tool to simulate designs during several phases of the VC, identifying improvements quickly and in a controlled environment. VP techniques can also be used to construction planning, staff training and human factors analysis (Zorriassatine, *et al.*, 2003).
In the following sections basic concepts involving PLM methodology and VP techniques will be discussed and applied into a simplified ship VC, in order to exemplify a possible way to deal with such complex systems in a time and cost efficient way.

Product Life-cycle Management and the Ship Design Domain

PLM is the activity of managing a company product all the way across their life-cycles in the most effective way (Stark, 2006), and it is one of the best known methods to maintain a good organization of the product different parts, services, costs and suppliers through all the cycles involving a product life, from conception to scrapping. The PLM *umbrella* embraces many other concepts, such as modularization tools, product and systems architecture, libraries, product data management (PDM) and enterprise content management (ECM), as illustrated in Figure 1.

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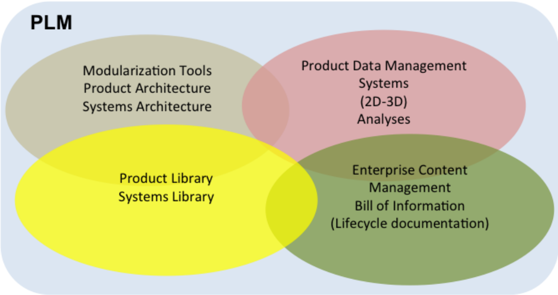

Figure 1 – PLM Umbrella

PLM involves not only control over the production, but also over all steps of the VC. One example is the scheduled maintenance of operational vessels, where the hull is cleaned and components repaired. If the charterer manages this process properly, it can reduce the time spent on non-profitable activities, while reducing failure risk of the system. This example illustrates the importance and effectiveness of PLM as method of control over the product. The final result is increased competiveness and lower costs.

PLM can be divided into 6 elements, illustrated in Figure 2 (CIMdata Inc., 2011). In short, *Database* is related to indexation tools and document management, *Modelling and Simulation tools* is composed by all the software used to design the vessel and virtual prototyping, *Value Chain Processes* are related to the management of the processes within the Ships VC, *Product Hierarchy* management is establishing the classification of all the ship systems and components, *Product Management* administrates all the information related to every component and *Project Management* connects every process to the entire vessel life-cycle.

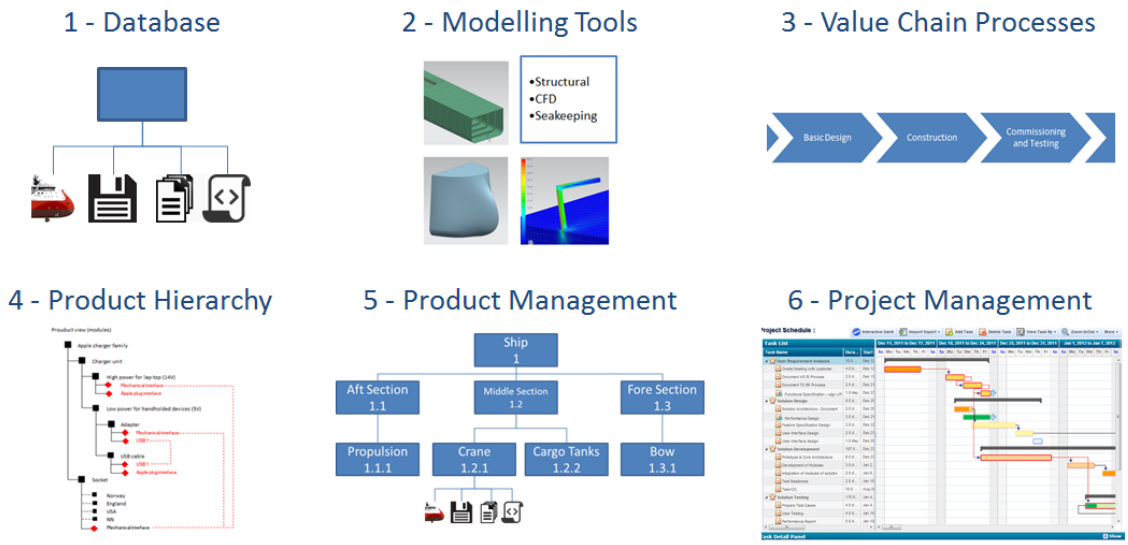

Figure 2: Product Life-cycle Management Elements

Ship Design and Virtual Prototyping

Nowadays the use of VP technics has become viable and even indispensable during the ship design task, mostly due to the increase of the computing power.

VP is, basically, a design tool, used during a product development phase. It consists of using virtual models instead of real prototypes to generate, analyze and verify the product feasibility according to different requirements and standards. With this approach, faults in the modeling and design process can be detected, before great investments are made. It reduces the need of physical modules in an early design phase and also reduces the costs involving redesign, since the prototypes are only made virtually. (Choi & Chan, 2004). Training is also a great advantage of the technique (OSC, 2015), merging diverse stakeholders in the same mission/scenario, each observing its own perspective (e.g. operational, technical, economical).

The VP methods can be divided, according to the modelling purpose: visualization, fit and interference of mechanical assemblies, testing and verification of functions and performance, evaluation of manufacturing and assembly operation and human factor analysis (Zorriassatine, et al., 2003).

Visualization can be used, for example, in conceptual design phases to have a first glance about what the conceptual ship design is going to be during sales argumentation, while during the detail design phase it can be used as an accurate visualization of the final vessel. Fit and interference of mechanical assemblies relates to the outfitting verification, as well as components interfaces, for example, in the vessel engines, rudders and thrusters are also focus of the VP.

Testing and verification of functions and performance are commonly used for crew training and analysis of the vessel behavior in duty. Such analyses are done using computer aided engineering (CAE) tools, as Computational Fluid Dynamics (CFD) software, for hydrodynamic analyses and finite element method (FEM) software, for structural analyses. This can also be used to test new equipment on board. Evaluation of manufacturing and assembly operation is useful in order to determine the ship construction and assemble phase. It is possible to simulate ship blocks construction and the blocks assembly operation to ensure that all processes are well defined and no problem will occur in the shipyard, as well as simulate shipyards with different block size constraints.

Human factor analysis can be used to evaluate the effect that the human interaction has with the vessel systems. It is possible, for example, to simulate the ship bridge or an engine room in order to measure crew performance, risk or operational training. Figure 3 presents the VP concept with a virtual continental shelf (Hildre, 2010)

Figure 3: Virtual Continental Shelf (Hildre, 2010)

PLM and Virtual Prototyping at the Ship Value Chain

A VC is a concept which aims to describe how a product life-cycle is constructed, from raw materials to the final product and then scrapping, through a series of processes which add value to the product with each activity. The VC objective is to help products development to be focused in the value-creation activity, creating the most possible value for the least possible cost. The value chain may be assumed thus the product life-cycle.

In order to apply the PLM concepts to a vessel, we are going to assume a simplified ship VC, which includes the most essential phases present during a vessel life-cycle. This VC can be observed on Figure 4, and each item will be discussed as follows.

Figure 4: Simplified Ship Value Chain

A - Conceptual Ship Design: It is during the conceptual design phase that main dimensions and most of the ship life-cycle cost is defined (Brinati, et al., 2007) and a set of technical documents is prepared which will be the basis to define the shipbuilding contract. At the conceptual design phase, the VP can be used in order to provide a preliminary analysis (such as resistance, seakeeping, structural resistance) together with vessel pre-visualization. This provides a good picture about what the vessel is going to be and it can be done using Computer Aided Design (CAD) software as Modelling Tools. On this case, the VP method used is, mainly, the visualization one. Similar vessels and previous projects documentation compose the Database on this phase. The main Processes are brief estimation and calculation in order to define vessel price and main dimensions. The Product Hierarchy is based on the vessel groups and main component requirements. The Product Management is based on an initial system breakdown. The Project Management is usually based on previous knowledge, from previous projects.

B - Basic and Detailed Ship Design: The Basic Design phase is the process of refining all the characteristics of the vessel such as, minimum plate thickness, engine power and other numerical analysis. Extensive work is done in documentation, both for approval of the classification society and for shipyard, preparing the technical specifications for the construction phase. The detailing can occur in parallel with the construction, as some outfitting elements are assembled at a late stage of the construction or after it. At this phase the use of Modelling Tools is more extensive. It is very common to use VP in order to refine the hull and structures modelling using CAD tools, perform analyses about the vessel behavior using CAE tools (such CFD and FEM), CAD for planning electric system, hydraulic arrangement and human factor analysis applied to systems design. On this case, the VP methods used are, mainly visualization, testing and verification of functions and performance and human factor analysis. The Database on this phase is composed by 2D and 3D Models, vessel equipment drawings, simulations, tank test results, analysis, specifications, rules and etc. The main Processes applied on this phase are detailed calculations and drawing, evaluation of the project by a classification society and project detailing. The Product Hierarchy will be a more complex and well defined one, with all systems and subsystems ready, usually SFI based (Fonseca & Gaspar, 2015). The Product Management is constructed over a complete system breakdown, based on the final design to the shipyard. The Project Management follows multiple-department and outsourced outfitting offices.

C - Construction and Assembly: In order to ensure a good usage of the shipyard time and avoid errors, VP is used to verify the fit and interference of mechanical parts and fixed outfitting, plan the construction steps and assemble order. On this case, the VP methods used are, mainly, visualization, fit and interference of mechanical assemblies and evaluation of manufacturing and assembly operation. The Database on this phase is composed by all the related components needed for the construction, constructions tools, technical designs, documentation from the detailed design and drawings, as well as a bill of information with the cost/hours of every part/task. The main Processes applied on this phase are blocks planning, construction, final assembly and outfitting. The Product Hierarchy includes the final product breakdown, with all components acquired and included. The Product Management adds the construction components to the ship system breakdown. The Project Management follows strict shipyard routine, with designer, owner and classification societies acting usually as external agents.

D - Commissioning and Testing: the objective of this phase is to verify if the vessel is able to perform as designed. This is done by a series of testing procedures to verify all project components, such as instruments and equipment, construction specifications and quality, modules, and vessel systems. Some critical performance factors, as vibration, comfort and general behavior are also supervised by classification societies. During the commissioning and testing the VP can be used in order to visualize the vessel model and evaluate the already done performance analyses or even performer new ones. There aren't mandatory Modeling Tools usually applied to this phase, but their real values should be measured and compared with the expected ones. On this case, the VP methods used are visualization, testing and verification of functions and performance. The Database on this phase is composed by sea trials values, scantling values and detailed ship manual. The main Processes applied on this phase are composed by all the needed testing procedures. The Product Hierarchy is the same as the last phase, namely, the final product breakdown, including all components. The Product Management includes a final description of the vessel ready to delivery and all subsystems and parts, with their actual data ready to delivery. The Project Management converges the end of the construction phase and delivery, with the product starting its operational phase at the end.

E – Operation: The operation is the longest phase of the life-cycle, where the vessel will perform its mission. Much of the VP during other phases will attempt to gain value on what is really performed here. Maintenance schedule plays also an important role, in order to ensure that the vessel will perform well during all its lifespan. One important VP process on this stage is Hardware in the Loop (HIL) testing, which consists in using real input values, obtained from a vessel to feed a control system and evaluate if it is generating the desired response, calibrating it if necessary. Other Modeling Tools usually applied to this phase are cargo planning and operation tools, spreadsheets software (stability, logistics) and so on. The Database on this phase is composed of vessel log, changed and to be changed components list, spare parts database and ship operation information. The main Processes applied on this phase are all the tasks executed by the vessel, as well as periodic local and dry dock maintenance, crew inspection and operation schedule. The Product Management includes components information, to be used for maintenance purpose. The Project Management is based on maintenance and operation schedules. Retrofit actions can also be simulated, with new equipment onboard or improvement of current capabilities.

F – Decommissioning: Once the vessel reaches its service time (usually, between 15 to 25 years) the ship can be refit and re-commissioned, sold or scrapped. This phase is a responsibility of the ship owner, who should guarantee that the process is in accordance to the actual regulation. The VP can be used as a tool to plan the scrapping process, in order to make the operation as safer and inexpensive as possible. On this case, the VP methods used are, mainly, visualization, evaluation of manufacturing and assembly operation and human factor analysis. The Database on this phase can be composed by structural plans, components and materials lists acquired during the other phases. The main Processes applied on this phase are decommissioning plan, components breakdown, recycling, scrap sale and etc. The Product Hierarchy includes all the vessel components which need to be decommissioned, and should include information about toxic and dangerous substances. The Product Management includes the detailed ship documentation. The Project Management is based on the decommissioning schedule.

INTEGRATED SHIP DESIGN PLATFORM

We propose an integrated design platform merging PLM and VP concepts in order to facilitate the ship design process. This platform benefits from the organizational concepts from PLM methodology, as well as VP techniques used to simulate main VC phases, from design visualization to construction. Having a well-defined and implemented integrated design platform can really help the designers to get the most from the product VC, such as modularization approach.

Existing PLM in Ship Design

Every design company has already some sort of PLM, even if not integrated. Ships are designed and analyzed; Yards receive all the drawings and owners and users are able to operate and schedule maintenance of the real product. What differentiates the current system from what we are proposing is strongly connected to the integration.

Let us take for instance the VC phase between the sales, design and the construction. The final products of the sale is a concept able to convince the owner that she should invest in that ship; the design products are the thousands of drawings required by the yard, while the final product of the yard is the ship itself. Current practice is that a department works on the concept, on an exclusive 3D model, while designers in other departments recreate the same model in several other models with much re-work until the final basic documentation. It is not rare for the shipyard to re-do many of the drawings to adjust the outfitting.

In the following section we suggest some ways to implement this integrated PLM/VP platform in ship design.

Project Template and Conceptual Design

For the sake of exemplification, we assume that an owner desires a platform supply vessel (PSV). A template containing performance indicators can be used to help the client understand his real needs and what can be offered to him as starting point in terms of past design (standard solutions) or new design (custom solutions). Common PSV performance indicators at this stage are: Deck Area, Cargo Volume, Deck Equipment, Service Speed, Fuel Consumption, Station Keeping, Low Speed Maneuverability and Operability.

For a project developed inside a virtual environment it is possible to obtain an economic analysis when the inputs and external projections for the market are accurate and there is data about similar vessels, with similar operational profiles and financing options. This kind of approach is advantageous to the client and the designer, since it helps one to narrow the projects main characteristics in an early stage, saving time, and allows the other to have clear expectations of the offered product price and characteristics in a multi-perspective. Ulstein group, for instance, considers in this phase two main perspectives (Ebrahimi, *et al.*, 2015), focusing on technical, operational and commercial aspects (perspective A) and smart, safer and greener aspects (perspective B).

At the end of this process, data about the new project is generated and needs to be properly stored for reference in the next cycles of the value chain. Having this kind of information at this time of the design development is only possible through the use of an efficient Database, which is at the disposal of the designer.

Project Database

The project database is an essential part of the PLM methodology. It aims to be a unified database for all the design phases, where all the information about the project is stored. The data relates to many different information sources, such as owner specification, analyses, 2D drawings and 3D models. This approach allows for an improved integration between offices responsible for different tasks in the designing process, which can be located around the globe and allows a good control over distinct stages of the same project, but that are intertwined, as for example, when one office in Norway is working with general arrangement and another in Brazil is working with structural analysis. A common database allows interaction and feeding one model based on the other, as well as re-use of the 3D model, decreasing the risk of miscommunication and rework. Modern PLM tools allow multi-user/department access with security levels, versioning and share. The project database is updated at each new process done during the project development, with more information being added to the objects, which fill the database.

During design, data is usually connected to a physical part of the ship, and a well-established Product Hierarchy may add the data search process, focusing on a visual language instead of just words. An example is shown in Figure 5, where it is possible to see a representation of the discretization of the propulsion system and its relation to the products; full lines mean direct relation and dashed lines indicate constraints.

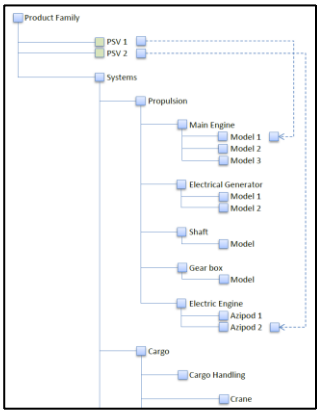

Figure 5: A Product Hierarchy for PSV

Each block includes all the data (drawings, receipts, manuals, analyses) from that group. Modern modularization techniques allow the inheritance of parent information, facilitating the re-use of current information (Hildre, *et al.*, 2010) (Chaves, *et al*., 2015).

Project Management

The project workflow is, basically, an organizational method (e.g. Gantt chart), where all the project phases are laid down in a timeline, being possible to see when each process is supposed to begin, end and when some processes overlap with each other. This is essential to visualize the project processes order and schedule and correct possible delays. A proper PLM software must connect these processes with the deliveries (documents, parts, construction), in a same database previously discussed. Figure 6 presents a simplified Gantt chart of how the Project Management can be conducted for a PSV design process, integrating its whole life-cycle.

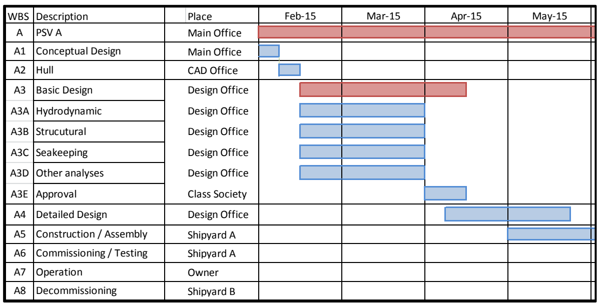

Figure 6: Project Management for PSV

Basic Design

On the basic design phase, several analyses are deeply performed in order to well define the vessel characteristics and behaviors, as well as the detailing of all systems and subsystems of the vessel. The final product of this phase is a large amount of drawings delivered to the yard, and it can benefit tremendously from a PLM and VP integrated tool.

During the basic design phase, the use of VP tools is very extensive. The use of CAE software, such as CFD and FEM tools, is well spread and the accuracy of the obtained results, when the software is correctly used, is very good. Modern PLM tools (Siemens, 2015) allow the re-use of the same 3D models to automatically create 2D drawings.

The next step is the detailed design, when cabling, piping and outfitting are done. During the detailed design phase, all the drawings, specification, components, parts and processes needed are defined and all the data generated is stored on the project database. All the detailed design is done in a virtual environment, where the components can be easily laid out and all the drawings automatic created.

Ideally, a designer would like to create our concept, simulate in the VP environment and, magically, press a button that would generate all the necessary 2D drawings that should be delivered to the shipyard.

Construction

On the construction phase, the vessel is divided in mega blocks, in order to be constructed at the shipyard. The mega blocks sizes are defined based on the yard capacity, and an ideal PLM system would be able to incorporate documentation for a same ship constructed in different yards. The integrated database should provide the material and components list, the construction workflow and all the needed construction drawing. The construction workflow can be defined using VP tools, like CAD software. This can avoid complications during the construction process and schedule delays.

Commissioning and Testing

At this time, the quality of the design and construction are rated, which will directly impact in the clients perception of quality and path the way to future business, this it is to gather information from the tests to which the vessel is subject. This data will be used by the operator to determine his income expectances, the vessels real limitations and capabilities.

A good design procedure should store this data and use to perfect the mathematical models of the basic and conceptual design phases, this will allow for an increased precision of the virtual prototypes. The main information obtained in this stage comes usually from vibration, at least some sea keeping characteristics, maneuvering and station keeping.

Operation

The Operation phase is also a piece of modern PLM systems. It could be connected to real operational log, for instance the rate at which the equipment is deteriorating and the vessel as whole requires maintenance. Again, the information gathered here should not be dismissed, since it can feed future conceptual designs, creating a better solution, optimized to the environment and with lesser limitations, decreased repair time and maintenance.

This phase is also crucial for training simulators and controller calibration. The characteristics of the vessel in a real operational environment should be used to feed, test and calibrate VP tools and systems; the response generated is compared to the required in the real life.

An ideal PLM system would be able to connect to onboard information, such as ship's response to different sea states, operational profile and cargo, while measuring fuel consumption and capacity to perform the offloading procedure at the platform.

Decommissioning

Decommissioning is the means of ending the life-cycle and it can be planned in advance through the use of information of previous designs iterations. It is highly dependable of the market circumstances and is difficult to predict with high accuracy. However, it can be improved by an active database. For instance, during scrapping, the database would provide information about structure, copper, steel and other materials, as well as any toxic components that require special care. If the owner desires to sell the vessel, then it will provide all the information necessary to the new owner. Finally, in case of refitting and re-commissioning, the new equipment, maintenance procedures and updates will be catalogued; furthermore the information of modules and systems used in current designs can be accessed and implemented to the old vessel, with minimal need of new analysis.

CONCLUSION

The motivation for this work was a lack of literature applying PLM techniques in ship design when we started to research how such methods could improve the virtual prototypes developed at the Ship Design Lab (HIALS, Norway). Most of the found literature consists of software advertisement (Siemens, 2015) (DNV GL, 2015). Rather than a deep theoretical paper, our

intention was to introduce and merge both concepts under the ship design perspective, looking for principles to apply PLM into ship design VP.
It is observed in current praxis a lack of unification among the VC tools, as well resistance to install and try brand new technologies due to the strong traditional aspect of the ship design industry. A 3D model used in concept will usually not be used for structural analysis. 2D CAD drawings, document editors, spreadsheets and presentations tool are indeed the only tools widely used during the whole value chain. In the database side, the most common tool is the mapped drive, without modern assembly / tag / filtering options.
In this sense, the same ships that were already decided in the initial phase needed to be redone and recreated in several other software, mainly due to the lack of integration among applications. Therefore, an integrated PLM platform is the one which re-uses and builds up former designs, with a same language among the six PLM elements.
We believe that a virtual environment would add up to it, allowing the designer to really use former designs database, building up new concepts based on the previous information, as well as re-using advanced 3D models for many VC phases (sales, concept, basic, construction).

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