LINCOLN Integrated Solution Supporting the Design of Specialized Connected Vessels

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Abstract: The maritime industry has been working to apply unique solutions capable of improving design and development performances (Koenig, Narita, & Baba, 2002; Liker & Lamb, 2001; Milanovic, 2016; Radovic & Macclaren, 2004). Over the past several decades, the industry has faced changes related to the increasing complexity of the dynamic global market. Activities to meet these challenges have been carried out in the marine space (e.g. aquaculture, renewable energy, environmental monitoring, accident response and clean up), however, design methodologies have remained rather unchanged, regardless of demand for the incorporation of new technologies and materials. Literature and multiple case studies have been utilized to develop a design approach, that aims to transform the design process for the extension of serviceability and reduction of design time. This paper describes an innovative maritime design framework, based on the comprehensive usage of design methodologies, (economic and environmental) sustainability analysis and Internet of Things (IoT) in vessel design.

Keywords: Lean Design; Internet of Things; HPC Simulation; Life Cycle Assessment; Life Cycle Cost, Maritime Design

1. Introduction

Maritime industry and transport continues to be a hugely important part of the global economy due to diversified economies that rely on the sea to deliver valuable raw material, components and finished products (Corbett & Winebrake, 2008; European Commission, 2017). Surrounded by 136,000 km of coastline, a blue economy of 5.4 million jobs and almost €500 billion a year of gross added value, Europe has traditionally been a world leader in the maritime sector. In the last decades, new business activities were born along the European sea coastline, such as aquaculture and renewable energy, beside the intensification of more traditional ones like blue tourism, surveying, emergency and recovery response. This marine business diversification brings new activities and requires specialized operations, the maritime industry is challenged to develop new value-added solutions, products and services that can accommodate changing demands (Ricci, Rhodes, Ross, & Fitzgerald, 2013).

To focus on industrial repositioning, the European maritime sector needs to reduce the negative impacts of vessels by incorporating new technologies and materials that are unfamiliar to many of the engineering and design practices in the industry today (i.e. tools, methods, techniques) (Luglietti, Wurst, Sassanelli, Terzi, & Martín, 2018; Thanopoulou & Strandenes, 2017). At the same time, to remain competitive it must deal with cost reduction, improved design, optimal production time and the ability to diversify its business offer. The Product-Service paradigm is one of such approach to accomplish this task. It seeks to promote new vessel development that emphasizes service to stakeholders, while creating new market segments that can be targeted.

This paper presents a set of unique design methodologies, that leverage mature solutions, and innovative new Internet of Things (IoT) real time data feeds can work together in order to advance vessel sustainability (economic and environmental) and meet the changing economic and operational conditions of the marketplace. The combination of those components leads to the introduction of an innovative design framework able to address the lean development of eco-innovative vessels through a real time IoT data driven approach. The authors are exploring this novel design approach in the LINCOLN Lean Innovative Connected Vessels European Project (Commission, 2018). The aim of this paper is to present the foundations of the design framework. that were developed based on literature, grounding the overall research framework in of the research.

2. State of Art

This literature investigation focuses on how design in the maritime industry is managed and how the repositioning of vessel designs based on new market demands are being managed. Additionally, to cover the research purpose of including sustainability aspects and data driven design, it continues with the environmental dimension represented by LCC/LCA methods, Knowledge-based engineering Methodology (KbeML) and IoT in the maritime sector.

2.1. Overview of Vessel Design

Historically, new vessel designs have largely been based on existing designs with minor breakthrough innovations, bringing the industry forward. Vessel design is a complex, iterative and multifaceted process, influenced by a number of factors (both internal and external) (Vossen, Kleppe, & Randi, 2013). Depending on the vision or requirements set forth by the customer, designers are required to develop cost efficient vessels capable of performing specific tasks, while maintaining strict adherence to both international and national rules or regulations (Rebentisch et al., 2016).

However, finding the best balance within these restrictions is a challenge for the designer, engineer, system integrator, and the shipyard.

One of the most common vessel design processes is the spiral design process. The design spiral is a conceptual model of a process for maritime vessel design (Mistree, Smith, Bras, Allen, & Muster, 1990). The establishment of requirements is the first step of this process and is a fundamental starting point before entering the concept design phase, leading to preliminary power estimations, hull shape, and preliminary cost estimations (Christina, Senior, Kleppe, & Engineer, 2016; Erikstad, 2011; Gaspar, Ross, Rhodes, & Erikstad, 2012; Mistree et al., 1990; Schaffner, Ross, & Rhodes, 2014). Within each phase of the process, solutions become specific and options are set, culminating in a design ready for authorization. Incremental development and improvement have been developed and applied to maritime (Harvey, 1959; Mistree et al., 1990; Thanopoulou & Strandenes, 2017).

2.2. Lean Design in the Maritime Industry

Lean design is a growing area within engineering and manufacturing systems and increasingly relevant in the design and development of complex systems. Lean design involves all design activities dealing with the creation and generation of products and is an integral part of the overall product and process development phase (the phase of design, comes after the concept phase and does not include process planning required within manufacturing systems) (Rossi, Morgan, & Shook, 2017).

Academic publications on lean in shipbuilding are limited due to the novelty and the restriction of the concept, particularly related to the approaches being employed. However, process efficiency, delay rectification and cost control are all principal areas where work has been undertaken and measured improvement has been demonstrated (Koenig et al., 2002; St et al., 2001; Storch, Lim, Storch, & Lim, 1999). According to (Liker & Lamb, 2001) elements of lean can be found throughout the industry however there are few organizations that utilize lean principles in an organized manner.

The maritime industry has been working to advance vessel development approaches by focusing heavily on production time and quality (Koenig et al., 2002; Liker & Lamb, 2001; Milanovic, 2016; Radovic & Macclaren, 2004). A key difference between automotive companies that have adopted skills/approaches and methods from the Toyota and the maritime industry is that in general vessel design and development prohibits the utilization of assembly lines since vessels are designed and developed in limited or single cases. Features that characterize the shipbuilding industry focus primarily on the design and development of complex one-of-a-kind products (Longva, 2009; Salem, Solomon, Genaidy, & Minkarah, 2006). Lean vessel design and development is a very specialized field of lean and is seen as "one of the extensions beyond Lean Construction" (Dugnas & Uthaug, 2007).

2.3. Lifecycle Cost - Assessment

Life cycle thinking is not just a way to examine environmental impacts of activities, but also a way to comprehend and visualize a broader set of upstream and downstream consequences of decisions in development planning and implementation (Allaverdi, Herberg, & Lindemann, 2013). The Lifecycle Cost Assessment (LCA) includes the mapping of stakeholder involvement in both upstream and downstream processes, the designation of stakeholder roles, and identification of all resources and costs required for each aspect of the design (Thabrew, Wiek, & Ries, 2009).

Life Cycle Assessment is a structured, comprehensive and internationally standardised method (ISO 14044, 2008). It quantifies all the relevant emissions and resources consumed, both directly and indirectly, and the related environmental and health impacts and resource depletion issues that are associated with the entire life cycle of any goods or services (in general terms, of a product) (Fitzgerald & Ross, 2012; Luglietti, Rosa, Terzi, & Taisch, 2016). Life Cycle Assessment is a vital and powerful decision support tool, complementing other methods, which are necessary to help effectively and efficiently make consumption and production more sustainable (European Commission -- Joint Research Centre -- Institute for Environment and Sustainability, 2010). The LCA approach is called from cradle to grave because it considers the impacts from raw materials extraction to the disposal of waste. The approach may be extended "from cradle to cradle" if the closing of the loop with the material recovery and secondary raw material production has been considered (Boustead, 1996).

2.4. Knowledge-Based Engineering

Knowledge-Based Engineering (KBE) can be defined as the process of gathering, managing, and using engineering knowledge to automate the design process by usage of a so-called KBE system (Kulon, Broomhead, & Mynors, 2006; Prasad, 2005). KBE solutions allow to automate design and development steps or can be used for an automated detailing and examination of design variants and in consequence extensively support the optimization of a given (mechanical) design against defined constraints and requirements. Further, KBE can enable a broader variety of detailed design studies of a given master-concept by usage of a rule-based approach for an automated detailing and examination of design variants and in consequence extensively support the optimization of a given (mechanical) design against defined constraints and requirements (La Rocca & Van Tooren, 2007).

KBE reduces the time and cost required for the development of products and systems, thanks to captured and re-used product and process-related engineering knowledge as well as to the possibility to (partially) automate the belonging repetitive design tasks (Skarka, 2007; Verhagen, Bermell-Garcia, van Dijk, & Curran, 2012). As provided by (Stokes, 2001) timesaving – ranging from several hours to several days – can be achieved by KBE solutions.

Regarding commercial application in maritime, support from software providers for vessel design is rare. Though methods for the definition of hull forms, the steel structure as well as outfitting, like e.g. piping, are provided (Zimmermann, 2010).

2.5. IoT in Maritime

According to (Røstad & Henriksen, 2012) studies on the leisure boat market, boat industry lacks of data on how customers actually use their products. This results in a product design process based on experience (looking backwards) and input from certain customers or key persons, thus subjective to judgments. In the Internet era, 'things' are connected to the web (Vermesan et al., 2009) and information can come also from the Internet of Things capabilities to capture, transmit, analyze and reuse, in short and even in real time, product usage information, providing a huge time and quality advantage (Porter & Heppelmann, 2014).

In the maritime industry, the use of information in the design decision-making, deriving from integrated sensors, can be utilized to validate simulation models for boat hull behavior (von Stietencron, Hribernik, Røstad, Henriksen, & Thoben, 2017). In addition, Product Lifecycle Management (PLM) and Intelligent Maintenance concepts have been introduced, driving to Intelligent Products and Service Extensions for the marine sector (Terzi, Bouras, Dutta, Kiritsis, & Garetti, 2010). Further results have been exploited in the HOLONIX iCaptain commercial IoT solution, based on a market available black box, for the leisure boats sector (I-Captain, 2017).

3. Research Approach

The purpose of the research is to encompass challenges in maritime design by proposing a novel design approach able to address sustainability issues and highly efficient use and reuse of knowledge (either internal to companies or externally acquired through real time IoT or simulations).

To do this, the research approach starts with a literature review (as shown in Section 2) to develop a comprehensive foundation for addressing the different elements that go together in the development of the design approach suitable to meet the above discussed maritime industry design needs. Building on literature review, an empirical research has been conducted to delineate specific market needs as well as requirements a design approach should have to meet the research objectives in a way that is meaningful for the analysed industry, therefore three SME business cases operating in different maritime sectors have been selected as case studies to complement literature state of the art in the novel design framework development.

In each business case, interviews and on-site visits were undertaken to understand how the selected companies design maritime vessels and which unique, approaches, methodologies and tools could be developed. Through the identification of existing practices as well as the incorporation of best practices (identified through literature and based on internal or commercial data) a novel design approach was constructed to satisfy the unique needs and expectations of the maritime cases. From there, a comprehensive list of steps and sub-procedures are introduced into design process to improve efficiency and reduce waste within the cases. The overall novel design framework, where lean design approach plays a central role, is detailed in Section 4.

4. LINCOLN Vessels Design Approach

The LINCOLN approach will on one hand support vessel designers, shipbuilders, researchers and digital developers in their joint daily activities through a sustainable lean development methodology, on the other hand it will enable vessel operators to serve coastal activities more effectively also through the connection of the specialized vessels to an IoT platform. Based on the industry context analysis and business case needs, the overall novel framework for vessels design has been developed as composed of the following blocks:

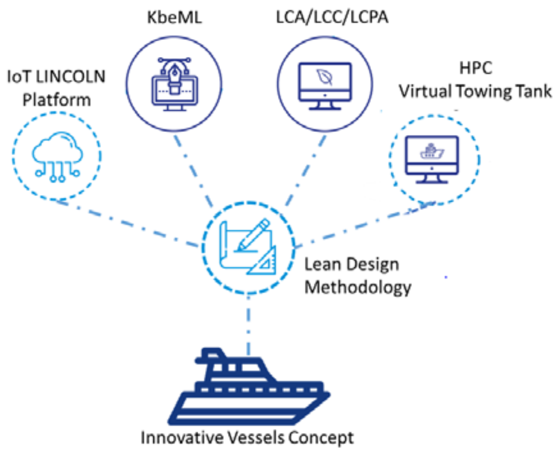

Figure 1: LINCOLN Vessel Design Approach

- IoT: a set of digital tools and IoT solutions needed to support specialized vessel design and operations, enabling, also SMEs, to record and manage tests data from prototypes and to provide services for their vessels through LINCOLN professional platform.
- KbeML: aims exactly at providing a formal approach for capturing required engineering knowledge enabling re-use of knowledge, monitoring of critical design parameters, and supporting design optimisation etc.
- High Performance Computing Virtual Towing Tank: a semi-automated virtual towing tank, based on HPC, where designers can simulate hull behaviour in different conditions, accelerating design choices.
- Lifecycle environmental and economic assessment supports sustainable vessel design through the evaluation of materials and technologies while reducing emissions, resources consumption and waste.
- Customizable Lean Design Methodology for Maritime: supports vessels design and development, and represents interlinked design aspects that are being introduced to SMEs in the maritime sector, to provide a lean solution to support the design phase.

LINCOLN aims to make it possible for designers and engineers to tailor the design methodology in order to leverage KbeML, LCA and automates knowledge transfer into other IT-Systems such as a CAD Application, and a

HPC environment, which uses real data to enhance the fluid dynamics simulations datasets. This closes the loop of information between vessel design and its operation phase, including information of real product usage into the design phase and also providing tools to support continuous improvement of the vessel through HPC based simulations (Røstad & Henriksen, 2012). This information can be used, through the integrated ability of the methods and technical quantitative tools provided in LINCOLN in the design phase, to continuously enhance the specialized vessels design. Through this backwards stream of information, designers can be aware of the strengths and issues of the vessels in their operative conditions that they usually don't know during the design phase. In the following sections the main elements introduced in Figure 1 are explained.

4.1. Customizable Lean Design Methodology

The maritime industry is one of the most recent industries that has been working to apply unique solutions capable of improving their development performances (Milanovic, 2016). To facilitate the optimization of this initiative, an evaluation of diffused strategies was undertaken to develop a Lean Transformation Framework (LTF), that incorporates Set-Based Concurrent Engineering (SBCE) and State of Art in the field to maximize value while minimizing waste and resources in a sustainable and environmentally conscious manner. The concept of LTF was first introduced by the Lean Enterprise Institute by John Shook to combat delays and complications being faced in adoption and implementation of lean in product (Shook, 2018). Focusing on the implementation of lean tools, approaches and methodologies, the roles of subsystems and independent components in the design and development process are assessed through a holistic approach that can be applied to every level of the development process by considering people, processes and technology (Morgan & Liker, 2006).

The Customizable Lean Design Methodology targets SMEs in the maritime vessel design and engineering sector, including those involved in LINCOLN as well others that are seeking to improve or implement elements of lean into their organization. The methodology offers a customizable set of tasks and steps that can be easily modified to facilitate the successful implementation of lean in various maritime design process or organizations. Through a systematic approach, established business needs, and high level methodological requirements identified within LINCOLN were utilized to frame the basis for how the methodology would behave and interact throughout implementation. The culmination of business needs considers the greater organization involved in vessel development.

The methodology is built upon organizational objectives and business case commitments to deliver and increase stakeholder value. Through a series of questions, rather than dictative steps, the LTF methodology for maritime focuses on obtaining support within the organization to promote a path for continuous improvement in the design process (Rossi, Taisch, & Terzi, 2012; Shook, 2018). The principal considerations of the methodology are based on Shook (2018) to address:

- Purpose: *What is the value for the stakeholder?*
- Process: *How can the industry/organization improve to better deliver the identified value?*
- People: *What skills, attributes, or characteristics are needed/required to engage in these processes to best deliver value to the stakeholder?*
- Leadership and Management: *What is the management system and leader behaviors utilized to achieve goals and objectives?*
- Basic thinking: *What considerations and values/goals will be used to guide the lean transformation of the organization? The set of foundational things such as how to carry oneself, "attitude"*

With respect to the selection of independent methods that were consolidated to create the LTF, they were identified based on their suitability to deliver skills or approaches based on the business needs and high-level requirements. The listed methods and practices focus on the outputs they can facilitate. The outputs adopted correspond to the five areas of organizational improvement related to the five LTF principles to distinguish how they could be best leveraged. Through this process, an easy-to-implement methodology was developed that allows businesses to adapt the methodology to satisfy their specific needs.

4.2. LCC/LCA LCPA Tool

The objective of the LCPA-Tool is to support a comprehensive decision-making process for design alternatives in the early design stage using a sustainability approach. This includes the following categories:

1) The economic viability of design alternatives will be assessed using the net present value (NPV) concept and the payback time as key performance indicators.
2) The environmental impact from construction, operating and recycling of different vessel designs will be evaluated using the global warming potential (GWP). The acidification potential (AP), the eutrophication potential (EP) and the release of particulate matter (PM 10) act as key performance indicators during ship operation.
3) The use of resources will be attributed using the Cumulative Energy Demand (CED) as a key performance indicator. This applies for the well to tank approach for fuels, the use of relevant materials for production and energy consumption on the shipyard for building and operating of the ship. This approach ensures that all energy consumption (including their related GHG-emissions) related for production of the fuels, relevant materials and on shipyard is considered. To increase the transparency of the cumulated energy demand, a split of fossil energy resources and renewable energy resource is preferred but could not be implemented in the current version of the LCPA-Tool due to time constraints and lack of information. In case of renewable bio-mass as feedstock for production of energy carriers, the land use as a resource is of significant influence but could also not be implemented due the same reason.
4) The societal impact of emissions from energy provision and conversion is well documented and commonly known as external costs (ExterneE,

NEEDS, UBA). To analyze the economic impact of emissions or to consider the effect of internalizing external costs in the LCPA-Tool, corresponding assumptions have been made for these external costs and can optionally be linked to the Net Present Value.

The LCPA-Tool will assess different designs against the baseline design. It can be stated that the quantitative prediction of values for KPIs is dependent on vessel type, operational profile, fuel type, technology employed and fuel prices. Trade-offs between the individual KPIs are expected and can be presented in a transparent way. Thus, the objective of the LCPA-Tool will support the decision-making process for design alternatives on a rational basis using sustainable design aspects.

4.3. KbeML

Knowledge Based Engineering can be defined as the process of gathering, managing, and using engineering knowledge to automate the design process by usage of a so-called KBE system (Kulon et al., 2006; Prasad, 2005). Through the development of a Knowledge based Modeling Language (KbeML), it can be used to facilitate the codification and representation of design & engineering knowledge in a graphical way and at the same time it enables an automated knowledge transfer into other IT-Systems such as a CAD Application, by its underlying formal XMI based syntax which can be parsed by applications. Main KbeML objectives are:

- Providence of a Neutral format (standard) to avoid the encapsulation of knowledge (rules & equations) in proprietary files or by proprietary applications,
- Capabilities which enable the post-processing of the modeled dependencies (e.g. documentation or simulation). This results in the requirement of having a semantic meaning behind the defined elements of the proposed notation,
- Visual representation of dependencies to support a common understanding amongst different domain specialists. This is based on the understanding that complex products & systems typically require interdisciplinary teams of different domain specialists,
- Enabling a Re-use of Engineering knowledge & avoidance to extract, codify and arrange knowledge in each development project repeatedly,
- Capability to represent product usage information and data in terms of sensors & sources.

4.4. HPC for Virtual Towing Tank

The high-level idea undergoing the development of the Virtual Towing Tank web application is to enable designers to simulate vessels hull more easily and at early design stages, in order to define more precisely reliable design solutions before moving to hull prototyping and to do towing tank analysis and seakeeping only on a very limited set of well selected concept designs (von Stietencron et al., 2017). To reach this point, an appropriate standardization of the input, output and of the computational tools must be defined. This workflow is firstly based on a-priori knowledge of the physics of the problem and then tailored to perform well on the 'average' case of interest of the given industrial partner. Different Computational Fluid Dynamics (CFD) templates are then obtainable customizing the default one to specific needs.

The expected benefit is to allow a 'designer user' to take advantage of complex state of the art CFD tools without the need to handle the inherent complexity. More precisely the 'designer user' will be able to handle in just a few mouse clicks a relevant set of key-parameters (KPARs) of the hull hydrodynamics including: resistance curve, attitude, hull pressure distribution, waves distribution, wetted surface area and any other derived quantities. This is a set of KPARs that match the typical towing tank session. Through the Virtual Towing Tank application these analyses can now be performed via a web browser in only a few hours.

4.5. Digitalization and IoT solution

The LINCOLN IoT platform enables transfer and storage real-life data for vessels and weather conditions including the ability to import data from other sources (like e.g. operating manuals, vessel build-info, etc.). The system also enables analyses of data and provision of answers to data enquires from users.

In this approach, the product information originating from any phase of the vessel lifecycle can be reused in another one, generating a closed-loop PLM. The installation of a modular data acquisition, called Marine Gateway (MG), and integration device for PLM purposes, the sensor digitalization system, connected to the IoT platform, introduces the Intelligent Vessel (Figure 3).

The vessel is the main source of data and information on itself through the on-board sensor digitalization platform. Boat and its equipment profile data and information are always available, searchable and updatable through the platform. The closed loop approach of the operational vessels data allow the shipyards to keep a close relationship with their customers. This ensures the maximum service efficiency and improves the design of next vessels generation. Customers and other value chain actors take fully advantages from the growing services offering. The overall vision of the above approach and prototypes was developed during the BOMA project ("Boat Management", 01.12.2011 - 30.11.2013, EU FP7).

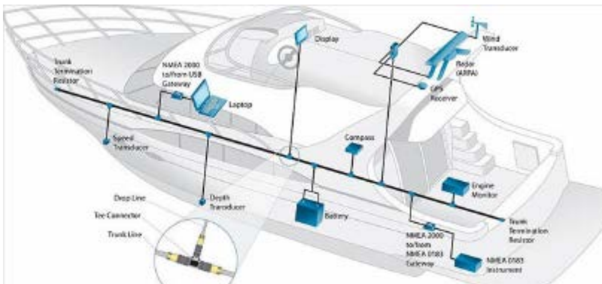

Figure 3: LINCOLN IoT Gateway

In LINCOLN platform also, data consumed by weather prediction algorithms are included and relayed directly to the designers and the vessels operators. To this a weather station is installed on board of a pilot vessel and it operates continuously, providing all the appropriate needed initial data. The weather application algorithm which is designed, developed and tested to provide wind speed (and in future wave height) forecasts including early warning for extreme wind potential (Georgoulas, Kolios, Karvelis, & Stylios, 2016; Karvelis, Kolios, Georgoulas, & Stylios, 2017; Kolios, Petsios, Loukadakis, & Stylios, 2015) is integrated with the MG on board of the vessels.

Major benefits from the development and the operational use of this system are:

- Provision of added-value to the IoT platform through real-time monitoring of meteorological parameters and early warning regarding extreme weather;
- Improvement of activities and services of vessels;
- Enhancement of safety in ports and vessel services.

5. Concluding Remarks

This paper sets the basis of a broader research, conducted within the LINCOLN Project, aiming to allow SME shipbuilders to take advantage of new tools and methods to increase stakeholder value. The aims of this research, as stated, originate in the needs identified within the maritime industry and literature to improve the design of specialized vessels in a sustainable, cost advantageous manner through specialized methodologies and tools. Different design options have been considered, to evaluate datasets coming from real-time data to gauge and select the best concept and improve the quality of the resulting vessel. This has successfully allowed the context of this research to include environment and real data, for better and higher quality and more efficient design.

Based on the developed methods and tools introduced in Section 4, the LINCOLN Design Approach is expected to give designers a complete view of the design process and to abridge the duration of its steps through the vessels lifecycle. This can then be measured through the developed IoT solution that integrates a unique platform through which the collected data and the Customizable Lean Design Methodology can leverage this knowledge for design optimization. To date, during vessel development the LINCOLN Design Approach has finalized the assessment and definition of functional and technical requirements. As well as have allowed for preliminary sea trials to be conducted based on the IoT platform to measure accuracy and data processing capabilities.

While work is ongoing, several benefits have been detected, specifically a faster pace for design variation of specialized vessels, and the transferring of improved design skills that support the development of customized and cost-effective vessels has been demonstrated.

After the development of the tools and methodologies, work will be undertaken to test and quantify the improvement levels facilitated by the LINCOLN Design Approach. Through implementation in the three business cases the methodology will be validated to confirm the objectives set forth in the project. This will allow for the ultimate determination if the methodology needs to be adjusted to better serve the purpose of supporting such a challenging industry.

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