25th National Congress on Maritime Transportation, Ship and Offshore Construction

Rio de Janeiro, Brazil. 10th at 12th November 2014

Towards a Complexity Metric for Ship and Offshore Structures

Prof. Jean-David Caprace, UFRJ/COPPE, Rio de Janeiro/Brazil, jdcaprace@oceanica.ufrj.br
Ing. Adrian Constantinescu, DN-T, Liège/Belgium, c.adrian@dn-t.be
Prof. Ionel Chirica, UGAL, Galati/Romania, Ionel.Chirica@ugal.ro
Prof. Philippe Rigo, ULG, Liège/Belgium, ph.rigo@ulg.ac.be

Abstract:

This paper introduces a complexity metric for ships and offshore structures. The goal is to provide the designers and managers with such information throughout the design process so that an efficient design is obtained at the first design run. Real-time assessment of complexity and quality measurements is rather imperative to ensure efficient and effective optimality search, and to allow real-time adjustment of requirements during the design. Application on a Handling Tug Supply boat (AHTS) show that the new method is effective in giving a complementary aid to decision process for ship designers.

1 - Introduction

”Simplicity is the ultimate sophistication”, attributed to Leonardo da Vinci (1452-1519).

”Simplicity is the soul of efficiency”, Richard Austin Freeman (1862-1943), Freeman (1911)

”If you can’t explain it to a six year old, you don’t understand it yourself”, attributed to Albert Einstein (1879-1955).

These quotes are showing how the simplicity, i.e. the opposite of complexity, is seen along the past centuries. Simple is beautiful. Complex is ugly. The more you have, the more you want and the more complex things get. People believe that big business needs to be complicated but it does not. We make it complicated ourselves because we think that this is what is needed for success. Big does not have to be complex. Often, small and simple is more powerful than big and complex. Racing into complexity is rarely the solution. We must be able to see the bigger picture, to focus on what really counts, what really brings results and what your real priority should be. Only then, once you know this, we can make things simpler.

This proposition finds also support in a compilation from Davies (2010) with the analysis of word frequency from a database of the English corpus containing over five million books. Although not all articles relate to engineering, the authors over many examples of how this quantitative analysis of culture can be used as evidence for scholars in many fields, reflecting the written dynamic of society through the last century quantitatively. Figure 1 presents a plot from this database, supporting this contention, with the frequency of words ”complex”, ”complexity” and ”complexes” in the English Corpus from the period 1810 through 2012. The corpus demonstrates that the frequency of these words is constantly increasing since the industrial revolution.

Figure 1: Frequency of words “complex”, ”complexity” and ”complexes” (word per million) in the English Corpus from the period 1810 through 2012, using data from Davies 2010

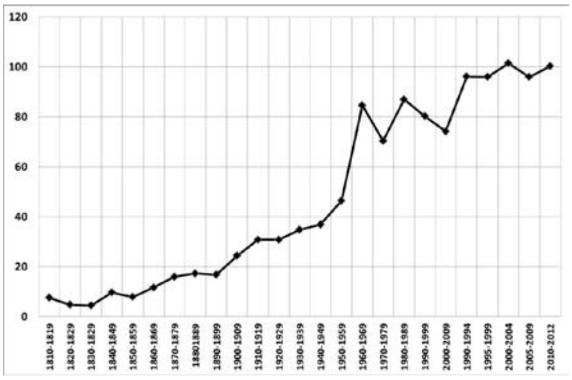


Figure 1 - Frequency of words “complex”, ”complexity” and “complexes” (word per million) in the

English Corpus from the period 1810 through 2012, using data from Davies 2010

2 - Background

Ship and offshore design was in the past more of an art than a science, highly dependent on experienced naval architects, with good backgrounds in various fundamental and specialized scientific and engineering subjects, alongside with practical experience. The design space (multitude of solutions for the design problem) was practically explored using heuristic methods, namely methods deriving from a process of trial and error often over the course of decades. Gradually, trial and error methods were more and more replaced by gained knowledge.

Today ship and offshore design can be viewed as an ad hoc process. It must be considered in the context of integration with other design development activities, such as production, costing, quality control, etc. In that context, it is possible for the designer to work on a difficult product, requiring high material or labor cost, and containing some design flaws that the production engineers have to correct or send back a new design before production. Any adjustment required after the design stage will result in a high penalty of extra time and cost. Deficiencies in the design of a ship will influence the succeeding stages of production and its operation. In addition, to design a ship which fulfils producibility requirements, it is also desirable to design a ship that satisfies risk, performance, cost, and customer requirements criteria. More recently, environmental concerns, safety, passenger comfort, and life-cycle issues are becoming essential parts of the current shipbuilding and offshore industry.

Is the shipbuilding industry the same as other manufacturing industries? The answer is definitely ”no”. However, many basic management principles hold for the different industries. In a broad sense, the organization is the same. Moreover, the mechanical process in ship construction is not so very different. We can find welding, electrical work, piping, woodwork and painting in other industries like the automobile industry, aeronautical industry as well as in the construction industry. Then how does shipbuilding management differ from these industries or any other ”repetitive” manufacturing? The difficulty of building a ship or an offshore structure is significant as it combines small series, short time to market, high complexity, bad working conditions, low standardization, confined space and bad accessibility, iterative design spiral loop, etc. These elements justify why it is not possible to directly apply the recent developments coming from other industries like automobile or airplane industry to the shipbuilding industry.

Nowadays productibility has become a major design attribute for shipbuilding industry. If a ship cannot be manufactured or assembled efficiently, it is not properly designed. To increase the productibility of ships, the scientific community and the shipyards have developed the concept of Design For Production (DFP) which can be defined as ”Design to reduce production costs to a minimum, compatible with the requirements of the vessel to fulfil its operational functions with acceptable safety, reliability and efficiency”.

DFP optimizes all the manufacturing functions (fabrication, assembly, test, procurement, delivery, service, repair, etc.) that reduce the production work content while still meeting the specified design requirements and quality. The goal is to include the impact of design decisions on the production process. Time pressures on commercial ship contracts result in the overlapping of phases of design development, procurement and production. This makes the impact of engineering changes more difficult to manage. There is a need to systematically study the detail design process and its impact on construction with the objective to improve the process and its integration with construction. DFP can significantly reduce the costs, since ships can be quickly assembled from fewer parts. Thus, ships are easier to build and assemble, in less time, with better quality. Designers will save time and money by the reduction of the production complexity.

Today, ship designers and shipyards use various CAD/CAM tools to aid in the design and production of ships. Nevertheless, none of these software’s are able to give real time information to the designer regarding the efficiency of his design in terms of production, operation, maintenance and life cycle costs. Indeed, cost assessment for ship CAD/CAM software developers is often considered as a tedious and time consuming task which is very specific and different for each shipyard. There is a need to systematically study the detail design process and its impact on construction with the objective to improve the process and its integration along the life periods of the product (construction, operation, disposal). The development of a complexity analysis must be viewed as a alternative to cost assessment which might be similar for all shipyards.

In many heavy industries such as shipbuilding industry an integrated approach and a unified measure of product complexity in a holistic way is still lacking. There is no doubt that a wider application of complexity assessment has an immense potential. Since different approaches use different measures for concept design evaluation (e.g. Design for Quality minimizes rework due to poor quality, while Design for Assembly cuts assembly time and Design for Operation cuts the operational inefficiencies) it is not clear how those diverse results can be judged and compared. In this context, there is an obvious need for holistic and unified views on design concept assessment.

3 - Needs addressed

The description and understanding of the complexity in the design stage remains an open problem in the shipbuilding industry, (Gaspar et al, 2012) and (Gaspar, 2013). In contrast with the relative simplicity involved by few degrees of freedom, the behavior of ships cannot be simply understood from knowledge about the behavior of their individual parts. Despite many years of research in this field (Alexiou et al., 2010), it is very hard to find a formal definition of a “complex system” in the literature. Complexity is a term normally used to describe a characteristic, which is hard to define and even harder to quantify precisely.

In general, complexity often tends to be used to characterize something with many parts in intricate arrangements, (Simon, 1962). Actually, in science there are various approaches to characterizing complexity, as diverse as they are different. We can take into account: engineering, IT technology, management, economy, arithmetic, statistics, data mining, life simulation, psychology, philosophy, information, linguistics, etc. This is just a small sample of the enormous diversity of considerations given to the concept of complexity. Many definitions tend to postulate or assume that complexity expresses a condition of numerous elements in a system and numerous forms of relationships among the elements, (Bonchev and Buck, 2005). At the same time, what is complex and what is simple is relative and changes with time.

In a series of observations about complex systems and the architecture of complexity, Simon (1996) highlights some common characteristics:

- Most complex systems contain a lot of redundancy.
- A complex system consists of many parts.
- There are many relationships/interactions among the parts.
- The complex systems can often be described with a hierarchy; redundant components can be grouped together and considered as integrated units (modularity - standardization).

A hierarchy is a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach the lowest level of the elementary subsystem. In their dynamics, hierarchies have a property, near decomposability, that greatly simplifies the description of a complex system, and makes it easier to understand how the information needed for the development or reproduction of the system can be stored in reasonable way.

In the everyday use of the word “complexity”, a part A may be considered more complex than B, if A is more difficult to design and to manufacture than B. This subjective measure of complexity is however not sufficient for engineering analysis.

Complexity has captured the interest of engineers for many years, and a lot of various definitions are given in the literature, Rodriguez et al. (2002). Nowadays, more and more systems and technologies contain an overwhelming complexity. This issue requires methods to break them down into a more understandable way, hence the need to define and measure complexity.

The shipbuilding is a worldwide industry, dominated by industrialized countries like South Korea, Japan and China. In this highly competitive sector, innovation is a key factor for success. Besides building highly complex structures, such as LNG, LPG, drilling ships, semi-submersible platforms, FP- SOs, OSVs, PSVs, AHTSs, etc., Brazilian shipyards are forced to increase their manufacturing efficiency in order to become competitive with low labor cost countries. A complexity metric is a way to reach this objective.

Various researchers have recognized the importance of objectively measuring complexity, as an aid to addressing the cause of such engineering and management related problems, Chryssolouris (1994), Little (1997) and Calinescu (2000). Industry has already attempted to measure complexity using empirical measures. The problem is that it results in a proliferation of possible measures, ElMaraghy (2012) and Milner and al. (2013): typically the number of items in the ship, analysis of production sequence and assemblies, etc. Having so many metrics induces problems. How do you know you are using the most appropriate ones or that you have sufficient accuracy? How can you tell if complexity is reduced if one measure falls but another rises?

4 - Objectives

As the complexity of ship and offshore structures increases, the Life Cycle Costs (LCC) of the ship will typically increase as well. Also, a complex ship is commonly the result of a lengthy and complicated, and therefore, costly design process. Furthermore, because of the interconnection of various components and sub-assemblies in a complex ship, the engineering change process is often a complex and cumbersome task. Next, the manufacturing of a complex ship entails adaptation of complex process plans and sophisticated manufacturing tools and technologies. Additionally, a complex ship result in a complex supply chain which introduces various managerial and logistic problems. Finally, serviceability in a complex ship is a challenging issue due as well to the existence of numerous failure modes with multiple effects having varying levels of predictability.

Therefore, it is beneficial to objectively measure the complexity of the design of ships and offshore structures in order to remove the non-cost-effective details. The complexity measure of a design will guide the designer in creating a product with the most cost effective balance of manufacturing and assembly difficulties. In terms of the manufacturing processes of ships, assembly costs and quality of the end product, complexity plays a vital role in the achievement of the best design. Unfortunately, little has been achieved in the area of complexity metrics that can be used in a useful way. One survey by Tang and Salminen (2001) shows that from a series of studies devoted to complexity, only 20% have attempted to produce some sort of quantification, thus considerable further research is required to make complexity a practically useful concept.

The outlook of this paper is the development of the means to quantify the complexity of ship and offshore structures and the definition of measures to be used in conjunction with other metrics such as the assessment of production, operation, logistic and maintenance efficiency. Complexity is not defined in a quantifiable manner by the authors cited here, and thus considerable further research is required to make complexity a practical useful concept for shipbuilding industry.

The overall driving force of the study is to integrate ship design model with complexity assessment including all conception and design parameters to explore most of the design alternatives in the early stage of the design process. The proposed innovation is to provide the designer with a powerful methodology and efficient models, which allow real-time monitoring of the future performance of the vessel, so that designers can evaluate different design alternatives and choose the best one.

5 - The complexity model

This paper explores the relationships between several complexity factors for both ship and offshore structures. Developments have been focused on structures (i.e. mainly steel parts) and outfitting (only piping parts and not electrical systems, HVAC, etc.).

The overall design complexity were considered here as a combination of the compactness complexity, the assembly complexity, the material complexity and the shape complexity:

- Compactness complexity – C_{cp} – Ability to perform the manufacturing of individual parts of the products. It is very common to say: "The more there are components in a product the simpler are the individual parts". The opposite is also available: "The less there are components in a product the more complex are the individual parts".
- Assembly, sequence, process complexity – C_{as} – Ability to easily assemble the components of a product. It is very common to say: "The more there are components in a product the more the product is complex to assemble".
- Shape complexity – C_{sh} – Ability to perform bending of plates and stiffeners with complex shapes such as double and simple curvatures.
- Material complexity – C_{mt} – Ability to use different types of material in a product. It is very common to say: "The more there are materials in a product the more the product is complex".

The model is given in equation 1, where C_T represents the total complexity or aggregated complexity and $w_1, \ldots, w_i$ represents numerical constants called weighting factors.

$$C_T = \frac{w_1 C_{cp} + w_2 C_{as} + w_3 C_{mt} + w_4 C_{sh}}{w_1 + w_2 + w_3 + w_4} \qquad (1)$$

We proposed to calibrate the weighting factors of equation 1 by using the minimization of the linear correlation coefficient between the total complexity and the production time of each ship block. Calculation and validation of the weighting factors were performed on a real passenger ship in Caprace and Rigo (2013). The results demonstrated the efficiency of the methodology.

Nevertheless, in this paper the results are presented using unitary weighting coefficient because the production times were not available for the presented test case.

Compactness complexity – C_{cp}

The shape complexity, sometimes called shape factor or compactness is a numerical quantity representing the degree to which a shape is compact. In this study, we assume that the more a steel part has a complex shape (not compact) the more it is difficult to manufacture.

In the literature, various compactness measures are used for 2D shapes and 3D solids, Valentan et al., (2008). These classical measurements of shape complexity for 3D solids relates in large part to the enclosing surface area and the volume while for 2D shape it relates in large part to the perimeter and the surface area.

The most common shape complexity measurements for 3D shapes is the sphericity (see equation 2), defined by Hakon (1935), is the ratio of the lateral surface of a sphere (with the same volume as the given solid) to the surface area of a 3D solid. This ratio is maximum (= 1) for a sphere and minimum (= 0) for an infinitely long and narrow shape.

$$\psi = \frac{A_S}{A} = \frac{\pi^{1/3}(6V)^{2/3}}{A} \tag{2}$$

where	ψ	is the sphericity,
	A	is the lateral surface of the solid,
	A_s	is the lateral surface of the sphere,
	V	is the volume of the solid.

Finally, shape complexity C_{sh} can be determined for each individual steel component of the ship with equation 3. The average shape complexity of a set of parts such as a ship assembly can be evaluated with equation 4.

$$C_{cp} = 1 - \psi \tag{3}$$

$$C_{cp} = \frac{\sum_{i=1}^{n} (1 - \psi_n)}{n} \tag{4}$$

where	C_{cp}	is the shape complexity,
	ψ	is the sphericity,
	n	is the number of part inside the assembly.

Assembly complexity – C_{as}

Measuring the assembly complexity in a ship structure represents the measurement of the level of the diversity and the interconnectedness of the parts. The more there is variability in the design parameters, the more complex the design becomes. A ship with modular architecture, in which sub-systems have fewer functional interdependencies, should have lower coupling complexity than a ship with integral architecture. It should be noted that high performance is not necessarily a result of complexity. In other words, increased interdependence of various modules and assemblies in the ship is not necessarily translated into improved ship performance.

The method used to establish a quantitative measure of assembly complexity in this research is based on the definition of the complexity of hierarchical systems provided by Ceccatto (1988) and reviewed recently by Shannon (2001), Equation 5 gives the formulation of the assembly complexity.

$$C_{as} = C\left[\bigcup_{i=1}^{n} T_i\right] = \sum_{i=1}^{n} C(T_i) + N_T \log_2(2^{k_T} - 1) \tag{5}$$

where	$C_{as} = C\left[\bigcup_{i=1}^{n} T_i\right]$	is the assembly complexity of a forest composed of n non-isomorphic trees,
	$\sum_{i=1}^{n} C(T_i)$	is the complexity of the n non-isomorphic subtrees,
	N_T	is the number of elements at the lower level of the tree,
	k_T	is the number of branches non-

isomorphic.

Material complexity – C_{mt}

Considering the stiffened structure of ships, the material complexity has been defined for an assembly by equation 6.

- For the plates C_{pt} – the material complexity is the number of the different combinations between plate thickness and material type. For instance, an assembly containing 10 steel plates of 20 mm, 5 aluminum plates of 20 mm and 3 steel plates of 15 mm, the complexity will be equal to 3.
- For the stiffeners C_{st} – the material complexity is the number of the different combinations between profile types, profile scantling and material types. For instance for an assembly containing 35 steel bulb profiles of 100×6 mm, 10 steel bulb profiles of 100×8 mm and 5 aluminum bulb profiles of 100×8 mm, the complexity will be equal to 3.
- For pipes C_{pi} – the material complexity is the number of combinations between nominal diameter, pipe thickness and material types.

$$C_{mt} = C_{pt} + C_{st} + C_{pi} \tag{6}$$

Shape complexity – C_{sh}

The construction of ships obviously involves a large number of steel plates and shapes which form the hull surface panels. These plates and shapes need to be formed so that the hull shape can be developed.

The forming complexity depends largely of the curvature of the plates, Parsons et al. (1999). Two parameters have been used to classify the forming of the hull plates: the Gaussian curvature *K* and the ratio between the two principal curvatures *R*. The Gaussian curvature is defined as the product of the two principal curvatures (see equation 7) while *R* is defined as the ratio between the two principal curvatures (see equation 8).

$$K = k_1 \times k_2 \tag{7}$$

$$R = {}^{k_1}\!/_{k_2} \tag{8}$$

Firstly, if the Gaussian curvature is positive, which means k_1 and $k_2 > 0$ or k_1 and $k_2 < 0$, the shape of the surface is either convex or concave. Where *K* is zero, the surface is ruled, developable or planar. In a planar surface, both k_1 and k_2 are zero; while in a ruled surface, either k_1 or k_2 is zero. Where K is negative, the shape of the surface is saddle-shaped involving reverse or opposite curvature in two directions.

Secondly, if the ratio *R* between the two principal curvatures is low, it means that a double curvature is involved, while when the *R* is high it means a curvature in only one direction is involved.

The curvature can be evaluated both on the centroid of the plate (for low accuracy measure) or on 225 points (grid of 15x15) for each hull plate. Later, the average of the values can be evaluated to classify the forming complexity of the plates. Table 1 gives the different values of the curvature coefficient in function of the values of the Gaussian curvature *K* and the ratio between the principal curvatures *R*.

Table 1 - Values of the curvature coefficient c

		R	
		High	Low
		One direction	*Double Curvature*
K	High	2	7
	Moderate	1	5
	Low	0	0
	Moderate reverse	1	8
	High reverse	2	11

Shape complexity is given by equation 9 where *c* represents the curvature coefficient given in Table 1 and *n* the number of analyzed points of each steel plates. It should be noted that the shape complexity only have been assessed for curve plates parts.

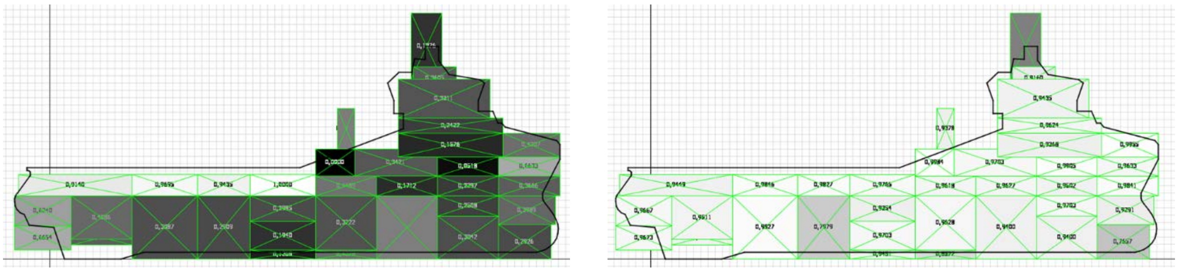
$$C_{sh} = \frac{1}{n}\sum_{i=1}^{n} c_i \tag{9}$$

6 - Case study

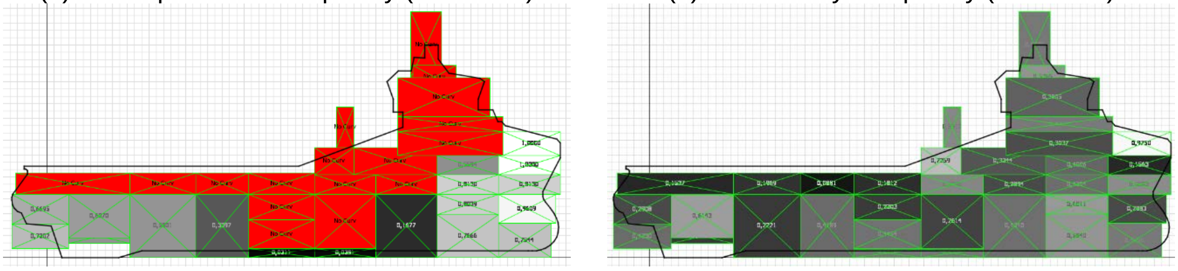
Complexity model has been applied to an Anchor Handling Tug Supply boat (AHTS) of 75 meters length that has been divided in 83 blocks for the construction. Table 2 presents the quantity of structural and outfitting entities that were considered for the study.

Table 2 – Quantity of structural entities

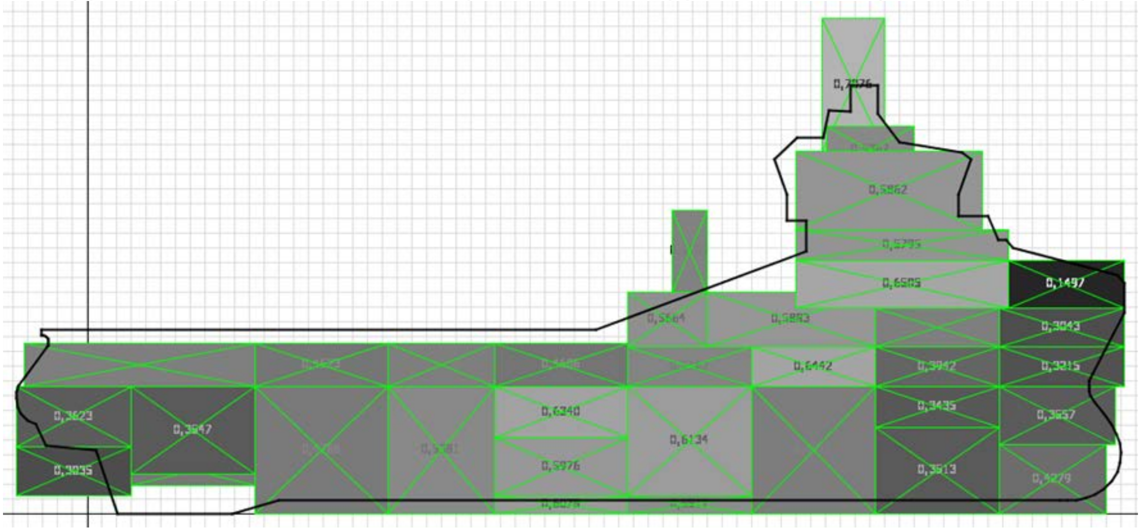
Entities	Quantity
Plates	16889
Profiles	5831
Stiffeners	6748
Pipes and accessories	1332
Assemblies	5037
Blocks	83



(a) – Compactness complexity (starboard) (b) – Assembly complexity (starboard)



(c) – Shape complexity (starboard) (d) – Material complexity (starboard)



(e) – Total aggregated complexity (starboard)

Figure 2 – Complexity factors of an Anchor Handling Tug Supply boat. Black color represent high complexity while white color represent a low complexity value. Only starboard blocks are represented.

The main outcome of the test case is presented in Figure 2 where we can see the relative complexities of each ship block at starboard, i.e. the compactness, the assembly, the shape and the material complexity as well as the aggregated total complexity. The darker the block are, the higher the complexity.

By analyzing the figures, it is interesting to note that the high complexity is generally located in the bottom part of the ship as well as in the fore and aft part whereas the ship hull has a big curvature. Nevertheless, other areas of the ship do not have uniform complexity. Some blocks are much more complex than others. We can mention here for instance that:

- The highest compactness complexity appear on the block where the main towing winches are installed
- The superstructure parts presents a higher compactness complexity mean

- There is dissymmetry's between starboard and portside blocks complexity of the ship explained by the installation of specific equipment's such as crane
- The upper deck blocks are presenting high material complexity which means that standardization could be improved
- Assembly's complexities as shown various inconsistencies of the assembly planning of the ship. For instance, one specific block presented an assembly complexity 10 times higher that the average (outlier) which should lead to a modification of the design

The managers can define an upper and a lower complexity limit for each type of block in order to control the design. Moreover, the composition of the complexity metric with the four factors can orient the designer to revise the appropriate design variables in order to reduce the global complexity of the ship during the design phase. By arranging the structural details and outfitting parts of a ship in a way that enhances the modularity of steel components, standardizing the scantling and simplifying the shape of the components, it is possible to eliminate unnecessary welding's, lengths of piping, ventilation ducting, and many other sources of production and maintenance cost. All of these efforts will result in a reduction of man-hours, material cost and construction time, resulting in a reduction in recurring construction costs.

Experience has shown that structural detailed arrangements that were made during the early stages of design were often carried through detail design without any attempt at optimization. The system deals with the geometric details of the design and highlights the relative complexities of ship sections. It quickly provides measurements of complexity but not yet in real-time. Therefore, it is particularly suitable in design, where fast response to design modifications is quite imperative for the search of optimality.

7 - Conclusions

Systematic and objective analysis of complexity in ship and offshore industry is important for several reasons. First, it helps design engineers to develop a better understanding of various aspects of complexity and thereby evolve toward simpler design solutions. Second, it enables design automation tools to systematically assess different design alternatives based on their inherent complexities.

These methodologies will provide:

- an aid for designers and managers in order to compare various design alternatives on the basis of complexity,
- an environment which supports strategic decisions made as early as possible to make ship and offshore structures more cost-effective,
- a monitoring of the sources of complexity which helps to determine the consequences of decision making early on during the design process,
- a spotting of the sources of complexity which helps to reduce ”design effort”, that is, shortening production time and cutting project costs.

Fundamentally, these methods will provide design engineers with objective, quantifiable measures of complexity, aiding rational design decision making.

The measures proposed are objective as they are dependent not on an engineer's interpretation of information, but rather on the model generated to represent the ship and offshore structures. This objectivity is essential to using the complexity measures in design automation systems. A prospective computer-aided system should also be capable of assisting innovative design. It should not just provide a limited series of conventional solutions. To this end, design engineers should be provided with well-defined and unambiguous metrics for the measurement of different types of complexities in engineered artefacts. Such metrics aid designers and design automation tools in objective and quantitative comparisons of alternative design solutions, cost estimation, as well as design optimization.

8 - Future work

As an important part of shipbuilding, outfitting refers to the process of fabrication and installation of non-structural components, including the main propulsion system, pumps and piping systems, electrical system, air conditioning, etc. In many instances and especially for offshore structures, outfitting represents as much as 50% of the cost of the ship and also as much as 50% ship construction time. However, as a result of the disturbances by unexpected delays, system variations, capacity limitations, and technological constraints, scheduling of outfitting processes is very complex and can delay the entire ship production system.

Therefore, next development will focus the improvement of the outfitting complexity assessment considering not only piping but also electrical systems, HVAC, specific offshore equipment's, etc.

9 - References

ALEXIOU, KATERINA, JOHNSON, JEFFREY, AND ZAMENOPOULOS, THEODORE. Embracing Complexity in Design. Taylor & Francis, 2010.

BONCHEV, DANAIL AND BUCK, GREGORY A. Quantitative measures of network complexity. In Danail Bonchev and Dennis H. Rouvray, editors, Complexity in Chemistry, Biology, and Ecology, pages 191–235. Springer US, 2005.

CALINESCU, A., EFSTATHIOU, J., SIVADASAN, S., SCHIRN, J. AND H. L. HUACCHO. Complexity in Manufacturing: An Information Theoretic Approach. Conference on Complexity and Complex Systems in Industry, pages 19–20, 2000. University of Warwick, UK.

CAPRACE, J.-D. AND RIGO, P. A Real-Time Assessment of the Ship Design Complexity. Computer-Aided Design, 44(3):203–208, 2012.

CECCATTO, H. A. The Complexity of Hierarchical Systems. Physica Scripta, 37:145–150, 1988.

CHRYSSOLOURIS, G. Measuring complexity in manufacturing systems. Technical report, University of Patras 26110 Greece, 1994.

DAVIES, M. The corpus of contemporary American English as the first reliable monitor corpus of English. Literary and Linguistic Computing, 25 (4):447 - 464, 2010.

ELMARAGHY, WAGUIH, ELMARAGHY, HODA, TOMIYAMA, TETSUO AND MONOSTORI, LASZLO. Complexity in engineering design and manufacturing. Annals - Manufacturing Technology, 61(2):793 – 814, 2012.

FREEMAN, RICHARD AUSTIN. The Eye of Osiris. 1911.

GASPAR, HENRIQUE M., RHODES, DONNA H., ROSS, ADAM M. AND ERIKSTAD, STEIN OVE. Addressing complexity aspects in conceptual ship design: A systems engineering approach. Journal of Ship Production and Design, 28(4): 145-159, 2012.

GASPAR, HENRIQUE M. Handling Aspects of Complexity in Conceptual Ship Design. PhD thesis, NTNU, 2013.

HAKON, WADELL. Volume, Shape and Roundness of Quartz Particles. Journal of Geology, 43:250–280, 1935.

LITTLE, G., TUTTLE, D., CLARK, D. E. R., AND CORNEY, J. A. Feature complexity index. Proceedings of Institution of Mechanical Engineers, 212:405–412, 1997. Proceedings of Institution of Mechanical Engineers.

MILNER, TYLER, VOLAS, MICHAEL AND SANDERS, ALBERT. Systems engineering methodology for linking requirements to design complexity and manufacturing trade space constraints. Procedia Computer Science, 16(0):947 - 956, 2013.

PARSONS, M., JONG-HO, N., AND SINGER, D., A Scalar Metric for Assessing the Producibility of a Hull Form in Early Design. Jounal of Ship Production, Vol.15, No.2, pp.91-102, 1999

RODRIGUEZ TORO, C., TATE, S., JARED, G. AND SWIFT, K. Shaping the Complexity of a Design. IMECE2002, page 8, November 2002.

SHANNON, C. E. A mathematical theory of communication. SIGMOBILE Mob. Comput. Comun. Rev., 5(1): 3–55, January 2001.

SIMON, HERBERT A. The architecture of complexity. In Proceeding of the American Philosophical Society, volume 106, pages 467-482, December 1962.

SIMON, HERBERT A. The Sciences of the Artificial. Mass.: MIT Press, Cambridge, 1996.

TANG, V. AND SALMINEN, V. Towards a Theory of Complicatedness: Frame- work for Complex Systems Analysis and Design. 13th International Conference on Engineering Design, page 8, Augustus 2001.

VALENTAN, J., BRAJLIH, T., DRSTVENSEK, I., AND BALIC, J. Basic Solutions on Shape Complexity Evaluation of STL Data. Journal of Achievements in Materials and Manufacturing Engineering, 26, January 2008.