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A Complexity Metric for Practical Ship Design

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Abstract

The paper introduces an innovative complexity metric for practical ship design taking into account the shape complexity of steel parts, the assembly complexity of steel components and the material complexity of the structure. The goal is to provide the designer 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 and validation on a real passenger ship show that the new method is effective in giving a complementary aid to decision process for ship designers.

Keywords

Design complexity; Cost assessment; Shipbuilding; Cruise vessel; Passenger ship; Design optimization.

Introduction

Ship design was in the past more of an art than science, highly dependent on experienced naval architects, with good backgrounds in various fundamental and specialized scientific and engineering subjects, alongside with practical experience (Papanikolaou et al., 2009). 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 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 labour 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 (Olcer et al., 2004). Deficiencies in the design of a ship will influence the succeeding stages of production. In addition to designing a ship that 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 industry.

Design for production

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 (Ou-Yang et al., 1997). To increase the productibility of ships, the scientific community and shipyards has 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 fulfill 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 (Moyst et al., 2005). 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* (Caprace, 2010). Complex designs are more fragile and lead to more surprises which are always bad. Complexity leads to longer development schedules; it directly causes design errata; it fosters suboptimal tradeoffs between competing goals; it makes follow-on designs much more difficult; and it is cumulative, with new designs inheriting all of the complexity of the old and with new complications layered on top (Colwell, 2005).

Objectives

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) 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.

As consequences of these lacks, methods and tools connecting technical design parameters to production performance, allowing technical experts to quickly assess the impact of design options and parameters on the overall ship performance are obviously needed.

The key issue of the paper is to provide at the designer an new innovative model to reliably estimate and verify the complexity of different design concepts at different stages of product development. With the aid of computers it is now possible to study a large number of varying design parameters and to arrive at a ship design which is not only technically feasible but, more importantly, is the most economically efficient in term of production.

Limitations

The main obstacle to this approach is the lack of friendly reliable complexity and quality performance models that can be integrated into a complex design process as used in the shipbuilding industry. Traditional models and analysis methods frequently do not provide the required sensitivity to consider all the important variables impacting performance, cost, production, and ship life cycle.

Industry has already attempted to measure complexity using empirical measures. The problem is that this results in a proliferation of possible measures: typical examples include the number of items in the ship, analysis of production sequence and assemblies, etc. Having so many metrics offers 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 bring reduced if one measure falls but another rises?

Paradigm

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 et al. (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.

Therefore, it is beneficial to objectively measure the complexity of design ships in order to systematically reduce their inessential details. This complexity measure of a design should be able to guide the designer in creating a product with the most cost effective balance of manufacturing and assembly difficulty. The goal is to provide the designer with such information throughout the design process so that an efficient design is produced in the first instance.

The overall driving force of the project 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 a powerful methodology and efficient models, which allows real-time monitoring of the future performance of the vessel, so that it can evaluate different design alternatives and choose the best one.

How to define complexity?

The description and understanding of the complexity in the design stage remains an open problem in the shipbuilding industry. 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, 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 usage, 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.

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 contains 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

Complexity has captured the interest of engineers for many years, and a lot of various definitions are given in the literature (Rodriguez et al., 2003). 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.

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 et al., 1997; Calinescu et al., 2000). Our first objective is to decide what complexity is. Then a model of how to measure it can be produced.

Definition of a practical design complexity

Designing is a heterogeneous, fuzzily defined, floating field of various activities and chunks of ideas and knowledge. Therefore, design is a complex process (Jonas et al., 2004). This complexity stems from time varying design requirements and the voluminous solution spaces to be explored. Detailed design requirements generally include requirements for design quality measurement. Systematic assessment of such qualities is a traditional bottleneck in design, in particular for the shipbuilding industry. Assessment of such qualities is imperative to evaluate the satisfaction of design requirements, which is an essential component in design optimization. Satisfaction assessment guides the search for optimal design solutions. Real-time provision of complexity and quality measurements are quite imperative to ensure efficient and effective optimality research, and to allow real-time adjustment of requirements during the design.

Some decisions taken at the early design stages often fail to deliver outputs that meet the expectation of customers (Austin et al., 2002). These failings are attributed to a lack of understanding of complexity and can result in a number of costly changes and even to a redesign. It has been suggested that to reach a better understanding of a project, its complexities should be measured so that new approaches can be developed to systematically reducing complexity (Chryssolouris et al., 1994).

Complexity implies time, quality, cost, performance, etc. Several factors that will influence product complexity have been identified such as the number of components, the number of interactions/ connections, the number of assembly operations, the number of subassemblies, the number of branches in the hierarchy, the number of precedence levels in the hierarchy, the type of interactions/connections, the properties of interactions/ connections, the type of components, geometry, shape, material, production process, size, density, accessibility, weight, etc.

Our research explores the relationships between these complexity factors. The overall design complexity has been considered here as a combination of the shape complexity, the assembly complexity and the material complexity:

- Shape, manufacturing complexity – C_{sh} – 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”.
- 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 following model is given in equation 1, where C_T represents the total complexity and $w_1, \dots, w_i$ represents numerical constants called weighting factors.

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

Shape complexity – C_{sh}

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 (Bribiesca, 2000; Bribiesca, 2008; Haralick, 1991; Youssry, 1982; 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.

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

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.

$$C_{sh} = 1 - \psi \qquad (3)$$

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

where	C_{sh}	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). Equation 5 gives the formulation of the assembly complexity.

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

where	$C_a = C\left[\bigcup_{i=1}^{n} T_i\right]$	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 sub-trees,
	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.

$$C_{mt} = C_{pt} + C_{st} \qquad (6)$$

Application

To investigate the relative complexities of the structural parts of a ship (i.e. steel structure), ten different passenger ships built in European shipyards were selected for the purpose of the experiment. The average number of individual steel components is about 200 000 per ship. The study has focused on the complexity analysis of the 3500 structural sections (small blocks), each one containing about 500 individual steel components. The complexity value was determined by the equation 1 which takes into account the 3 complexity components detailed above: the *shape complexity*, the *assembly complexity* and the *material complexity*. Currently, these measures are calculated automatically but not yet in real time. Nevertheless an automated system can be developed to compute the complexities using a machine-interpretable model in the CAD/CAM model.

The weighting factors of equation 1 have been evaluated through a minimization of the linear correlation coefficient r_{xy}^2 between the total complexity and the production work of ship sections (see equation 7). A simple gradient descent optimization algorithm was used here. The r^2 linear coefficient went from 0.7102 to 0.7557 which represents a gain of 6%. Fig. 1 represents the dot clouds diagram of the optimized linear correlation between the total complexity and the production time.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)S_x S_y} \qquad (7)$$

The main outcome of the test case is presented in Fig. 2 where we can see the relative complexities of each ship section i.e. the shape complexity, the assembly complexity, the material complexity as well as the global complexity evaluated thanks to equation 1. 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 don't have uniform complexity. Some sections are much more complex than others. We can mention here for instance that the complexity of the three access tower for passenger with lifts and stairs appear very well in Fig. 2 (b).

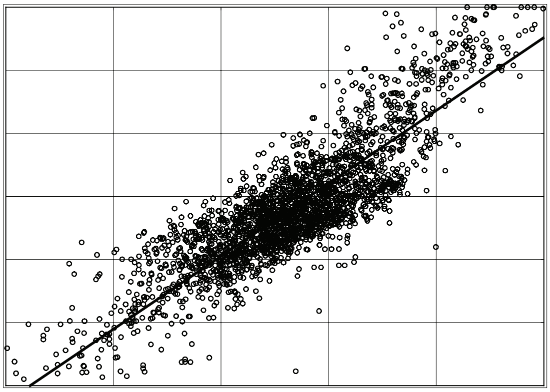
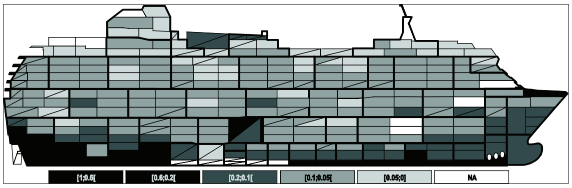
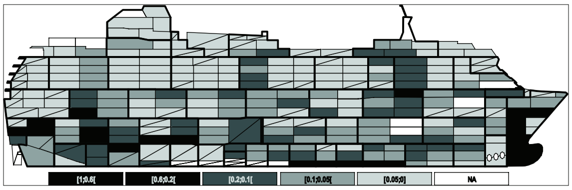


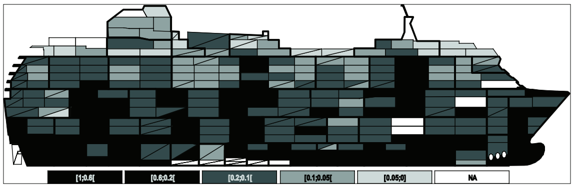
Fig. 1: Diagram of the total complexity versus the production time ($r^2 = 0.7557$)



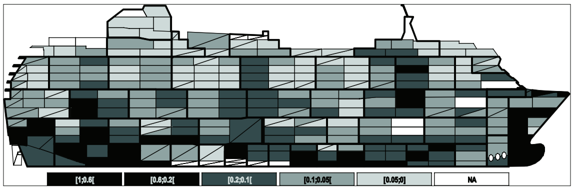
(a) 3D shape complexity



(b) Assembly complexity



(c) Material complexity



(d) Global complexity

Fig. 2: Complexity of a passenger ship

An upper and a lower complexity limit for each type of section can be defined by the managers to control the design. Moreover the composition of the complexity index with the three factors i.e. shape complexity, the assembly complexity and the material complexity, can direct 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 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 weldings, 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 (Wilkins, 1993) 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.

Conclusion

Discussion

Complexity can be seen as a critical problem in design that is needed to be reduced as much as possible. For example, complexity is associated with the difficulty of solving design problems, the combinatorial size of the search space, and the variety of the generated designs. Notably, the complexity of solving design problems occurs not only because these problems are often intractable, ill-defined or ill-understood, but also because they involve many different participants, with many different goals and needs.

In order to solve these problem, different kinds of ship design complexity were investigated and a complexity metrics based on shape, assembly and material complexity were put forwards. To validate the proposed measures, the production efforts of a set of passenger ship sections were compared to the complexity value. A significant correlation was obtained that means that the relation between complexity and design was successfully implemented.

The complexity measurement is an imperative basis for systematic optimality search, which is the essential process in design. The definition and the control of the upper limit of this metric will provide a good management tool to improve the overall design performance of ships. Thus, the real art of engineering, which is the assessment of a proposed design from every angle and vantage point to make sure a design will achieve its goals and prove reliable over its intended lifespan, can be more easily reached.

We are well aware of the risk of creating a model that is mathematically viable but may not reflect reality because of the quantity of assumptions made during the design process. The idea, nevertheless, is to define a model to make the complexity more approachable and, perhaps, even practical. Nobody has ever succeeded in giving a definition of the complexity which is meaningful enough to enable one to measure exactly how complex a system is. Ships cannot and should not be reduced to one single complexity measure. A ship is not only the end result but is also an entire system of manufacturing, transport and economic evolution. Complexity should be seen as a decision tool aid.

Why not just simplify everything?

Why not just make everything simple? As Einstein said, everything should be as simple as possible, but no simpler. To achieve some end, certain physical systems must have a minimum amount of complexity. No isolated pieces of that system are very useful themselves, but taken as a whole, they could achieve something very useful indeed. It is the basic notion of irreducible complexity. The measure and control of complexity is then a way to reach the irreducible complexity of systems.

A designs complexity must serve projects major goals. If your design is complicated but coherent, challenging but understandable, you may have struck a good balance between irreducible complexity and the projects goals (Colwell, 2005).

Future work

The previous research studies have been limited to:

- a ship's structure (i.e. mainly steel parts and not outfitting);
- complexity assessment during the production of ships (i.e. not on maintenance complexity, dismantling complexity, etc.);
- large passenger ships.

These limitations might prevent an extensive use of the methodology. Additional researches and developments are thus required to overcome these limitations.

The present research proposes to extent the previous developments with the following points.

The improvement of the methodology to take into account simultaneously of the complexity of steel structure as well as the outfitting components (HVAC, pipes, electrical cables, etc.) is vital. At the moment, European shipyards mainly produce ships with high added value because the less complex vessels are usually produced in Asia where labor is cheaper. In this type of ships, equipment (cables, plumbing, ventilation pipes, siding, furniture, etc.) and the associated work of setting up represent a significant portion of the total price of the vessel. For example, 80% of the price of a cruise ship is related to the equipment. It therefore seems necessary to include these elements inside the actual developed tools.

The development of complexity assessment method to take into account the dismantling of ship during their design is essential. There are limited studies and strategies with regards to whole cycle of dismantling and recycling in terms of optimum and sustainable dismantling and recycling procedures/model. Such model should indicate cost effectiveness, energy efficiency, environmental and human safety as well as supporting industry to properly recycle, re-use and dispose waste materials. Introduction of disposal complexity assessment coupled with the real industrial players will provide the necessary expertise to develop such a key design performance indicators that does not exist actually.

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