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A real-time assessment of the ship design complexity

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ABSTRACT

The paper introduces an innovative complexity metric for passenger ships taking into account the shape complexity of steel parts, the assembly complexity and the material complexity. 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.

1. Introduction

1.1. 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 behaviour of ships cannot be simply understood from knowledge about the behaviour 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 [1]. 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, [2] 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.

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 [3]. 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.

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

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sufficient accuracy? How can you tell if complexity is bring reduced if one measure falls but another rises?

Various researchers have recognised the importance of objectively measuring complexity, as an aid to addressing the cause of such engineering and management related problems [4–6]. Our first objective is to decide what complexity is. Then a model of how to measure it can be produced.

1.2. Different kind of complexities

According to the literature, design complexity is generally divided into two topics: the shape or topology complexity and the assembly complexity.

Shape or topology complexity. In applications such as Finite Element Modelling (FEM), the mesh generation is defined in terms of polygons which determine the polygonal face of the mesh. The notion of shape complexity is important to measure how oblong a polygon is in order to measure the mesh's quality. Several algorithms for triangulation of the mesh have been used and, in some of them, shape complexity is a factor for determining the resolution [7].

Kyprianou [8] pioneered feature recognition techniques for the purposes of classifying shape for automated part coding. Since the feature recognition has been applied to many aspects of design, different measures of complexity have been established depending on the precise application.

Various algorithms have been offered to assess the geometric similarity of 3D models. Considerations such as the number of faces in a model, the number of sides of a polygon, curvedness, symmetry, number of turns, degree of compactness, angular variability and crinkliness have all been used to quantify shape complexity [9,10].

Assembly complexity. Although complexity research in design has focused on component shape, some attempts have been made to quantify the complexity of an assembly. In defining measures to select a optimal assembly sequence from those that are geometrically feasible, [11,12] define sequence complexity in terms of the number of insertions, reorientations, total assembly operations and the depth of the product's structure hierarchy [13,14], and more recently [15] have introduced a complexity measure which, besides being quantifiable, encodes the relevant properties of hierarchical systems. This measure is related to the diversity or lack of self-similarity in hierarchical trees. In their present form, these metrics are more suited to the analysis of algorithm complexity.

1.3. Objectives of a ship design complexity metric

As the complexity of a ship 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 results 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 a ship's design in order to systematically reduce the inessential details. The main objective of this study is to define a quantitative measures of complexity that can be evaluated from a ship's model at the early stage of the project design. 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.

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 [16] 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.

One outlook of this work is the development of the means to quantify the complexity of a ship and the definition of measures to be used in conjunction with other metrics such as the assessment of production cost. 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.

2. Definition of a ship's 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 [17]. 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 optimisation. 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 [18]. 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 [4].

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 sub-assemblies, 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.

In order to evaluate a product with respect to all these design and production aspects it is important to consider complexity in many different ways. Indeed, when we try to reduce the complexity of a product by reducing the number of parts another issue can arise. As parts are integrated or eliminated to optimise assembly with respect to part count and assembly operations, inevitably more complex components are created and more complex insertion processes are required [19]. The overall assessment requires that the time and cost of production is minimised, but this obviously requires a compromise between manufacturing overheads, assembly processes and part count.

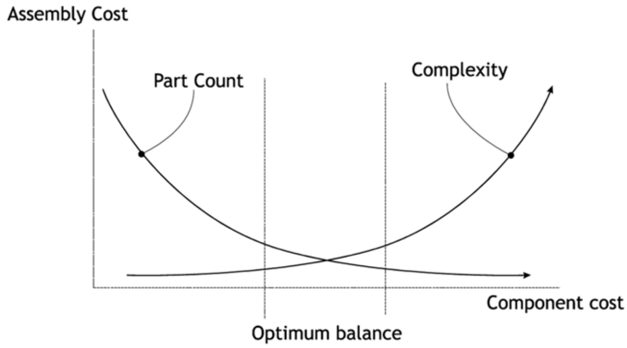


Fig. 1. Influence of component complexity and part count on cost [20].

We can therefore deduce the following statements (see Fig. 1):

- A large number of *simple* components leads to a complex assembly and therefore a high cost.
- A small number of *complex* components also leads to a complex assembly and once again high cost.

Implicit in these assumptions is the fact that the higher the number of parts the more costly the assembly. But the reverse is also true, the higher the complexity of parts the more costly the assembly.

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 more simple are the individual parts". The opposite is also available: "The fewer there are components in a product the more complex are the individual parts". (See Fig. 1.)
- 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 Eq. (1), where C_T represents the total complexity and $w_1, \ldots, w_i$ represents numerical constants called weighting factors.

$$C_T = \frac{w_1 C_{\mathrm{sh}} + w_2 C_{\mathrm{as}} + w_3 C_{\mathrm{mt}}}{w_1 + w_2 + w_3}. \tag{1}$$

2.1. 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 [9,10,21–23]. 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.

However, all these shape factors have the same following properties:

- They are dimensionless.
- They are invariant under geometric transformations such as: translation, rotation and scaling.
- They are applicable to all geometric shapes.

The most common shape complexity measurements for 3D shapes is the *sphericity* ψ (see Eq. (2)), defined by [24], 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 a 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 Eq. (3). The average shape complexity of a set of parts such as a ship assembly can be evaluated with Eq. (4).

$$C_{\mathrm{sh}} = 1 - \psi \tag{3}$$

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

where C_{sh} is the shape complexity,
ψ is the *sphericity* or the *circularity ratio*,
n is the number of part inside the assembly.

2.2. 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 a 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.

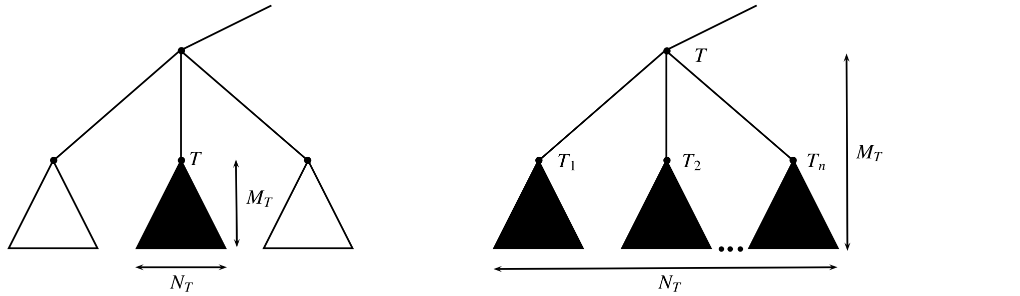
The method used to establish a quantitative measure of assembly complexity in this research is based on the definition of the complexity of hierarchical systems provided by [14].

We will consider a hierarchical assembly tree structure composed of N elementary elements at the lowest level, described by trees of constant depth M (see Fig. 2(a)). For indistinguishable elementary elements, [13] prove that the only distinction between nodes in the tree is in the structure of sub-trees, which defines the diversity of the global structure. Thus, we can conclude that the total diversity $D(T)$ of a hierarchical structure is given by the Eq. (5).

$$D(T) = F(T) \prod_{j=1}^{k} D(T_j) \tag{5}$$

where $D(T_j)$ denotes the diversity of the j sub-trees in the forest,
k is the number of non-isomorphic sub-trees,
$F(T)$ is the form factor of the root T of the forest.

The recursive nature of this definition is well-suited to a hierarchical assembly tree structure, in which each sub-tree



(a) Generic forest with sub-tree generated by node T. (b) A blow-up section of the sub-tree T showing its own sub-trees.

Fig. 2. Hierarchical assembly structure.

represents a particular stage in the global assembling of the product. The form factor $F(T)$, is a function of the number k_T of non-isomorphic elements, $T1, T2, T3, \ldots, T_k$ in which T diversifies. As shown by [13], this can be seen from the fact that the total number of interactions I_T among the distinct elements of the tree that take place through the node T is simply related to k_T by the Eq. (6).

$$I_T = (2^{k_T(m)} - 1) \tag{6}$$

where $k_T(m)$ depends on the number of the lower levels that we consider in order to decide whether or not two sub-trees are isomorphic.

Besides this dependence on k_T, the form factor should also contain some information on the relative importance of the T clustering level contribution to the global diversity. In other words, a node which subtends a fat tree should have a larger contribution to the total tree complexity than one at the same height but with only infertile branches.

Based on these definitions, [14] proposes a formulation in order to assess the complexity of hierarchical systems. He defines a complexity measure of hierarchical tree structures as described in Eq. (7).

$$C(T) = \log_2 D(T). \tag{7}$$

Thus the complexity of a forest composed of n non-isomorphic trees is given by Eq. (8).

$$C\left[\bigcup_{i=1}^{n} T_i\right] = \sum_{i=1}^{n} C(T_i) + \log_2 F\left[\bigcup_{i=1}^{n} T_i\right]. \tag{8}$$

This equation with the prescription of how to compute the form factor $F(T)$ (see Eq. (6)) provides a way of calculating the complexity of a hierarchical assembly tree structure. In order to make it reflect the relative importance of each node in the structure, as measured by the number of final leaves it subtends, we may choose the last term of Eq. (8) to be given by Eq. (9).

$$\log_2 F\left[\bigcup_{i=1}^{n} T_i\right] = N_T \log_2(2^{k_T(m)} - 1). \tag{9}$$

Thus the fat trees and their clustering will be the major contributors to the overall complexity of the system. Finally, Eq. (8) can be written in the form of Eq. (10). We will consider that $m = 1$ for simplicity. It means that we will only explore the root node of the T sub-trees in order to check their isomorphism.

$$C_{as} = C\left[\bigcup_{i=1}^{n} T_i\right] = \sum_{i=1}^{n} C(T_i) + N_T \log_2(2^{k_T} - 1) \tag{10}$$

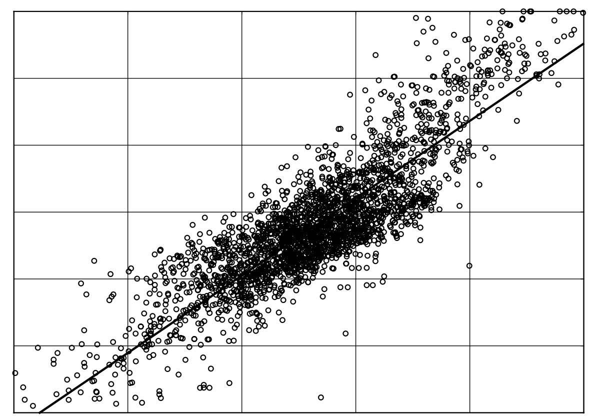


Fig. 3. Diagram of the total complexity versus the production time ($r^2 = 0.7557$).

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 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.

2.3. Material complexity—C_{mt}

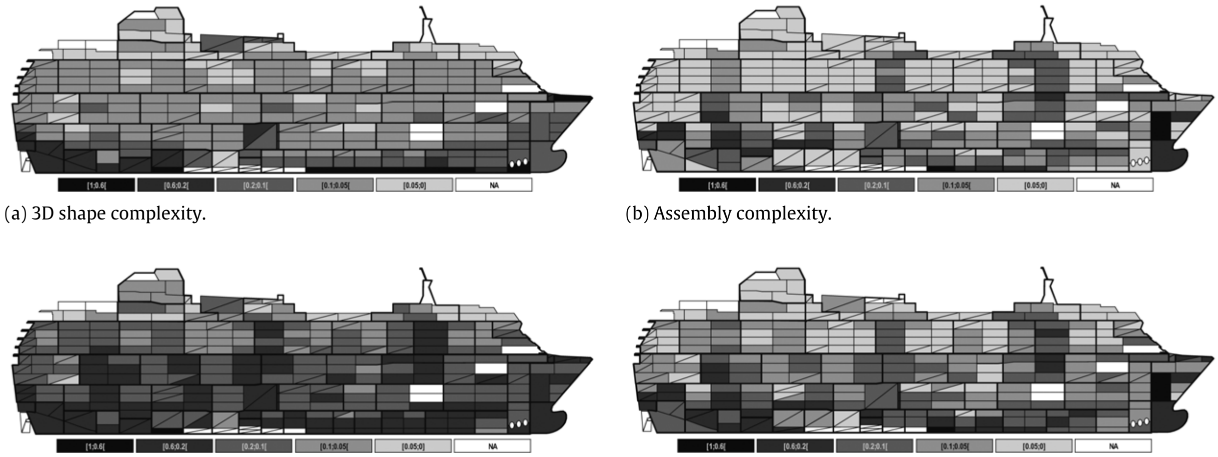
Considering the stiffened structure of ships, the material complexity has been defined for an assembly by Eq. (11).

- 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 aluminium 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 aluminium steel bulb profiles of 100 × 8 mm, the complexity will be equal to 3.

$$C_{mt} = C_{pt} + C_{st}. \tag{11}$$

3. 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



(a) 3D shape complexity.

(b) Assembly complexity.

(c) Material complexity.

(d) Global complexity.

Fig. 4. Complexity of a cruise ship.

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 Eq. (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 Eq. (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 Eq. (12)). A simple gradient descent optimisation algorithm was used here. The r^2 linear coefficient went from 0.7102 to 0.7557 which represents a gain of 6%. Fig. 3 represents the dot clouds diagram of the optimized linear correlation between the total complexity and the production time.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y}. \tag{12}$$

The main outcome of the test case is presented in Fig. 4 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 Eq. (1). By analysing 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 sections are much more complex than others. We can mention here for instance that the complexity of the three access towers for passengers with lifts and stairs appear very well in Fig. 4(b).

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, standardising 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 [25] that structural detailed arrangements that were made during the early stages of design were often carried through detail design without any attempt at optimisation.

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.

4. Conclusions

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 problems, 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.

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.

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