Handling Complexity Aspects in Conceptual Ship Design

Henrique M. Gaspar[1] , Adam M. Ross[2], Donna H. Rhodes[2] and Stein Ove Erikstad[1]

April 10

ABSTRACT

In this paper we present strategies to handle complexity during the conceptual phase of ship design. We introduce the issue by summarizing key ship design advancements during the last six decades, showing the growth in information, which leads to a more complex system. A definition of complexity based on the amount of information necessary to define the system is then discussed, placing the ship as a complex system. A general approach to handle complexity is presented, based on decomposition and encapsulation. Five main aspects of complexity are presented (structural, behavioral, contextual, temporal and perceptual), linking challenges of the conceptual phase to each of the aspects. As case example, techniques to handle the five aspects of an offshore support vessel design are briefly presented. The last section discusses the benefits of the five aspects classification and proposes possible uses and extensions.

KEY WORDS

Conceptual Ship Design; Systems Engineering; Handling Complexity

INTRODUCTION

Information Growth in Ship Design

The idea of a ship as a system, that is, as a *complex unit formed by many often diverse parts, subject to a common plan or serving a common purpose* (Oliver *et al.,* 1997) is so well established in the design field that, from Evans (1959) until nowadays, it seems impossible to discuss the design problem without discussions about a system. The challenge of determining which kind of information[3] is necessary in order to establish if a certain system is a *good* system or not has been a central question in the ship design community (Andrews, 2009).

It is possible, however, to affirm that some type of information appeared as relevant just after a certain base was developed. For instance, no optimization algorithm for calculating hull resistance would be valid if the formulation to do the first estimations based on the hull shape were not first developed. In the same way, the focus on environmental performance is a much more modern trend than common technical disciplines, being almost nonexistent on ship design references older than 20 years.

With the attempt to organize this continuous increase in information, we present in Figure 1 a timeline of the main information growth for every decade. Far from being a definitive proposal, this simplification illustrates some of the main information advancements in ship design through time, via examples of one reference for each significant type of growth.

It is important to keep in mind that the objective of this timeline is to raise the idea that information in ship design is continuously growing, in the direction of high interactions and less rigid boundaries. The choice of the references work mainly as examples, since it is impossible to compile in such a small figure all of the branches that ship design had and has. An advanced study on the development of the ship design task is presented in the IMDC state of the art reports (Andrews *et al.* 2009*;* Papanikolaou *et al.,* 2009)

[1] Norwegian University of Science and Technology – Department of Marine Systems
[2] Massachusetts Institute of Technology – Systems Engineering Advancement Research Initiative
[3] Information is sometimes used as synonymous of knowledge, as pointed by Hagen (1993): *I will not distinguish between information and knowledge (...), since it would seem like a philosophical question that is beyond the scope to discuss at what point information become knowledge.*

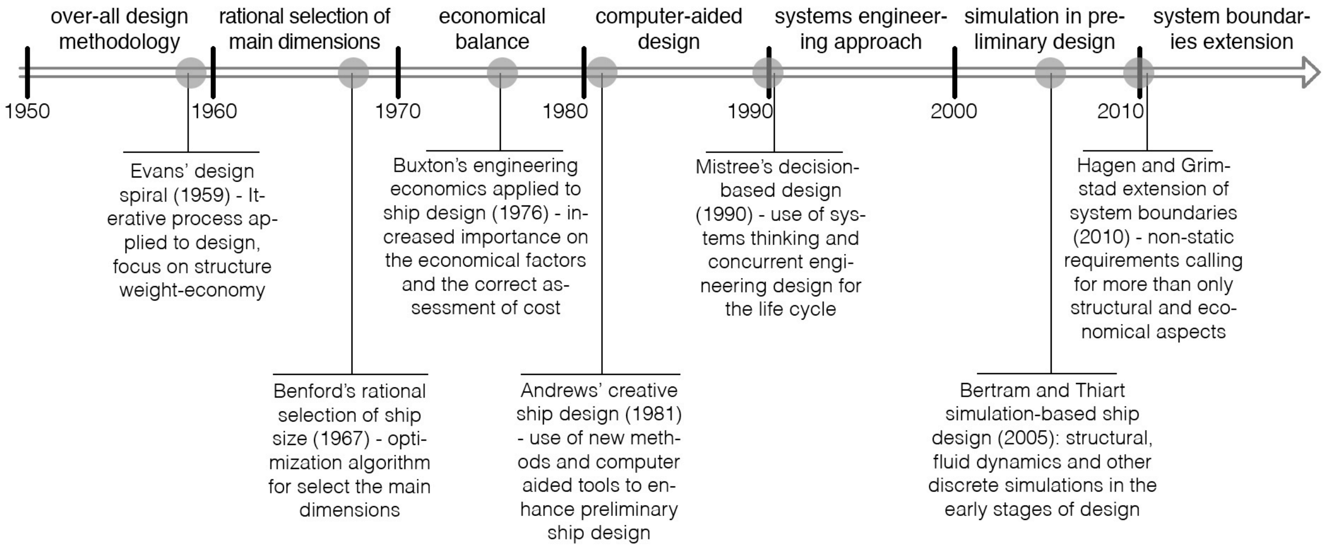

Figure 1 – Simplified timeline for information growth in ship design through decades.

A brief explanation of the information advancements from Figure 1 is made as follows: Evans (1959) developed an overall design methodology in his design spiral. This single-point procedure made possible a series of technical advancements in the following years. The work of Benford (1967) exemplifies the rational selection of the main dimensions and capabilities, with one of the first algorithms to explore the iterative nature of design towards a more efficient vessel. The increase of the shipping activity during the 70s and oil issues drove several works on the right assessment of the cost in the shipping activity, exemplified by Buxton (1976).

Andrews (1981) brings a more serious discussion of creativity into design, defending the use of new methods and computer-aided tools in the early stages, since the computational capacity became more accessible in the 80s. The establishment of systems engineering (SE) methods, such as concurrent engineering, brought to the ship design a broader system thinking, extending the single-point over-all methodology, exemplified by Mistree's decision-based design review of the paradigm (1990). The new century brought a high computational power available, stimulating the use of many type of simulations during the early stages, to give support to the traditional empirical methods. Bertram and Thiart (2005) present a compilation of these simulations, discussing fluid dynamics and other discrete methods during design.

A current concern is the necessity of taking into account other type of information in design, rather than pure technical or economical, since new elements are now gaining importance, such as environmental performance and risk. Hagen and Grimstad (2010) present a discussion of these new elements, proposing an extension in the boundaries of design. This extension is not only in terms of more refined methods and calculations, but a call to bring into the early stages other aspects. By extension of the boundaries the authors require a design able to include new technologies, environmental concerns, operational profiles and fleet interaction during the early stages. In other words, the traditional structural-behavioral aspects no longer cover all the information necessary to define a design in the early stages.

In the case of our timeline, other authors would probably select different examples, maybe even different type of information growth, but hopefully reach the same conclusion as us: there is a constant increase in the amount of information required to design a ship, and it is necessary to have methods able to handle this new information and to bring other type of insights during the preliminary stage.

This call for new perspectives leads us to raise the following open research questions (RQ):

1. Which general principles from complex systems theory can be used to handle the new information?
2. How should the traditional structural/behavioral classification be extended in order to incorporate the new information on the conceptual phase?
3. Which novel and established techniques can be used to handle this extended classification?

The following sections present a partial answer to these questions, proposing a general approach to handle complexity (RQ1); later, a taxonomy of five aspects of complex systems is used in the ship case (RQ2), with discussion of some of the novel techniques in the light of this taxonomy (RQ3). An offshore support vessel (OSV) design is used as an example to illustrate the approach.

Complexity and Information

Systems engineering relates the complexity of a system to its number of components and connections (Oliver et al., 1997). This traditional approach has significant influence from the ideas organized by Simon (1962), in his *Architecture of Complexity*. Simon proposes that how complex or simple a system is critically depends upon the way in which we describe it. This hierarchical approach to complexity decomposes the system until it can be understood.

The idea of complexity becomes clear when we embrace a few arguments from algorithm information theory and Kolmogorov's definition of complexity (Kolmogorov, 1983). In simple terms, Kolmogorov asserts that the more information an object requires to be defined, the more complex it is. Our object is thus the system. Suh also develops the idea of information connected to the complexity of design, proposing that the violation of the information axiom, *to minimize the information content of the design will maximize the probability of success*, will result in complexity in the system (Suh, 1990, 2005).

In summary, our definition of complexity is based on a broad engineering systems definition (Magee and de Weck, 2004), connecting the fundamental idea of hierarchization with arguments from information theory. Therefore, the complexity that we talk about in the following is defined as the amount of information necessary to define a system, including its components, behaviors, contexts, circumstances, processes, patterns, relationships, and other relevant aspects.

HANDLING COMPLEXITY

General Approach: Decomposition and Encapsulation

Simon defines hierarchy as a primary scheme to architect complex system (Simon, 1962). This hierarchization consists on observing a system as a unit composed of a *large number of parts that interacts in a non-simple way*, meaning that it can be divided into a finite number of subsystems, each of may be further subdivided. Therefore, the **decomposition** is the way to handle the ability of a system to be separated into basic elements (decomposability), making it more comprehensible. Simon, however, realizes the difficulty of decomposing a complex system into completely independent parts, due to the high level of interaction that some systems may have, and he then proposes that a system with many interactions among the parts and with other systems can therefore be near decomposable. This near-decomposability is thus a *major facilitating factor* to the understanding of the system.

A good decomposition leads to the **encapsulation** of the parts, that is, a construct that facilitates the bounding of the information according to one function/process, constraining the part into a common ideal rationality/to-do purpose. Information encapsulation is thus *a way to accomplishing a bounding strategy,* as observed McClamrock (1995). By encapsulating the parts of the system within a criterion, normally functional, one can focus on the overall behavior of the subsystem as a black box, with respect only to its inputs and outputs, and later compare this result according to the big picture of the behavior of the system. The encapsulation also establishes an interface for each of the part (modules), allowing some sort of interaction, for instance trade of information or a physical connection.

This approach of decomposing and encapsulating the information goes in line with Suh's axiomatic design theory (1990), when he defines a good design as an independent one (independency axiom), with the minimal amount of information necessary to define this part (information axiom). Suh's methods, however, are rarely used in maritime design problems due to the strong dependence among the parts of the system, leading to a violation in the independency axiom. Figure 2 illustrates these two general strategies.

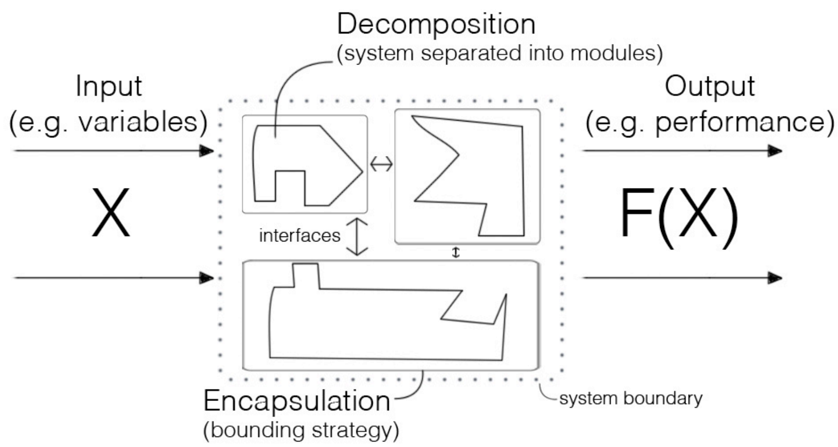

Figure 2 – Decomposition and encapsulation as strategy to handle complexity.

Hierarchization in Ship Design

The classical approach of decomposition of hierarchic systems is well used in engineering. It serves as a strategy to handle the information necessary to describe the boundaries of the ship. Figure 1 exemplifies the ship as a hierarchical system, made up of subsystems and components, and as an element of a large maritime transportation system.

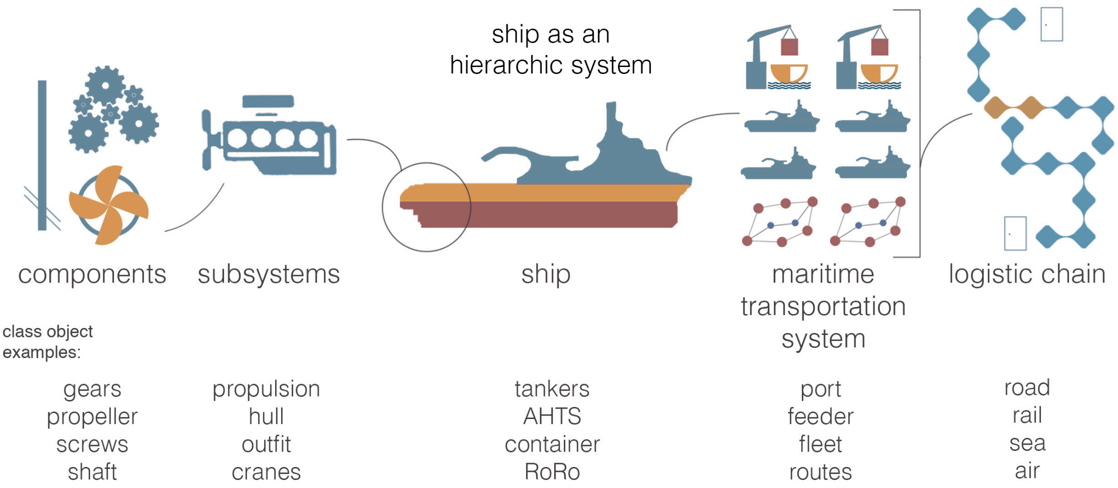

Figure 3 – Classical approach of a ship as a hierarchic system, decomposing into parts and encapsulating them according to a certain function/process.

As established, the division of the ship into subsystems (for instance propulsion and hull) thus allows a better comprehension of the effects of each part to the system as a whole, as well as relations to the other subsystems. The traditional ship design process takes into account this division, and accommodates the high-level interactions effects that the subsystems may have. Any preliminary design methodology, such as Evans-Buxton-Andrews spiral (Mistree *et al.,* 1990) or System Based Ship Design (Levander, 2006; Erikstad and Levander, 2012), then uses this principle of *divide and conquer* to design each of the subsystems, and through interactions to design a ship.

Five Aspects of Complex Systems

The traditional design methods are strongly linked to the mapping between form and function that the design task requires (Coyne *et al.,* 1990). In other words, design relies on model based engineering approaches to derive a behavior (technical/economical) from a physical structure. As discussed in the introduction, this traditional division does not fully take into account the new kind of information necessary to define and design a ship in present day. New elements, such as environmental performance, risk and future uncertainties can no longer be ignored/constrained, and require a taxonomy to be incorporated during the early stages.

Rhodes and Ross (2010a, b) propose five essential aspects for the engineering of complex systems. The benefit of this decomposition is to include the current model-based systems engineering approach, which embraces the behavioral and structural current state of the practice, and add three other aspects: contextual, temporal and perceptual. These three aspects extend these boundaries, giving attention to a systems environment with unprecedented levels of information. Table 1 provides a brief definition of the five aspects.

Table 1: Five Aspects of Complex Systems (adapted from Rhodes and Ross, 2010a)

Traditional	**Structural:** related to the form of system components and their interrelationships **Behavioral:** related to performance, operations, and reactions to stimuli	*State of the practice* systems architecting and design, and emerging model-based systems engineering approaches
New aspects	**Contextual:** related to circumstances in which the system exists **Temporal:** related to dimensions and properties of systems over time **Perceptual:** related to stakeholder preferences, perceptions and cognitive biases	New constructs and methods seek to advance *state of the art*, for example: Set Based Design, Ship Design and Deployment Problem, Epoch Modeling, Epoch-Era Analysis, Multi-stakeholder negotiations, visualization of large data sets

s

This classification works as well as a taxonomic framework, that is, a useful way to organize *information in order to share knowledge with others* (Rhodes & Ross, 2010b). This effort to organize information reflects in a characterization of the complexity in engineering. As follows, we apply this characterization on the conceptual ship design problem.

HANDLING COMPLEXITY IN CONCEPTUAL SHIP DESIGN

Five Aspects Applied to a Ship as a System

Gaspar *et al.* (2012) present an introduction of the five aspects applied to the ship as a system. The *structural* aspect is related to the arrangement and interrelationship of the functional and physical objects in the ship. This complexity is directly related to the ship as a large, self-contained system with a large number of highly integrated systems and with many parts. All basic systems must be provided by the vessel itself within a very limited contained volume, and all changes to any system part tends to interact and influence other systems through complex relationships.

The *behavioural* complexity derives from the form-to-function mapping. Technical performance analysis, such as resistance and propulsion, seakeeping, manoeuvring, stability and structural, are both mathematically complex and computationally intensive. Those analyses rely to a large degree on empirical methods and simulation based tools, such as finite element analysis and computational fluid dynamics. Adding to this the economical, risk, safety and environmental performances results in a behaviour evaluation function that is both complex and inherently multi-objective.

The *contextual* aspect defines external operating circumstances to which the system is subjected. It consists of the external entities, interfaces and factors that affectthe behaviour of the system, and should be taken into account when designing it. Examples of context aspects are the market variables (e.g., demand, contract, taxes, prices), regulations, rules and preferences.

The *temporal* aspect of complexity refers to changes over time during the system lifespan. Shifts and uncertainties in the context are also handled in this aspect, for instance the uncertainty related to the operational profile of the ship, or due to future contract scenarios.

The *perceptual* aspect relates to how the system is interpreted from the perspective of system stakeholders. It considers individual stakeholder preferences, and how preferences vary across stakeholders. It must answer such questions as *How is decision X perceived by stakeholder Y?* This aspect deals with quantitative (for instances key performance indicators) and qualitative ("gut feeling") characteristics of the design.

Figure 2 presents an overview of the 5 aspects, within the traditional ship design boundary, that must be incorporated in a complex systems approach (adapted from Gaspar *et al.,* 2012).

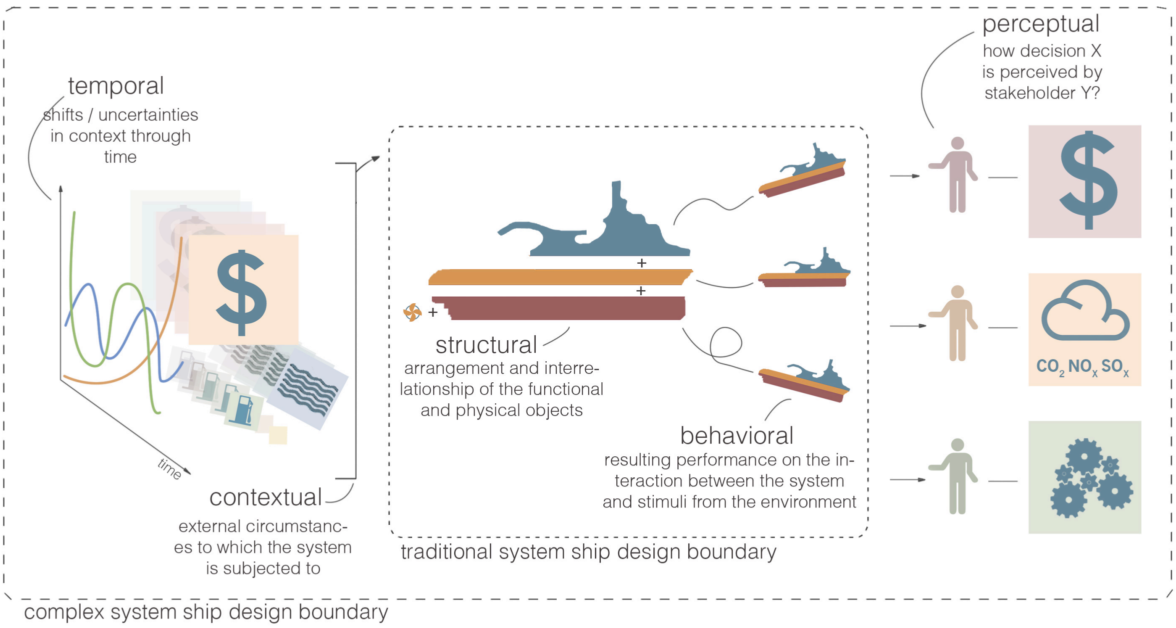

Figure 2: Five aspects of complex system applied to ship design (adapted from Gaspar *et al.,* 2012)

Techniques to Handle Complexity in Early Stages of Design

The objective of this section is to present a concise literature review on few traditional and novel techniques used in ship design in light of the five aspects taxonomy, in order to exemplify how these techniques use the general approach of decomposing and encapsulating to handle complexity.

Structural

The structure/behavior pair aggregates the aspects that are vastly covered through the traditional model-based techniques. The structure is decomposed and encapsulated in subsystems and components, as shown in Figure 1. Modern approaches transform the classical subsystem into modules. Andrews (1998, 2006) also utilizes the systemic thinking and complex systems terminology when justifying his comprehensive methodology for ship design , and a creative approach to ship architecture (2003). Andrews uses, for instance, the building block approach as a design method; once applied it produces *a more informed and information rich preliminary design*. The method presents a functional break down of the system into semi-independent building blocks as a design technique. This strategy can be understood as a means to handle structural complexity. An extensive study on this and other modularization techniques is discussed by Erikstad (2009), which presents an overview of modularization related to shipbuilding, emphasizing the modularization task, platform technologies in the product development and tendering phase of the process.

An example of recent research focusing mainly on the structural aspect of complexity is exemplified in the maritime case by Caprace and Rigo (2010), with a purpose of assessing complexity at the concept phase. The approach can be considered an introduction to complexity thinking in the conceptual phase, suggesting a metric to compare ships on a basis of structural complexity. The formulation proposed is based on the type and configuration of the ship. The metric is, however, strongly focused on the structure and general configuration, leaving out other aspects that should also be addressed when discussing complexity.

Behavioral

Decomposing the behavioral aspect commonly means to decompose the expected performance of the ship into key performance indicators (KPIs) by the use of model-based tools. New approaches to estimate the behavior take into account not only empirical data, but also rely on the simulation of the system. As presented by Bertram and Thiart (2005), the advancement of computational methods in the last decades has developed, enabling more reliable simulation based ship design. As observed by the authors, the design behavior is evolving from experience based (e.g. regression analysis tools) to simulation ones (e.g. discrete tools), allowing applications in structures, fluid dynamic, discrete events, such as oil spilling, cargo handling and ship evacuation and economic efficiency (Schneekluth and Bertram, 1998). These advancements permit increased information to be handled during the conceptual phase, necessitating a discussion on the impact of the simulation in ship design, such as the work of Andrews and Pawling (2009).

Some optimization techniques develop this aspect in order to handle uncertainty in the input data, such as fuzzy logic modeling (Gray *et al*., 2010) and identification of an optimal design, such as the ship design and deployment problem (Erikstad *et al*., 2011).

A compilation of the main advancements and challenges in computer applications for ship design and analysis is discussed by Sharma *et al*. (2012), looking at computer-aided design, geometric representation, hydrodynamics, structure, production and experimental testing.

Contextual

The challenge for the contextual aspect is the transition between constraint context parameters, usually technical and economical, towards a more extensive and flexible decomposition, able to incorporate new social elements in the early phases (such as environmental performance and risk assessment). Uncertainties in context parameter as well as shifts/changes must also be taken into account.

Andrews (2003) defends a more open observation of the initial requirements, proposing an elucidation rather than “pure engineering”. Hagen and Grimstad (2010) defend this wider scope, calling for a context that includes the transportation system, iterating the process from the bottom (e.g. air emissions) up to the transport chain requirements (e.g. transport demand). The work also presents an overview of the current changes in the ship design domain, namely: technology (shipping business, design tools, propulsion efficiency, new materials), operational/logistics changes and new ship design requirements, with the observation by the authors that *environmental performance must be ranked much higher as an evaluation / decision parameter than before*.

Environmental issues have gained importance during the last decade (Gaspar and Balland 2010). The idea of how a ship should be designed to be considered environmentally friendly is not yet clear to the community. It can include several areas, such as energy efficiency, low emissions, biohazard, and toxin free, among others. Several studies are currently being developed, mainly with the objective of addressing energy efficiency and air emissions. Examples include: hull optimization (Hochkirch and Bertram, 2009); design of machinery configuration taking into account environmental KPIs (Gaspar *et al*. 2010); and air emission controls optimization (Balland *et al*. 2011).

Risk is another important context factor to be incorporated in the early stages. Risk-based design is a methodology *to support and nurture a safety culture paradigm in the ship design process, by treating safety as a design objective rather than a constraint* (Vassalos, 2009). A compilation of the recent methods, tools and applications of risk-based ship design is presented by Papanikolau (2009).

In a higher level approach, the decomposition of general context parameter is handled by the Epoch Era Analysis (EEA) (Ross and Rhodes, 2008). The EEA method proposes a useful representation of the context, as an interval of time with a static set of contextual factors, termed an *epoch*. Several epochs create a dynamic interval of time, a time-ordered set of contexts are defined as an *era*. Context parameters are related to certain categories (e.g. market, technology, policy and regulations) and decomposed into *epoch variables*. Each epoch contains a fixed set of context parameters, and the sum of all epochs defines an epoch space, representing the group of possible contexts for the particular system.

Temporal

One common approach to handle the temporal aspect is life cycle assessment (LCA). The technique is strongly related to sustainability, in that it quantifies the performance of a specific parameter (e.g. environmental load, economical performance) through the whole lifespan of the system. Cabezas-Basurko *et al*. (2008) present a study to encapsulate environmental, economical and social sustainability in the preliminary ship design, proposing a holistic approach to maintain sustainability.

One of the limitations of the traditional methods, however, is the simplification of different context through time. This limitation is justified by the increase in design complexity when design to a large number of shifts/uncertainties in the context through the lifespan of the system. The EEA method represents a *divide-and-conquer* approach to handling temporal complexity, as exemplified in the maritime case by Gaspar *et al.,* (2012). It captures alternative expectations about the future by formulating distinct epochs (set of contextual parameters) with a fixed operating context, for which the performance of each alternative design can be analyzed. These epochs can then be combined into many possible eras, each representing a possible lifecycle scenario for the vessel.

Perceptual

The perceptual aspect is the one that addresses the challenge of satisfying the *diversity of stakeholder stylistic preferences* (Rhodes and Ross, 2010b). To be able to answer if *design A* is more efficient than *design B* will require a formal construction of the system KPIs, customized to each stakeholder's preferences. However, the possibility of analyzing a large number of designs (design space) towards a large number of possible scenarios (epoch and era space) results in a huge amount of data (information) to be handled.

To handle this data implies, for instance, the study of sensitivity analysis, uncertainty and robustness of the design. Buxton (1987) and Erichsen (1989) discuss the traditional trade-offs, based in the variation of the initial data and their effects on the KPIs. Usual methods consist of:

- Marginal cost of *X* (for instance the cost in emission by changing main vessel parameters as dimensions, coefficients, ratios and design speed).
- Pareto frontiers, traces and sets, comparing two conflicting performances (e.g. air emissions and cost of abatement methods; or profit and fuel cost due to different epochs).
- Response surface methods and other multi-objective criteria methods to calculate KPI trade-offs (Whitfield *et al*. 1999)
- Systems engineering techniques, such as tradespace exploration and Responsive Systems Comparison method (Ross *et al.,* 2009) or valuable changeability analysis (Fitzgerald and Ross, 2012)

Another common way to approach a multi-criteria study is the decomposition of stakeholder preferences in factors and the weighting of factors, in an Analytical Hierarchy Process (AHP). Winnes and Ulfvarson (2006) apply systems engineering and life cycle assessment methods to define an AHP for the ship design task, using scoring functions to quantify different domain indicators. It consists of selecting relevant figures of merit (e.g. KPIs) and putting a weight factor on them. The use of scoring functions normalizes different KPIs in the range 0-1, to allow comparison. The best design, using this method, isthe one with the highest sum of the all parts.

Table 2 summarizes the decomposing and encapsulating approach to handle complexity in each of the aspects

Table 2: Examples of ship design techniques to handle complexity in each of the aspects

Aspect	Decomposing	Encapsulating	Techniques Examples
Structural	Modularization: identify near independent modules; Definition of criteria to create modules	Modularization: define inputs and outputs of each module; Definition of interface criteria to connect one module to another	Building block based design (Andrews 1998, 2006); Modularization techniques (Erikstad 2009); System based ship design (Levander, 2006); Structural Complexity Assessment (Caprace and Rigo, 2012)
Behavioral	Functional breakdown, dividing the system into subsystems according to a task to be performed , then evaluating the behavior of each subsystem, for instance, via simulatio or regression analysis	Response Surface and other methods to encapsulate data from simulation	System Based Ship Design (Levander, 2006); Simulation based design (Bertram and Thiart, 2005); Impact of simulation (Andrews and Pawling, 2009); Set-based design (Singer, 2009); Ship design and deployment problem (Erikstad et al., 2011)
Contextual	Take into account multiple operational profiles, with different context parameters in each	Standard and customized operational profiles	Epoch-era analysis (Ross et al., 2008, 2009); new elements into context: Air emission control (Balland et al., 2011), Risk analysis (Papanikolau, 2008), Environmental performance (Gaspar and Balland, 2010)
Temporal	Epochs: divide the life span of the system in epoch variables; each epoch represents a snapshot of certain period of time	Eras: encapsulate changes and uncertainties into eras, that is, a time-sequenced set of epochs.	Lifecycle assessment (Cabezas-Basurko et al., 2008); Temporal uncertainty (Ross et al., 2008, 2009; Gaspar et al., 2010); Valuable changeability analysis (Fitzgerald and Ross, 2012)
Perceptual	Requirements elucidation for different stakeholders	Multi-objective methods, such as AHP, Pareto, .	Multi-objective methods (Ehitfield et al., 1999); AHP and Scooring functions (Winnes and Ulfvarson, 2006); Responsive systems comparison method (Ross *et al.*, 2009); Requirements elucidation (Andrews, 2003)

CASE EXAMPLE – OSV DESIGN

For illustrative purposes, let us consider a simple example of how to handle the five aspects in the early stages of an OSV design. For such vessels, trades and operating duties are more complex and diverse than for most other ships. The combined range of transportation work (supply), functional work (anchor handling/towing), and operating conditions (North Sea, Brazilian Coast, Arctic, African Coast, Gulf of Mexico) forms a large number of potential missions (Gaspar *et al.*, 2010). Each aspect can be handled as follows.

Table 3: General approach applied to Offshore Support Vessels

Aspect	Decomposing	Encapsulating
Structural	Breakdown of the structure according to function, via system based ship design	Grouping in two main systems: task related and ship systems
Behavioral	Analytical tools to handle each of the main performance attributes	Grouping attributes according to the spiral process (form, performance, economics)
Contextual	Breakdown of the context parameters such as new technology, mission, regulation or market condition	Encapsulate fixed contexts into epochs
Temporal	Decompose the possible changes in context though time via a sequence of epochs	Capture a possible future scenario within an era
Perceptual	Requirements breakdown according to stakeholders preferences	Multi-objective presentation of the data, via Pareto frontiers and other techniques able to capture trade-offs.

Structural

The structural aspect is handled by the generic breakdown of the structure based on the functionality of each part. The method is based on the system-based ship design (Levander, 2006), and an example of the application to OSVs is presented by Erikstad and Levander (2012). Table 3 shows the functional decomposition of the OSV structure into task-related system and ship systems.

Table 3: OSV systems: functional breakdown (Erikstad and Levander, 2012)

Task Related Systems	**Cargo Spaces:**	Dry Cargo Decks; Liquid and dry bulk cargo; Cargo handling and equipment
	Anchor Handling and Towing:	Winches and reels; Rope and chain storage; Handling equipment
	Offshore Construction:	Lifting equipment; Construction equipment; Diving equipment; Spaces in accommodation
Ship Systems	**Ship Structure:**	Hull; Forecastle; Deckhouse
	Ship Outfiting:	Offshore operation support; Ship equipment; Rescue and Fire fighting
	Accommodation:	Crew and client spaces; Service spaces; Technical spaces in accommodation
	Machinery:	Machinery main components; Machinery systems; Ship systems
	Tanks and Voids:	Fuel and lube oil; Water and sewage; Ballast and void

Behavioral

The behavioral aspect is handled by the analytical tools used to evaluate each of the subsystems decomposed by the functional breakdown. The system-based ship design assumes that *the design should start from the mission specified for the ship; the mission statement settles tasks, capacity and performance (…) as consequence the design task structure to "define systems and functions – estimate size and weight – select dimensions – check performance"* (Erikstad and Levander, 2012). This process is observed in Figure 3.

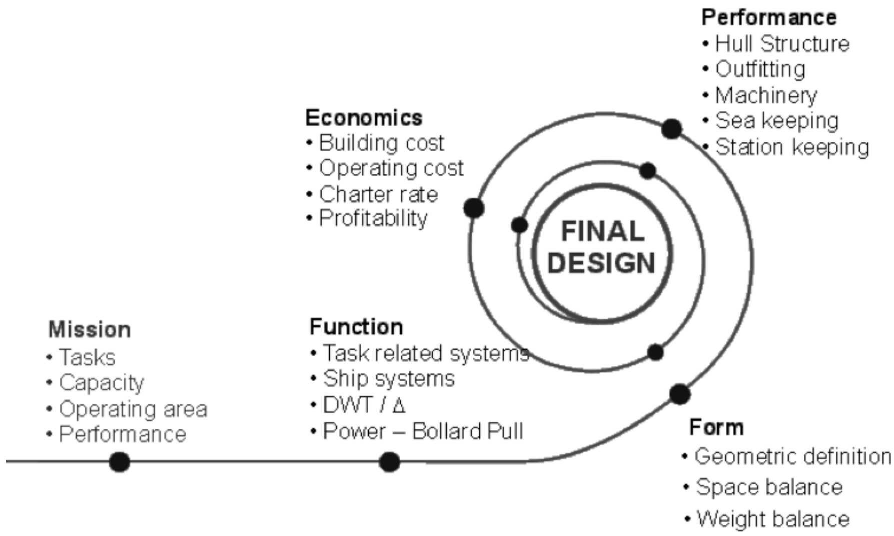

Figure 3: System based ship design spiral (adapted from Erikstad and Levander, 2012)

Context

The mission of the ship is strongly related to the context and needs. These needs are not static, and vary according time, through uncertain ways. In the OSV case, the context parameters are related to the following categories (Gaspar et al., 2012):

- Field Development: The opening of a new market may require different technology installed on board, such as ice class for an oil and gas field in the Arctic or ultra deep water equipment for operate in the Brazilian waters.
- Technology Development: A new technology may require a different type of fuel, or strengthened steel foundations of the hull and main deck, altering the capabilities of a vessel.
- Policy / Regulations: Future regulations may create a new emission control area (ECA), such as limitation in SO_X or NO_X levels (SECA/NECA); or new rules related to dynamic positioning or fire-fighting, or even an mandatory air emission control to prevent environment harmful emissions.
- Market: Shifts in the market can also trigger a new epoch, with alterations in the fuel and freight price, high or low demand condition and potential spot market options.

The process observed in the *Behavioral* aspect must thus be performed for each of the possible contexts. The EEA approach is a way to handle it, since it decomposes the context categories into epoch variables. A set of variables defines an epoch vector, and each vector defines an epoch. The process is presented in Figure 4.

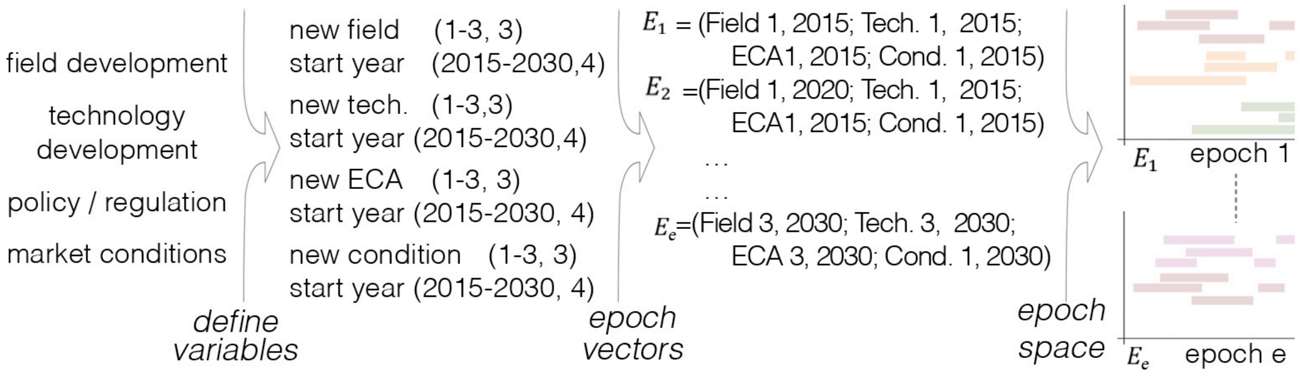

Figure 4: Decomposition of context parameters into epochs (adapted from Gaspar *et al.*, 2012)

Table 4 presents an example of the epoch variables with categories, units, scale, range, steps and weight applied to the OSV case.

Table 4: Example of epoch variables for four context parameters categories (Gaspar *et al.*, 2012)

Category	Epoch Variable ε_e^n	Unit	Scale (continuous or discrete)	Range (min-max)	Steps	Weight
Field development	New field (e.g. Brazilian pre-salt)	Field	Discrete	1 – 3	3	1
					4	1
	Start Year	Year	Continuous	2015 - 2030		
Technology Development	New Technology (e.g Fuel Cells commercially available)	Technology	Discrete	1-3	3	1
					4	1
	Start Year	Year	Continuous	2015 - 2030		
Policy/ Regulations	New ECA	ECA	Discrete	1-3	3	1
	Start Year	Year	Continuous	2015-2030	4	1
Market Conditions	New Condition	Condition	Discrete	1-3	3	1
	Start Year	Year	Continuous	2015-2030	4	1

Temporal

The temporal aspect is handled by using static *chunks* of the context (epochs) in order to construct the system lifespan via EEA. In this way, epochs are used as modules that can be combined to create the entire timeline of the system, that is, the eras. Figure 5 illustrates this process.

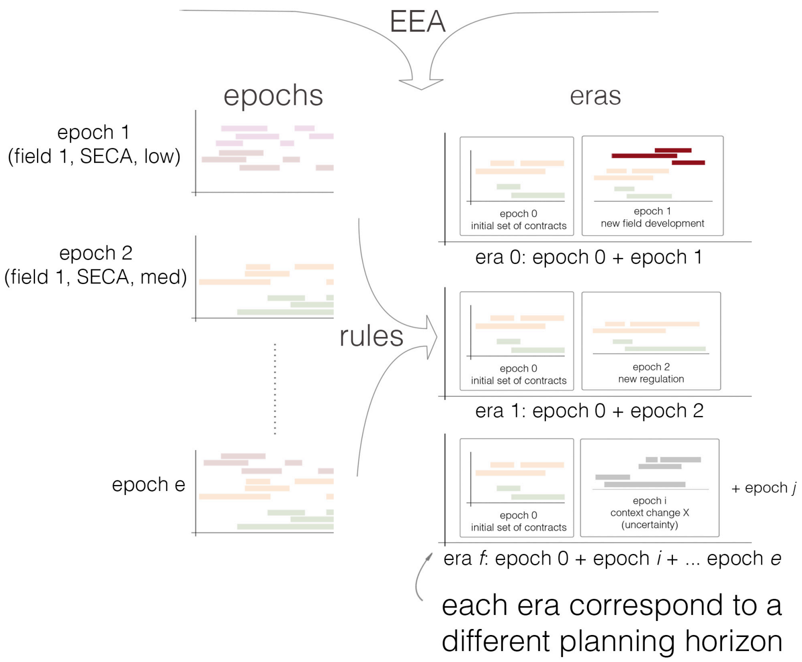

Figure 5: Encapsulating a set of epochs to construct eras (adapted from Gaspar *et al.*, 2012)

As final result, the era allows the study of a specific design performance through the whole lifespan, as illustrated in Figure 6.

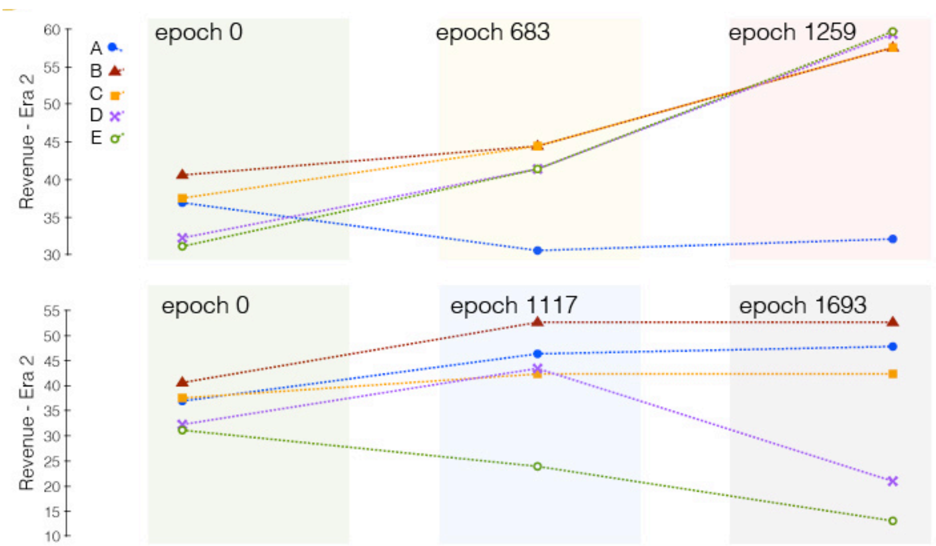

Figure 6: Design performance through epochs in two eras (adapted from Gaspar *et al.*, 2012)

Perceptual

The perceptual aspect is handled by the study of the analysis data towards a multi-stakeholder criteria. It includes the previously discussed techniques of multi-objective analysis. As an example, Figure 7 illustrates the Pareto frontier in a comparison between two eras, with the performance of five designs compared side by side.

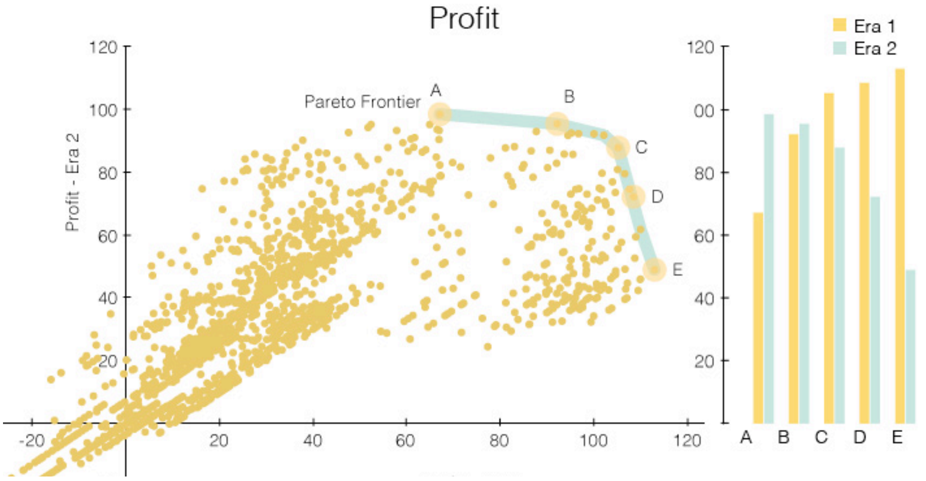

Figure 7: Pareto frontier to compare design in two eras (adapted from Gaspar *et al.*, 2012)

CONCLUDING REMARKS

In this paper we presented a simplified timeline of the significant type of information growth through several decades in ship design. From this, we have characterized the conceptual ship design task as a complex system problem and proposed a general approach to handle this complexity, based on decomposing and encapsulating. We introduced and applied the five aspects of complex systems to the early stages of conceptual ship design, and later, we discussed several traditional and novel techniques to handle the information related to these five aspects. The design of an OSV was used as example.

Instead of only dealing with information of the traditional structural-behavior approach, the five aspects extend the ship design task. By adding the conceptual, temporal and perceptual aspects into the early stages, the designer is able to address the additional information that nowadays is necessary to identify a good design.

In order to handle these five aspects, we introduced a general methodology, based on the decomposition and encapsulation of the information. This method represents a divide-and-conquer approach to the five aspects, and can be summarized for the conceptual ship problem as follows:

- Structural aspect – Modularization, such as the building block approach.
- Behavioral aspect – Functional breakdown, such as the system-based ship design
- Contextual aspect – New context elements (e.g. environmental rule or technological development) and context parameter decomposition (epochs)
- Temporal aspect – Lifecycle and Epoch-Era Analysis
- Perceptual aspect – Multi-objective analysis tools (e.g. Pareto plots/trace/sets, response surface and AHP) and implementation of new systems engineering methods (e.g. tradespace exploration)

It is possible to realize that the structural and behavioral aspects are well-handled by the traditional ship design approaches, linking form-function to the basic design process.

The benefits of the new taxonomy are better observed with the handling of the other aspects. As exemplified in the OSV case, the multi-epoch and era analysis allows for the modeling of uncertainties, handling the contextual aspect. The temporal aspect is also observed in these phases, including changes in the context over time, and creating trade-offs among the designs under different scenarios. The lifecycle analysis process may propose strategies to adapt designs in order to perform better across unfolding era uncertainties.

The perceptual aspect is greatly exploited by the use of *If that, then this options*, that is, it utilizes multi-objective techniques (e.g. Pareto sets) to evaluate which design will perform better in a specific stakeholder preferred scenario.

Thus, our conclusion is that the use of complex system theory, with the decomposition and encapsulation of the information and later the discretization of the system in five aspects is an efficient approach to handle complexity in the early stages of the ship design problem, providing a modular approach to understand the design information.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding for this research provided through SHIP-4C KMB project (NTNU, Norway), and MIT Systems Engineering Advancement Research Initiative (SEAri). The authors would also like to thank Océane Balland and Siri Solem (NTNU) for their contribution during the research.

REFERENCES

ANDREWS, D., "A comprehensive methodology for the design of ships (and other complex systems)". Proc. R. Soc. Lond. A, 454:187–211, 1998.

ANDREWS, D., "A creative approach to ship architecture", International Journal of Maritime Engineering, 2003.

ANDREWS, D., "Marine design: requirement elucidation rather than requirement engineering", IMDC Athens, 2003.

ANDREWS, D., "The use of simulation in preliminary ship design". CCAS 2005, 12th Intl Conf on Computer Applications in Shipbuilding; 23-26 Aug 2005.

ANDREWS, D., "Simulation and the Designing Building Block Approach in the Design of Ships and Other Complex Systems". Proc. R. Soc. Lond. A, 462:3407-3433, 2006.

ANDREWS, D., PAWLING, R. "The impact of simulation on preliminary ship design", 10^{th} IMDC, Trondheim, 2009.

ANDREWS, D. PAPANIKOLAOU, A., ERICHSEN, S., VASUDEVAN, S., "State of the art report on Design Methodology", 10^{th} IMDC, Trondheim, 2009.

BALLAND, O., ERIKSTAD, S.O., FAGERHOLT K., "Optimized selection of air emission controls for vessels", Maritime Policy and Management, Taylor & Francis, Accepted for publication, 2011.

BERTRAM, V., THIART, G. D., "Simulation-based Ship Design", Oceans-Europe, 2005.

CABEZAS-BASURKO *et al.,* "Methodology for sustainability analysis of ship", Ship and Offshore Structures, 3:1, 1-11, 2008.

CAPRACE, J.D., RIGO, P., "Ship complexity assessment at the concept design stage", J. Mar Sci Technol 16:68-75, 2011.

COYNE, R. D. *et al.,* "Knowledge-based design systems", University of Sydney, Addison-Wesley Pub. Company, 1990
ERIKSTAD, S. O., "A decision support model for preliminary ship design", PhD thesis, NTNU, 1996.

ERIKSTAD, S. O., LEVANDER K., "System Based Design of Offshore Support Vessels", submitted to the 11^{th} IMDC, Glasgow 2012.

ERIKSTAD, S.O., S. SOLEM AND FAGERHOLT K., "A Ship Design and Deployment Model for Non-Transport Vessels" *Ship Technology Research,* vol 58, no 3, september 2011, pp 132-141.

EVANS, J. H., "Basic design concepts" A. S. N.E. Journal, 1959.

FITZGERALD, M.E. AND ROSS, A.M., "Sustaining Lifecycle Value: Valuable Changeability Analysis with Era Simulation," 6th Annual IEEE Systems Conference, Vancouver, Canada, March 2012.

GASPAR, H. M., BALLAND, O., "Approaching Environmental Performance in Conceptual Ship Design", 11th International Symposium on Practical Design of Ships & Other Floating Structures (PRADS), Rio de Janeiro, 2010.

GASPAR, H. M., ROSS, A., ERIKSTAD, S. O., "Handling temporal complexity in the design of non-transport ships using epoch-era analysis". Submitted to the Transactions of RINA, 2012.

GASPAR, H., *et al.*, "Efficient Design of Advanced Machinery Systems for Complex Operational Profiles", *9th COMPIT Gubbio, Italy. p. 434-448*, 2010.

GRAY, A. W., DANIELS A. S., SINGER D. J., "Impacts of Fuzzy Logic Modeling for Constraints Optimization". American Society of Naval Engineers, 2010.

HAGEN, A., "The framework of a design process language". PhD thesis, NTH – Trondheim (Nor. Univ. of Sci. and Tech), 1993.

HAGEN, A. AND GRIMSTAD, A., "The Extension of System Boundaries in Ship Design", Transactions of RINA, vol. 152, 2010.

KOLMOGOROV, A. N., "Combinatorial foundations of information theory and the calculus of probabilities", Russian Math. Surveys, 38:4, 1983.

LEVANDER, K., "System based ship design", NTNU, 2006.

MACCLAMROCK, R., "Existential cognition: computational minds in the world", Chicago - Univ. of Chicago Press 1995 (pp 102).

MAGEE, C. L., DE WECK O. L., "Complex System Classification". 14th INCOSE, 2004.

MISTREE, F. *et al.*, "Decision-based design: A contemporary paradigm for ship design", SNAME Annual Meeting, San Francisco CA, November 3, 1990.

PAPANIKOLAOU A. (editor), "Risk-based ship design – Methods, tools and applications", Springer, October 2008.

PAPANIKOLAOU A., Andersen, P., Kristensen, H. O., Levander, K., Riska, K., Singer, D., Mckenney, T., Vassalos, D., "State of art report on design for X", 10^{th} IMDC, Trondheim, 2009.

RHODES, D.H., AND ROSS, A.M., "Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods", 4th Annual IEEE Systems Conference, San Diego, CA, April, 2010a.

RHODES, D.H., AND ROSS, A.M., "Shaping Socio-technical System Innovation Strategies using a Five Aspects Taxonomy", EuSEC 2010, Stockholm, Sweden, May 2010b.

ROBERTS, C.J., RICHARDS, M.G., ROSS, A.M., RHODES, D.H., AND HASTINGS, D.E., "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration", 3rd Annual IEEE Systems Conference, Vancouver, Canada, March 2009.

ROSS, A.M., AND RHODES, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis", INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008.

ROSS, A.M., MCMANUS, H.L., RHODES, D.H., HASTINGS, D.E., AND LONG, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System", AIAA Space 2009, Pasadena, CA, September 2009.

SCHNEEKLUTH H., BERTRAM V., "Ship Design for Efficiency and Economy", Butterworth-Heinemann, 1998.

SHARMA, R., KIM, T., STORCH, R. L., HOPMAN, H. J. J., ERIKSTAD, S. O., "Challenges in computer applications for ship and floating structure design and analysis". Computer-Aided Design, 44, 2012.

SIMON, H., "The architecture of complexity". Proceedings of the American Philosophical Society, 106(6):467–482, 1962.

SUH, N. P., "The principles of design", MIT Press,1990.

SUH N. P., Complexity - Theory and Applications. Oxford University Press. 2005.

VASSALOS, D., "Design for safety" *in* "State of the art report on design for X", 10^{th} 10^{th} IMDC, Trondheim, 2009.

WHITFIELD, R. I. *et al.,* "The application of multi-objective robust design methods in ship design", 10^{th} ICCAS, 1999.

WINNES H., ULFVARSON A., "Environmental improvements in ship design by the use of scoring functions", Journal of Engineering for the Maritime Environment, 2006.