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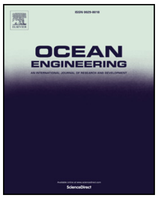

Characterizing general arrangements and distributed system configurations in early-stage ship design

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ABSTRACT

General arrangement and distributed system design is a complex problem that is a fundamental aspect of ship design. Current approaches to this design problem employ a paradigm of using automated tools to generate and analyze potential vessel solutions. These approaches rely on the generation and optimization of vessel models based on design parameters. Created vessel models are then evaluated and compared to understand how parameters influence possible vessel characteristics. This process is time and resource intensive, which limits its application in early-stage design when many critical arrangement and distributed system design decisions are made. In this paper a new approach is proposed to complement the automated tool-based paradigm. For a vessel with a defined set of systems to be arranged and connected, the approach measures the probabilistic arrangement and distributed system configuration, without generating vessel models. This efficiently provides leading indicators of the expected design outcomes and resultant vessel characteristics, which can help guide early-stage decisions and lead to better applications of resource-intensive design tools. In this paper, methods supporting this approach are presented and application is demonstrated on a naval frigate concept design.

1. Introduction

Designing a ship's arrangement and distributed system configuration is a complex and integral step of the ship design activity (Andrews, 1998; Carlson and Fireman, 1987). It requires designers to layout compartments and components as well as integrate multiple systems. The resulting solution needs to arrange all of the vital components and compartments and connect all of the interdependent components through the distributed system configuration. In early-stage design, developing arrangements and system configurations plays a fundamental role in helping designers understand and refine requirements (Andrews, 2012a). However, because designing arrangements and systems is difficult, designers often rely on automated tools to develop solutions. In order to use these tools, significant modeling, design, and computation effort is required. This can make automated tools difficult to implement and inflexible when used in novel ship design. These issues are detrimental in early-stage design, when arrangement and system configuration alternatives are best explored quickly and fluidly. This paper proposes a faster and more flexible way to explore general arrangements and distributed system configurations in early-stage design.

The presented method is analytic and determines how early-stage arrangement decisions will affect the rest of the arrangement and distributed system configuration design. The approach blends statistical mechanics methods from network science and Bayesian probability to infer how a design is likely to change from design decisions. Given some design decisions - for example, where a space will be located - the method determines the *expected* arrangement and system configuration based on the possible design permutations.

Considering the expected design can provide new insights into the complex interdependencies between arrangement and system configurations. Relative to automated arrangement tools, the analysis can be computed quickly and requires significantly less modeling and design effort to execute. Additionally, it provides information about the distributed system configuration that is not typically provided by automated methods. The insight this provides can inform critical early-stage design decisions that heavily influence the vessel's cost and performance (Andrews, 1986).

During early-stage design, vessel layouts and distributed systems are considered at low-fidelities to measure concept feasibility and requirement satisfaction (Andrews, 2011, 2016). This allows designers to make sizing and layout decisions with confidence that an acceptable distributed system can be designed for the vessel. To facilitate decision-making, designers typically generate and analyze many models of

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potential vessels. They use the models to develop a *credible* theory about the overall design problem (R. J. Pawling and Andrews, 2011). For example, a designer might use the results of ship synthesis to narrow in on a machinery room location or to eliminate a ship concept because it has a high risk of being infeasible.

This approach is exemplified by the use of Design Space Exploration (DSE) and optimization method that generate solutions to the ship arrangement problem. There has been a proliferation of automated and semi-automated design tool including Intelligent Ship Arrangements (Daniels et al., 2010; Parsons et al., 2008), Design Building Block Approach (Andrews, 2012b; Andrews et al., 2006; Mcdonald, 2009; R. Pawling, 2007), Bin-Packing (Duchateau, 2016; B. J. van Oers, 2011; B. van Oers et al., 2010), and others (Brown and Thomas, 1998; Brown and Waltham-Sajdak, 2015). In distributed system design, there is a growing a suite of semi-automated design and analysis tools, for example (Chalfant, 2015; Chalfant et al., 2012; Chalfant et al., 2015; Fiedel et al., 2011; Trapp, 2015). There are a limited set of automated tools that consider both arrangements and distributed system design explicitly, for instance the tools described (Brown and Waltham-Sajdak, 2015).

There are three fundamental drawbacks to trying to understand the ship design problem by creating and analyzing possible solutions. First, many solutions need to be created, analyzed, and differentiated to inform decisions. The tools that create a solution are often complex and may be biased by implicit design drivers in their structures or databases (Gillespie, 2012). This means that new methods and tools need to be developed every time a novel vessel is designed. Second, it is resource intensive to establish the modeling, algorithms, and analysis method that generate solutions. Because the process is intensive, designer may resort to making design decisions that facilitate the reuse of existing tools. Anecdotally, this has been observed to be a significant decision driver in naval design and can artificially constrain the design of novel vessels.

Third, most automated methods do not address both the arrangement and distributed system design problems explicitly. In arrangement methods, the impact of distributed system design is typically implicit. In distributed system design methods, arrangements are usually provided as input. In both cases, the interdependence between arrangements and distributed system design is not rigorously investigated. These three drawbacks mean that the information provided by DSE and similar approaches often require detail and resources that are incompatible with early-stage design and may not capture the interdependencies driving design outcomes.

This paper proposes a new and complementary approach for considering arrangement and distributed system design. The approach considers how a decision will influence the expected physical system solution, without requiring the population of vessel solutions. The physical system solution describes an arrangement of components within the vessel and the distributed system connectivity between them (Brefort et al., 2018). The presented analysis assesses the probability of a particular physical system solution occurring given the uncertainty and ambiguity in existing vessel design.

Given a vessel concept, a network representation is used to evaluate the expected properties of vessel solution ensembles as a function of interdependent arrangement and distributed system design decisions. Here, a solution ensemble represents the set of all physical system solutions that are possible given the vessel's mathematically plausible arrangements and distributed system configurations. Applying analysis from the statistical mechanics of random walks, the properties of solution ensembles can be calculated analytically. From this analysis, different arrangement concepts can be compared based on their ensemble properties.

Determining and comparing the characteristics of solution ensembles provides a leading indicator for solution characteristics. The results can help characterize the relationships between early-stage arrangement decisions and expect design solutions. Using this information, designers can guide decision-making towards more desirable solutions and lead to more efficient application of resource-intensive design tools. This approach can efficiently provide feedback on the expected outcomes of early-stage decisions while addressing the arrangement and distributed system design interdependence.

The proposed approach is an extension of other network-based analysis for early-stage ship design. At its core, the employed network representation relies on the relational models of ship arrangements in Gillespie (Gillespie et al., 2013) and distributed systems in Rigterink (Rigterink, 2014). Shields et al. (Shields et al., 2017; Shields et al., 2016) combined these methods to generate and analyzed distributed system routing ensembles. In those applications, ensembles helped elicit the relationships between arrangements and distributed system configuration characteristics. However, the methods were limited to the shortest-path routings of distributed system connectivity. Furthermore, potential solutions had to be generated and evaluated individually to estimate the solution ensemble characteristics. The presented method eliminates these limitations, making the ensemble results more general, reliable, and efficient to create.

The remainder of this paper provides and demonstrates the modeling and analysis framework that facilitates finding the expected design solution. The results illustrate that the impact of early-stage decisions on the vessel's arrangement and distribution system configuration can be measured before design solutions are generated. The outline of this paper is as follows. In Section 2, the network representation for vessel arrangements and distributed systems is defined. In Section 3, the ensemble analysis approach is detailed. First, the analysis for a single path in the vessel between two spaces is defined. Second, multiple path results are combined to measure the probability of component arrangements within the vessel. Third, the probabilistic arrangements are used with path results to calculate the expectation of the distributed system configuration. In Section 4, the proposed method is applied to an artificial example to demonstrate the analysis and results, and then the method is applied to a frigate concept design. Section 5 concludes the paper.

2. Network representation for arrangements and distributed systems

Network science provides a powerful toolset for describing and analyzing arrangements and distributed systems in early-stage design. To facilitate a network-centric approach, arrangements and distributed systems are broken down into interdependent architectures as described in (Brefort et al., 2018). The *physical architecture* describes spatial relationships in a system's environment. The *logical architecture* describes systems and system connectivity. Applied to the naval case, the physical architecture typically represents zone-decks in the vessel and the usable connections between them. The logical architecture represents the systems components and their functional relationships, e.g. an electrical generator is functionally related to a fan room through the power the generator provides. The *physical system solution* is a configuration of the logical architecture connectivity within the physical architecture. For example, the cable routing from the electrical generator to the fan room. The physical system solution is a mapping of nodes and edges in the logical architecture graph to nodes and edges in the physical architecture graph. Using notation from (Kurant and Thiran, 2006), this mapping is denoted as $M(S)$. An example is sketched in Fig. 1.

For this work, the physical architecture network represents zone-decks within a vessel. Zone-deck are represented as nodes and the usable adjacencies between zone-decks are edges. The logical architecture is multi-layered, where each network layer represents a different system type. In a layer, critical components or functional spaces that contain critical components (e.g. the machinery room) are represented as component nodes. Functional connections between component nodes are represented as edges within a layer. For example, a