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The use of network theory to model disparate ship design information

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ABSTRACT: *This paper introduces the use of network theory to model and analyze disparate ship design information. This work will focus on a ship's distributed systems and their intra- and intersystem structures and interactions. The three system to be analyzed are: a passageway system, an electrical system, and a fire fighting system. These systems will be analyzed individually using common network metrics to glean information regarding their structures and attributes. The systems will also be subjected to community detection algorithms both separately and as a multiplex network to compare their similarities, differences, and interactions. Network theory will be shown to be useful in the early design stage due to its simplicity and ability to model any shipboard system.*

KEY WORDS: Distributed systems; Network theory; Early stage design; Evacuation.

INTRODUCTION

Ships are extremely complex systems comprised of many smaller but equally complex subsystems that often have unforeseen interactions and interdependencies. This paper introduces a network theory based approach to quickly model and analyze the design of these systems and their interactions. The goal of this work is provide a new way of handling ship and ship system design information in the early design stage. All too often, information about the interactions of ship systems is only captured in detailed CAD models that are not available in the early stages of design. The lack of knowledge of these interactions can lead to substantial redesign in later stages or, in extreme cases, unforeseen failures in completed ships.

The paper will begin with a brief introduction to relevant network theory concepts, the network representations of three ship systems are developed and each system is analyzed individually. The systems to be analyzed are a passageway system with a focus on evacuation and personnel movement, an electrical system with focus on robustness, and a fire fighting system also with a focus on robustness. The individual systems will be analyzed using the network concepts of density, centrality, and community structure. Following the individual analysis, the three systems will be analyzed as a whole using a multiplex network which will enable the evaluation of disparate systems in a common framework. The paper will conclude with a brief summary and a discussion of possible directions for future research.

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MOTIVATION

Existing general arrangement tools are capable of generating feasible layouts, but lack the underlying knowledge regarding why layouts are configured as they are. Network based methods, developed at the University of Michigan (Gillespie, 2012), can be used to bridge this gap as they provide a unique perspective to the traditional view of ship arrangements by relying on the relationships between ship board elements and components. A network analysis expands the scope of the general arrangement process and helps to manage complexity by revealing underlying character and structure, providing insight into the function of a complex system. Quality three dimensional distributed system layouts are difficult to generate, thus the ability to evaluate the design drivers prior to the general arrangement process through a network approach would be of value. Identifying the disparate ship design information in the form of design drivers captures the abstract concept of designer intent while modeling design rules and best practices. These metrics indicate the underlying personality and style of the design (Pawling et al., 2013). By modeling ship systems as networks, the designer can evaluate network metrics to further understand the design space.

Graph theory also has been shown to be useful as a model for the facilities layout problem (Hassan and Hogg, 1987; Singh and Sharma, 2005). Graph theoretic principles can also be combined with optimization methods for solving the facilities layout problem for single floor facilities (Azadivar and Wang, 2000) and multi-floor facilities like ships (Lee et al., 2005). These methods tend to focus on layout generation whereas the method and tools presented in this paper concern themselves with analysis, though it would not be difficult to integrate the metrics introduced in this paper into an optimization framework to aid in ship layout generation.

While graph theoretic and network science based approaches employ the same modeling framework, graph theory applications tend to be small and rely on the graph to be planar (Fleck, 2013). Network science provides methods for understanding the complex layout problem on a larger scale while addressing the disparate and uncoordinated set of rules and guidelines that are evolutionary over a period of time within a ship design. As a result, network based approaches are appropriate for complex ship design systems and for bridging the gap between space-only arrangements and distributed system layouts (Gillespie and Singer, 2012).

Network theory can also be used to model the structure of design tools (Parker and Singer, 2013) and give insight into the fundamental relationships between variables with those tools. These relationships can be used to predict the outcomes of larger design structures. This paper will focus more on the modeling the design rather than the tools used to create said design but will be cognizant of the designer bias that may drive the design to a specific solution.

NETWORK THEORY BACKGROUND

This section serves to introduce basic network theory nomenclature and metrics used in this paper. For a more comprehensive discussion of network and graph theory the authors recommend the textbook written by Newman (2010).

Network structure

Networks, which are also called graphs depending on the context, consist of a collection of nodes connected by edges. The networks described in this section and the next are known as simplex networks in that the nodes and edges represent only one type of entity and connection, respectively. For this work, networks will be represented mathematically using an adjacency matrix A, which represents the connections between the nodes. The two most basic kinds of networks are undirected and directed networks. In an undirected network the adjacency matrix is symmetric and the links between nodes represent any connection between them. A directed network on the other hand has an asymmetric adjacency matrix and the edges represent a link from one node to another.

Fig. 1 displays an unweighted, undirected network with its adjacency matrix. In this kind of network, an edge is represented by the number 1 in some element of the matrix showing a connection from node i to node j. If the edges are something other than one this is what is called a weighted network. Weighted networks allow for capturing how strong a link between two nodes or from one node to another is (depending on if the network is directed or undirected). In this paper, only undirected, weighted networks will be used.

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