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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

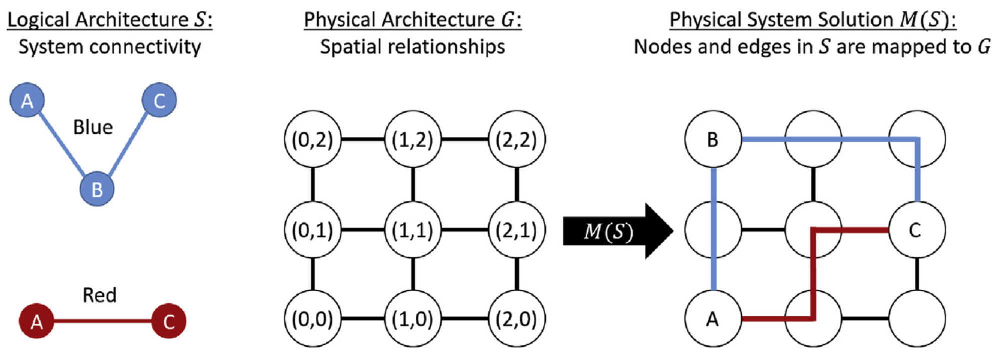

Fig. 1. Example of a logical architecture, physical architecture, and physical system solution networks. The logical architecture describes systems and their connectivity, where nodes are components in the system, edges are connections between components, and layers represent different system types, e.g. Red and Blue systems. The physical architecture describes the spatial relationships in the system's environment. The physical system solution is a mapping of the logical architecture to the physical architecture. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

generator and fan room are represented as nodes in the electrical power and chill water distribution layers. In the electrical power layer, an edge between them denotes that they are functionally related. In the chill water distribution layer, the generator and fan room would not have an edge because the neither the generator or fan room produce chill water that the other uses.

Feasible vessel arrangements and distributed system configurations require a definition of a satisfactory mapping of the logical architecture to the physical architecture. Depending on the stage of the design, there may be a near infinite number of possible mappings that need to be evaluated. However, regardless of the design stage, each possible mapping is a composite of paths in the physical architecture that facilitate the relationships in the logical architecture (Shields et al., 2017).

Physical system solution mappings can be broken into the mapping of individual nodes and edges in the logical architecture to the physical architecture. Nodes in the logical architecture map to nodes in the physical architecture. This represents the location of that component in the environment. To denote this mapping, the ith component node $c_i \in S$ is mapped to its corresponding location node $u_i \in G$ by the mapping $M(c_i)$. Edges in the logical architecture map to paths in the physical architecture. This represents the route through the physical architecture that connects two components on a logical architecture edge. To denote this mapping, the edge between the ith and jth components (c_i, c_j) in layer l of S is called e^l, the mapping $M(e^l)$ is the path through G that connects the respective locations u_i and u_j that correspond to c_i and c_j.

To generate a physical system solution, each component or functional space node in S is mapped to a location node in G. Then every logical architecture edge, $e^l = (c_i, c_j)$ in each layer S^l is mapped to a path in G. The mapping of a system layer S^l is called $M(S^l)$ and the mapping of the complete logical architecture is called $M(S)$. Once $M(S)$ generated, it represents a physical system solution for the defined logical and physical architectures.

In early-stage design, the mappings of components and paths is often ambiguous or uncertain. For example, component and functional space mappings may be ambiguous if the designer has not assessed the possible locations it could be placed. If the mapping had been assessed, but there was not a selection between locations, the mapping may be uncertain (e.g. 75% chance it goes to one location and 25% it goes to another). To account for this, mappings can be looked at from a probabilistic perspective. The probability that some set of node and edge elements E in the logical architecture maps to a location node i in the physical architecture is called p_i^E and the mapping to edge (i, j) in the physical architecture network is called p_{ij}^E. If the probability of the mapping is unknown, it is denoted as $p_{ij}^E = x$, where x is an unknown probability. Fig. 2 sketches a probabilistic mapping of component nodes to locations.

3. Evaluating solution ensembles

The objective of this paper is to assess the expected outcomes of the physical system solution ensemble given the logical and physical architectures. The desired values are the probability that a physical system solution for the physical and logical architectures use the individual elements of the physical architecture. This represents the probability that a randomly drawn solution would use each part of the physical architecture. The following methodology will use ensemble analysis to explore three cases of distributed system design: when there is a known arrangement, an uncertain arrangement, and an ambiguous arrangement. The first case occurs when each component represented by nodes in S is mapped to a location represented by a node in G. This describes a case where the designer is able to define the arrangement of components within the vessel. The second case occurs when components may be mapped to more than one location with varying probability. This describes when the designer is uncertain as to exact location of components. For instance, when a component is equally likely to be two adjacent zone decks, but the exact location is not decided. The third case occurs when components may be mapped to more than one location with unknown probability. This describes when the designer knows possible locations, but does not know/care where the component will be placed.

Ensemble characteristics of possible solutions for logical and physical architecture can be investigated by enumerating each path $M(e^l)$ for all edges in S and then creating solutions from all combinations of paths. However, it is not practical to implement an enumeration because the number of possible solutions quickly becomes intractable when G and S are non-trivial. Thus, for complex vessel design it is not possible to exhaustively evaluate the ensemble properties. To remedy this issue, a probabilistic approach is used.

In the probabilistic approach, an ensemble perspective of the solutions is built up from the ensemble characteristic of each path $M(e^l)$ that makes up the physical system solution. First, the probability of each path in $M(S)$ using an element in G is calculated. For a given path between two nodes in G, this measures how likely that path is to pass over each node and edge in G. Second, the probabilistic path results are combined to provide the probabilistic mapping for any ambiguous arrangement mappings. Third, the complete set of arrangement mappings are combined with results from the first step to calculate the probabilities that any physical system solution uses each node and edge in G. This provides the probability of an arrangement and distributed system design given the logical and physical architecture. The supporting analysis follows.

The first step, determining the probability distribution of a path through G, is facilitated by the mechanics of random walks. If a path between two nodes in G can be described as a random-walk, then the probability that the path uses a given node or edge in G can be calculated by analyzing the structure of G. Given a path from node u to node v (excluding paths that do not lead from u to v), the probability that the path uses a node element i is defined as p_i^{uv}. The probability that any

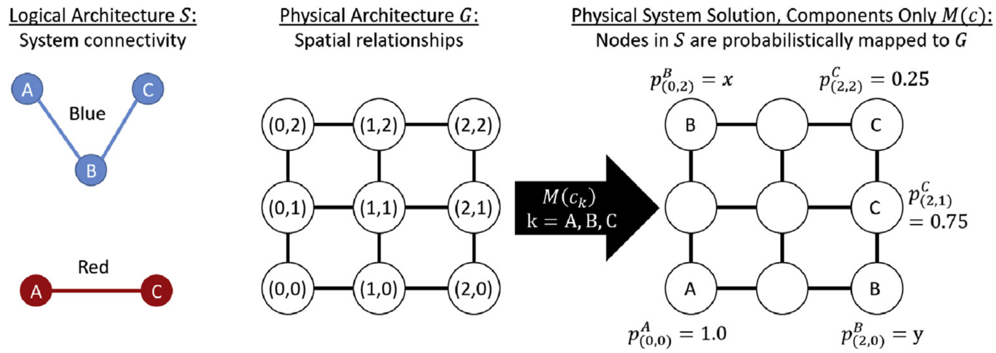

Fig. 2. Example of probabilistic mappings to the physical system solution. The probabilistic mapping of component c to locations i is denoted as p_i^c. Here, component A has a 100% chance of mapping to location (0,0), component B is mapped to (0,2) and (2,0) with unknown probability, and component C is mapped to (2,1) with a 75% probability and (2,2) with a 25% probability.

path from u to v uses edge (i, j) is defined as p_{ij}^{uv}. Newman (2005) showed that these probabilities can be found by evaluating the flow of electrical current from u to v over the network G, assuming that each edge in the network has resistance $\Omega = 1$. The steps for the calculation, as defined by Newman (2005) are:

1. Construct the matrix $D - G$, where D is the diagonal matrix of node degrees and G is the adjacency matrix.
2. Remove any single row, and its corresponding column from the matrix. For example, the last row and column.
3. Invert the resulting matrix and then add back in a new row and column consisting of all zeros in the position from which the row and column were previously removed (e.g. the last row and column). Call the resulting matrix T, with elements T_{ij}.
4. Calculate p_{ii}^{uv} for each node in G as:

$$p_i^{uv} = \frac{1}{2}\sum_j A_{ij}|T_{iu} - T_{iv} - T_{js} + T_{jt}|, \quad \text{for} \quad i \neq u, v.$$

5. Set $p_u^{uv} = 1$ and $p_v^{uv} = 1$ to denote that the walk must include the beginning and ending nodes.
6. Calculate p_{ij}^{uv} for each edge in G as:

$$p_{ij}^{uv} = A_{ij}|T_{iu} - T_{iv} - T_{js} + T_{jt}|.$$

The probability of path routing can be extended to account for uncertainty in vessel arrangements. Mathematically, this is uncertainty in the mapping of nodes in S to locations in G. For example, node c_k in S may have 50% chance of being located at both node u and v in G (i.e. $p_u^{c_k} = p_v^{c_k} = 0.5$). Another node c_l in S is located at w in G. In this case, the probability of the path between c_k and c_l using an element in G would be the weighted sum of probabilities for each combinations of locations, $c_k = u, c_l = w$ and $c_k = v, c_l = w$; $p_{ij}^{c_k c_l} = 0.5 p_{ij}^{uw} + 0.5 p_{ij}^{vw}$. This can be generalized to,

$$p_{ij}^{c_k c_l} = \sum_{c_k}\sum_{c_l} p_u^{c_k} p_v^{c_l} p_{ij}^{uv},$$

where the summation over c_k and c_l are over their possible locations, and p_{ij}^{uv} is calculated as described previously. This is the foundational calculation for determining the ensemble characteristics of the physical solution mapping. Next, it will be applied to find the probabilistic mapping of components with ambiguous locations in the vessel.

The second part of combining the path results is to combine the probability distributions for the individual paths and resolve ambiguous mappings in the physical system solution. In this case, the possible nodes that u can map to may be known, but the probabilities those mapping may be unknown. For example, node c_k in S could be mapped to node u or v, but the designer has not chosen the likelihood of either event. In order to analyze this case, the physical architecture network must be temporarily altered to evaluate the probabilities $p_u^{c_i}$ and $p_v^{c_i}$ for $M(c_i)$.

To evaluate the case where the mapping $M(c_k)$ is unknown, but could go to many possible nodes in $U_k \in G$, first a supernode s is added to G with edges to each possible node in U_k, e.g. (s, u) for $u \in U_k$. This alteration allows the probability that a distributed system routed to the supernode through each of the edges (s, u) for $u \in U_k$ to be calculated. These probabilities, $p_{su}^{c_i c_j}$, represent the probability that each logical architecture edge (c_k, c_l) maps c_k to u. Thus, single edge probabilities can be treated as evidence that the component is mapped to a location. This evidence can combined using Bayes' Thereom to find the overall mapping probability given every edge in the logical architecture that involves node c_k. Assuming that each edge routing is independent and there is no initial preference for the mapping, the probability of component c_k mapping to node u is,

$$p_u^{c_k} = \frac{\prod_{(c_l, c_m)} p_{su}^{c_l c_m}}{\sum_v \prod_{(c_l, c_m)} p_{sv}^{c_l c_m}},$$

for $v \in U_k$ and for all edges (c_l, c_m) containing c_k in S,

where $p_{si}^{c_k c_l}$ can include uncertain mappings as described previously. If multiple ambiguous mappings exist, then supernodes are added to G for each such mapping. The calculation of $p_{si}^{c_k c_l}$ between two ambiguous mappings is calculated using the respective supernodes instead of v.

Once ambiguous mappings are resolved, the probabilities of each mapping location are used to combine the individual path results to get the probabilistic mapping of the physical system solution. Here, the objective is to calculate, for each node and edge in G, the probability that the physical system solution uses that element. This generalizes to the probability that a subset of logical architecture edges $E \in S$ maps to the elements of G. The probability of the mapping $M(E)$ to an element is called p_{ij}^E and is calculated using the probability that any edge mapping $M((c_k, c_l) \in E)$ uses $(i, j) \in G$. However, due to the uncertainty in component locations, this needs to be summed over the set of possible component arrangements and the probability of that arrangement occurring. Using the complement of the probability that no edge uses the element (i, j), the complete summation is

$$p_{ij}^E = \sum_{u_0 \in U_0} \dots \sum_{u_n \in U_n} p_{u_0}^{c_0} \dots p_{u_n}^{c_n} \cdot \left(1 - \prod_{(c_k, c_l) \in E} \left(1 - p_{ij}^{u_k u_l}\right)\right),$$

where u_k is the location of component c_k given its possible locations $U_k \in G$ and $p_{u_k}^{c_k}$ is the probability that c_k is located at u_k. If E contains all edges in S, then p_{ij}^E gives the probability that element $(i, j) \in G$ is used in the physical solution mapping $M(S)$. Smaller subset, such as the edges in logical architecture layer $E = S^l$, give the probability that the system mapping $M(S^l)$ uses (i, j). Applied to every element in the physical architecture, this give the desired probabilistic mapping of the vessel's arrangement and distributed system design.

To summarize, the method for calculating the ensemble probabilities of an arrangement and physical system solution, which is the expectation of finding each component and the distributed system at each location in vessel, is as follows:

1. Calculate the probability of locations each ambiguous mapping.
2. Calculate $p_{ij}^{u_k u_l}$ for each pair of component locations (u_k, u_l) that exists between connected components in the logical architecture.
3. Combine the probabilities of each logical architecture edge in layer l to calculate p_{ij}^{E} for $E = S^l$.
4. Combine the probabilities of each logical architecture layer in S to calculate p_{ij}^{E} for $E = S$.

4. Examples and applications

In this section, a number of examples are provided to illustrate the properties and use of the expected design outcomes approach to vessel arrangement and distributed system design.

4.1. Simple example

First, a small case demonstrates the application of this approach on a 3-by-3 physical architecture and a logical architecture with three components. The components in the logical architecture have fixed, uncertain, and ambiguous mappings to the physical architecture. The physical architecture, logical architecture, and results for by system types are sketched in Fig. 3. It should be noted that the logical architecture network is unweighted as the method does not consider the relative strength or importance of connections between component nodes. Probabilistic mapping results for the individual systems $M(S^l)$ and the overall logical architecture $M(S)$ are shown in Table 1.

As the figure and table show, the ensemble analysis provides a picture of expected distributed system configuration and arrangement. This quickly provides information about the likely characteristics of the physical system solution. It can also generate valuable insight into the expected design outcomes. For example, using the logical architecture mapping, an underlying distribution for Component B's location is calculated. Without ensemble design analysis, Component B's location would remain ambiguous or be incorrectly assumed as uniformly distributed between its possible locations. Furthermore, generating the routing information would require an enumeration of all possible component arrangements and distributed system configurations. Even for this seemingly trivial case, there are 4884 possible solutions if only paths without repeated nodes are considered, and many more if random walks are considered. This illustrates why the enumeration approach is impractical in more complex applications.

Table 1
Probabilistic mapping results for nodes in the example in Fig. 2. In each mapping, node (0,0) is always included because $p_{(0,0)}^{A} = 1.0$. Nodes (2,2) and (2,1) are the possible locations of node C in the logical architecture and have mapping probabilities greater than their respective p^C. This is the result of paths component locations using those nodes.

Node	$M(S^{Blue})$	$M(S^{Red})$	$M(S)$
(0,2)	0.546	0.188	0.630
(1,0)	0.631	0.531	0.827
(2,2)	0.472	0.406	0.582
(0,1)	0.592	0.469	0.783
(1,1)	0.500	0.500	0.750
(0,0)	1.000	1.000	1.000
(2,1)	0.907	0.875	0.953
(1,2)	0.469	0.281	0.609
(2,0)	0.683	0.313	0.781

4.2. Ship design example

Now, an early-stage ship design examples is given. The example is based off of the bin-packing automated arrangement approach and provides a comparison of automated tools and the proposed analytic approach. Comparing bin-packing results to the probabilistic mappings demonstrates how the probabilistic mapping can effectively characterize design problem outcomes.

van Oers introduced the automated bin-packing as a method generate vessel arrangements in (B. van Oers et al., 2010). He demonstrated the method on a simplified frigate, shown in Fig. 4. In the demonstration, he explored how the frigate's arrangement changed when the location of certain components was altered. Specifically, he showed the vessel's baseline configuration with the flight deck in the aft and an alternative arrangement with the flight deck towards the bow.

The frigate arrangements were generated by seeding a genetic algorithm with initial positions for primary system components locations. This is an example of using automated tools to understand the design problem. Many possible arrangements are generated, evaluated, and improved upon to understand how a decision will change a vessel design. Using the analytic methods presented here, some of the same arrangement relationships as well as distributed system design relationships can be elicited directly, instead of inferred from vessel models.

First, the frigate is converted into its physical and logical architectures. The physical architecture describes the relationship between zone-decks in the vessel. This is modeled with only the longitudinal relationships between zones, but three-dimensional arrangements can be modeled by including transverse zone-decks and their relationships.

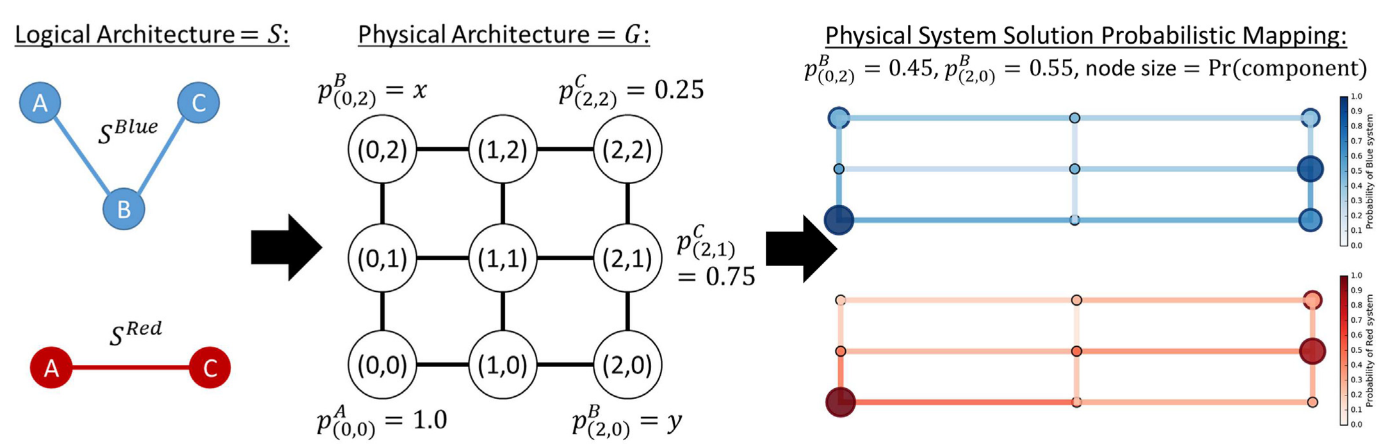

Fig. 3. Probabilistic mapping results for the logical and physical architectures sketched in Fig. 2. The ambiguous mapping $M(B)$ is resolved through the probabilistic approach, $p_{(0,2)}^{B} = 0.45$ and $p_{(0,2)}^{B} = 0.55$. Because the location of node B is interdependent with the placement node A and C, assuming that $M(B)$ is a uniform does not represent its true distribution over its possible locations.

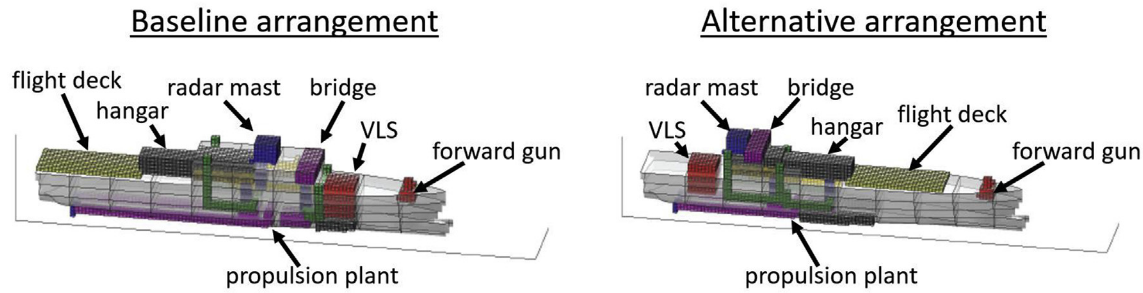

Fig. 4. Simplified frigate arrangements generated by the bin-packing approach, reproduced with permission from (B. J. van Oers, 2011).

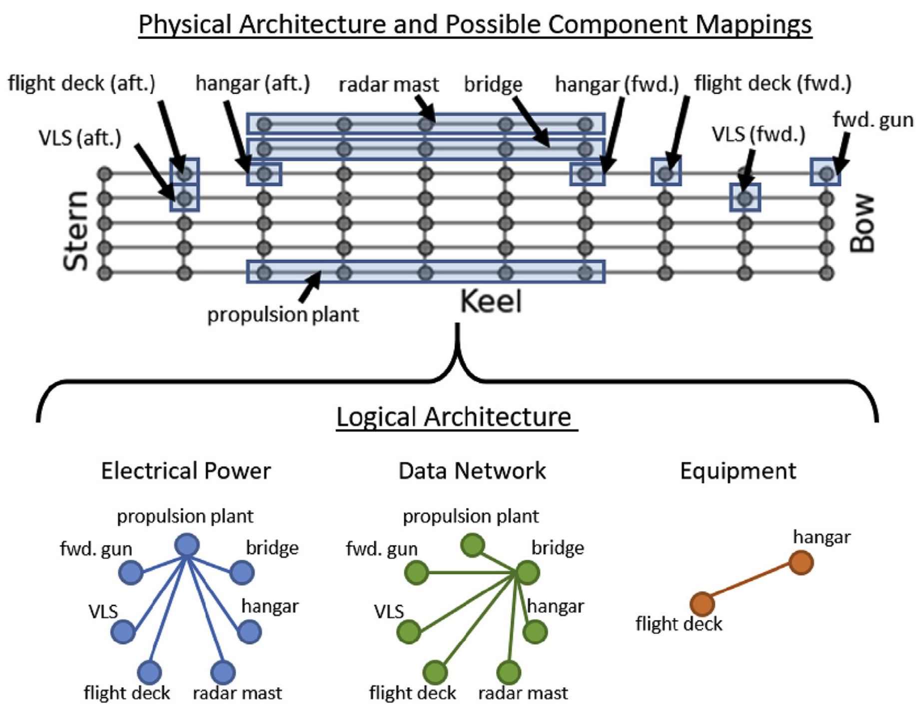

Fig. 5. Physical and logical architectures for the frigate concept in Fig. 3. Zone-decks in the vessel are converted into a network with component placements (blue boxes) representing the two arrangements in Fig. 4. Primary components/functional spaces are connected in three logical architecture layers. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The logical architecture describes the primary system components and their relationships in terms of the electrical power, data network, and equipment movement (e.g. helicopters from the hangar to flight deck). Second, the probability of creating either arrangement is investigated. Each component is mapped to their locations in both the flight deck aft arrangement and flight deck forward arrangement. The probability of each mapping is left ambiguous to see if there is a tendency to map toward one arrangement or the other. The network representations are shown in Fig. 5.

Results of the probabilistic mapping in Fig. 6 show that, given the architectures, there is not a significant difference in probability of the flight deck being forward or aft. In the bin-packing demonstration, the two solutions placed components close to the initial locations given to the genetic algorithm. This suggests that component locations are not strongly driven to one arrangement or the other. If true, this matches the ensemble results that the two solutions are almost equally likely to occur across a random draw.

While the bin-packing results are influenced by naval architecture considerations, the ensemble analyses suggest that there is a preference for the propulsion plant location which could arise from the implicit distributed system considerations. Fig. 6 shows that there is a high probability (51%) that the propulsion plant is located in the position

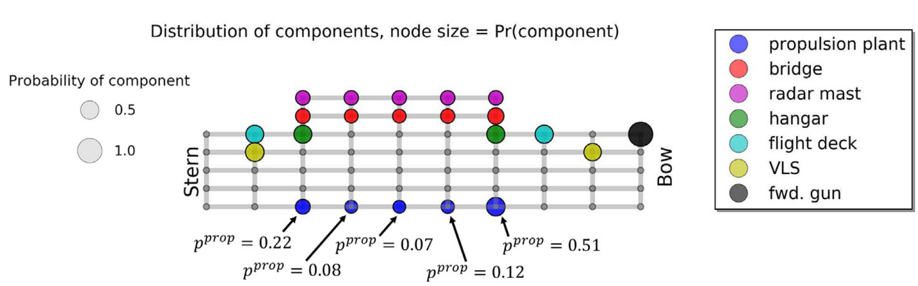

Fig. 6. Probabilistic arrangement mapping for the frigate concept represented in Fig. 5. Component and functional spaces are color-coded and the probability of a component mapping to a location is denoted by the node size. The propulsion plant mapping p^{prop} is shown explicitly. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

closest to the bow. This also appears to coincide with the bin-packing solutions. In the baseline configuration, the propulsion plant is located at the zone-deck represented by the highest probability mapping. In the flight deck forward configuration, the propulsion plant is initially seeded at the stern of the ship (10 m), but is placed near midships (~40 m). This distance between initial seeding and final component location in the bin-packing solution, indicates that the propulsion plant is drawn forward in the bin-packing arrangements.

The distributed system configuration is not generated in the bin-packing demonstration, but can be investigated with the proposed methods. Fig. 6 shows the probabilities of system mappings for electrical power systems. Mapping results near the propulsion plant indicates that there is an 65% chance that the electrical power distribution exists on the vertical edge over the most forward propulsion. This is 11 percentage points higher than the next highest propulsion plant location. Additionally, there is a high probability of the distribution system existing along the keel. One zone-deck higher, the probability of transverse routing is on average 21 percentage points lower. This suggests vertical cable trunk from the propulsion plant is likely to be needed forward in the vessel and is expected to route transversely along the keel and then vertically. Probabilities higher up in the vessel show that certain areas in the physical architecture are highly likely to have the electrical power system mapped to them. Regardless of the exact arrangement, these areas should be designed to accommodate electrical cabling. In contrast, the regions near the bow and stern on lower in the vessel are relatively unlikely to have the electrical power system located there.

Variations to the logical architectures would affect the characterized design outcomes. For example, loops in the logical architecture would increase the probability that the components in the loops are close to each other. Furthermore, the loops would increase the probability that distributed systems exist in the physical architecture network between the looped components. Also, a propeller is not included in the model. If it was included, it would increase the probability of the propulsion plant being placed at the aft nodes in the physical architecture network.

In terms of the electrical power distribution system design, results in Figs. 6 and 7 estimate the design characteristics despite the arrangement uncertainty and limited distributed system information. The influence of a design change can also be evaluated. To demonstrate, watertight subdivision is enforced with transverse bulkheads that prevent system routings between zone-decks on the lowest three decks. Results for the electrical power system mapping in Fig. 8 show that this creates a high probability of transverse routings directly over the subdivisions. From a distributed system design perspective, the high probabilities suggest where the electrical power distribution bus should be located. Furthermore, the probabilities indicate this bus location is invariant with respect to the flight deck forward and flight deck aft arrangements. While this is intuitive from a ship systems design perspective, it is notable that the analytical approach replicates design intuition.

The subdivision also influences the arrangement probabilities. While there is still no discernable preference towards the flight deck forward or flight deck aft arrangement, the propulsion plant location is more evenly distributed across its possible location. In the subdivision example, the largest difference between propulsion plant locations is 23 percentage points. In comparison, there is a 44 percentage point difference without subdivision. This suggests that subdivision decisions can significantly influence the propulsion plant location by constraining its connectivity with other components in the vessel.

Subdivisions also shift the probabilistic location of the bridge. In the subdivision case, the bridge has a 40% chance of being located at its forward most location, versus a 28% chance without subdivision. When the subdivisions constrain connectivity with the propulsion plant, the bridge and propulsion plant are more likely to be arranged closer together because there is less variation in the routings. In effect, limiting the routing variations from the propulsion plant to the bridge pulls the two node locations in-line with one another. This effect is compounded by the coupling between the bridge and propulsion plant in both the information and electrical power system.

These results indicate that the interdependence of distributed systems and arrangements create a relationship between the zone-deck subdivision, the distributed system design, and the arrangement of the propulsion plant and bridge. Because the probabilistic outcome analysis accounts of the interdependence of arrangements and distributed systems, these design relationships and their influence on the solution can be efficiently identified and measured. Considering these interdependencies provides new and useful information to designers, for instance the coupling between the bridge and propulsion plant location.

5. Conclusions

Design of vessel arrangement and distributed systems is complex task with many constraints, numerous interdependencies, and near infinite possible solutions. Traditional naval architecture design employs automated tools to enumerate many of these possible solutions and interrogate them to identify design decisions that produce desirable designs. In novel vessel design, the automated approach is often overly case-specific and too resource intensive to be used in concept design.

In this paper, an analysis approach which finds the expected vessel arrangements and distributed system configuration is proposed. This approach considers the potential outcomes of a design, without generating vessel models, to help guide design decision-making and higher-fidelity investigations. The proposed approach employs a network model of a vessel's physical and logical relationships to create a probabilistic mapping of arrangements and distributed systems. In essence, this provides the probability of an arrangement and distributed system configuration randomly occurring. Using this information, the vessel design can be characterized despite design uncertainty and ambiguity.

In the future, this approach will be tested on more difficult problems, including those in 3-dimensions and multi-hull configurations. In these more difficult problems, the design characterizations may be less pronounced than in the small design example in this paper.

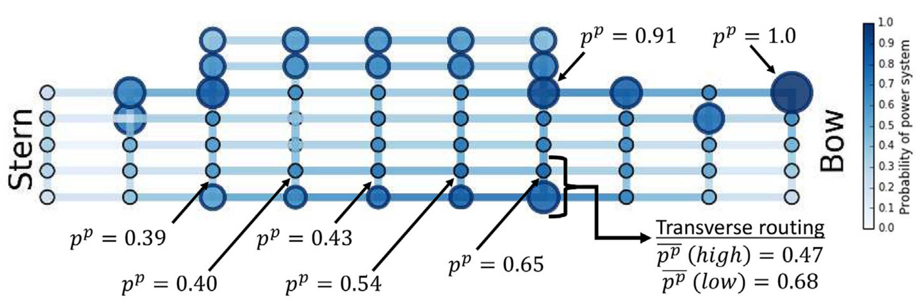

Fig. 7. Probabilistic electrical power system mapping. Colors on each element represent p_{ij}^p the probability of the electrical power distribution system existing at a location in the physical architecture. The size of the large nodes represents the probability that a component is located at that node. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

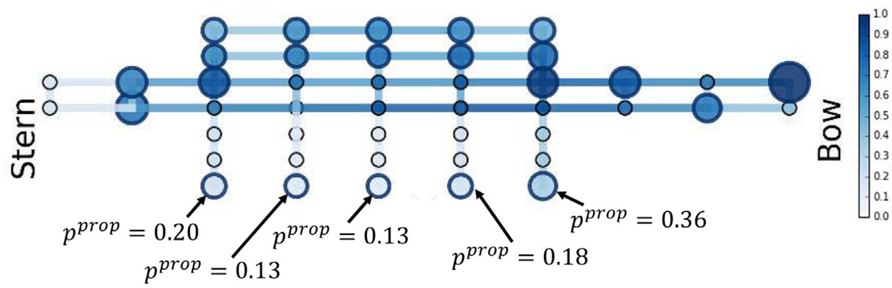

Fig. 8. Probability of electrical power system mapping with subdivision. Colors on each element represent p_{ij}^{p} the probability of the electrical power distribution system existing at a location in the physical architecture. The size of the large nodes represents the probability that a component is located at that node. The propulsion plant mapping p^{prop} is shown explicitly. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Developing methods to apply statistical analyses, such as hierarchical clustering, on the mappings of individual layers and edges may help elicit the influence of components on one another. In addition, sampling arrangements and system configurations from the probabilistic mapping would allow performance metrics to be evaluated. For example, this would allow complexity – such as the knowledge-based complexity (Shields, 2017) – or functional requirements to be considered. Other analyses may address incompatibilities between systems and spaces as well as traditional naval architecture analyses.

The approach taken in this paper can help mitigate the design risks that arise from making early-stage design decisions. The probabilistic approach provides new information about what to expect from one of the most complex and influential aspects of ship design. A number of examples demonstrate the value of addressing early-stage arrangements and distributed system configurations with this approach. Moreover, the authors hope that the approach of analyzing the structure of a design problem to indicate what designers should expect from its solutions will be expanded into other realms of the ship design activity.

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