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Characterizing Three-Dimensional General Arrangements and Distributed System Configurations Utilizing an Architecturally Normalized Current Representation

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ABSTRACT

Designing ships involves intricate layouts and multifaceted systems—ranging from mechanical to operational—that must be interdependent and thus precisely arranged. Traditional automated tools, though effective, are often too resource-intensive to be feasibly employed during the critical early stages of design. This paper builds on prior work that introduced an innovative solution: a network-based, architecturally normalized current representation, which offers a computational method to predict system arrangements in two dimensions without generating detailed vessel models. Our method's advantage lies in its ability to guide early-stage design decisions, thereby optimizing the use of subsequent, more resource-intensive design tools. This study extends the method to a three-dimensional framework, capturing more nuanced system-to-system interactions and yielding more realistic ship arrangements. A methodology was proposed to support this three-dimensional extension and demonstrate its applicability through a case study focused on the conceptual design of a naval frigate.

KEY WORDS

Early-Stage Design; Complex Systems; General Arrangements; Distribution Systems; Design Network Analysis.

INTRODUCTION

The advent of three-dimensional (3D) modeling in naval architecture heralds a transformative era in ship design, one that transcends the conventional two-dimensional (2D) paradigms and unlocks a new dimension of possibilities. This paper critically extends the 2D network-based approach by Shields et al. (2018), tailored for ship design, into a more sophisticated and spatially comprehensive 3D framework. The methodology by Shields et al. (2018), notable for its computational approach to guide early-stage design decisions, established a novel approach in naval architecture by simplifying the multifaceted interplay of ship layouts and systems. However, STERN et al. (2015) highlights an inherent complexity of modern naval vessels, with their intricate spatial configurations and interdependent systems, which then necessitates a shift to a 3D perspective that can encapsulate these complexities with greater fidelity.

The objective of this study is thus twofold: to validate the feasibility of transitioning to a 3D network-based ship design algorithm and demonstrate its efficacy in addressing the spatial dynamics integral to modern ship design. The transition from

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2D to 3D is not just an incremental step but offers a different approach to naval architecture, one that captures the knowledge without necessarily going into high-fidelity models, which has inherent challenges as proposed by Jeong et al. (2017). This methodology is particularly advantageous in the early stages of design, where the flexibility to explore a set of configurations and their implications on the overall design is paramount.

To elucidate the practical application and efficacy of this 3D algorithm, this paper presents a proof-of-concept study centered on the conceptual design of a naval frigate. This case study, chosen for its complexity and relevance, serves as a testbed to underscore the algorithm's potential in navigating the intricate landscape of naval vessel design. By demonstrating the algorithm's utility in a real-world scenario, the authors aim to establish its role as a pivotal tool in the modern naval architect's toolkit, contributing significantly to the evolution of ship design practices.

The migration to 3D design in naval architecture represents not just an advancement in design techniques but a paradigm shift in conceptualizing and actualizing naval vessels. Brefort et al. (2018) also highlights the need to offer the ability to preempt and address design challenges in early-stage design, and provide a knowledge-based view of the vessel's architecture. By conducting a proof-of-concept with a naval frigate design, this study aims to demonstrate how 3D modeling can enhance early-stage design decisions, offering a more comprehensive and flexible approach to naval architecture. This incremental transition offers a greater understanding into a vessel's operational and structural inter-dependencies, necessary for a design to consider during early-stage design.

BACKGROUND

A network-based approach may utilize two types of centrality within its algorithm: betweenness centrality and eigenvector centrality, as highlighted in Shields et al. (2018)'s work. Newman (2010) defines betweenness centrality as the number of times a node acts as a bridge along the shortest path between two other nodes. A node with high betweenness centrality in a naval design network might represent a critical component or design feature that connects various subsystems or design areas, highlighting its influence on information or workflow across the design process. Eigenvector centrality considers not only the number of connections a node has but also the quality of those connections. A node connected to other highly connected nodes has high eigenvector centrality. In naval design, this could identify key components or systems that are not only well-connected but also linked to other central elements, amplifying their influence.

Eigenvector Centrality

Eigenvector centrality $C_E(v)$ assigns relative scores to all nodes in the network based on the principle that connections to high-scoring nodes contribute more to the score of the node in question than equal connections to low-scoring nodes. The eigenvector centrality of node v is defined as:

$$C_E(v) = \frac{1}{\lambda} \sum_{t \in M(v)} A_{vt} C_E(t) \tag{1}$$

where:

1. $M(v)$ denotes the set of neighbors of v
2. A_{vt} is an element of the adjacency matrix A of the network, which is 1 if v and t are connected and 0 otherwise
3. λ is a constant (specifically, the largest eigenvalue of A)

This can be represented in a more compact form using the eigenvector equation:

$$A\vec{x} = \lambda\vec{x} \tag{2}$$

where $\vec{x}$ is the eigenvector corresponding to the largest eigenvalue λ, and the components of $\vec{x}$ are the eigenvector centralities of the nodes.

In naval design, nodes (design elements of systems) with high eigenvector centrality are those that are not only well-connected but also connected to other well-connected nodes, indicating their strategic importance in the design's overall effectiveness and efficiency.

Betweenness Centrality

Betweenness centrality $C_B(v)$ of a node v quantifies the extent to which v lies on the shortest paths between other nodes. It is defined as:

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{3}$$

where:

1. σ_{st} is the total number of shortest paths from node s to node t
2. $\sigma_{st}(v)$ is the number of those paths that pass through v

This metric highlights nodes that serve as critical connectors or bridges within the network, which in the context of naval design, could represent elements or systems critical to the integration or interoperability of different components.

Impact on Centrality Metrics

Changing requirements within the network impacts the centrality metrics in different ways.

For betweenness centrality, changing a requirement may affect the betweenness centrality of certain nodes by altering the shortest paths through the network. Newman (2005) proposes that nodes that previously acted as critical bridges between different parts of the design might see their betweenness centrality decrease if the change bypasses them, highlighting alternative pathways or components that have become more critical. Conversely, the introduction of new requirements or the modification of existing ones could elevate the strategic importance of previously peripheral nodes, as they become pivotal in connecting various components of the design.

For eigenvector centrality, the eigenvector centrality of a node reflects its connection to other influential nodes. As highlighted by Newman (2006), changing a node, hence requirement, could shift the network's structure of influence, affecting which nodes are considered central. A requirement change could make certain nodes more central if they are now more directly connected to or dependent on other highly central nodes. This shift can reveal which elements of the design are gaining or losing importance in the context of the overall system architecture and where design efforts may need to be concentrated.

These changes to centralities inform the designer mathematically in 4 ways:

1. **Identifying Critical Components:** By tracking the percentage-value changes in centrality measures, designers can identify which components have become more or less critical to the design's functionality. This can guide resource allocation, highlighting where additional analysis or robustness might be necessary in the design.
2. **Understanding System Interdependencies:** Changes in centrality can also reveal previously unnoticed interdependencies between components. Designers can use this insight to anticipate potential cascading effects of changes throughout the system, leading to more resilient designs.

3. **Highlighting Opportunities for Optimization:** Significant changes in the network's structure, as reflected by centrality measures, can uncover opportunities for optimizing the design. For instance, reducing the betweenness centrality of overloaded nodes can lead to a more balanced and efficient design.
4. **Informing Design Iteration:** By quantitatively assessing how a single requirement change affects the network, Shields (2017) suggests that designers can make more informed decisions about subsequent iterations, potentially exploring alternative solutions that balance centrality across the network more effectively.

Ultimately, the iteration of designs in the representation of a network, with changing requirements, provides a dynamic tool for designers to quantitatively assess and optimize the design process. This approach not only aids in making informed decisions but also enhances the overall design by understanding and leveraging the complex interplay of its components, also concurred by Shields (2017).

To define the impact on the centrality metrics mathematically:

1. $G = (V, E)$ as the graph representing the design network, where V is the set of nodes (including requirements, components, and systems) and E is the set of edges (representing relationships or dependencies between these elements)
2. $C_B(v)$ as the betweenness centrality of node v
3. $C_E(v)$ as the eigenvector centrality of node v
4. v_r as the node representing a specific requirement that is being changed
5. $G' = (V', E')$ as the modified graph after changing v_r

The change in betweenness centrality $\Delta C_B(v)$ for a node v due to the modification of v_r can be represented as:

$$\Delta C_B(v) = C'_B(v) - C_B(v) \tag{4}$$

where $C'_B(v)$ is the betweenness centrality of v in the modified network G'.

Similarly, the change in eigenvector centrality $\Delta C_E(v)$ for a node v due to the modification of v_r can be calculated as:

$$\Delta C_E(v) = C'_E(v) - C_E(v) \tag{5}$$

where $C'_E(v)$ is the eigenvector centrality of v in the modified network G'.

Informing the Designer

The impact of changing a requirement on the network can be further analyzed by examining the aggregate changes in centrality across all nodes. For example, the average change in betweenness centrality can be computed to understand how the design's connectivity or integration points shift. Similarly, examining the distribution of changes in eigenvector centrality can reveal how the overall influence landscape of the design has been altered.

Quantitatively, a designer can use these percentage-based changes to make better-informed decisions:

1. **Prioritization of Components:** If $\Delta C_B(v)$ or $\Delta C_E(v)$ significantly increases for certain nodes, those components may require additional focus or resources.
2. **Reevaluation of Dependencies:** Large percentage changes in centrality measures might trigger the need to perform a reevaluation of dependencies and relationships within the design to optimize performance or resilience.

3. **Iterative Optimization:** By systematically modifying requirements and analyzing the resulting changes in centrality, designers can explore the design space more thoroughly and identify different configurations, and their associated trade-offs.

The mathematical representation allows designers to illuminate and quantify the impact of requirement changes in the design network, providing a basis for better-informed decision-making and optimization throughout the design process.

METHODOLOGY

In this exploration into the three-dimensional realm, the approach was multifaceted, encompassing both theoretical development and practical application. At the heart of this methodology is the expansion of Shields et al. (2018)' two-dimensional network-based approach, reengineered to consider the complexities and spatial intricacies of 3D ship design. This progression was not a straightforward task; it required a deep understanding of both the established principles of naval architecture with three-dimensional modeling in the form of a network.

The primary challenge was to develop an algorithm capable of accurately representing a ship's layout and systems in three dimensions. This required a significant enhancement of the original 2D model, integrating vertical spatial dynamics alongside the conventional horizontal plane. The 3D model had to account for factors such as vertical access routes, stack effects, and the vertical distribution of weight, which are crucial in naval architecture but were not considerations in the 2D approach.

A crucial aspect of the methodology was the incorporation of spatial dynamics within the 3D model. This included understanding how different spaces within a ship interact, how systems are routed through these spaces, and how these aspects impact the ship's overall functionality and performance. The model needed to be sensitive to the nuances of distribution, ensuring that every probability was accounted for and computed.

To demonstrate the practical applicability of the 3D model, the conceptual design of a naval frigate was chosen as a case study. This choice was driven by the inherent complexity in frigates, which offered a fine balance between weaponry, propulsion, living quarters, and other critical systems. The case study aimed to show how the 3D model could be used to explore various design configurations, assess their feasibility, and optimize the layout for operational efficiency and effectiveness.

A key focus of the methodology was its application in the early stages of design. The ability to visualize and manipulate a ship's design in three dimensions from the outset allows for a more informed decision-making process. It opens up new avenues for exploring design options, foreseeing potential issues, and making strategic decisions that significantly impact the final design.

The final phase of the methodology involved analyzing the results obtained from the naval frigate case study. This analysis aimed to determine the effectiveness of the 3D model, its impact on early-stage design decisions, and its potential role in future naval architecture practices. The discussion also highlights the limitations of the current model and suggests areas for future research and development.

DEVELOPMENT OF PROOF-OF-CONCEPT

In transforming the theoretical aspects of the three-dimensional naval architecture model for real-life applications, the approach was centered around developing a robust proof-of-concept. This phase was crucial to demonstrate not just the technical feasibility but the practical utility of the model in real-world scenarios. The focus was on the intricate process of translating complex naval architectural concepts into a functional and interactive 3D model, in the form of a naval frigate.

Pivotal to the development strategy was the use of centrality matrices. These matrices were employed as a means to measure ”decision influence” within the ship design. Essentially, these ”decision influence” matrices allowed the authors to quantify the impact of each design decision on the overall layout and functionality of the ship. By analyzing the centrality of various components and spaces within the ship, designers could understand how changes in one area might ripple through to others, thereby influencing the entire design network.

Another significant area of the development process involved the integration of 3D dynamics into the model. This was a step from the 2D scope of naval architecture, which focused more on the side layout. The aim was to fully utilize the three-dimensional space to elucidate how 3D elements such as the combination of horizontal and vertical weight distribution affect the ship’s overall design and performance.

For the proof-of-concept, the naval frigate presented a sufficiently comprehensive challenge, offering a broad spectrum of variables to test the model’s capabilities. The model, built upon Shield’s previous work, was simulated with a design scenario to assess the design feasibility over multiple configurations and predict the operational efficacy.

The simulation process involved iterative runs to test various configurations and layouts. The model was repeatedly fine-tuned to adapt to the dynamic requirements of naval frigates, incorporating feedback loops that allowed for continuous improvement of the design process. The changes to centrality matrices were tracked and normalized in these simulations, providing quantitative data that informed the decision-making process at every step.

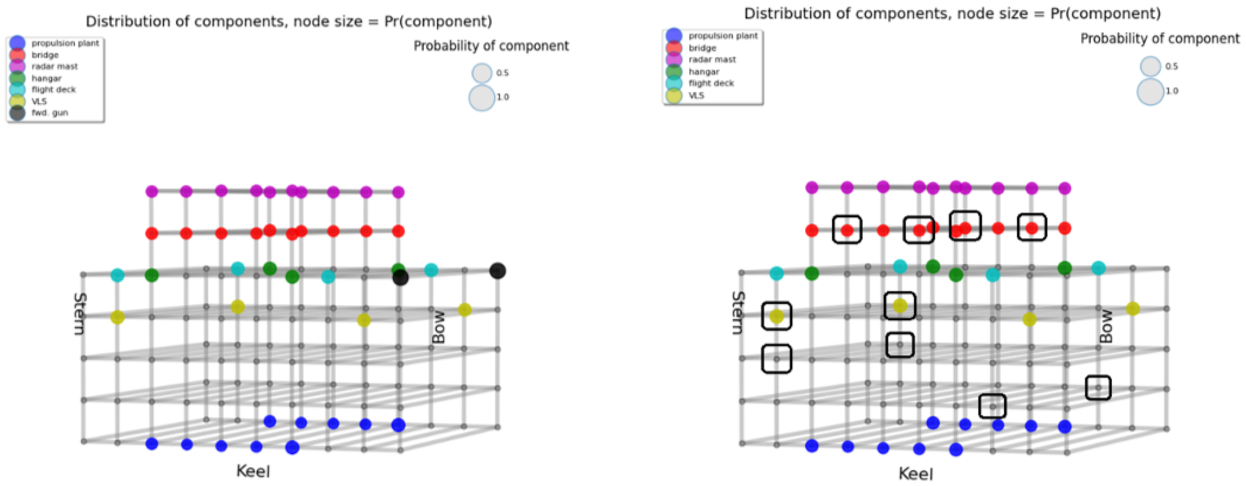
RESULTS

The methodology, detailed in the earlier section, quantifies the resultant shifts in the network’s dynamics, particularly focusing on the betweenness and eigenvector centralities of pivotal components such as the bridge, VLS, and supporting pipes. This investigation illuminates the intricate interdependencies within naval systems, showcasing how alterations in a single design element can precipitate significant reconfigurations across the network, also seen in Shields (2017) work. The enhanced roles of specific components, underscored by their changes in centralities, highlight their critical importance in maintaining operational efficiency and design integrity. This nuanced understanding of design element interplay advances our capability to navigate the complex landscape of naval architecture, fostering more informed decision-making and innovation in naval design practices.

Mathematically, Shields et al. (2018) proposes that a shift in centralities reflects a re-evaluation of the importance of certain nodes (such as the bridge, VLS, and supporting pipes) within the network. This change indicates how central a node is in the context of the entire network, taking into account not just the number of connections, but also the significance of those connections. High centrality values post-removal of the naval gun imply these components play a more crucial role in maintaining the network’s functionality, highlighting their increased influence on the ship’s design and operational efficiency.

By quantifying the shifts in centralities of critical components, the method offers insights into these elements’ enhanced roles. This approach highlights the interdependencies within naval systems and guides more informed decision-making for future design strategies, emphasizing the importance of considering component significance and system-wide impacts in naval architecture, which is detailed in the following sub-sections. The results will first discuss the impact of design changes through eigenvector centralities, which will highlight components which has a greater influence on operations. The study will then discuss components that require greater consideration, discussion, or impact to support the design through betweenness centralities. Finally, the study will investigate the impact of fidelity on eigenvector centralities by expanding the 3-D space.

Eigenvector Centralities as a measure of influence and importance



(a) gun **(b)** no gun

Figure 1: gun in the general arrangement vs no gun (eigenvector centrality)

In Figure 1(a), the presence of the gun is illustrated by a network where the gun node possesses a size proportional to its centrality. Surrounding components display varying degrees of centrality, suggesting a more dispersed distribution of influence across the network. The network appears balanced, indicating that the removal of any single component—while impactful—would not drastically destabilize the system or design.

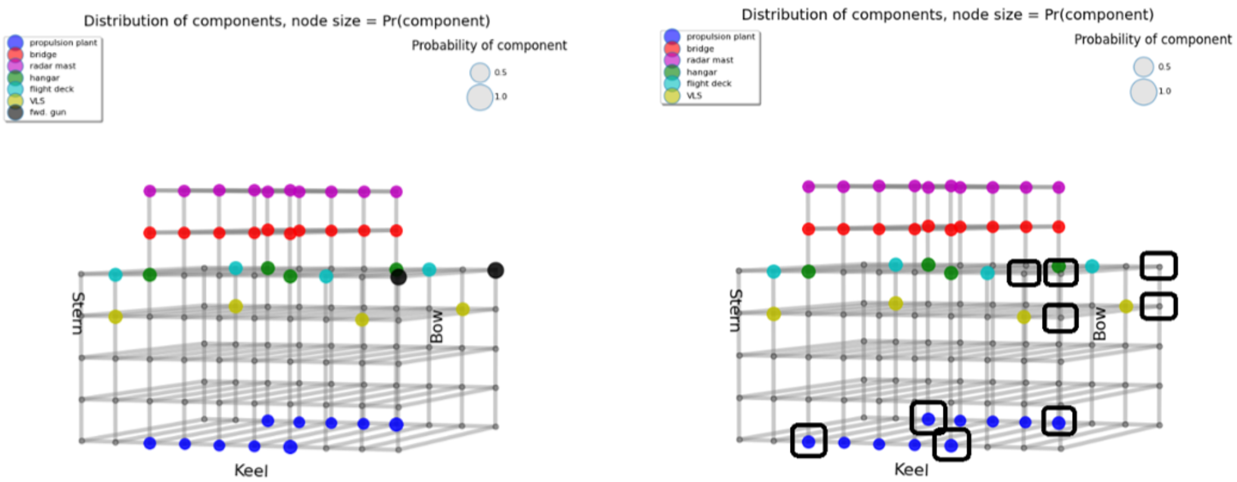
Contrastingly, Figure 1(b) reveals the aftermath of the gun's removal. Notably, the bridge, VLS, and supporting pipes emerge with significant changes to their eigenvector centralities, signified by their "highlighted" node representations. This highlights a shift towards a more centralized network architecture, where the influence is now concentrated among fewer components. Referencing Newman (2005), the resultant configuration suggests that these elements have assumed more critical operational roles in the absence of the naval gun, potentially becoming new focal points for maintaining the vessel's functionality.

The changes in centralities within the naval design network provide critical insights for designers. The changes in eigenvector centralities for key components like the bridge, VLS, and supporting pipes following the gun's removal indicate these elements have become more crucial in the network's functionality. This shift towards a more centralized network structure informs designers about potential new focal points in ship functionality, meaning:

1. **Resource Allocation:** The design team may need to prioritize the bridge, VLS and supporting pipes for further development and robustness checks, ensuring they are capable of handling their critical roles effectively.
2. **System Redesigns:** The bridge, VLS, and supporting pipes might need to add redundancy to enhance the resilience of these parts to mitigate risks associated with potential failures.

The 3D model provides a more nuanced view of system interdependencies compared to traditional 2D models, which tend to simplify complex relationships. In 3D, the spatial configuration and the relative placement of components are captured, revealing how changes in one part of the system can affect others in a way that flat representations cannot. This validation of our hypothesis underscores the importance of considering three-dimensional interactions in naval design to fully understand and anticipate the impacts of alterations within the ship's architecture. The increased centralities observed in the 3D model after the removal of the naval gun reflect this depth of analysis, validating the hypothesis that certain components will grow in operational significance when a major system is removed.

Betweenness Centralities as a measure of criticality



(a) gun **(b)** no gun

Figure 2: gun in the general arrangement vs no gun (betweeness centrality)

Figure 2's graphical sub-section presents a visualization of betweenness centrality within the naval ship's design network, with two distinct configurations: one with the gun (a) and one without (b). The combination of Newman (2010)'s definition and Shields et al. (2018) research could then define betweenness centrality as a measure of a component's role as a conduit or bridge within the network—its importance in connecting different parts of the ship. The graphical comparison powerfully illustrates the redistribution of this measure among the ship's components.

In configuration (a), with the gun present, the betweenness centrality is relatively evenly distributed across the network, suggesting a balanced design with multiple pathways for operational flow and no single point of over-reliance. The hangar, propulsion plant, and supporting pipes exhibit centralities indicative of their role but are not overly dominant.

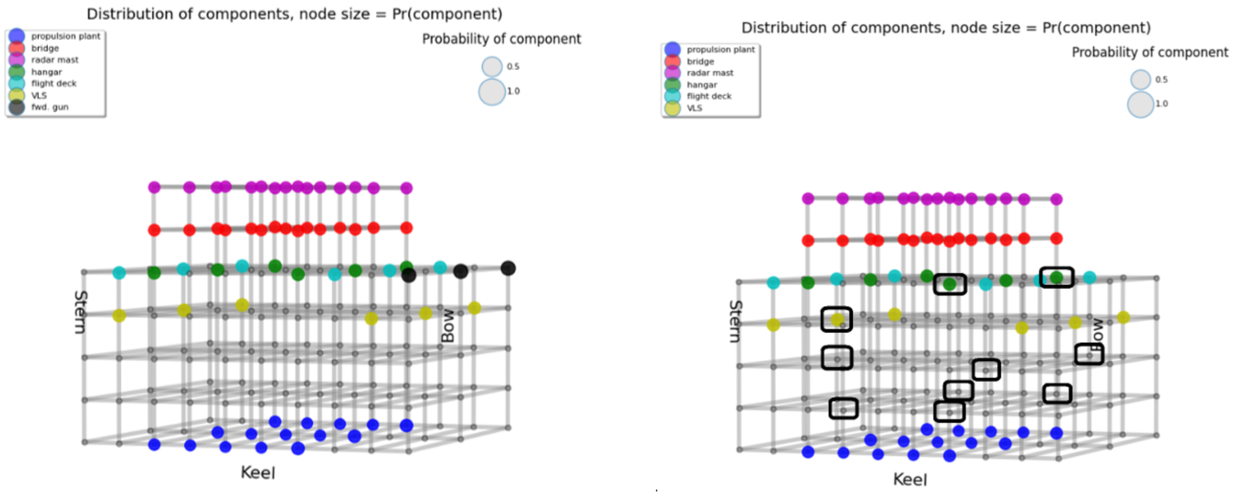
Configuration (b), however, tells a different story. Here, the removal of the naval gun has led to a significant change in the betweenness centrality of the hangar and propulsion plant, with supporting pipes towards the front also becoming more prominent. This shift points to a reconfiguration of operational pathways, now heavily reliant on these components. The increased centrality of the hangar and propulsion plant suggests they are now key nodes, critical for the ship's performance and structural integrity.

The betweenness centrality information can be utilized by naval designers in several practical ways:

1. **Identifying Key Components:** Designers can prioritize the hangar and propulsion plant for enhanced robustness and reliability in design specifications.
2. **Redesigning Flow Paths:** The hangar and propulsion plant are major conduits, which means the design team needs to ensure efficient flow paths and reduce potential bottlenecks in ship operations through these conduits.
3. **Improving Operational Resilience:** By reinforcing the hangar and propulsion either through redundancies or armoring, designers can improve the overall resilience of the ship, ensuring it remains operational even if key components are compromised.
4. **Strategic Modifications:** Designers can strategically plan mid-life upgrades to the hangar and propulsion plant, which could have significant impacts on the ship's functionality.

The variations between these two configurations reveal the adaptable nature of naval design networks. Referencing Newman (2005)'s research, the variations demonstrate how the removal of a single component can lead to a redistribution of functional importance across the network, necessitating a reassessment of design priorities. This validates the hypothesis that naval design is a dynamic and interdependent system, where changes in individual elements can have far-reaching impacts. By providing a quantifiable measure of component significance, the betweenness centrality analysis offers designers a powerful tool for assessing potential modifications and their ramifications. It underpins the need for comprehensive simulations and modeling in naval architecture to ensure that designs are both robust and flexible, capable of accommodating changes while understanding the trade-offs on operational effectiveness.

Extending the 3D layers



(a) gun

(b) no gun

Figure 3: 3 guns, eigenvector centrality gun vs no gun comparison (eigenvector centrality)

As the study extends the fidelity of the model in the analysis of eigenvector centralities depicted in Figure 3, three potential positions for the guns in the ship's design are compared against a configuration without any guns. The three-layered representation of nodes offers a different understanding of the influence exerted by the supporting pipes within the ship's network, highlighting a significant change in their centrality in the absence of the gun. This reinforces the point on the need for the design team to consider adding redundancies within the supporting pipes network, highlighted in the earlier sub-section.

This extension of an additional layer within the network underscores the heightened impact that supporting structures have in the absence of key offensive components, offering critical insights for future design considerations where Knight et al. (2015) highlights the need for flexibility and adaptability may be required for subsequent downstream upgrades.

The comparison between Figures 1 and 3, which illustrate the eigenvector centralities in two different configurations of naval ship design, reveals the nuanced shifts in the ship's structural network. In Figure 1, the removal of the naval gun impacts the centrality of the bridge, VLS, and supporting pipes, demonstrating their increased operational significance. In contrast, Figure 3 expands this analysis to a three-layer node view, uncovering the broader influence of supporting pipes throughout the ship's design, especially in the gun's absence. This expansion provides a deeper understanding of the role that the pipes play in the ship's resilience and design adaptability.

The information from the analysis can be used by naval designers in several ways:

1. **Prioritizing Component Enhancement:** By identifying which components like the supporting pipes gain in central-

ity, designers can prioritize these for enhancements, ensuring they are robust enough to handle increased responsibilities.

2. **Redesigning for Resilience:** Recognizing components that become more central to the ship's functionality allows designers to focus on redesigning these elements to enhance the overall resilience of the ship.
3. **Risk Management:** The analysis helps in assessing potential risks associated with the removal or modification of major components and planning mitigations accordingly.

In the context of naval design, the comparison between Figure 1 and Figure 3 suggests a shift in the functional significance of the ship's components when the naval gun is removed. Specifically, the three-layer eigenvector centrality analysis in Figure 3 emphasizes that the supporting pipes increase in importance, indicating they may take on a more central role in maintaining the structural and operational integrity of the ship. This suggests that in the absence of the gun, the ship's design compensates by relying more on other elements to maintain its performance capabilities.

DISCUSSION

The comprehensive analysis of the naval ship design network in the absence of the gun, as demonstrated by the shift in centralities, offers an insightful perspective into the future of naval architecture. This paradigmatic observation in network behavior, where supporting infrastructural components like pipes accrue shifts in centrality, necessitates a reconsideration of their role within the structural integrity and operational efficiency of naval vessels.

From a mathematical viewpoint, Newman (2001) definition suggests that eigenvector centrality could elucidate the relative influence of a node within the network. As presented in the earlier section, as the supporting pipes gain prominence in the absence of the gun, it indicates that these components have now become instrumental nodes through which significant portions of the network's operational pathways are mediated. This increase in centrality suggests that the design's resilience is now more heavily reliant on the robustness of these elements, which may not have been primary factors in the initial design considerations.

The implications for future ship design are substantial. The conventional approach to naval architecture, as described by Pawling et al. (2017), which is generally characterized by a siloed focus on individual components rather than their interactions, may no longer be sufficient. Instead, Shields (2017)'s proposal of a holistic view that embraces the interconnectivity of all ship elements and their contributions to the overall network is required. This shift towards an integrated network perspective will enable naval architects to create designs that are inherently adaptable, and capable of withstanding the removal or malfunction of critical components without significant loss of functionality.

Moreover, the study's findings highlight Knight et al. (2015)'s point on the importance of modularity in design, where components can be removed or replaced with minimal disruption to the broader system. In the context of rapidly evolving military technologies and strategies, such modularity becomes indispensable. It ensures that ships can be upgraded or reconfigured in response to emerging threats and operational requirements without necessitating complete redesigns, thus extending the vessels' operational lifespans and enhancing their return on investment.

Furthermore, the network-centric approach to design implicates the potential impact of these findings on naval architecture education and practice. The current training may need to evolve to incorporate principles of network science and systems thinking, equipping the next generation of naval architects with the tools and perspectives necessary to design the resilient and responsive vessels required for future maritime challenges.

In conducting a detailed analysis of ship design using network science methodologies, the authors confronted significant challenges while implementing a component arrangement algorithm. The desired outcome was to programmatically determine an optimal design where specific components, such as the flight deck and forward gun, were preferentially distanced. Utilizing Newman (2005)'s random walk betweenness centrality measure, the algorithm inadvertently amplified the centrality scores of nodes adjacent to crucial components, regardless of the targeted arrangement. This unexpected result presented a quandary: how to penalize configurations where the flight deck was undesirably positioned near the forward gun.

The challenges were compounded by the algorithm's nature, which globally enhanced centrality scores based on proximity to key nodes, influencing unrelated calculations. A simplistic solution like removing front flight deck nodes to refocus the algorithm on aft sections contradicted the objective of establishing a proof of concept. The essence of the endeavor was to reduce manual labor in developing more efficient designs—options that are not immediately apparent to designers.

Addressing this challenge necessitated a reevaluation of the algorithmic approach. The study nuanced adjustments to the algorithm, accounting for these centrality distortions. Potential solutions involved introducing penalty factors within the centrality calculations or developing a multi-criteria optimization framework that could simultaneously consider proximity preferences alongside other design requirements.

These adjustments had to be carefully balanced to not undermine the overall integrity of the ship's network. The intricacies of the design elements' interplay needed meticulous consideration to ensure that operational efficiencies were not sacrificed. The insights derived from these explorations are vital for naval architecture, pointing towards a future where computational algorithms can significantly augment human expertise in early-stage design, leading to innovative naval vessels engineered for optimal performance and resilience.

The integration of such algorithmic solutions holds the potential impact on naval architecture. By automating complex design decisions, this approach could significantly streamline the design process, allowing for rapid prototyping and testing of various configurations. This would not only save time and resources but also enable the exploration of a broader design space, potentially unveiling novel configurations that human designers may not intuitively consider.

CONCLUSION

Our research revealed a fundamental reconfiguration of the naval ship design network when key components such as the naval gun are altered. The significant increase in the eigenvector centralities for supporting structures like pipes upon the gun's removal indicates a shift towards a design that compensates for the loss by redistributing functional importance across the network. This insight is vital for future naval designs, where resilience and adaptability must be engineered into the vessel from the outset. It suggests that naval architecture is entering a phase where flexibility and robustness are not merely desired but required, laying the groundwork for innovative approaches in ship design. These findings pave the way for future research to develop algorithms that can more effectively navigate the complex trade-offs between design intuitiveness and computational optimization.

The advances in network-centric naval architecture presented in our study hint at transformative possibilities for future ship design. Pioneering research can progress towards developing advanced algorithms that not only predict but also adaptively recalibrate the ship's design network in response to changes in component configurations. There is potential for creating intelligent design systems that can autonomously optimize layouts for operational efficacy, considering factors such as spatial constraints and mission-specific requirements. Additionally, investigations into the resilience of these networks against unforeseen failures could lead to the evolution of ships with unprecedented structural robustness. Future research directions are poised to harness machine learning to predict and propose optimal designs, significantly reducing the iterative cycle of design and testing, and to employ virtual reality for immersive design evaluation, which could revolutionize the conceptualization phase of naval engineering.

CONTRIBUTION STATEMENT

MD: Conceptualization; data curation, methodology; software; writing – original draft. **WT:** Conceptualization; data curation, methodology; software; writing – original draft. **ADM:** conceptualization; supervision; writing – review and editing

CWA: supervision; writing – review and editing **DJS:** supervision; writing – review and editing.

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