# Seeing Arrangements as Connections: The Use of Networks in Analysing Existing and Historical Ship Designs

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ABSTRACT: A growing trend in computer aided ship design, particularly in the early stages, is the utilisation of approaches and numerical methods developed in other disciplines. Examples include genetic algorithms, financial methods of risk assessment and the use of network science. Networks can provide an abstract mathematical representation of many types of connected features, properties and information, such that the associated network analysis metrics and approaches can offer new ways of investigating and evaluating ship designs. This paper reports on ongoing UCL investigations into the application of network science in assisting human analysis of the general arrangements of existing ship designs. This work includes designs of complex service vessels (research vessels) as a comparison with naval ships and makes use of freely available network analysis software. This project makes use of the experience in naval vessel concept design at UCL by enabling a comparison of expert judgement and interpretation of designs with the quantitative network metrics. This paper describes the network analysis approach adopted, the findings for the arrangements analysed, and also discusses the future work required to further the approach.

## 1 INTRODUCTION

### 1.1 *Background to the Study*

The Marine Research Group, part of the Department of Mechanical Engineering at UCL (2018) conducts research into various aspects of maritime design and technology, in both Naval Architecture and Marine Engineering. One long-running theme, of particular interest to the authors, is ship general arrangements, including arrangements evaluation methods, architecturally-centred design methods that integrate configuration into the earliest stages of design (Andrews, 2003), and the problem of how to effectively teach arrangements design to undergraduate and postgraduate Naval Architecture students (Pawling et al, 2015).

This paper describes progress to date on an ongoing US Navy Office of Naval Research (ONR) sponsored collaborative international project to investigate various aspects of arrangements design. Previous collaborative outputs of this project have included an IMDC State-of-the-Art report (Andrews et al, 2012) and joint papers on the subject of style in design (Pawling et al, 2013, 2014) and a new taxonomy for describing distributed systems in ship design (Brefort et al, 2017).

The various partners in the project are undertaking independent research projects, with significant cross-pollination of ideas, and one area that UCL is investigating is the application of networks to arrangements design, with a particular emphasis on designer-centred processes, allowing the designer to “see” the general arrangement in a new, non-geometric, way. The ongoing UCL investigation of the application of networks to investigate developed general arrangements draws inspiration from four sources; a notable series of “comparative naval architecture” papers, previous UCL considerations of the meaning of “style” in ship design, considerations of topology and connectivity in the field of architecture and urban design, and the significant past work carried out by the NICOP project partners in this area.

### 1.2 *Comparative Naval Architecture*

Comparative naval architecture has its origins in the 1970s Cold War, with the need for NATO to understand the capabilities of Soviet warships without having access to reliable technical information. A type of reverse engineering, it assumes that the designers of the ships under investigation made rational decisions using the information available to them; but that those decisions may not be consistent across a range of international designs The practice was carried out using primarily numerical analysis (Kehoe, 1976) which included an attempt to re-design a US Navy vessel using Soviet practices and style, and also more holistic analysis including some internal arrangements (Kehoe et al 1980a, 1980b). As more information became available on Soviet vessels at the end of the Cold War such comparisons have been undertaken at a more detailed level, such as that by Brower & Kehoe (1993). Most recently this approach has also been applied to passenger vessels (Sims, 2003), with a particular emphasis on how safety was considered.

Generally these studies only included limited information on the general arrangement, such as the high-level breakdown in volume allocation shown in Figure 1 (Kehoe et al, 1980b), or simple profile views.

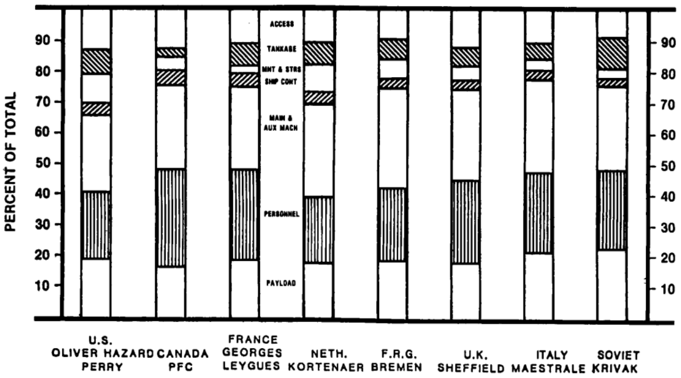


Figure 1: Volume allocation in NATO and Soviet frigates (Kehoe et al, 1980b)

The UCL arrangement study described in this paper draws on existing ship designs, with the aim of examining the potential for networks to be used in comparing arrangements of vessels differentiated by nationality, era, and role.

## 1.3 *Style in Ship Design*

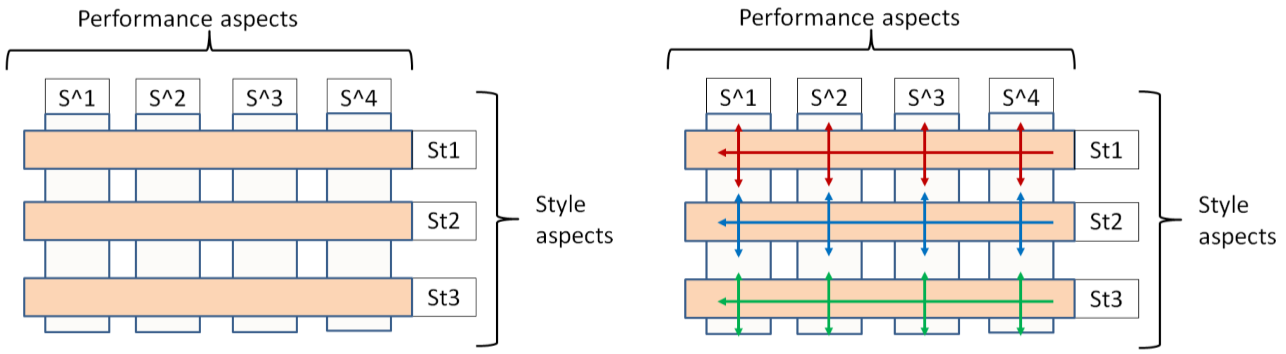
"Style" was introduced as a conceptual component of design methodology by Simon (1970), and first applied to ship design by Brown and Andrews (1981) in their "$S^5$" summary of the naval architects considerations in ship design; Speed, Seakeeping, Stability, and Strength and Style. Andrews (2012) provided a listing of topics classed as "Style", which is repeated as Table 1.

These stylistic issues were proposed to be subtly different to other aspects of ship performance in that they bring a collection of disparate whole-ship design issues, incorporating engineering sciences, managerial and user-focused issues. A novel definition of style was proposed, that it is a type of design information possessing several key characteristics; that it is cross-cutting, groups information, and is able to accommodate uncertainty (Pawling et al 2013). These characteristics are illustrated in Figure. 2

Table 1: Aspects of style in naval ship design (after Andrews, 2012)

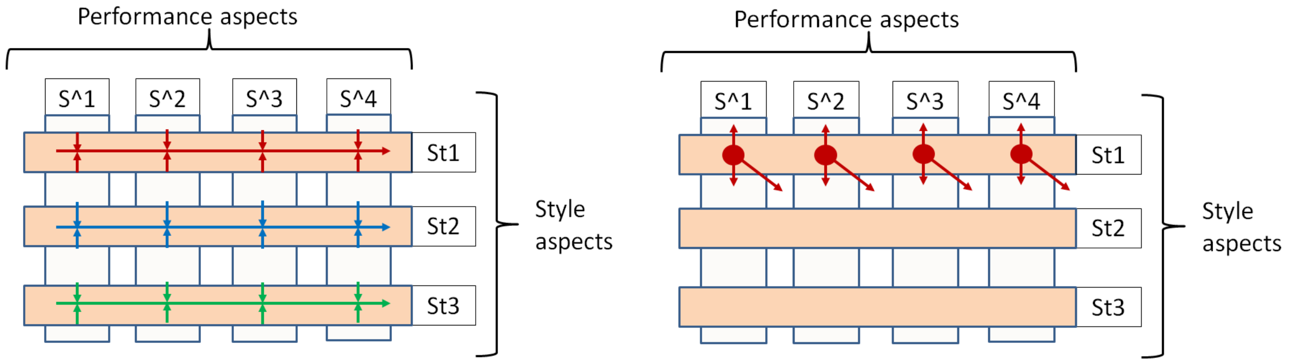
| Stealth | Protection | Human factors | Sustainability | Margins | Design issues |
|---|---|---|---|---|---|
| Acoustic signature | Collision resistance | Accommodation standards | Mission duration | Space | Robustness |
| Radar cross-section | Fire-fighting | Access policy | Crew watch policy | Weight | Commercial standards |
| Infrared signature | Above water weapon effect | Maintenance levels | Stores level | Vertical center of gravity | Modularity |
| Magnetic signature | Underwater weapon effect / shock | Operation automation | Maintenance cycles | Hotel power | Operational serviceability |
| Visual signature | Contaminants protection | Ergonomics | Refit philosophy | Ship services | Producibility |
| | Damage control | | Upkeep by exchange | Design point (growth) | Adaptability |
| | Corrosion control | | Replenishment at sea | Board margin (upgrades) | Aesthetics |

Style was proposed to be "cross-cutting", in that a given style decision will impact across multiple performance areas. The implication of this is that style in design is also a way of grouping information about design decision that have such predominately cross-cutting impacts. Finally, it was proposed that design solutions occur at the conceptual intersection of technical performance requirements and stylistic decisions (Figure 2d). Regarding the use of networks to analyse arrangements, the objective of the UCL study is to investigate whether networks can detect "style", in the form of network characteristics and metrics.



a. Style as cross cutting

b. Style influences different areas



c. Style groups information

d. Solutions occur at the intersections

Figure 2: The main characteristics of style as a type of information in ship design as proposed by Pawling et al (2013)

## 1.4 *Ways of Thinking About Space*

Large inhabited structures such as ships, building and even cities present problems of understand what "space" and "arrangement" mean. Although a ship is of course a 3D construct in Cartesian space, the internal arrangement can be viewed in different ways. A simple 3D model, such as that in Figure 3 is technically correct, but is not always straightforward to understand – the implications of this in education having been considered by Pawling et al (2015) and Collette (2015).

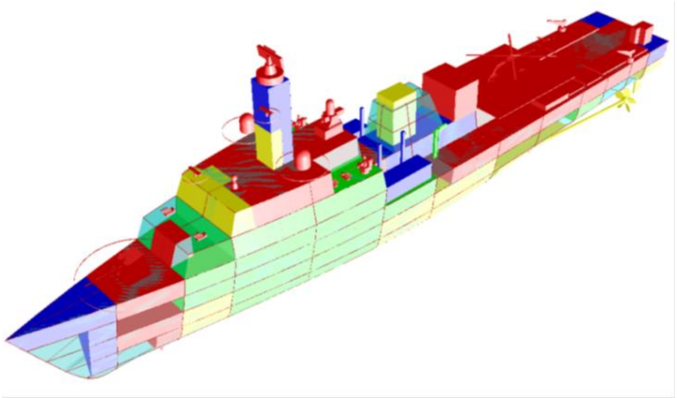


Figure 3: A 3D spatial model of a ship design

"2.5D" representations of the ship design (originally defined as "2D+" by the first author, (Pawling, 2007)) are frequently used, which show the design as a series of stacked decks with interconnections. These are also frequently used to effectively convey the logic behind a design, such as the internal flow in an aircraft carrier, shown in Figure 4.

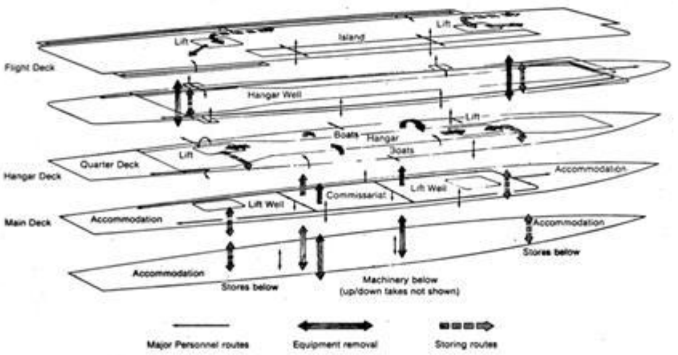


Figure 4: The internal flows in an aircraft carrier – an example of a 2.5D layout representation (Honnor and Andrews, 1982)

A more abstract definition of ship arrangements is the contact diagram, which has been used to develop layouts for accommodation spaces (Cain & Hatfield, 1979). Figure 5 shows a typical contact diagram for the superstructure of a cargo vessel. Contact diagrams allow the layout to be built up from functional requirements, through the topology, to the contact diagram, and then to a geometry (Klem, 1983). More recently they were used by Dicks (1999) in the prototype demonstration of the Design Building Block approach, and Andrews (2003) incorporated some numerical comparison of relationships.

This type of abstract thinking about the nature of complex spaces has seen greater use in other fields. The seminal paper by Alexander (1965) used set and graph theory to examine the structures of notional cities, making a (social) argument for a lattice, rather than tree-type underlying structure. With the increasing application of CAD to (land based) architecture, the capability to consider topology and geometry in different ways has become more practical, e.g. Medjdoub & Yannou, (2000). Although it still frequently has a highly conceptual, theoretical basis, e.g. Savaskan (2012).

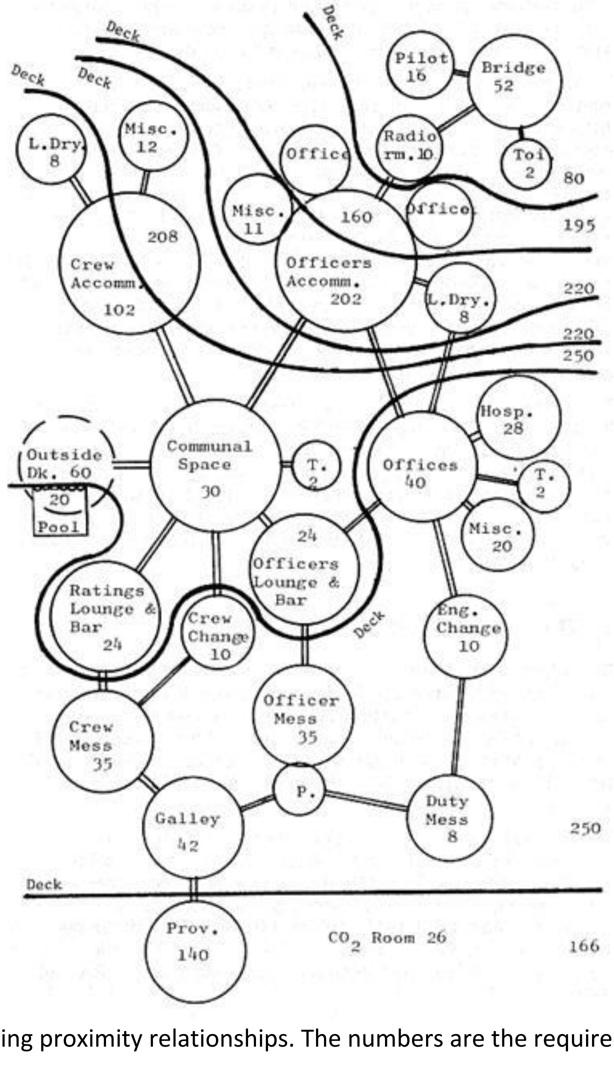


Figure 5: A contact diagram showing proximity relationships. The numbers are the required areas (Cain & Hatfield, 1979)

Work at the Bartlett School of Architecture at UCL has led to the development of the concept of “Space Syntax”, which applies aspects of network theory to existing and proposed urban landscapes, both to determine underlying emergent structures (Al-Sayed et al, 2012) and to guide proposals for development (Hillier, 2009). Notably this abstraction is suitable for application at a range of scales, from buildings to cities, (Hillier, 2014), and an early version was applied to ship design by Andrews (1984).

# 2 NETWORKS

## 2.1 *Networks and Matricies*

A network is a collection of points, called vertices or nodes, joined by lines, called edges or arcs, Newman (2010). The edges can have no direction or be uni-directional. Networks can also be represented in matrix form, and Figure 6 illustrates a simple directed network and its associated matrix.

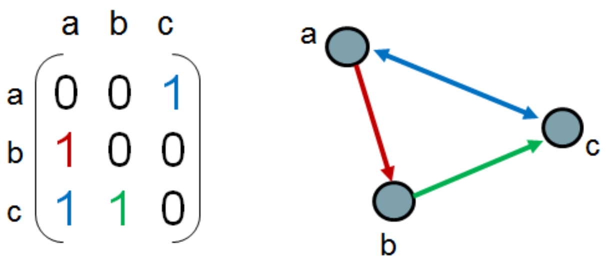


Figure 6: Matrix representation of a directed network of three nodes (after Collins et al. (2015))

The nodes and edges can support additional information, typically numerical weights or textual data, which can be stored in additional matricies with the same dimensions as that representing the connections in the network. Early applications of networks to determine the behaviour of AI were known as Semantic Networks and described a decision making tree, as shown in Figure 7 (Sowa, 1992).

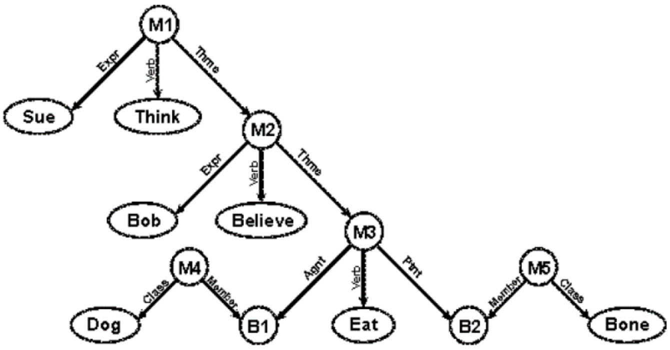


Figure 7: A semantic network representing a simple sentence, “Sue thinks that Bob believes that a dog is eating a bone” (Sowa, 1992)

Networks are suited to application to problems that can be described in terms of connected entities. The entities can be represented by the nodes, or by the edges, and could be physical, conceptual or operational. Network methods can be made more sophisticated by integrated multiple networks representing the same system. One of the more recently significant applications of network theory is in understanding (and potentially manipulating) social structures as the “connectedness” of modern society increases (Easley & Kleinberg, 2010).

## 2.2 *Network Analysis*

Newman (2010) and Mrvar (2018) provide a detailed description of the various quantitative methods that have been developed to analyse networks, both at the whole-network level, and with regards to individual nodal properties. Many of these metrics are best used in a relative manner, comparing nodes to one another, rather than as absolute values. The metrics used in the UCL study are described in Section 4, but they can be broadly summarized as relating to degree, centrality, or communities (modules).

Degree refers to the number of connections of the node, and can incorporate directionality, as shown in Figure 8. Any weighting on the edges can be incorporated in degree metrics.

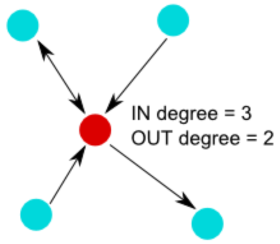


Figure 8: The degree of a node

Centrality measures relate to the connections between nodes and come in three broad groups; degree, closeness and betweeness. Degree centrality is a measure of the number of direct connections a node has. Closeness centrality is a measure of how close a node is to all other nodes in a network. Betweeness centrality evaluates the extent to which a node lies in the shortest path between pairs of nodes in a network, as shown in Figure 9. Eigenvector centrality is a variant of closeness centrality, in which the centrality of surrounding nodes influences the centrality value assigned.

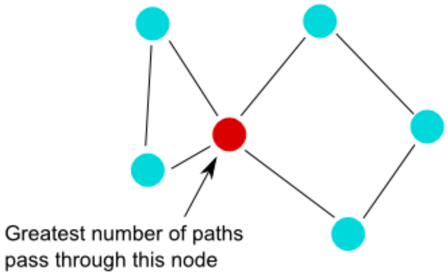


Figure 9: Betweenness centrality

Communities or modules are clusters of nodes with more arcs within the cluster than between clusters, as illustrated in Figure 10 in which there are more arcs inside the cluster than among clusters.

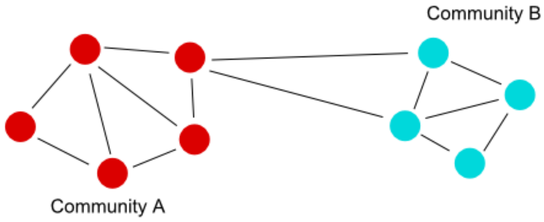


Figure 10: Communities in a network

## 2.3 *Applications of networks to ship design*

The earliest application of network science to ship design was by MacCallum (1982), who used them to represent and explore relationships between ship design characteristics in computerized models, with a particular emphasis on understanding the interactions and influences between the parameters. Similarly Parker and Singer (2013, 2015) and Shields et al (2015) describe the application of modern network models to investigate ship design models and the flow of information in the design process.

More recent applications have focused on the potential applications of network science to arrangements design, as has been the case in land-based architecture. Gillespie (2012) used networks to examine emergent design drivers that could be detected from databases of arrangement preferences (i.e. without generating layouts first), this work making particular use of numerical methods to detect communities as shown in Figure 10 (Gillespie et al, 2013). Kilaars et al (2015) combined networks with automated approaches to layout generation, which are capable of producing a large number of possible arrangements, needing subsequent down-selection, with Roth (2017) examining networks metrics as a possible method to differentiate between design options.

Another recent application of network science is in the modelling and analysis of distributed systems, with various levels of abstraction. Rigterink et al. (2014) applied community detection methods to ship hotel services, such as electrical systems. Of particular interest in the design of naval vessels is the use of networks to evaluate survivability of distributed systems (Shields et al, 2016, 2017).

## 3 PREVIOUS UCL APPLICATIONS OF NETWORKS TO SHIP DESIGN

UCL has engaged in a variety of investigations of the application of network science to ship design, including submarine concept design, layout preference analysis, surface ship concept model analysis and ship survivability.

### 3.1 *Submarine Concept Design*

Collins et al (2015) described ongoing PhD research into the use of networks to address issues of knowledge and uncertainty in the integration of new technologies, applied to submarine design. Submarine design is traditionally very conservative and the objective of this work is to improve understanding of the relationships and interactions in submarine concept design by representing the design model as a network of connections between variables. Numerical network metrics can then be used to determine the significance of various parameters. This has the aim of providing earlier identification of design features and parameters that will be disrupted by the addition of a new technology to the submarine.

### 3.2 *Layout Preference Analysis*

Pawling et al (2015) described the use of network analysis to investigate layout preferences in warship design. A database was populated with pairwise arrangement relationships (i.e. space A related to space B) and the NodeXL Excel plug-in (NodeXL, 2014) used to construct a network and conduct an analysis. This then illustrated those spaces (represented as nodes) were most significant in the network, and thus were afforded the greatest importance in that particular designer’s view of arrangements design. Figure 11 illustrates the betweeness centrality ranking of the nodes in the database of one designer’s preferences. The high closeness centrality of the Damage Control (DC) deck and the need for spaces to be split, indicates that this designer has a heavy preference for survivability in layout.

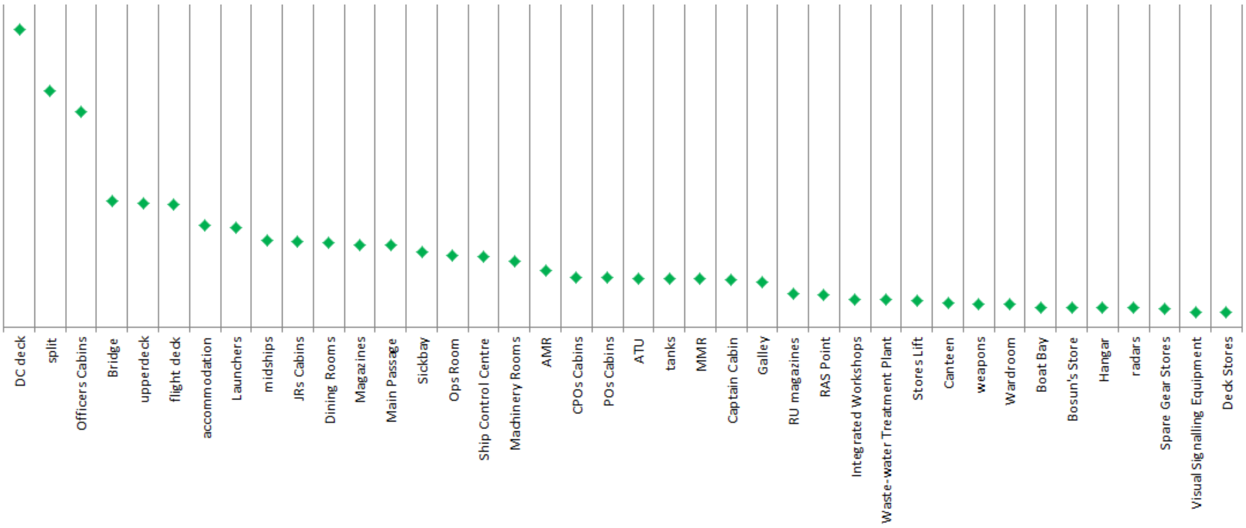


Figure 11: Ranking of spaces and arrangement features by closeness centrality (Pawling et al, 2015)

### 3.3 *Surface Ship Concept Model Analysis*

Pawling et al (2016) described a similar analysis to that of Colins et al (2015), with the network analysis software Pajek (Mrvar, 2018) used to investigate the significance of various parameters in the UCL MSc in Naval Architecture concept ship design model. This directed network, was used to examine influence within the concept design model via the proximity prestige metric, indicating that the most influencing parameter (node) changed as the concept design progresses, something not explicitly stated in the design documentation.

### 3.4 *Survivability*

Pawling et al (2016) also described the use of networks, again in Pajek, as a possible proxy for the modelling of blast effects after an explosion within the ship, due to a weapon impact. This was a comparative exercise, using a UCL model for internal blast developed as an MSc project (Edwards, 2015) as a baseline. The rationale for applying network methods to this problem was that blast is a phenomenon that propagates through connections (bulkheads) between entities (spaces) and thus can be represented as a network. In addition to the comparison of analytical capabilities, networks were considered as a possible means to visualise blast effects, as shown in Figure 12, where the relative size of the nodes represents the blast overpressure in a compartment and the thickness of the connecting edges represents the value of the failure criteria of the structure between them.

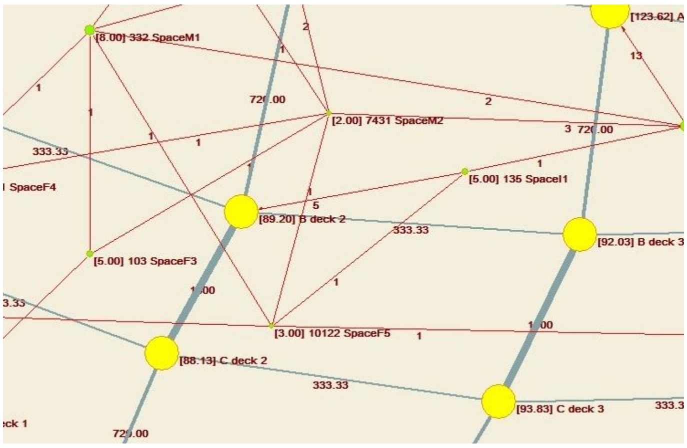


Figure 12: Section of a blast propagation network, including interconnecting ship systems

## 4 THE CURRENT UCL STUDY

### 4.1 *Introduction*

The latest UCL investigation of the application of networks to ship design is in the analysis of historical vessel designs, using a database of general arrangement drawings obtained from various sources. At the time of writing, this is an ongoing project and so this paper describes progress to date.

### 4.2 *Method*

#### 4.2.1 *Encoding*

The first step in the analysis was converting the general arrangements into a network model. Watertight and non-watertight doors, hatches, ladders and stairs were included in the model. Evacuation scuttles (which are only used in extremis) and other openings, such as serving hatches, were not included. Where it could be clearly identified from the general arrangement drawing, spaces with the same function connected by an arched opening (i.e. a doorway with no door in it) were treated as a single space.

In addition to the connections themselves, their direction was recorded (vertical or horizontal). For the spaces, some additional parameters were entered into the Excel databases:

I. Functional Group: Based on the breakdown described by Andrews and Pawling (2008) – Float, Move, Fight (i.e. main role), Infrastructure and Access.
II. UCL function: A more detailed functional breakdown based on the UCL MSc Ship Design Exercise weight break down system (WBS).
III. UCL weight group: A slightly more detailed version of the UCL function. For example, the “sanitary” function does not differentiate between showers and heads, but the weight group does.

For general arrangements not in English, the first authors’ extremely limited knowledge of French, German and Finnish was supplemented by Google Translate (Google, 2018). This is noted here as machine translation has little sense of context and so significant interpretation of the results was sometimes required, so this task requires a naval architect and alternative interpretations may exist.

An important note is the approach to external spaces, such as the upperdeck and superstructure decks. They were included in the baseline database for each ship, and a subsequent down-selection process removed all but the minimum required to connect the operational spaces in the vessel. This construction of an “external” and “internal” version of the network was both to investigate the impact of the upperdeck and to prevent “short cuts” appearing along the length of the ship that would be unrealistic in operation (i.e. one would not climb up the superstructure when one could use a passageway). The impact of this is discussed under the results (Section 5).

### 4.2.2 *Analysis*

This analysis, so far, has used the Gephi freeware software (Gephi, 2018). This decision was primarily determined by the relative ease with which networks can be transferred from Excel to this tool via Comma Separated Variable (CSV) file, and metrics generated. The Pajek software is capable of more sophisticated analysis (hence its use in previous work) and it is likely to be used in further work based on progress so far. Additionally, Gephi has an easy-to use Graphical User Interface (GUI) and this is of great utility to occasional users. The NodeXL Excel plug-in also used in previous work was not adopted here due to compatibility issues with the latest versions of Microsoft Windows and Office software.

All networks were un-directional and no weighting was applied to the edges or nodes, although Gephi represents multiple connections between two nodes as a weighting on a single edge.

Noteworthy is the fact that even on an obsolete computer (3.4GHz dual core Pentium D and 32 bit operating system) the numerical analysis was effectively instantaneous; the greatest processing time was demanded by the layout algorithms used to generate visualisations of the network Thus a frigate-sized network took approximately 30-60 seconds to remove the majority of overlap between edges in the visualisation.

### 4.2.3 *Metrics*

Numerical metrics were generated for the overall networks and the individual nodes.

#### 4.2.3.1 Overall Network Metrics

Table 2 summarises the numerical metrics measured for the overall network of each general arrangement (with and without external access).

Table 2: Overall network metrics

| | |
|---|---|
| Number of nodes and edges | The number of unique spaces (nodes) and connections (edges) in the general arrangement network. |
| Average degree: | The average number of edges per node. |
| Average weighted degree: | The average sum of the weights of the edges of nodes; this will account for multiple connections between two nodes. |
| Network diameter: | The maximum distance, in terms of intermediate edges, between any pair of nodes in the network. |
| Network radius: | The minimum eccentricity of any node in the network. |
| Graph density: | The ratio of actual connections between nodes to the potential connections between nodes. |
| Modularity: | A measure of the strength of subdivision of the network into modules (communities). Higher values indicate a higher ratio of connections within modules to those between them. |
| Number of communities | The number of communities (modules) in the network. The calculation of modularity and communities features a random component and so the exact values for both will vary between calculation runs. |
| Average clustering coefficient: | A measure of the tendency of the nodes to cluster together (separate from modularity). |
| Average path length: | The average number of steps along the shortest paths for all possible pairs of nodes in the network. |

#### 4.2.3.2 Individual Node Metrics

Table 3 summarises the individual node metrics examined in this study. Some relate to the overall network metrics.

Table 3: Individual node metrics

| | |
|---|---|
| Degree: | The total number of unique connections to the node. |
| Weighted degree: | The total number of connections to the node (space) including multiple connections between spaces. This will be equal to the degree for most spaces. |
| Eccentricity: | The maximum distance from a node to the most distant node. |
| Closeness centrality: | An aggregate measure of the means distance from a node to all other nodes. |
| Betweenness centrality: | A measure of the extent to which a node (space) lies on the paths between other nodes. Most relevant for access routes. |
| Modularity class: | The module (community) in which the node lies. |
| Eigenvector centrality: | A measure of centrality where the centrality of each node is proportional to the sum of the centralities of its' neighbours. This indicates if a node is in a well-connected region of the network. |

### 4.2.4 *Visualisations*

In addition to the numerical metrics, one objective of the study is to explore possible network visualisations that could be of use in investigating the general arrangement. It is possible to visualize the complete network, and several numerical approaches, known as force-directed layout algorithms, are available to arrange the many nodes in some layout, generally one that minimises the number of edges that cross. Figures 13a and 13b compare the same arrangement network visualized using the Gephi implementations of Fruchterman Reingold (1991) which represents the nodes as masses and the edges as springs, so tending to place the nodes an equal distance apart, and Force Atlas 2 (Jacomy et al, 2012), which distorts the locations of nodes in an attempt to spatialise the connections between them.

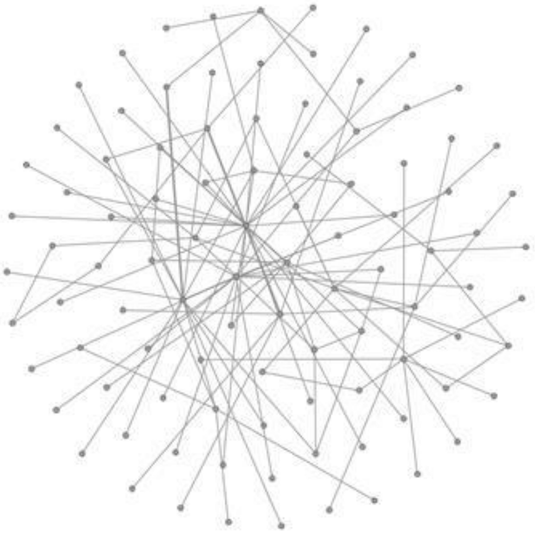


Figure 13a: Fruchterman Reingold visualisation of a layout network

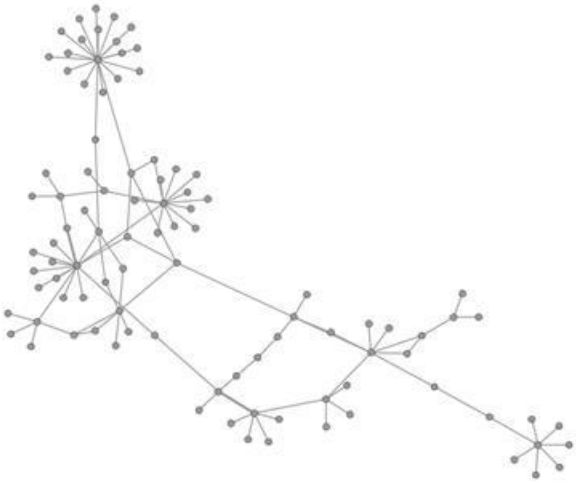


Figure 13b: Force Atlas 2 visualisation of the same layout network

Further to these direct visualizations of the network, ways of exploring the distribution of network properties by node (and the associated characteristics of the space, such as functional group) were investigated. Figure 14a shows an example visualisation, where each diamond represents a space, arranged from left to right in order of decreasing normalized centrality (or some other network metric as indicated where appropriate), and banded by Functional Group (FLoat, ACCess, MOve, FIght, INfrastructure, ACcOmmodation and SToRes), with certain spaces highlighted.

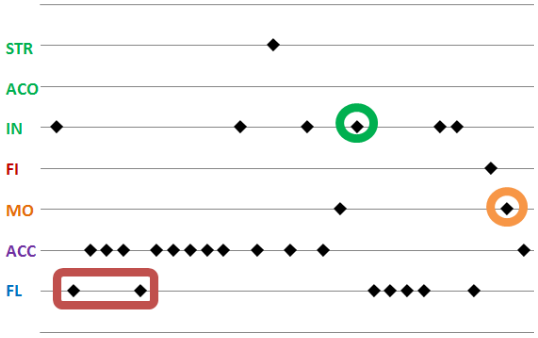


Figure 14a: Banded and ranked visualization of node centrality

Figure 14b shows the same information in a cumulative line graph, where the coloured lines represent the cumulative entries of the Functional Groups, and the dotted line shows the decreasing value of the centrality measure. Comparative visualisations such as this are considered to be of more use, due to the relatively abstract nature of some of the network metrics, in that their absolute values do not have a direct physical meaning.

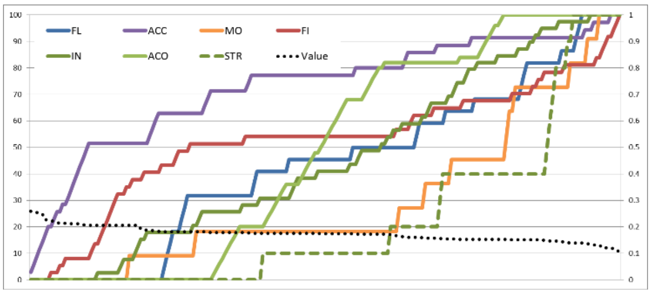


Figure 14b: Cumulative visualization of node centrality

## 4.3 *The example ships*

The selection of example ships to be analysed was largely driven by the availability of complete, labelled general arrangement drawings, with the intention of examining a selection of drawings from a range of eras, nations and roles. Of particular interest is the comparison between warships and research vessels, as both are complex service vessels. Table 4 summarises the vessels that have been encoded into network form so far, along with their principal particulars. Some of the naval vessels are designs that were proposed but lost out to competitors, or were developed further prior to construction.

Table 4: Vessels examined in the study to date

| Name | Type | Year | Built | Nation | Displ. (tonnes) | Overall Length (m) | Overall Beam (m) | Accom. |
|---|---|---|---|---|---|---|---|---|
| DDL | Guided missile destroyer | 1970 | No | UK for Australia | 4200 | 129.6 | 14.6 | 263 |
| GPF | Guided missile frigate | 1962 | No | Canada | 3300 | 121.3 | 14 | 240 |
| DDH | Anti-submarine frigate | 1965 | Yes (after changes) | Canada | 3800 | 129.1 | 14.7 | 244 |
| Aconit | Anti-submarine frigate | 1970 | Yes | France | 3870 | 127 | 13.4 | 232 |
| DD-692 Long Hull | Anti-submarine destroyer | 1947 | Yes (after changes) | USA | 2220 | 114.6 | 12.5 | 309 |
| EPV Louhi | Patrol vessel | 2007 | Yes | Finland | 3450 | 71.4 | 14.5 | 40 |
| Falkor | Research vessel | 1981 | Yes | Germany | 2260 | 82.9 | 13 | 42 |
| Meteor | Research vessel | 1986 | Yes | Germany | 5125 | 97.9 | 16.6 | 63 |
| Armstrong | Research vessel | 2015 | Yes | USA | 3204 | 72.5 | 15.2 | 44 |

## 5 RESULTS

### 5.1 *Overall Network Metrics*

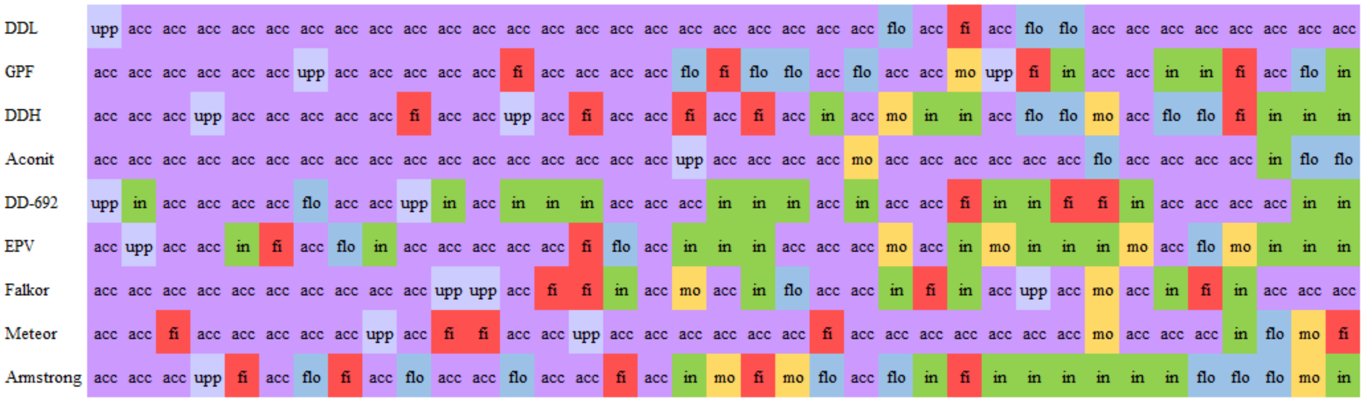
Table 5 summarises the overall network metrics for the designs analysed for this paper. The suffix “EXT” means that all external decks are included, “INT” means that only the minimum are included. For some ships it was not possible to remove the decks and leave a viable network, so for those vessels only a single network was created.

Examining these results, we see that the average degree is larger than we might expect, indicating that large numbers of spaces in real ship designs have more than one connection with another space. Examination of the distribution of degree for the designs shows that between 55 and 70% of spaces have only a single connection. It is the case that the statistical average is pulled up by a small number of access routes with a large number of connections. However, in each design there are some highly-connected non-access routes, as illustrated by Figure 15, which shows, for each vessel the 40 spaces with the highest degree.

Table 5: Summary of the overall network metrics for the designs analysed

| Design | Network Size | | Average Degree | | Network Dimensions | | | Graph Density | Modularity | Communities | Average Clustering Coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nodes | Edges | Un-weighted | Weighted | Diameter | Radius | Average Path Length | | | | |
| DDL INT | 269 | 282 | 2.097 | 2.134 | 16 | 8 | 6.831 | 0.008 | 0.846 | 16 | 0.017 |
| DDL EXT | 270 | 289 | 2.141 | 2.193 | 15 | 8 | 6.286 | 0.008 | 0.833 | 17 | 0.04 |
| GPF INT | 199 | 215 | 2.171 | 2.191 | 12 | 6 | 5.279 | 0.011 | 0.816 | 13 | 0.101 |
| GPF EXT | 204 | 223 | 2.186 | 2.225 | 12 | 6 | 5.264 | 0.011 | 0.808 | 12 | 0.098 |
| DDH INT | 205 | 217 | 2.117 | 2.127 | 12 | 6 | 4.877 | 0.01 | 0.825 | 13 | 0.123 |
| DDH EXT | 207 | 221 | 2.135 | 2.155 | 13 | 7 | 4.959 | 0.01 | 0.816 | 11 | 0.117 |
| Aconit INT | 221 | 231 | 2.09 | 2.109 | 18 | 9 | 7.388 | 0.01 | 0.848 | 13 | 0.078 |
| Aconit EXT | 225 | 240 | 2.133 | 2.16 | 15 | 8 | 6.73 | 0.01 | 0.829 | 14 | 0.075 |
| DD-692 INT | 145 | 152 | 2.097 | 2.124 | 21 | 11 | 8.841 | 0.015 | 0.815 | 11 | 0.044 |
| DD-692 EXT | 150 | 170 | 2.267 | 2.373 | 11 | 6 | 5.237 | 0.015 | 0.78 | 10 | 0.062 |
| EPV | 97 | 108 | 2.227 | 2.268 | 11 | 6 | 5.027 | 0.023 | 0.736 | 10 | 0.134 |
| Falkor INT | 126 | 138 | 2.19 | 2.222 | 16 | 9 | 6.716 | 0.018 | 0.785 | 10 | 0.137 |
| Falkor EXT | 133 | 148 | 2.226 | 2.271 | 15 | 9 | 6.8 | 0.017 | 0.789 | 12 | 0.138 |
| Meteor INT | 200 | 224 | 2.24 | 2.32 | 15 | 8 | 5.942 | 0.011 | 0.805 | 10 | 0.093 |
| Meteor EXT | 204 | 230 | 2.255 | 2.333 | 15 | 8 | 5.907 | 0.011 | 0.802 | 14 | 0.095 |
| Armstrong | 106 | 116 | 2.189 | 2.283 | 12 | 6 | 4.804 | 0.021 | 0.751 | 9 | 0.094 |

Notable in Figure 15 are the DDL; which has two parallel passageways along the length of the vessel, with consequentially very high levels of connection; the DD-692, which has a large number of highly connected infrastructure spaces; and the research vessels, which have highly connected labs and working decks (under the “Fight” functional group in this study).



| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DDL | upp | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | flo | acc | fi | acc | flo | flo | acc | acc | acc | acc | acc | acc | acc | acc |
| GPF | acc | acc | acc | acc | acc | acc | upp | acc | acc | acc | acc | acc | fi | acc | acc | acc | acc | flo | fi | flo | flo | acc | flo | acc | acc | mo | upp | fi | in | acc | acc | in | in | fi | acc | flo | in |
| DDH | acc | acc | acc | upp | acc | acc | acc | acc | acc | fi | acc | acc | upp | acc | fi | acc | acc | fi | acc | fi | acc | in | acc | mo | in | in | acc | flo | flo | mo | acc | flo | flo | fi | in | in | in |
| Aconit | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | upp | acc | acc | acc | acc | mo | acc | acc | acc | acc | acc | acc | flo | acc | acc | acc | acc | in | flo | flo |
| DD-692 | upp | in | acc | acc | acc | acc | flo | acc | acc | upp | in | acc | in | in | in | acc | acc | acc | in | in | in | acc | in | acc | acc | fi | in | in | fi | fi | in | acc | acc | acc | acc | in | in |
| EPV | acc | upp | acc | acc | in | fi | acc | flo | in | acc | acc | acc | acc | acc | fi | flo | acc | in | in | in | acc | acc | acc | mo | acc | in | mo | in | in | in | mo | acc | flo | mo | in | in | in |
| Falkor | acc | acc | acc | acc | acc | acc | acc | acc | acc | acc | upp | upp | acc | fi | fi | in | acc | mo | acc | in | flo | acc | acc | in | fi | in | acc | upp | acc | mo | acc | in | fi | in | acc | acc | acc |
| Meteor | acc | acc | fi | acc | acc | acc | acc | acc | upp | acc | fi | fi | acc | acc | upp | acc | acc | acc | acc | acc | acc | fi | acc | acc | acc | acc | acc | acc | acc | mo | acc | acc | acc | in | flo | mo | fi |
| Armstrong | acc | acc | acc | upp | fi | acc | flo | fi | acc | flo | acc | acc | flo | acc | acc | fi | acc | in | mo | fi | mo | flo | acc | flo | in | fi | in | in | in | in | in | in | flo | flo | flo | mo | in |

Figure 15: The Functional Groups of the spaces with the 40 highest degree in each design; external networks used in each case (colours indicate the Functional Group for the highlighted spaces – See Section 4.2.4)

Turning to the network dimensions section of table 5, it may be possible to see the significance of external access routes in the designs. The dimensions of the network for the DDL, GPF and DDH are far less affected by the removal of the upperdeck than Aconit or the DD-692 designs. In the latter case, the removal of the upperdeck edges and nodes significantly changes the network properties, and this is to be expected; the DD-692 design was developed late in the Second World War, during the US Pacific Campaign, whereas the other warships were designed for (or by designers who normally worked with) North Atlantic navies preparing for a conflict involving nuclear weapons, where ensuring good access inside the ship was paramount.

What can also be seen is that the overall parameters of the networks for the research vessels are less effected by the removal of the upperdeck. This may be a reflection of the provision of vertical stair towers in civilian designs, providing good internal access.

## 5.2 *Metrics by Node (Space)*

The three nodal metrics of initial interest are betweenness, closeness and eigenvector centralities. As betweenness centrality tells us how many paths pass through a node, it can potentially be used to evaluate the significance of a particular passageway to overall circulation. Figure 16 illustrates the effect of switching from Closeness Centrality to Eigenvector Centrality. The relative ranking of some functions, such as access, is strongly affected.

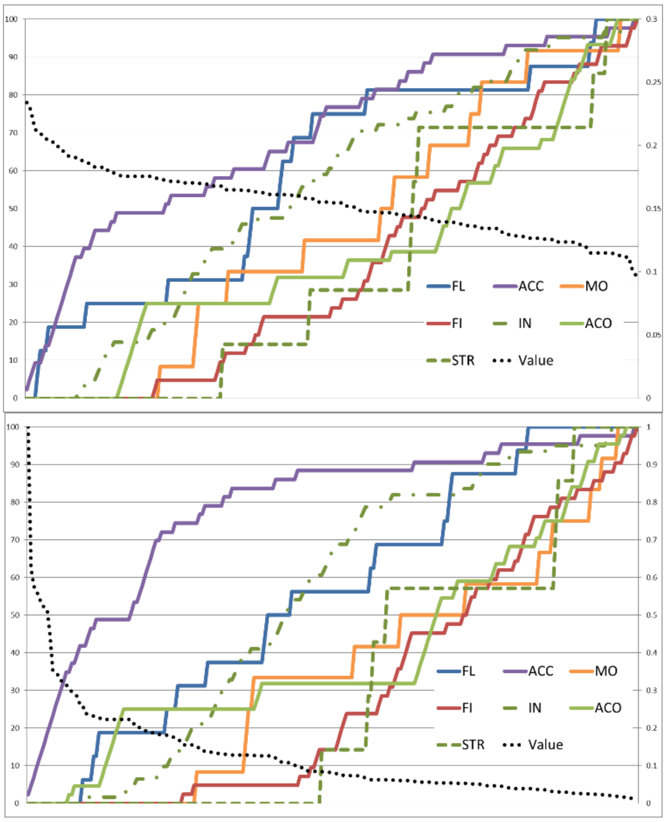


Figure 16: A comparison of ranking for closeness centrality (top) and eigenvector centrality (bottom) for the Aconit design

Closeness and eigenvector centrality both tell us how well connected a node is to the rest of the network, which may be used to evaluate the accessibility of a space from the rest of the ship. Eigenvector centrality is of interest as it effectively "weights" the spaces by their proximity to other well-connected spaces.

## 5.3 *The DD-692 Design*

Figures 17a, b, c and d show the functional banding of the distribution of betweeness, closeness and eigenvector centrality for the DD-692 "Long Hull" destroyer design. In these figures, the highest values are to the left of the diagram.

The first thing that can be seen is that several crew accommodation and mess decks (green box) have high values of betweenness centrality. Removing the upperdeck access, between Figures 17a and 17b, increases the relative significance of the mess decks to the overall accessibility of the ship. The highest betweenness centrality in a non-passageway space is assigned to a crew berthing space, highlighted in Figure 18. This is signifies the importance of non-dedicated passageways to overall access in ships of this period; examination of Figure 18 reveals a large number of watertight and hatches doors providing main longitudinal and vertical access through accommodation spaces.

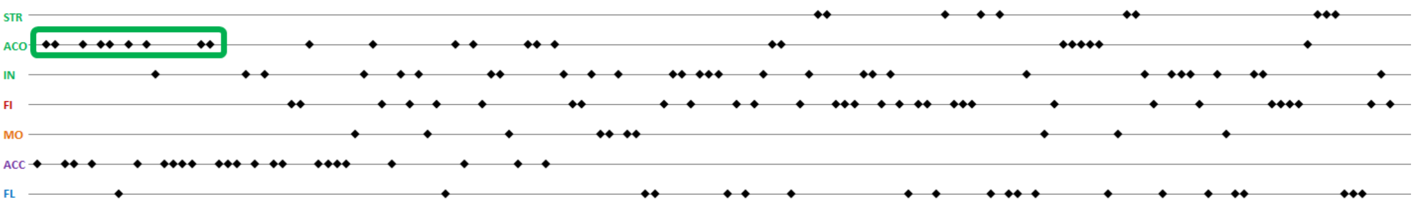


Figure 17a: Betweenness centrality, including upperdeck, with main crew accommodation highlighted

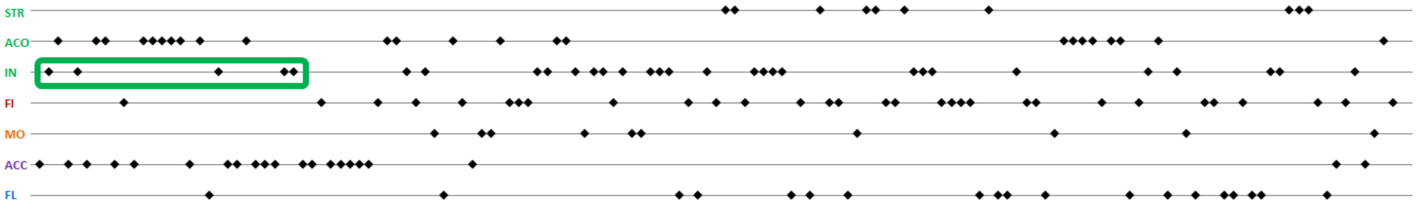


Figure 17b: Betweenness centrality, excluding upperdeck, with main crew mess decks highlighted

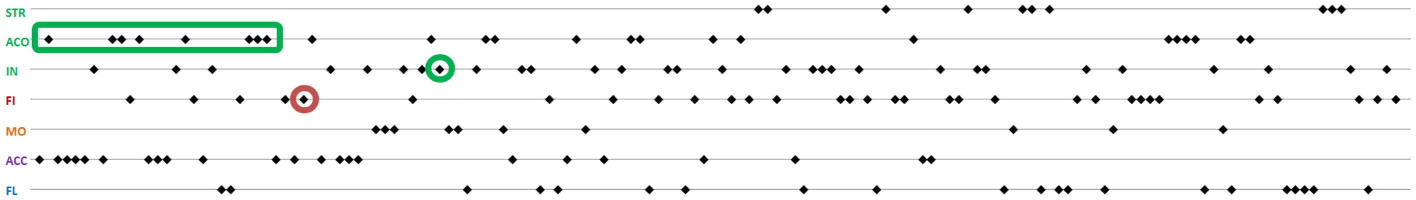


Figure 17c: Eigenvector centrality, including upperdeck, with crew accommodation, galley (green) and CIC (red) highlighted

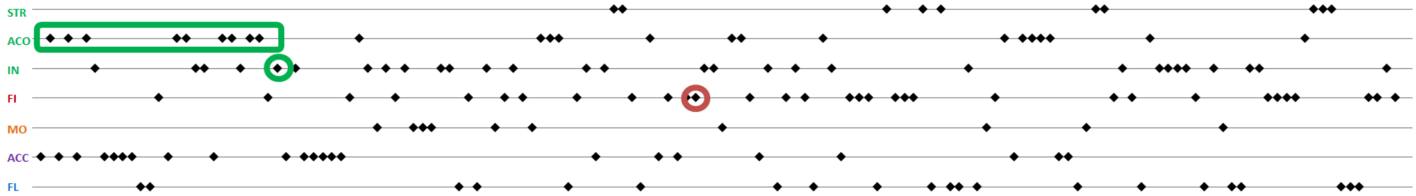


Figure 17d: Closeness centrality, including upperdeck, with crew accommodation, galley (green) and CIC (red) highlighted

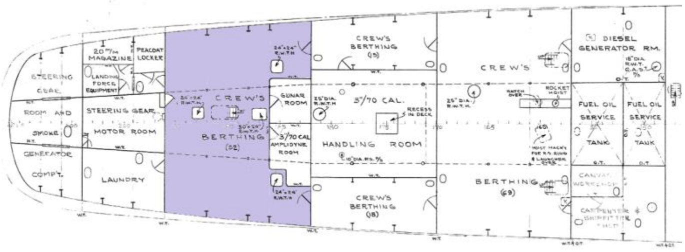


Figure 18: Crew berthing space in the DD-692 design with very high betweenness centrality

Figures 17c and 17d also indicate that the galley is in a location affording easy access to the rest of the ship. Given the significance of this space to daily operations, this is not unexpected. Another contrast between Figures 17c and 17d is the change in relative position of the CIC / Operations Room, from which the ship is fought. As it is in the superstructure, its closeness centrality is reduced, however the eigenvector centrality may better capture the impact of its proximity to several other important spaces, such as the captain's cabin and radio rooms.

Although these banded diagrams may indicate some trends in arrangement, the cumulative representation is required for further insight. Figure 19 shows the cumulative eigenvector centrality for the design (including upperdecks). The convex nature of the lines for ACCess and ACcOmmodation indicate that there are a smaller number of spaces with high centrality (connectivity). The FIght functional group, however, has a concave line, indicating that many spaces have low centrality. Inspecting the general arrangement, it is notable that the DD-692 has several weapon control spaces and magazines deep in the ship, with consequently limited access.

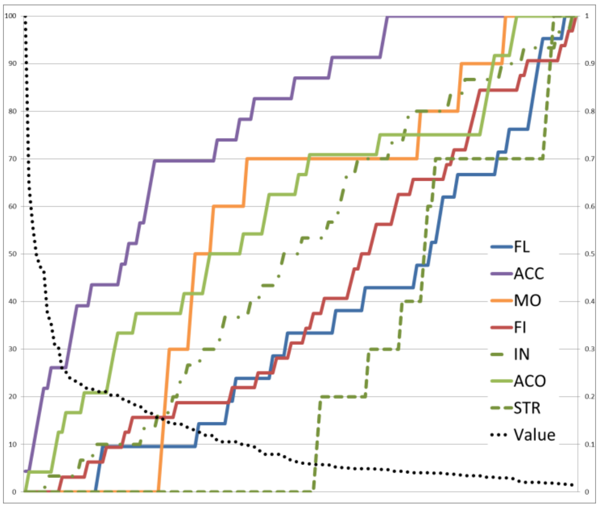


Figure 19: Cumulative eigenvector centrality

### 5.4 *Comparing Destroyers*

Figures 20a, b and c show the eigenvector closeness distributions for the DDL, DDH and GPF designs (without upperdeck, given their post-war design). These can be compared with Figure 17c. Notable is the apparent high priority given to officers accommodation, which has a higher centrality than in the DD-692. These ships also have more administrative spaces which are located in easily accessible locations, as shown by the high centrality of the offices.

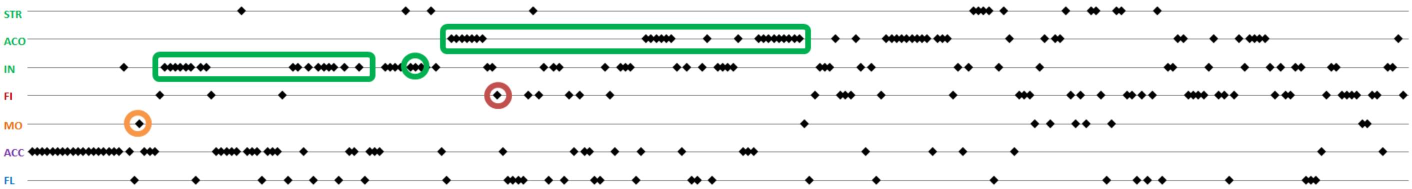


Figure 20a: DDL internal spaces in order of eigenvector centrality, with officers cabins (green rectangle), offices and admin spaces (green rectangle), galley (green circle), operations room / CIC (red circle) and machinery control room / SCC (yellow circle) highlighted

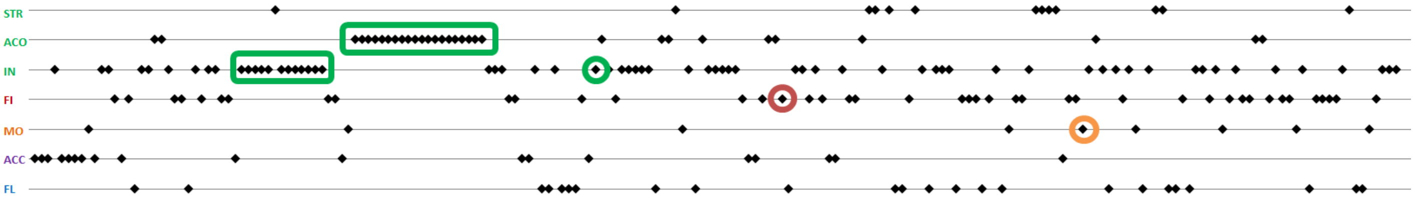


Figure 20b: DDH internal spaces in order of eigenvector centrality, with spaces highlighted as above

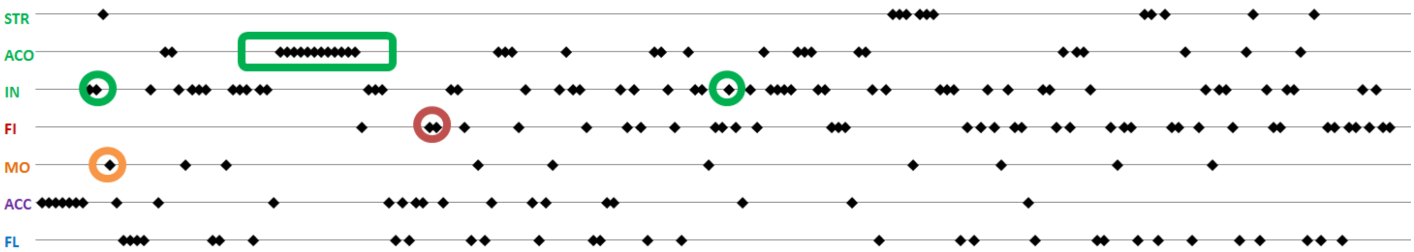


Figure 20c: GPF internal spaces in order of eigenvector centrality, with spaces highlighted as above, but with the dining halls highlighted instead of offices

The increase in both size and importance of accommodation and infrastructure spaces in post-war naval vessel design has been discussed in Brown (1988) and Brown & Moore (2003) and manifests itself in this network analysis. Comparing these with the older design (DD-962) also shows the a change in style to concentrated groups of accommodation spaces, in contrast to a smaller number of large messes in the later designs.

A key difference between the DDL and the other designs is that it has two longitudinal passageways on No.2 deck, and this is reflected in the large number of access spaces with high centrality values. The galley in all three ships has "middling" connectivity in the layout, but the GPF places the dining spaces in a well-connected location, effectively displacing, as the most connected spaces, the offices and admin compartments in the other two designs.

The contrast in relative ranking of the SCC can potentially be explained by examining its immediate connectivity. In the DDL, the SCC is on No.2 Deck and so benefits from the double passageways. In the DDH, it is again on No.2 Deck, but effectively in a cul-de-sac. The GPF locates the SCC lower in the ship, but retains watertight doors below the damage control deck providing access from the SCC to the machinery spaces. This drives the SCCs centrality higher. This practice was rapidly discontinued in post-war warships, with the SCC moved above the damage control deck (No.2 Deck) and no watertight doors fitted below the damage control deck. Although increasing survivability this has some impact on accessibility, and this appears to be reflected in the network analysis.

The apparently lower accessibility of the CIC in the DDH design corresponds to its location high in the superstructure – CIC location being one of the "stylistic" issues discussed by Kehoe et al (1980a, 1980b). Although CIC location in Figures 20a-20c does correlate with increasing height (by being in the superstructure), it is important to note that these are only relative within a single design, so smaller differences in centrality score, such as between the DDL and GPF, are not reliable indicators.

### 5.5 *A Non-NATO Warship: FS Aconit*

France withdrew from NATOs' command structure in 1966, but rejoined in 2009. Although the 1980's saw several joint warship projects between France and other NATO nations, eventually leading to the Horizon frigates (Brown & Moore, 2003). This separation may have had some consequences for warship design and development, and differences in national approaches have been documented by Ferreiro and Stonehouse (1994) and Ferreiro and Autret (1995).

Aconit differs from the other post-war warships in that it does not carry a helicopter, and relies on guns for air defence. At the detail level, several layout features were noted that contrasted with UK, US and Canadian practice, including; the location of some officers accommodation aft; the provision of a large number of small messes acting as entrance lobbies for accommodation areas; and large duplicated conversion machinery for the sensors and weapons on No.2 Deck (the latter is possibly due to a large number of 1960s' era weapons carried on a small frigate). Figure 21a and 21b illustrate the ranking for eigenvector centrality for external and internal spaces in the Aconit design.

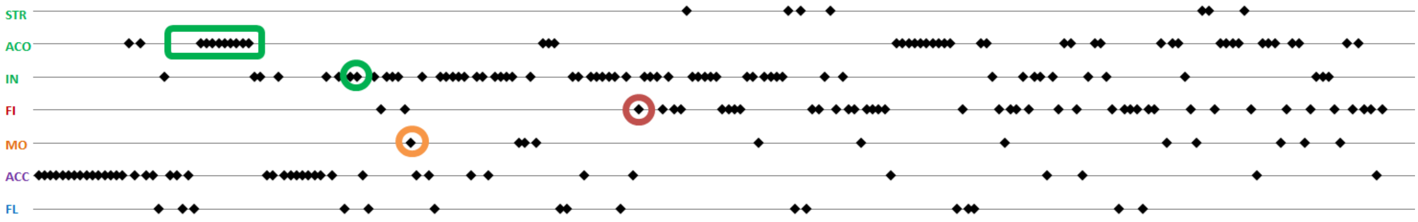


Figure 21a: Ranking of eigenvector centrality for Aconit including upperdeck, officers cabins, galley, CIC / operations room and SCC / machinery control room highlighted

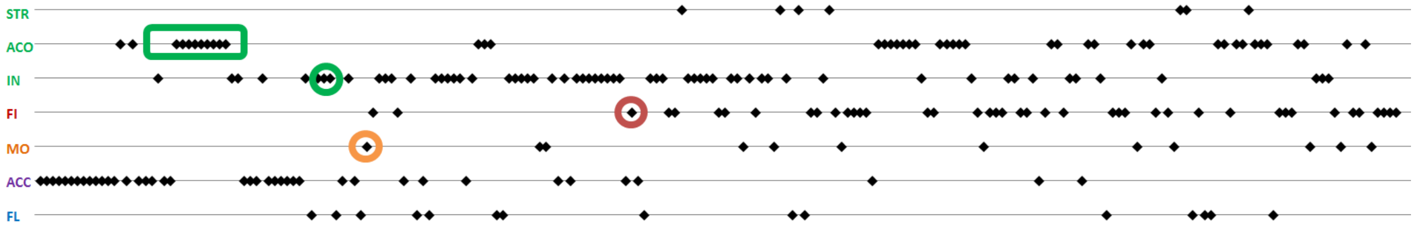


Figure 21b: Ranking of eigenvector centrality for Aconit exluding upperdeck, officers cabins, galley, CIC / operations room and SCC / machinery control room highlighted

Comparing these two figures indicates that the availability of the upperdeck has minimal impact on the accessibility of Aconit, and indeed the arrangement shows airlocks and decontamination areas, indicating that she was designed to be fought under conditions of NBCD contamination. Comparing the results with the destroyers, we see similar results; the galley and SCC, located on No. 2 Deck, are well connected, while the CIC / Ops Room, located in the superstructure behind the bridge, is less so. A difference between the designs is the large number of non-accommodation infrastructure spaces that have high centrality in the Aconit design. This is driven by the large number of small messes, which generally lead onto the main passageway or vertical access, and Figure 22 illustrates this with the betweenness centrality, highlighting these small messes.

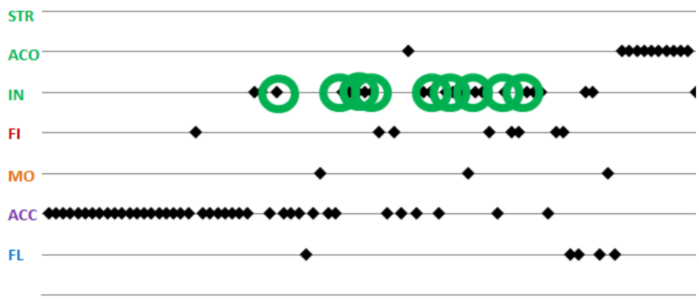


Figure 22: Betweenness centrality for Aconit, including upperdeck, with messes highlighted

### 5.6 *Research Vessels*

Research vessels were chosen as another type to be investigated, as they are service vessels, and their general arrangements are relatively readily available. Figures 23a, b and c illustrate the ranking of eigenvector centrality for the vessels, Falkor Meteor and Armstrong, respectively, with certain key spaces highlighted.

In all three designs, the scientist cabins have a higher centrality than the crew cabins, in common with officers on warships, and the tendency to concentrate cabins into groups can be seen.  The working decks aft have high centralities, with multiple connections via labs (even if single passageways are used elsewhere). This concentration and accessibility of the fight functional group (representing "research" in this case) can be contrasted with the less accessible Fight spaces in the warships, which are be dispersed to meet survivability requirements. As has been previously noted, the mess spaces are generally better connected than the galleys.

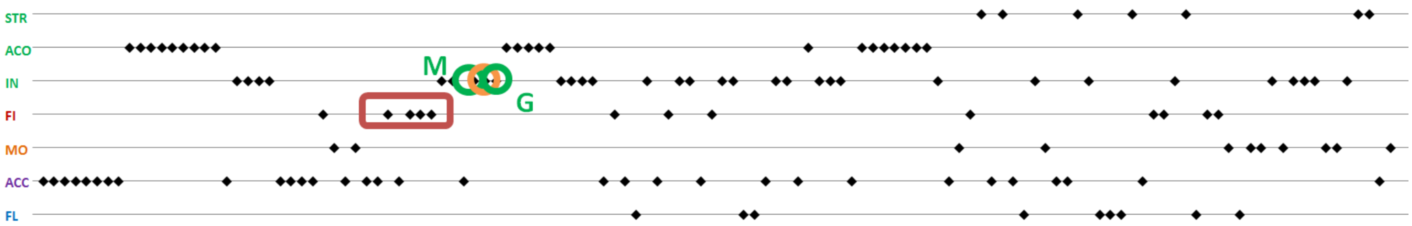


Figure 23a: Eigenvector centrality ranking for Falkor, with main mess (M), galley (G), working spaces and labs (red) and machinery control room (yellow) highlighted

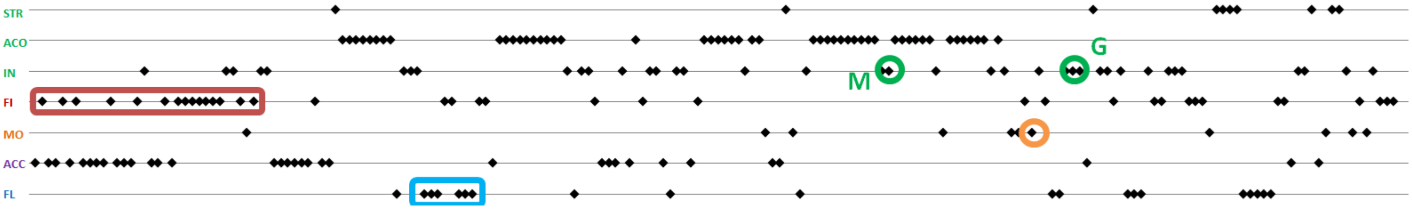


Figure 23b: Eigenvector centrality ranking for Meteor, with main mess (M), galley (G), working spaces and labs (red) and machinery control room (yellow) and workshops (blue) highlighted

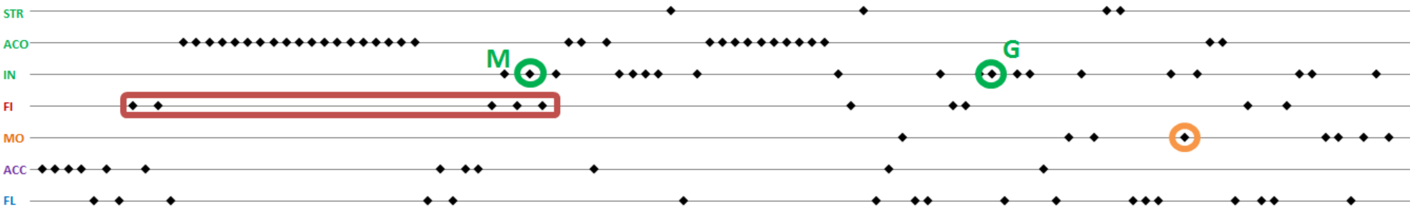


Figure 23c: Eigenvector centrality ranking for Armstrong, with main mess (M), galley (G), working spaces and labs (red) and machinery control room (yellow) highlighted

These vessels follow civilian practice in having the machinery control room / SCC low in the hull, close to the engine room. Falkor features watertight doors connecting the SCC to the surrounding spaces, this significantly increases its accessibility, at the cost of potential vulnerability after a collision. Notable on Meteor, the largest and most capable of the three vessels, is the provision of several workshops, which have a high relative centrality.

## 5.7 *EPV: The Smallest Network*

The EPV Louhi was included as the smallest network so far investigated. Given the comparative nature of the visualizations and metrics, problems may occur with their applicability to networks with small numbers of nodes. Figure 24 illustrates one issue; the small number of spaces leads to a highly discretized numerical range, with many plateau.

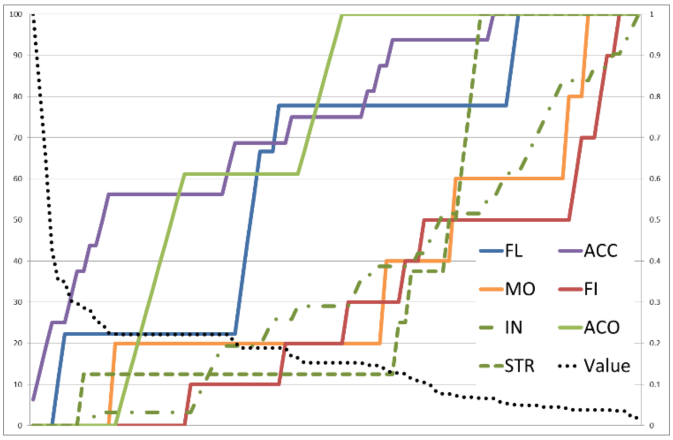


Figure 24: Cumulative eigenvector closeness for the EPV

Figure 25 illustrates the eigenvector centrality ranking for the EPV, with certain spaces highlighted. The main capabilities of patrol and environmental protection vessels are usually in the working deck and boats, and in the EPV the latter have a high centrality, having access directly off of the space with the highest betweenness centrality (a stairwell in the superstructure), shown in Figure 26. The EPV has an arrangement similar to an Offshore Support Vessel, with most functional spaces concentrated in the superstructure forward, and this leads to high centrality values for the bridge, mess and galley. The SCC is less accessible, however, being low in the ship.

It is notable that the working deck has a lower centrality than the working decks in the research vessels. However it has a high degree with seven connections to other spaces. The low centrality may be a result of the concept of operations (in research vessels the working decks are a regularly used transit route for equipment and samples to and from workshops and labs) but in an environmental protection vessel this flow is not present, so operationally could be seen as a “cul-de-sac”, where crew only occasionally go to carry out certain tasks, with far less requirement for connectivity.

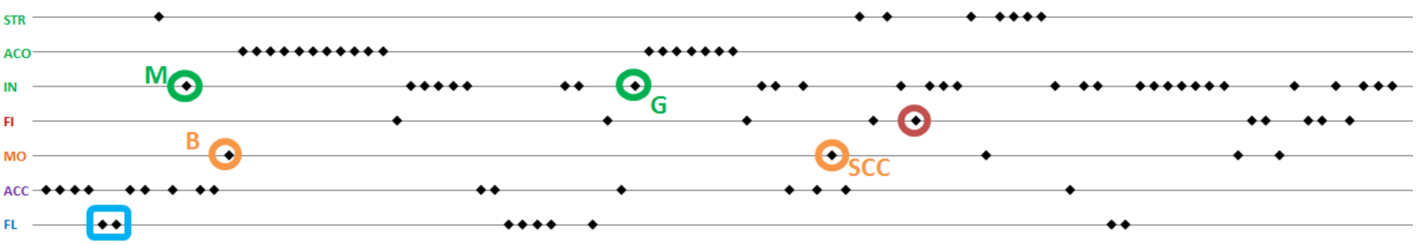


Figure 25: Ranking of eigenvector closeness for the EPV, with mess (M), galley (G), working deck (red), bridge (B), SCC and boat bays (blue) highlighted

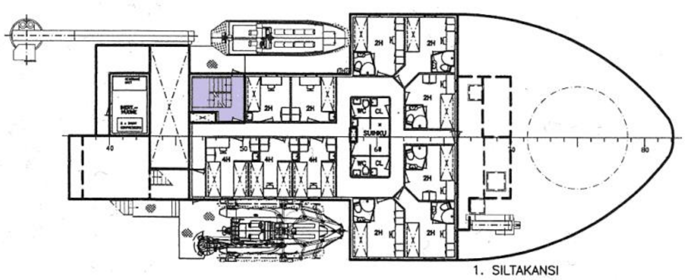


Figure 26: Partial GA of the EPV, showing the space with the highest betweenness centrality (Modified from Segercrantz, 2008)

## 6 THE SHAPE OF ARRANGEMENTS

Returning to the introductory sections which discussed conceptual models of ship arrangements, it is possible to visualize the complete network in a single image, as shown in Figures 13a and 13b so this can be used to examine the "shape of ships arrangements". At the time of writing, only simple illustrations produced using the "Force Atlas 2" (Jacomy et al, 2012) approach had been generated. Unfortunately the implementations of the graph layout codes in Gephi do not produce identical graphs each time they are run, and this makes comparing images a little difficult. It is possible to apply graphical effects to the nodes and edges based on numerical properties, such as colour-coding modules or a colour scale to indicate centralities.

Figure 27 illustrates the complete network for the EPV. It is perhaps notable that, despite the relatively small number of nodes in the EPV network, some distinct shapes are visible; the overall arrangement is characterized by multiple loops, which branch off into star-shaped geometries. The colour scheme, in which nodes with a higher betweenness are shaded more darkly, highlights the main access routes.

These geometric features are more pronounced in larger vessels, for example the research vessel Meteor, shown in Figure 28. This graph features multiple loops and several stars, consisting of both accommodation and other functional spaces.

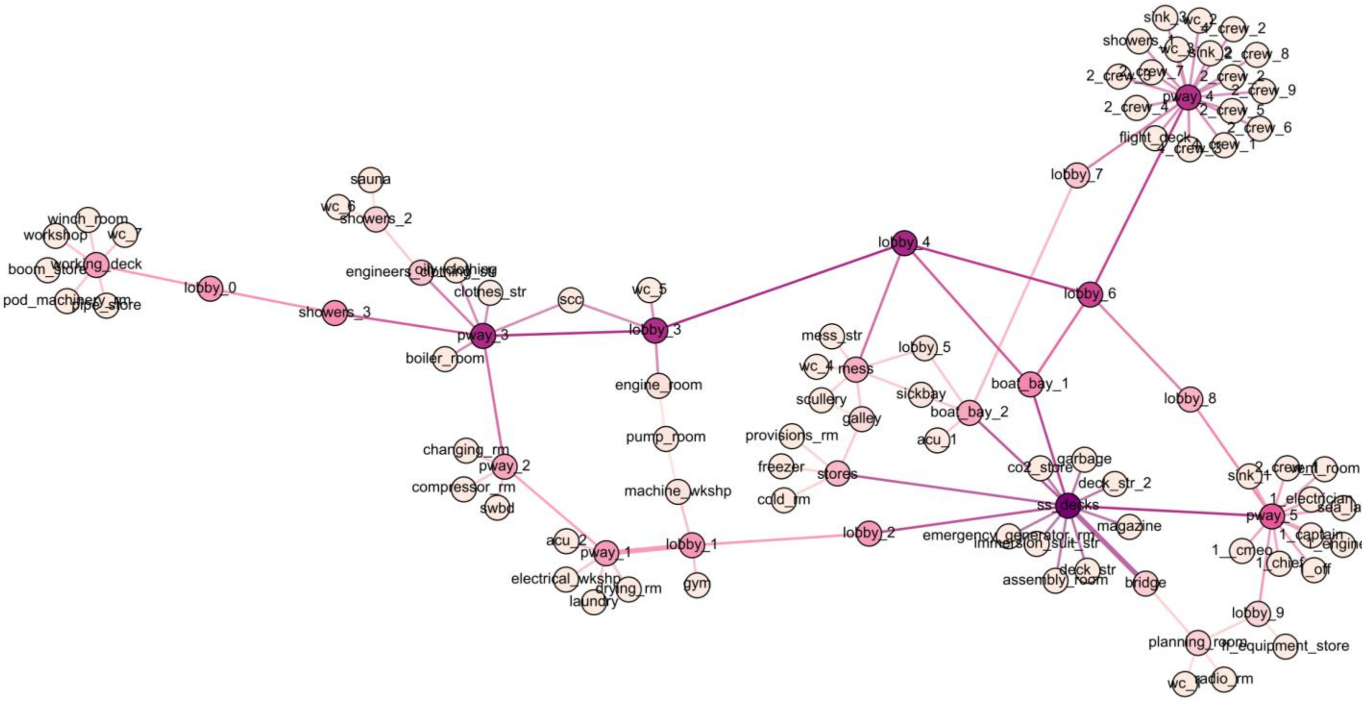


Figure 27: The complete network for the EPV, shaded by betweenness centrality

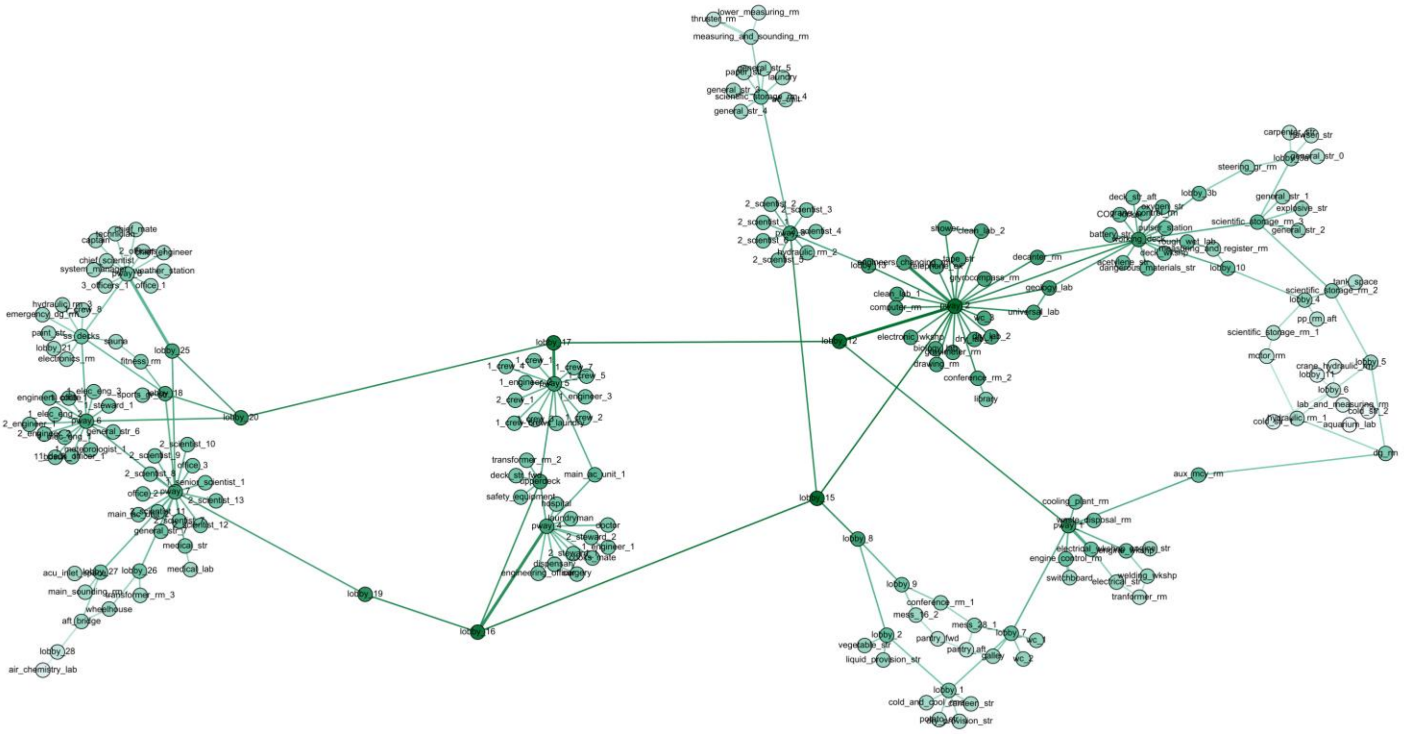
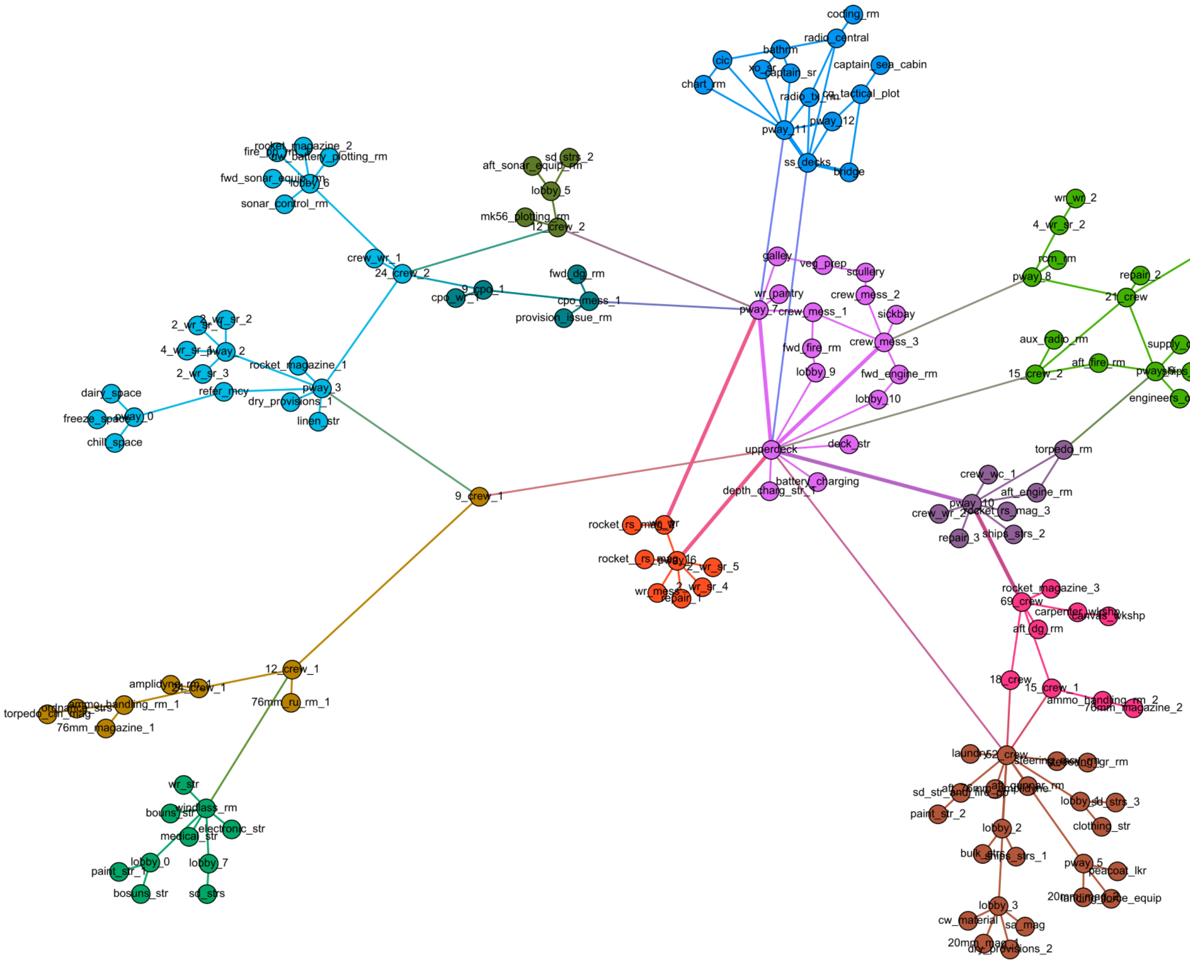
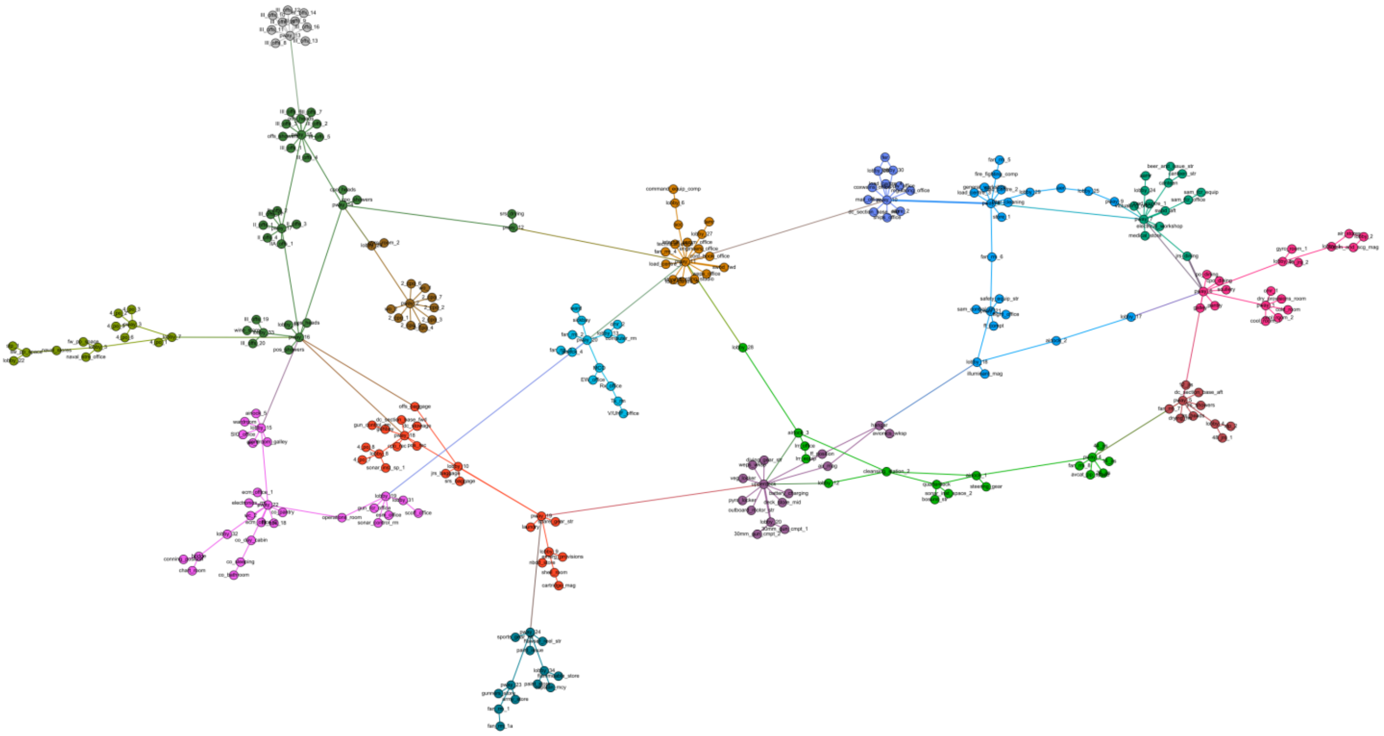


Figure 28: The complete layout network for Meteor, shaded by closeness centrality

Figures 29a and b compare the complete networks for the oldest and the most recent designs in the analysis conducted so far. These have been coded with contrasting colours randomly assigned to the different modules (communities) in each network. A stylistic change is apparent in the reduced complexity of the star-shaped geometries, and the loops in the older design are smaller, composed of less spaces. This visual change reflects the move to more dedicated access routes in post war vessels. The interleaving of the communities in the DD-692 network is a result of this increased interconnection in this older design.



a) DD-692 network (with upperdecks), coloured by communities of nodes (modules)



b) DDL network

Figure 29: Comparison of the DD-692 and DDL networks, coloured by communities of nodes (modules)

## 7 CONCLUSIONS

This paper describes progress to date on an ongoing UCL project to investigate the use of network science as a new way for designers to "see" general arrangements. As such, the work has examined ways of visualizing a relatively limited set of numerical network metrics, with analysis conducted using freeware software, and visualizations produced in Excel.

Several methods of visualizing numerical metrics in a comparative manner have been investigated: colour- and function-coded charts comparing different designs for a single metric by space; a functionally banded ranking visualization for various metrics in the designs; a cumulative plot of the same metrics; and a simple visualization of the overall network using established layout techniques.

The visualisations have allowed the authors to detect certain aspects of the "style" of the vessels, which correlate with the history of changes in warship design throughout the latter part of the twentieth century. Importantly, the visualisations retain a connection to the individual spaces and geometric layout of the design, as it is possible to identify which data point represents which space. It is considered that it is primarily this connection that allows the network metrics, when appropriately visualized, to be used as a new way to explore general arrangements, as the abstraction of network metrics alone would reduce their utility to the designer.

There are several possible criticisms of the analysis presented in this paper. Firstly, that the small number of examples makes drawing definite conclusions difficult. Secondly, the correlations described are dependent upon the authors' interpretation, and thirdly; correlation does not imply causation.

The small number of designs that have been addressed to date are being added to, to make the database more comprehensive – only a limited set could be fully explored at the time of writing. These include further patrol vessels and survey vessels.

It is not clear whether the interpretive nature of the analysis is a flaw particular to the investigations carried out so far; as one intention of this work is to develop new ways for the designer to examine the design, so some aspect of interpretation will always be present. The difficulty is in ensuring that such interpretation proceeds on a rational basis, and this is where the third criticism has significance. Considering the small number of arrangements examined so far, and the highly complex and emergent nature of ship arrangements in general, the possibility of illusory correlations being detected by the authors' interpretation cannot be ruled out.

Future work is partly directed at attempting to address these criticisms: the number and variety of ships will be increased; the range of numerical network metrics will be expanded, as only a limited set were used here; additional post-processing (such as statistical data) of the network metrics may also be of use in increasing confidence; and finally the functional meta-data assigned to spaces (functions and weight groups) may be incorporated into the analysis in a more numeric manner, as these could potentially form their own networks. These could then exist in parallel with the spatial connectivity networks which have been presented here.

Another key area for future research is in the potential application of this analysis in new ship designs. The analysis presented is considered to be best used as a tool to structure designer comparison of options, in a similar way to the land-based applications reported in the references. To develop a more extensive analytical approach network model metrics could be compared with other forms of simulation and analysis, such as the personnel movement simulations described by Andrews et al (2008), as this will assist in understanding correlations between network metrics and how the arrangement affects the ship's performance in specific scenarios.

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