A Network Science Approach to Understanding and Generating Ship Arrangements in Early-Stage Design

by

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To my mom, who long ago began encouraging my curiosity

and

to my new wife, who has been patient as I have exercised that trait

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ABSTRACT

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In recent years, automated approaches for creating ship general arrangements in early-stage design have been developed. These approaches seek to avoid "black box" implementations by keeping the designer involved in the layout generation and selection process, but they do not avoid it entirely. Existing methods first generate layouts, next evaluate each layout's quality, and subsequently filter out poor designs in an iterative process. In addition, desires to move toward full distributed system layouts in early-stage design have only led to more highly-refined CAD-style implementations requiring extensive modeling and computation time. This dissertation asserts that there is a need to shift away from the current trajectory toward higher-fidelity three-dimensional layout

models and re-vector toward a perspective that focuses on understanding and inherently respects the fundamental underlying relationships among elements within those models.

The research offered in this thesis uses network science to envision the layout problem from a new perspective. In this view, design relationships are information inputs into layout-related analyses rather than only post-processors for evaluating layouts. This is consistent with existing design processes in which human designers attempt to keep relevant relationships in the back of their mind at all times to inform decisions. Network nodes represent ship compartments and edges correspond to design constraints forming a relationship network.

First, network concepts of centrality and hierarchy are used to highlight and rank the embedded drivers of an early-stage arrangement prior to developing spatial layouts by directly analyzing the relationship network in a methodical and holistic manner. The obscured design intent of a notional WWII naval vessel is exposed using the hierarchical approach. Second, a network partitioning method is used to cluster shipboard elements into communities of mutually-compatible elements to minimize the degradation of other items located in the same region of the ship. These communities can form the basis of functional zone definitions. Varying the number of partitions reveals a multi-scale depiction of the relationship network. Third, the communities are assigned to structural zones based on cumulative zone preference values. Finally, two new visualization techniques help designers establish connections between the network of inter-element relationships and spatial ship arrangements.

Chapter 1
Introduction

Modern naval ships are so technically complex that the task of ship integration in itself represents significant technical risk.

– CDR Clark Graham, USN (1975)

Why is network anatomy so important to characterize? Because structure always affects function.

– Steven Strogatz (2001)

Ships, particularly naval combatants, are complex engineered systems that are created to accomplish multiple functions. Early-stage ship design decisions, including general arrangements, space allocation, and placement of equipment, influence the final ship size, configuration, risk, performance, and cost. Developing the three-dimensional compartment and component arrangements for these vessels is a challenging and time-consuming task partially because each layout includes hundreds or thousands of elements with interconnecting and sometimes conflicting relationships. The systems and subsystems that comprise a naval vessel are complex in and of themselves, but as CDR Graham's opening quote suggests, the true challenge is putting them all together.

It is the goal of this dissertation to use network science concepts and theory to study the general arrangement of these complex engineered systems at an early stage of design.

This research endeavor has focused on the application of complex networks to ship general arrangements in order to gain a more comprehensive understanding of the layout design space and to facilitate the generation of compartment and distributed system layouts based on that new knowledge.

1.1 Background and motivation

This section aims to describe the nature and context of the naval ship arrangements problem, particularly in early-stage design.

1.1.1 Nature of early-stage design

At its core, design is the act of making tradeoff decisions. Decisions are needed to constrain the design space and reduce the degrees of freedom in order to facilitate a narrowing of possible options to a set of feasible candidate solutions. The design space may be huge if the number of variables or disciplines is large or if the constraints on variables are loose. Early-stage design[1] is characterized by the need to make design decisions in an environment where little information is available. Mavris and DeLaurentis (2000) indirectly depict a circular process of making decisions (reducing design freedom) and gaining knowledge to make good decisions (Figure 1.1).

Foremost among the incomplete information may be definite design requirements (Figure 1.2). Requirements may be qualitative or quantitative. They may also be "fuzzy," having an element of flexibility or preference. The early-stage design process of complex systems may include iteration between design requirements and design products to understand the impacts of each on the other. Andrews (2011) notes the uniqueness of the early-stage design of physically large and complex systems, such as ships, offshore rigs, or chemical processing facilities. These systems are often very expensive, one-off projects that are designed from the ground up without the assistance of prototypes. The infeasibility of the validation phase of a design/test/validation process leaves a gap between requirements ideation and realization. This process is further discussed in

[1] The use of the terms *early-stage design*, *conceptual design*, and *preliminary design* are used generically and interchangeably. They refer to the entirety of the design process from initial concept exploration through contract design, including concept designs and feasibility studies.

Section 1.1.2 in the context of naval ships. Andrews et al. (2012) begins with an extended discussion of the preliminary ship design process, primarily in the context of layouts for warships.

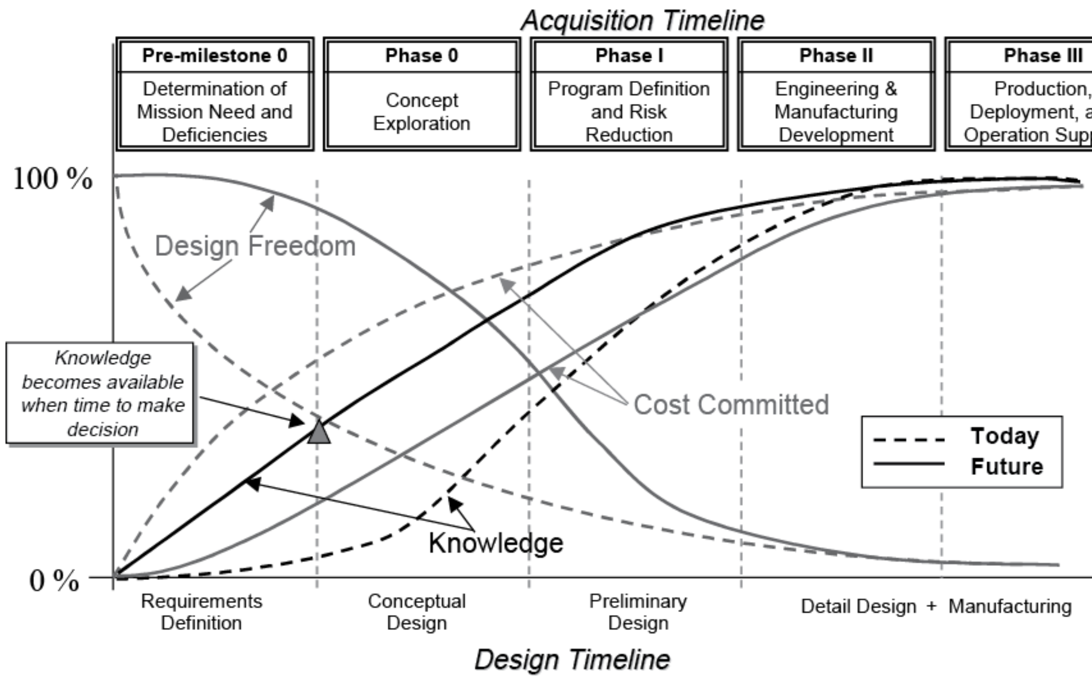


Figure 1.1: Depiction of the early-stage design environment. (Mavris and DeLaurentis 2000)

Despite possessing limited information, designers must conduct preliminary analyses to determine the lay of the design landscape. Leopold et al. (1972) assert,

> *A reasonably sophisticated, disciplined, and meaningful process of analysis and evaluation is essential at all stages at the concept design level to ensure that all design feature selections are based on specific rational grounds rather than intuitive decisions.*

In the field of naval ship design, there is a desire to incorporate more analyses and more advanced analyses earlier in the design process. A recent example of this is the addition of general arrangements as a follow-on analysis to (or an integral part of) the U.S. Navy's Advanced Surface Ship Evaluation Tool (ASSET) (ASSET 2007; Parsons et al. 2008).

This collection of ship synthesis models is used during early-stage design to calculate and balance the ship characteristics that drive size and cost.

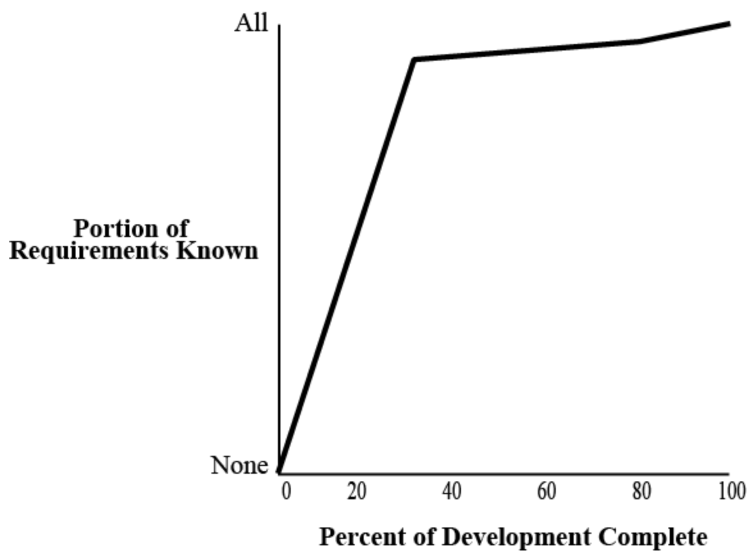


Figure 1.2: Incomplete knowledge of requirements early in the design process. (Bernstein 1998)

For the ships and complex systems of interest to this thesis, design is a multidisciplinary activity. For example, financial budgets may be fixed, and numerous (conflicting) objectives in disparate domains may be desired. Which goals can be achieved within budgetary or physical constraints depends on the relationships between the goals and the support systems required to achieve those goals. Some relationships may be tightly coupled. Secondary or tertiary constraints may be completely unknown at the outset. Relationships that are circular nature cause the design process to be iterative (Leopold et al. 1972). These relationships should be identified and understood in order to make informed decisions and limit rework.

1.1.2 Nature of naval ship design

Naval ships, particularly combatants, are unlike any other class of ships. Though commercial ship types rival naval vessels for size, Figure 1.3 shows that surface combatants have an outfit density two to four times their commercial counterparts. Submarines are even more complex. A related metric, *compensated gross tonnage*, also illustrates the vast difference between military surface vessels, submarines, and commercial ships. Compensated gross tonnage (CGT) is a shipyard productivity metric that accounts for differences in ship size and complexity (OECD STI 2007). Higher CGT coefficients indicate more work content per unit of production. In Figure 1.4, submarines rate an order of magnitude higher than surface combatants do. One goal of early-stage design is to maximize the probability of success in later stages of design. This is especially important in military design because the higher outfit density increases the probability of failure. The more items that must be put into the hull, the more opportunity there is for interactions and interference. Higher costs, production times, risk, and probability of cost and schedule overrun accompany increases in complexity (First Marine International 2005).

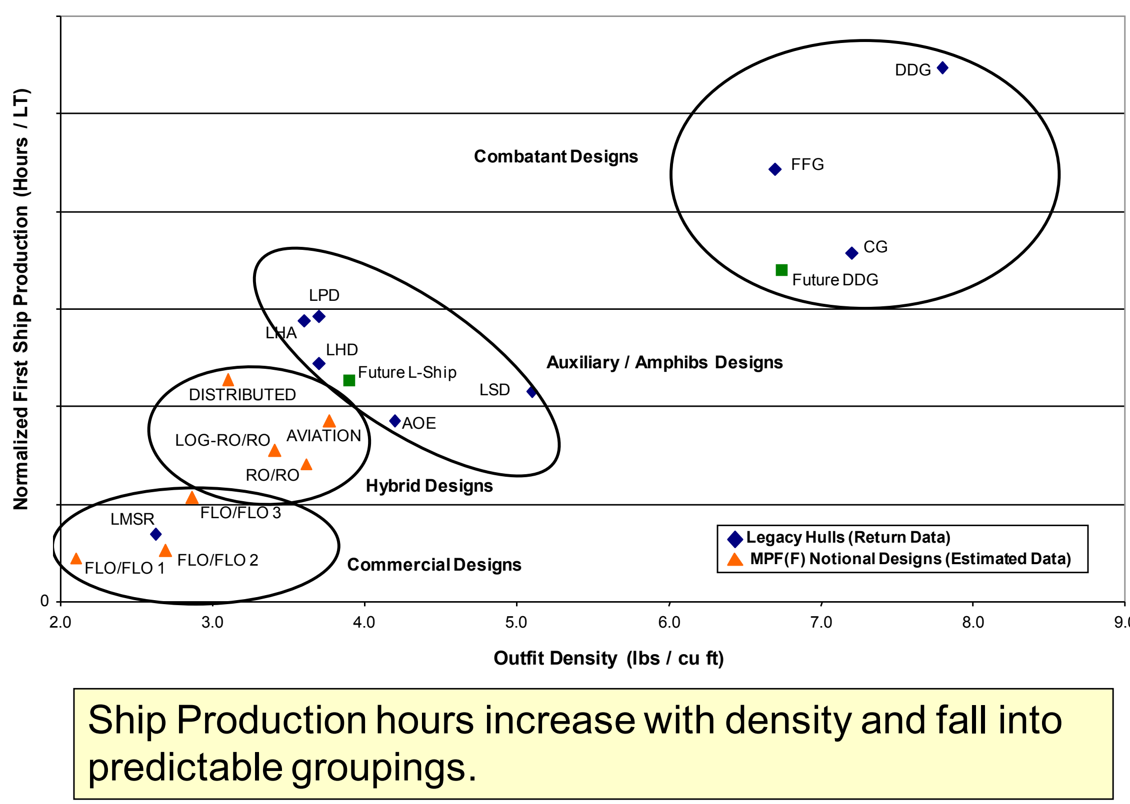


Figure 1.3: Relationship between outfit density and ship production hours (cost). (Keane Jr. 2011)

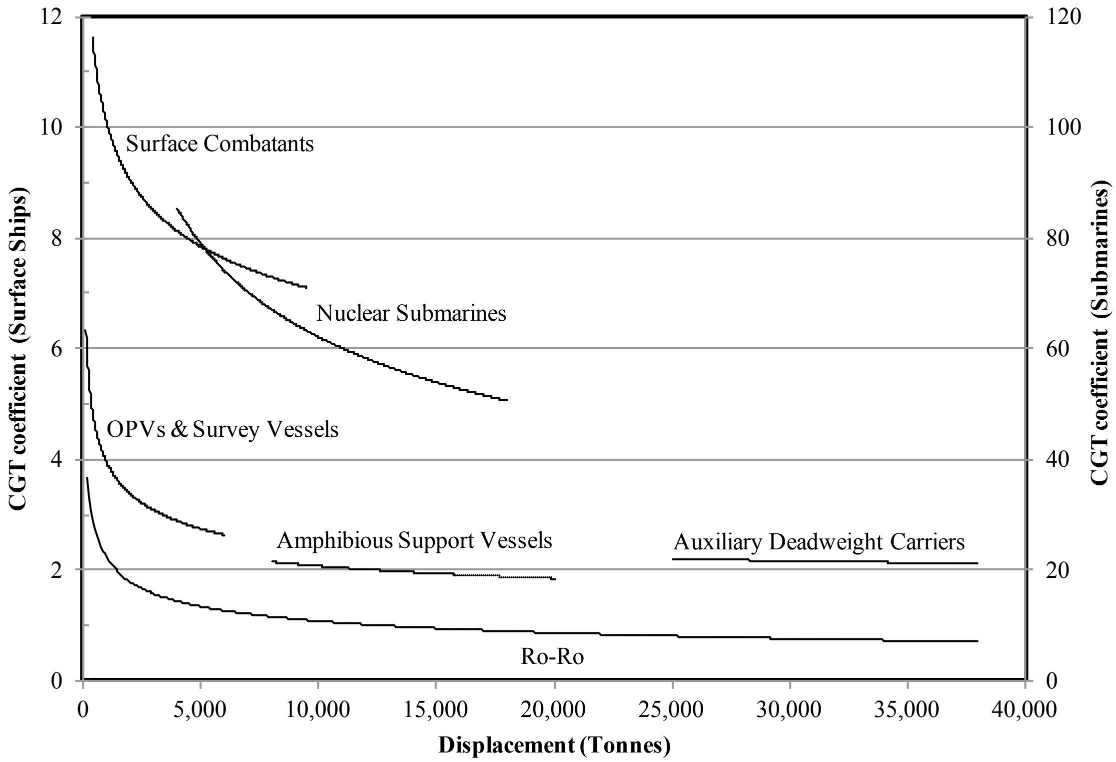


Figure 1.4: Compensated gross tonnage (CGT) coefficient by ship type. (Craggs et al. 2004)

Over the past 60 years, the cost of new naval ships has outpaced consumer product inflation by a significant margin. Of the 7-11% growth in cost (Figure 1.5), about half has been attributed to customer-driver, rather than economy-driven, factors (Arena et al. 2006). About one-quarter of the increase for surface combatants is due to complexity. The ship's mission requirements, its constituent systems, and the layout of those systems are key factors in the overall complexity of a vessel. From the naval architect's perspective, mission requirements and system selections may be non-negotiable. The remaining lever for managing a ship's complexity lies in the ship's arrangement.

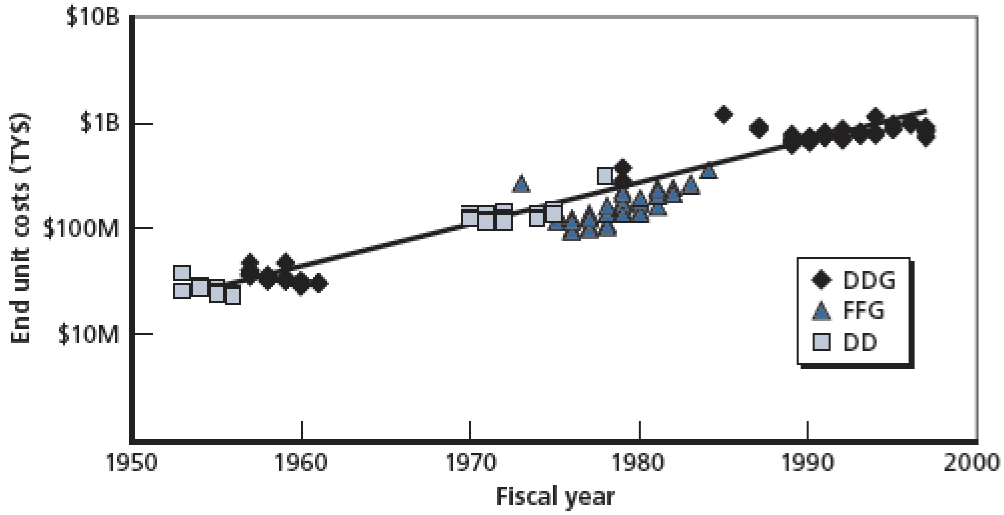


Figure 1.5: Cost escalation for selected surface combatants. (Arena et al. 2006)

One final notable characteristic of naval ship procurement relates to goal of design processes. Often, the purpose of generating naval designs is not to build ships, but rather to understand requirements. Hope (1981) notes:

> *One goal at the outset of any design is for the design team to reach a stable consensus on requirements, not only total ship and subsystem performance requirements, but also subsystem design requirements. Of course, while a stable consensus is sought, requirements will not remain completely stable during design. Indeed, some dynamic evolution is desirable because the lengthy time required to design a ship demands flexibility to exploit new opportunities and to meet unforeseen problems.*

Andrews (2003) argues that the separation of requirements clarification from design is not appropriate for warships because naval ship design falls into a category of problems termed *wicked problems*. This class of problems exhibits an intertwining of problem definition with problem solution, has no stopping criteria, and has just a single opportunity to "get it right." To complicate things further, there is no "right" answer, only good and bad ones (Rittel and Webber 1973). This is consistent with the assertion that the ship layout design space is flat, meaning there are many local optimums but no clear global optimum (Parsons et al. 2008).

1.1.3 Nature of ship arrangements

A ship general arrangement plan is a set of drawings that describe the physical layout of compartments and equipment on each deck. Figure 1.6 shows a detailed general arrangement plan for a small World War II naval vessel. Though this depiction is much more intricate than an arrangement plan generated in preliminary design, it illustrates the type of information contained in such a document. Traditionally, these plans have been 2-D representations, though advancements in computer modeling now enable the creation of three-dimensional (3-D) ship models. Two-dimensional arrangement plans are akin to the floor plans an architect develops for a home or office building.

An arrangement plan is also a tangible document that illustrates the complex tradeoffs that occur among system and subsystem design teams. Designing ship arrangements is a process of learning the characteristics of a ship and the interplay of the systems that are desired to be aboard it. Hope (1981) describes it in the following way:

> *General arrangement design, as a system engineering process, is a unique blend of experience and judgment combined with the systematic evaluation [of] performance. Its objective is to optimize the ship as a total system… The product of the process not only is a representation of design decisions, it also serves as a focal point for establishing an effective dialogue within the design community and also with the operational community.*

The arrangement of a ship has a unique feature in that it can both enable successful shipboard operations and constrain the performance of all subsystems. Keane Jr. (2011) notes that a stable ship layout is critical to producible, and therefore cost effective, designs.

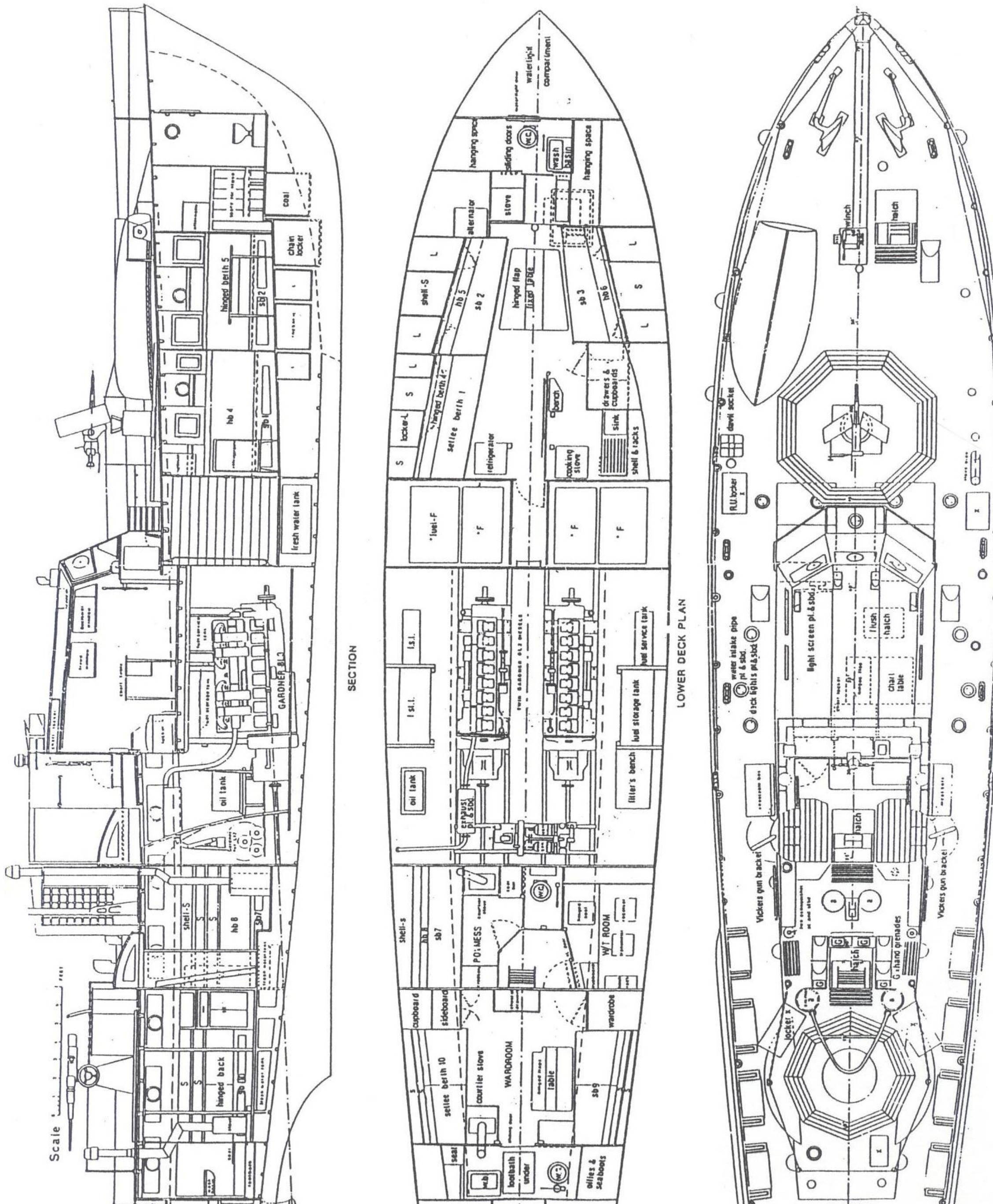


Figure 1.6: Detailed general arrangement of a small WWII naval vessel. (Thornycroft 1943)

Decisions regarding the location of compartments and major components are often made early in the design stage when design requirements and ship- and system-level impacts are not fully understood (Figure 1.1). These decisions constrain the design space and establish drivers of cost, performance, and risk early in the design process (Bernstein 1998). These realities apply in multiple phases of a ship's design. At the highest level, changes to ship missions or requirements that are desired mid-design are limited by commitments made to ship dimensions or systems. During the layout phase, decisions to locate systems or components in specific places necessarily (but possibly unknowingly) restricts, via desirable and undesirable interactions, where other components can be positioned.

The current process used in naval ship design is to define compartment boundaries and later add components to the appropriate compartments. The placement of one component has unknown consequences on the location and performance of other yet-to-be-located components. If flawed decisions are made early on, they will induce challenges throughout the process and they will be manifest in the final layout. In fact, the general arrangement drawing is the final output of the design process, but "the true products represented by the drawings are engineering and policy decisions made during the design" (Hope 1981). Poor ship layouts can lead to, for example, unnecessary cable and pipe bends that amplify the outfit weight and complexity challenges described in the preceding section, and in extreme cases, cause systems to fail.

Up to this point, developing a better understanding of ship arrangements has meant developing increasingly higher fidelity 3-D CAD models and balancing model fidelity with computational runtime. A variety of tools exists for creating highly detailed designs, but the level of information required by those tools is not available during early-stage design. A challenge that exists in many fields of study, early-stage design being no exception, is determining the appropriate level of fidelity for modeling. Referring to bottom-up ecological modeling approaches, (Grimm et al. 2005) summarize the predicament:

> *Finding the optimal level of resolution in a bottom-up model's structure is a fundamental problem. If a model is too simple, it neglects essential mechanisms*

of the real system, limiting its potential to provide understanding and testable predictions regarding the problem it addresses. If a model is too complex, its analysis will be cumbersome and likely to get bogged down in detail.

Upon reflection, however, it becomes obvious that the ship arrangements problem is more about managing relationships than about managing space. (An exception is submarines where volume and weight limitations are at least as important as the relationships.) By understanding and working with these relationships, feasible layouts should be able to be generated with less iteration. Designers intuitively do this, but the number of constraints can be overwhelming. With a desire to include higher fidelity analyses in preliminary design, this is becoming increasingly difficult for individuals to manage and optimize. As with the whole-ship design, there is no “right” arrangement, only good and bad ones. The truth of this statement is revealed in the appreciation that the optimization of ship arrangements is simply the minimization of sailor cursing.

1.2 Present study

Existing methods for creating ship arrangements and facility layouts do not account for the entire set of underlying inter-compartment or inter-component relationships in a unified manner. Methods are needed that respect and recognize, to the greatest extent possible, these fundamental relationships. Early-stage designs based on this principle are surmised to be better posed to transition successfully through detail design. Therefore, the work presented in this thesis will focus on a network of basic ship layout relationships, which are known to exist early in the design process.

1.2.1 A nonphysical challenge

The overarching challenge that guided the research effort described in this dissertation is presented as: *Develop a method to generate and analyze 3-D distributed system and compartment arrangements without designing a ship.*

The challenge led to questions such as, Can we evaluate an arrangement without having a physical layout? What would a non-spatial layout be? While these questions are not necessarily useful for practical implementation in a design office, they guided research investigations into new directions, including the use of networks.

Existing layout processes rely on the existence of a geometric model for analysis. The impetus for diverging from this established track is described in Chapters 2 and 3. However, at its core is the realization that the difficulty of generating ship arrangements lies in the unsystematic understanding and coordination of myriad relationships. The investigations presented in this thesis provide a methodical framework for handling concurrently the collective set of relationships embedded within a ship layout.

1.2.2 Current research scope

The investigations described in this thesis do not attempt to tackle the entire problem of understanding and generating ship general arrangements. Discussions in the chapters that follow are limited in two main areas. First, only the initial portion of the arrangements problem is considered, that is, the assignment of shipboard elements to structural zones of the ship. Secondly, all analyses include ship compartments, but do not include systems or components.

1.2.2.1 Allocations without geometry

The portion of the ship arrangements problem addressed in this dissertation is limited to the assignment of compartments to pre-defined zones of the ship. This has been dubbed *allocation* in the terminology used in the Intelligent Ship Arrangements schema (detailed in Section 2.3.3). The allocation process involves identifying the elements to be housed within structural zones of the ship, which are bounded by decks and major transverse and longitudinal bulkheads. Geometric representations of compartment boundaries are not created, and Cartesian coordinates are not assigned to compartments.

1.2.2.2 Inclusion of compartments, exclusion of systems and components

The overarching challenge (Section 1.2.1) included “3-D distributed system and compartment” arrangements. However, in the analyses conducted, only compartments are incorporated. While the inclusion of systems and components adds challenges in terms of problem size and availability of requisite information, the methods used and developed in this dissertation are sufficiently general to accommodate the additional items. The concepts and methods presented are applicable and extensible to the combined arrangement of ship compartments, systems, and components.

1.2.3 Novel contributions

This dissertation presents a new perspective for understanding and generating ship general arrangements, particularly in early-stage design. These contributions are built on the author's belief that managing the relationships among shipboard elements is the true challenge of integrating compartments and systems into a cohesive and functional early-stage ship layout. Specific novel contributions to the field include:

- Recognizing a need to shift away from the current trajectory toward higher-fidelity 3-D layout models and re-vectoring toward a perspective that focuses on understanding and respecting the fundamental underlying relationships among elements within those models,
- Re-conceptualizing the traditional set of design constraints used for concept evaluation as a network of design relationships to be used as an information source input for analyses,
- Identifying and applying methods for highlighting and ranking the embedded drivers of an early-stage arrangement prior to developing spatial layouts by directly analyzing the network of design relationships (constraints) in a methodical and holistic manner,
- Clustering shipboard elements (compartments, components, systems) into collections of mutually-compatible elements with the intent to minimize the degradation of other items located in the same region of the ship,
- Allocating communities of ship compartments to ship structural zones in a manner that respects each community's aggregate global location preferences to the greatest extent possible,
- Mapping and visualizing compartments' preferences – jointly with their associated compartments – for particular regions of the ship, providing insight into areas that may require specific attention when creating layouts,
- Developing a visualization technique that helps designers establish connections between networks of inter-element relationships and the completed ship arrangement.

These intellectual contributions form the core of this dissertation. Their overarching purpose is to facilitate the layout of compartments and distributed systems in a three-dimensional ship space in a novel manner. Concepts and methods explored and developed have been in support of providing naval architects a greater awareness of the fundamental relationships underpinning each design concept they create or critique.

1.3 Organization of dissertation

This dissertation is divided into 8 chapters. Chapter 2 presents an overview of existing research and methods related to ship general arrangements, while highlighting several topics identified as areas for future research. Chapter 3 lays out a new perspective for the arrangements process in early-stage design. It also provides the basic network science terminology used in subsequent chapters. Network terminology that is specific to an analysis is presented in the corresponding chapter. Chapters 4-7 form the core of this exposition and contain the methods and results. Chapter 4 explains how a designer can draw out the drivers of an arrangement without creating spatial layouts by analyzing the inputs. Chapters 5-6 describe a method for assigning compartments to ship structural zones to form the basis of a traditional general arrangement drawing. The method is divided into two major independent steps: discovering sets of compatible compartments (Chapter 5) and assigning sets of compatible compartments to structural zones (Chapter 6). In Chapter 7, a new way to visualize layout relationships in the context of a completed ship arrangement is presented. The final chapter, Chapter 8, summarizes the body of work presented and offers suggestions for future research.

Chapter 2
Overview of existing ship arrangements and facility layout research

This chapter provides an overview of existing research related to the general problem of facility layout and the specific application to ship compartment and system arrangement in early-stage design. Then, a brief description of four ship layout methods is provided. Major features of the Intelligent Ship Arrangements tool that are relevant to this research endeavor are detailed. The chapter ends with a depiction of the state of the art, including common capabilities and gaps in capabilities among existing methods.

2.1 Facility layout and ship arrangements

In this section, the general facility layout problem and its relationship to ship arrangements are discussed. The two topics are closely related, however, a significant and consequential difference relates to the extended scope and complexity of ship arrangements.

2.1.1 General facility layout

The act of arranging distributed systems is not new and has been extensively studied as the *facility layout problem* (FLP) in the fields of industrial engineering and operations research. This class of problems is concerned with the spatial arrangement of production areas and/or pieces of equipment, and often, the objective is to arrange these elements in a manner that minimizes measures such as total material handling costs (Drira et al. 2007) or connectivity costs (Barbosa-Póvoa et al. 2002; Jang and Rhee 2004). The FLP can be classified by many characteristics including discrete and continuous domains, areas with equal and unequal size, two- or three-dimensions, among others (e.g., Martin

2004, Fig. 2.1). When the layout problem consists of equal-sized modules, it is generally solved as a quadratic assignment problem, which is NP-hard (Ball et al. 1998; Drira et al. 2007) meaning it is unsolvable in polynomial time (Garey and Johnson 1979). Nick (2008) adds the space allocation problem for ship arrangements to this class of NP-hard problems. In the field of architecture, the FLP is known as Space Layout Planning (SLP) (Lobos and Donath 2010).

Though small FLPs can be solved exactly, ships typically have hundreds or thousands of compartments and components, making exact solutions infeasible. Heuristic methods are commonly used in these cases (Drira et al. 2007). Numerous methods have been used to solve the facility layout problem, including mixed integer linear programs (Jayakumar and Reklaitis 1996; Barbosa-Póvoa et al. 2002); graph theory (Muther 1973; Hassan and Hogg 1987; Rosenblatt and Golany 1992; Jayakumar and Reklaitis 1994; Ball et al. 1998); simulated annealing, genetic algorithms, and hybrids (Bland and Dawson 1994; Mavridou and Pardalos 1997; Mak et al. 1998); and multiagent systems (Sachdev 1998; Tarkesh et al. 2009).

For surveys of facility layout problem variations, formations, and solution techniques, see (Drira et al. 2007), (Singh and Sharma 2006), or (Shouman et al. 2001). Lobos and Donath (2010) survey approaches used in the architectural domain; their list spans collection of methods already mentioned. Much of the FLP literature described focuses on block layouts (relative locations and sizes of spaces) rather than detailed layout (machine placement, input/output locations, and flow paths within spaces), an area in which (Kulturel-Konak 2007) identifies a lack of research. In addition, Drira et al. note the need for additional research for the three-dimensional facility layout problem.

2.1.1.1 Differences between ship arrangements and the FLP

Creating ship arrangements is associated to the FLP, but is specific to the field of naval architecture. Drawing up the arrangements for complex ships such as naval vessels, cruise liners, or offshore platforms is different from designing layouts for manufacturing facilities or other complex vehicles such as airplanes or automobiles. Designing complex ships is more comparable to (though arguably more intricate than) planning small cities

(Heffron 1973), with the notable differences being that ships are (relatively) limited by available space, must have a limited response to the motions of the sea, and must be self-sustaining for weeks or months at a time. These vessels have a multitude of operational requirements; a "facility" may be a power plant, a water treatment and waste disposal facility, or a warehouse, whereas the ship likely contains *all* these elements as *sub*-systems in the form of the main propulsion and auxiliary power systems, potable and wastewater treatment systems, and storerooms for consumables, spare parts, and munitions. In addition, there are often medical, berthing, food service, commerce, and office complexes aboard the ship. A naval ship may have a hundred such highly integrated systems (Farrell et al. 1972; Leopold et al. 1972) that should be "considered to be a single integrated weapon system" that is the ship itself (Graham 1975). The scale and complexity of a ship arrangement is unlike almost all other engineering projects (Heffron 1973). In fact, Graham (1975) wrote that "modern naval ships are so technically complex that the task of ship integration in itself represents significant technical risk." The concern here is not the systems or sub-systems; rather, it is putting them all together. Though Graham's background may make him biased, he is quoted as saying, "Today's warships are the most complex, diverse and highly integrated of any engineering system" (Gates and Rusling 1982).

This risk of integration comes from the many layers and scales of interactions that exist. At the lowest level, there are interactions among components emitting things like noise or heat and components that are sensitive to those emissions (Jayakumar and Reklaitis 1994; Pimmler and Eppinger 1994; Gillespie et al. 2010). There are additional layers for items like piping, valves, fittings, and minor components; ducting; and wire and cable trays. Finally, each space must be integrated with its surrounding spaces and with the ship as a whole.

2.2 Progression of ship arrangements methodologies

The literature concerned with ship arrangements methodologies has been steadily increasing during the past 30 years (Hope 1981; Cort and Hills 1987; Andrews and Dicks 1997; Lee et al. 2005; Parsons et al. 2008; van Oers and Hopman 2010). While an interesting research topic itself, the impetus has been that navies around the world are interested in performing analyses that rely on system layouts during preliminary design in order to build confidence in the ultimate feasibility of candidate designs. The coupling between requirements and ship size, cost, and performance is due in large part to the arrangement of the vessel.

In the sections that follow, the evolution of early-stage design ship arrangement methods is given along with a succinct description of several advanced approaches. The pertinent features of two approaches, Intelligent Ship Arrangements and a system of communicating agents, are reviewed in detail as a backdrop for the current work. This chapter ends with a brief discussion of the state of the art in ship arrangements.

2.2.1 Evolution of ship arrangements methodologies

Doctoral dissertations by Pawling (2007), Nick (2008), and van Oers (2011) illustrate the recent history of computer-assisted ship design developments with respect to layout. The question might be asked, "How did these ship arrangements methods develop?" Figures 2.1-2.3 summarize the development path, which consists of three methodologies: manual design "optimization," computer-based optimization, and post-processing sets of feasible solutions.

2.2.1.1 Manual "optimization"

The traditional approach to ship arrangements includes drawing deck plans by hand, either on paper or within a generic computer aided design tool (Cort and Hills 1987; Andrews and Pawling 2003; QinetiQ GRC 2011). Cort and Hills (1987) note the hierarchical procedure of defining main compartments, followed by more refined functional compartment definitions, and lastly systems, as the only practical approach to the complex layout problem. The manual nature of this iterative process provides naval architects an intimate connection with the design and the design evolution. They identify opportunities and challenges within the layout through manual optimization. The knowledge gained is useful for providing feedback to the requirements elucidation process as well as for informing subsequent analyses (Figure 2.1). The Design Building Block approach (Section 2.3.1) is still closely tied to this method of generating layouts.

For ships with hundreds or thousands of spaces, this process is tedious and time consuming. As a result, candidate designs may be down-selected before advancing to higher levels of fidelity simply due to the excessive amount of time required to retain all options when modeling secondary and tertiary concerns (Singer et al. 2012, included as Appendix A).

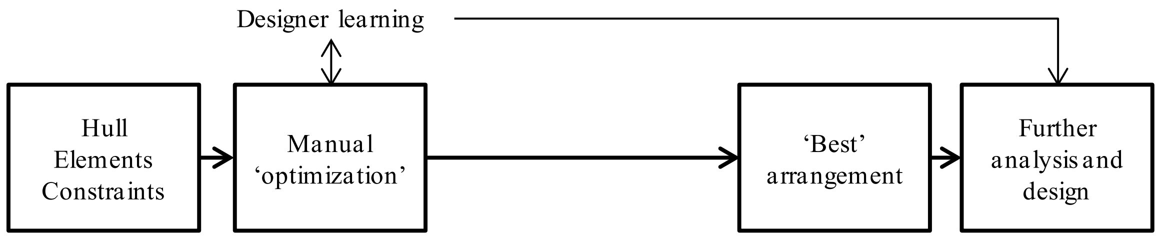


Figure 2.1: Manual "optimization."

2.2.1.2 Computer-based optimization

With the development of more powerful computers, (semi-)automated approaches were developed to increase the number of designs that could be generated and evaluated. The premise is that computers can generate and grade layouts faster than a human can. Elemental information and basic thought processes utilized in the manual approach were captured in database format, and rational evaluation mechanisms were developed (Cort and Hills 1987; Nick 2008; Daniels et al. 2009; van Oers 2011). Nevertheless, it is difficult to define mathematically every aspect that comprises a quality arrangement. Given the flat nature of the ship design space, creating an optimization algorithm that output a single "best" arrangement was not desirable (Figure 2.2); the set of feasible solutions is often a non-dominated set (van Oers et al. 2008) with potentially hundreds of design variables. This style of computer-based optimization takes designers out of the loop and removes all learning opportunities leaving it impossible to determine what drove the solution and what tradeoffs were made.

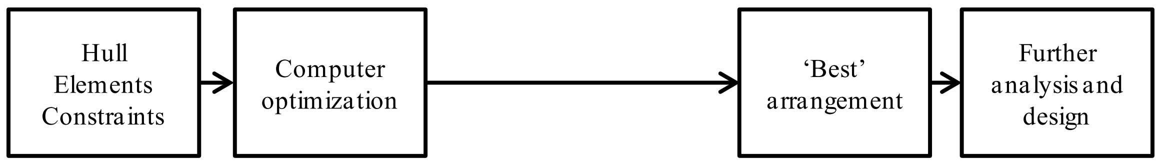


Figure 2.2: Computer-based optimization.

2.2.1.3 Post-processing the "best" designs

An experienced naval architect is assumed capable of identifying a quality layout upon seeing it, and therefore, different mechanisms have been developed to keep the designer involved. Rather than simply accepting the single highest-scoring solution from an optimization, a set of high-quality solutions are retained to be analyzed by human designers (Figure 2.3). Van Oers et al. (2008) and Wagner et al. (2010) have developed post-processing tools that allow designers to infer relationships and understand compromise decisions through rapid comparison of the set of potential solutions. Van Oers' method facilitates the understanding of requirements on resultant layouts, albeit in an ad hoc manner and only when input requirements are altered in a systematic way. The author does not believe their method is practical for understanding why specific configurations result in response to a particular list of requirements due to the time investment required for a thorough systematic study.

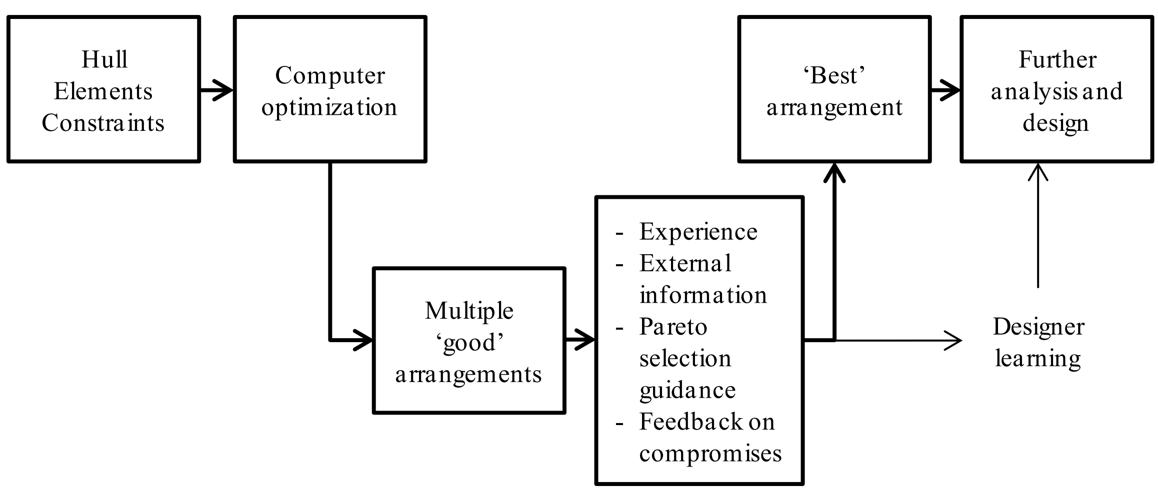


Figure 2.3: Computer-based optimization with designer selection.

2.3 Dedicated early-stage design general arrangements approaches

There are currently three well-developed early-stage ship arrangements tools. One is a manually-driven approach (UCL), and two are driven by evolutionary algorithms (U-M, TUD). Their characteristics are summarized in Table 2.1 (adapted from Singer et al. (2012), included as Appendix A). Slightly more detailed, yet still concise, descriptions of the methods can be found in (Andrews et al. 2012) and (Singer et al. 2012, included as Appendix A). A fourth pilot approach outlined by this author is provided as context leading to the new perspective presented in Chapter 3.

Table 2.1: Comparison of early-stage design ship arrangement tools' characteristics.

	UCL (§2.3.1)	**TUD (§2.3.2)**	**U-M (§2.3.3)**
Full ship design[2]	Yes	Yes	Deck plans only
Number of dimensions[3]	3-D	2.5-D or 3-D	2.5-D
Driver	Volume	Volume	Area
Layout generation	Manual	Automated	Automated
Optimization scheme	Manual	Genetic algorithm	HGA-MAS
Concepts generated	Few	Hundreds	Hundreds
Adaptable hull shape	Yes, manual	Yes, automated	No, fixed in ASSET

2.3.1 Design Building Block approach

The most comprehensive tool for creating concept-level layouts is the SURFCON module within the commercially available PARAMARINE ship design environment (Andrews and Pawling 2003; QinetiQ GRC 2011). The module was named for its SURFace ship CONcept deign capabilities, which are rooted in the Design Building Block approach (DBB or DBBA) developed at University College London (Andrews and

[2] Ability of the design tool to provide a full ship arrangement and analysis (e.g., weights, centers, stability, etc.) independent of other tools.

[3] 2.5-D is defined as 2-D deck plans on multiple decks with consideration for vertical connectivity from deck to deck.

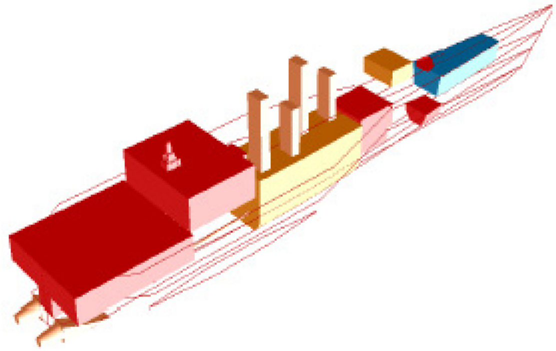
Dicks 1997; Andrews and Pawling 2003, and references therein). PARAMARINE is the only comprehensive preliminary naval ship design suite, incorporating requirements modeling and auditing, structural modeling, performance prediction, and other advanced analyses. The remainder of this section will focus on the Design Building Block approach rather than its implementation in PARAMARINE.

The Design Building Block framework is not an approach to design, but rather a generic approach to modeling complex engineered systems. Andrews emphasizes the importance of a spatial representation of the ship in preliminary design, rather than simply a numerical one. Thus, the DBBA was created to provide ship designers an architecture-oriented framework for generating visual, 3-D geometric ship layouts quickly at whatever level of fidelity is needed. The DBBA is hierarchical in nature, facilitating the use of generic "blocks" to reserve volume within a ship for particular functions. The DBBA prescribes a high-level block breakdown into four major functional groups: Fight, Move, Float, and Infrastructure. Each block, regardless of size, is categorized into one of these four groups. The block colors in Figure 2.4 are as follows: gray and blue for Float, yellow for Move, red for Fight, and green and purple for Infrastructure.

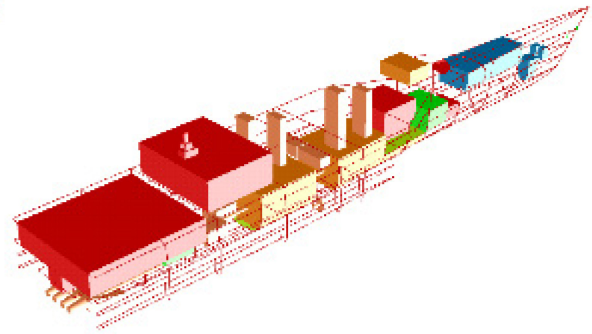
Early on, a ship may be defined by only a small number of major blocks that can be updated and subdivided as information becomes available from other disciplines. A design progresses as large functional blocks are decomposed into further-refined models of each block's contents to build confidence in the late-stage feasibility of the solution. Andrews and Pawling (2003; 2008) describe three major modeling phases encountered during the design of a littoral combat ship:

1. Topside and Major Feature Design (18-47 blocks),
2. Super Building Block Based Design (110 blocks),
3. Building Block Based Design (343 blocks).

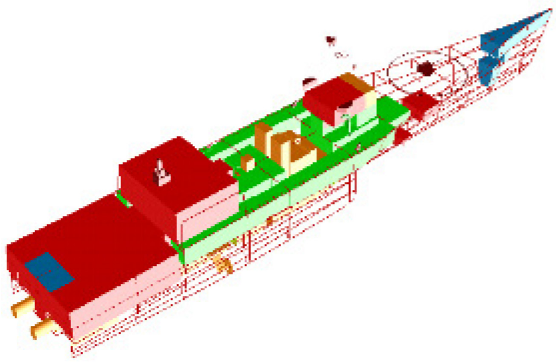
The Building Block Based Design is at a level of detail appropriate for traditional deck plan drawings. The corresponding levels of fidelity are illustrated in Figure 2.4.



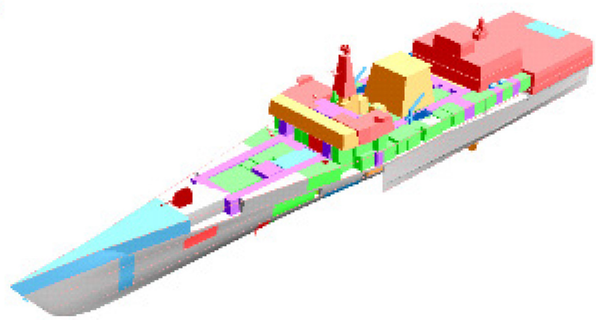
Initial DBB Configuration



Topside and Major Feature Design



Super Building Block Based Design



Building Block Based Design

Figure 2.4: Design Building Block representative levels of fidelity. (Andrews and Pawling 2008)

The DBBA is manually iterated (Figure 2.1) using integrated computer-assisted analysis. The designer's control of the reconfiguration process encourages creativity. The DBBA's implementation in PARAMARINE's naval architecture suite enables concurrent engineering through the integration of whole-ship, computer-driven analyses, which are unavailable in traditional 2-D CAD applications. However, designing layouts according to the DBBA remains labor intensive. Proficient users can generate tens of designs in a few weeks' time. A parametric model description and a graphical user interface facilitate rapid and radical changes to layouts, but the modeling aspect still takes time. Like all manual approaches, the DBBA requires design experience to be efficient. Learning is achieved through trial-and-error. Finally, the DBBA relies on a highly involved designer for understanding why certain designs are better than others are. For example, the ship's main drivers are identified by manually evaluating the perceived design space and balancing the ship's configuration at the Major Feature Design Stage.

2.3.2 A packing approach

At the Delft University of Technology (TUD), van Oers and his colleagues have paired a 3-D bin-packing approach with an evolutionary optimization algorithm in an effort to create feasible block layouts (van Oers and Hopman 2010; van Oers 2011). The optimization criterion is based on packing density alone. A set of whole-ship analyses (intact stability, speed and endurance, etc.) are included as constraints to ensure basic ship feasibility. Van Oers' packing approach emphasizes a posteriori consideration of feasible designs, rather than a priori specification of preferred constraints among objects. The objects are based on Andrews' Design Building Blocks (Section 2.3.1). The underlying ship model is parametric, allowing the computer-based optimizer to adjust the configuration of the ship hull and its contents with great flexibility. The size and shape of each block may be fixed or reconfigurable depending on its type. Block layouts can theoretically be generated at any level of fidelity as long as sufficient time and computing power is available. Currently, generating a set of ships filled with compartment-sized blocks can take several days to complete. A 2.5-D formulation constrains the allowable transverse positions to three "slices," but finishes in one-third to one-seventh the time of the 3-D version (van Oers and Hopman 2012).

The packing approach developed by van Oers can be divided into two phases: design generation and design selection. Van Oers advocates for a process in which many designs are generated up-front and subsequently evaluated by a naval architect because a design "compromise used at the start [of a design process] may not be the compromise the owner wants at the end, and secondly, it might not be possible to create a design that reflects the compromise used at the start" (van Oers 2011). The term *optimization* is used loosely above since the genetic algorithm is used simply to search for a large number of diverse, yet feasible, designs within the design space, not to identify an "optimal" configuration.

Van Oers et al. (2008) steer away from the traditional optimization perspective, arguing that “evolutionary algorithms tend to be distrusted by ship designers, who regard such tools as ‘black boxes’, which find ‘optimal’ designs, but fail to create acceptance by explaining why the resulting designs are to be regarded as the ‘best’.” Indubitably, the acceptance of any tool by the user community is essential if true advancements are to be realized in the field of naval ship design. The responsibility for down-selecting designs rests on a human designer, who explores the feasible design set to learn about tradeoffs and identify the “best” candidates for further analysis. This approach is modeled by Figure 2.3, where the majority of designer learning takes place while interactively assessing and down-selecting design variants from a large set of pre-generated alternatives. In Figure 2.5, for example, the user can select configurations with the Bridge positioned further aft, where accelerations are lower (van Oers 2011).

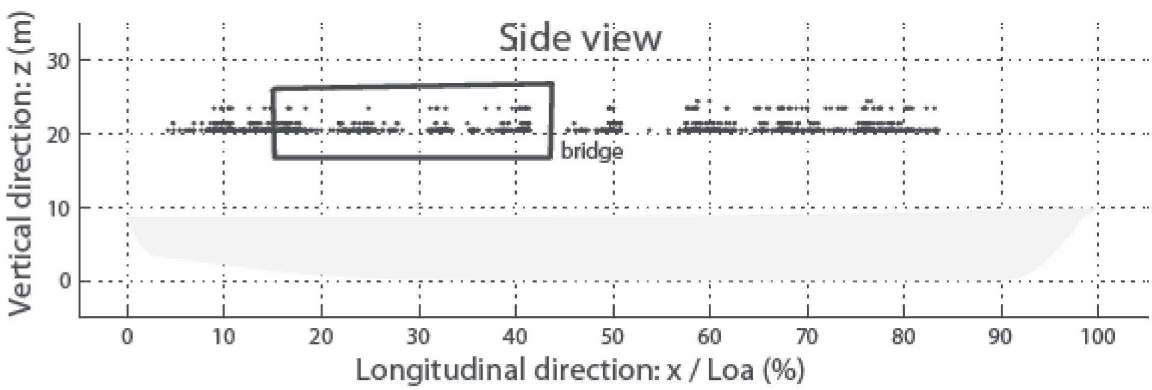


Figure 2.5: A posteriori selection of preferred bridge positions. (van Oers 2011)

2.3.3 Intelligent Ship Arrangements (ISA)

The author’s methods developed in the subsequent chapters are generic, though portions of the work have been implemented within the Intelligent Ship Arrangements (ISA) platform to demonstrate their merit. Therefore, features of ISA that are pertinent to this research are reviewed in detail. Readers familiar with ISA may proceed to Section 2.3.4 (page 30). ISA will be used to generate designs only in Chapter 4. Chapters 5 and 6 use alternative methods developed by this author.

The Intelligent Ship Arrangements computer application was developed at the University of Michigan (U-M) for the U.S. Navy (Parsons et al. 2008). Its primary goal is to

> *provide an optimization technology and design tool to assist the arrangements designer to create effective, rationally based surface ship arrangements with the maximum amount of intelligent decision making support.*

Due to existing capabilities of U.S. Navy design tools and processes, ISA solves only the space arrangement part of the total ship design problem. Currently, the U.S. Navy's Advanced Ship Synthesis and Evaluation Tool (ASSET) (ASSET 2007) is the conceptual ship design synthesis tool used to determine, among other items, the main dimensions of a hull with its major structural subdivisions, a list of ship spaces appropriate for a given ship type, and the placement of major machinery. The automated/semi-automated approach employed by ISA was developed, in part, with the goal of incorporating general arrangements quantification into the larger ASSET synthesis, enabling a feedback loop of layout quality into total ship design at an early stage. The Navy will soon begin distributing ISA with its Leading Edge Architecture for Prototyping Systems (LEAPS) product model software (LEAPS 2010). ISA formulates the problem in a 2.5-D space, where two-dimensional compartment layouts are created on multiple, discrete decks of a fixed hull.

2.3.3.1 Two-step allocation/arrangement process

The ISA method employs a two-step process for generating arrangements of ship compartments. The first step allocates the list of compartments to the structural zones of the vessel while the second step creates multiple (geometric) arrangement solutions for the allocation of the first step (Figure 2.6b). This follows the knowledge that each space *allocation* can have multiple geometrical arrangements, while each geometrical *arrangement* can be traced back to one unique space allocation. Thus, multiple arrangements are needed for each allocation to find the "optimal" allocation/arrangement combination.

Initial formulations of the process included two distinct and isolated stages, one for allocation and one for arrangement, enabling the designer to remain a part of the design process between stages (Figure 2.6a). A restructured version contains a single optimization loop (Figure 2.6b). The reasons for the reformulation are documented in (Daniels et al. 2009). All analyses conducted in this dissertation are limited to the allocation portion of the original, two-stage scheme (Figure 2.6a).

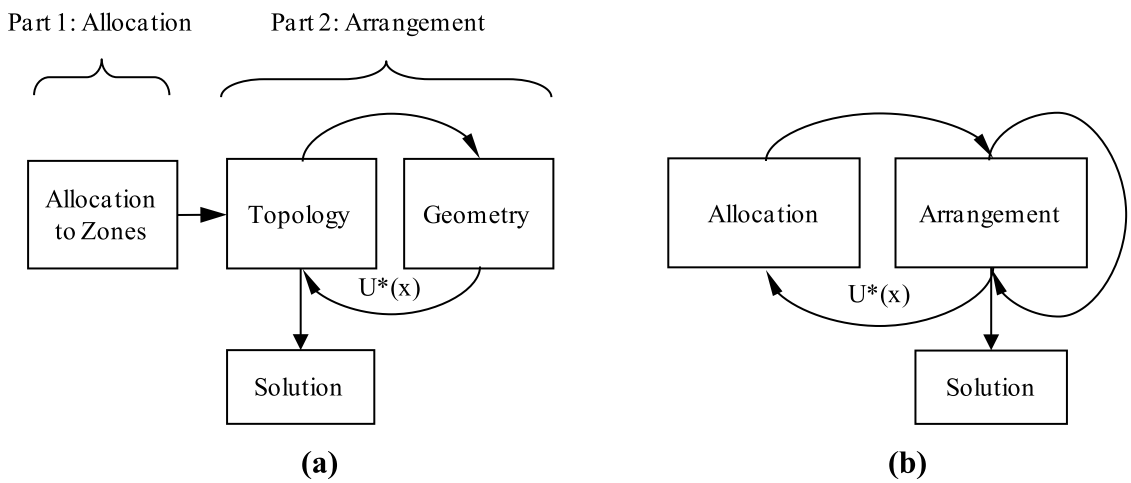


Figure 2.6: Intelligent Ship Arrangement's (a) initial two-stage and (b) current one-stage allocation and arrangement. Adapted from (Daniels et al. 2009).

2.3.3.2 Step 1: Allocation

The first step of the ISA method is the allocation of a pre-defined list of compartments to structural zones of the vessel. Each structural zone is subdivided by major bulkheads and decks and is fixed (Figure 2.7); that is, the structural zone arrangement does not change during the iterative process. Compartments do not have geometric boundaries in the allocation phase; an allocation is simply a listing of which spaces will be positioned in which zones. The allocation procedure considers fuzzy relative inter-compartment constraints, global location preferences, and zonal area utilization curves (Section 2.3.3.4).

Spaces are allocated to available structural zones by a Hybrid Genetic Algorithm - Multi Agent System (HGA-MAS). In this optimization scheme, the genetic algorithm is used to explore the design space by encouraging solution diversity, while the agents are used to provide intelligent search capabilities. Genetic algorithms are robust when used on highly multimodal problems with flat solution spaces, of which general arrangements is a prime example. The intelligence provided by the agents enables significant performance improvements over genetic algorithms alone. Several intelligent seeding mechanisms have been developed for allocating compartments to zones (Parker et al. 2011). Chapter 6 presents a new seeding scheme developed by the author.

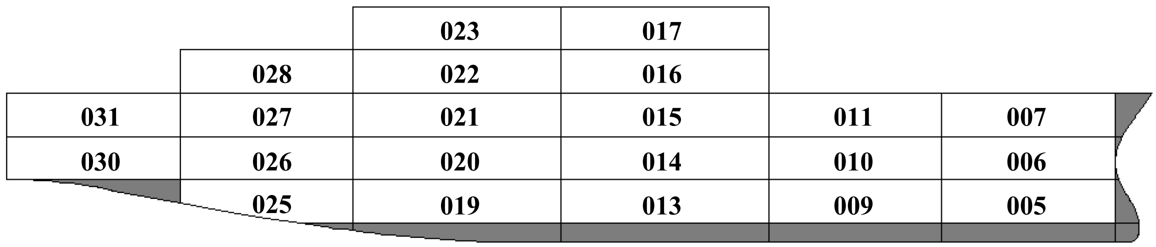


Figure 2.7: ISA structural zones. Gray zones are not available for allocation.

2.3.3.3 Step 2: Arrangement

After the compartment allocation has been defined, the second step of the ISA method is activated. The arrangement algorithm maps the centroids of each space to an orthogonal grid, which is a 2-D description of the structural zone deck plan. This is done to ensure that each space has sufficient area available around it to achieve its final size. As shown in Figure 2.6, the arrangement algorithm is called several times to find the "optimal" arrangement of the current space allocation before proceeding to the next generation and updating the set of allocations.

The arrangement step is also driven by fuzzy constraints. Compartments have individualized geometry constraints that address required area, aspect ratio, minimum dimensions, minimum segment width, and perimeter length. Spaces also have the same collection of relational constraints (adjacency, separation) between themselves and other compartments that were used during the allocation phase. The geometry-related criteria ensure that each space has its minimum required dimensions and that unwanted irregular shapes are avoided while the relational constraints control basic topology between spaces within the zone. The result is an arrangement of each structural zone according to its assigned topology (Figure 2.8).

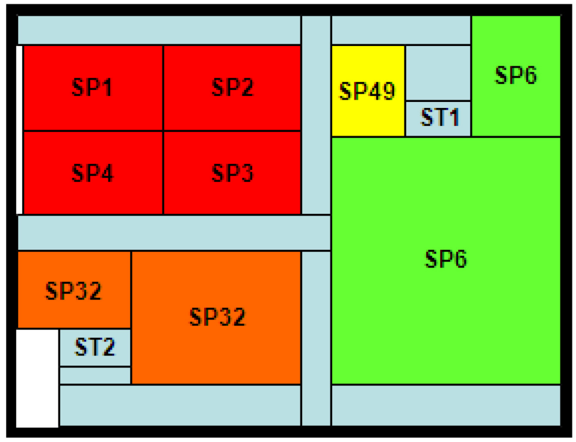


Figure 2.8: Example ISA structural zone arrangement. (Daniels et al. 2009)

2.3.3.4 Relative and global location constraints for compartments

ISA employs a fuzzy logic-based constraint system in order to capture the uncertainty of linguistic terminology commonly used to describe ship arrangements. Examples include two compartments should be "near" one another, a system should be installed "in the middle of the ship," or a compartment requires "about 10 square meters" of deck area. The constraints are based on design rules, best practice, and experience (Parsons et al. 2008). Constraint sets are ship type-specific meaning the set of constraints for a cruiser may differ from those of a destroyer. In ISA, two types of location-based constraints are used: relative location and global location. These constraints are stored in a constraint database, which will be used throughout the work presented in this thesis. The constraint database can be used outside of ISA as a standalone knowledge bank.

Relative location constraints specify the preference for a compartment to be located in a particular structural zone given the position of another compartment. They fall into two main classes: adjacency and separation. Preferences are given on a [0,1] scale where 0 signifies "full dissatisfaction" and 1 represents "full satisfaction". In Figure 2.9, relative zone index numbers are given along the top and left side of each image. Figure 2.9a shows that compartment P1 has a preference to be as close to compartment P2 as possible without being in the same zone as P2, which is located at zone index (0,0). Figure 2.9b illustrates a different relationship structure where it is desirable for P1 to be on the same deck as P2, with the highest preference being that they are located in the same zone. Zones beyond the extents specified in Figure 2.9b have a low preference of 0.05. A difference between the relationships represented in Figure 2.9a and (b) is (a) requires personnel movement only whereas (b) requires personnel and materiel movement.

P1~P2	-4	-3	-2	-1	0	1	2	3	4
2	0.50	0.60	0.80	0.80	0.80	0.80	0.80	0.60	0.50
1	0.50	0.60	0.80	0.90	0.90	0.90	0.80	0.60	0.50
0	0.50	0.60	0.80	0.90	0.05	0.90	0.80	0.60	0.50
-1	0.50	0.60	0.80	0.90	0.90	0.90	0.80	0.60	0.50
-2	0.50	0.60	0.80	0.80	0.80	0.80	0.80	0.60	0.50

(a)

P1~P2	-2	-1	0	1	2
1	0.05	0.05	0.05	0.05	0.05
0	0.50	0.80	1.00	0.80	0.50
-1	0.05	0.05	0.05	0.05	0.05

(b)

Figure 2.9: Two fuzzy relative location constraints.

Fuzzy global location constraints are expressed in a similar grid arrangement. However, each block in the 2-D grid represents a single structural zone in a profile view of the ship with the bow to the right. An example global location constraint for the Ship's Office is provided as Figure 6.2 (page 114). Compare Figure 6.2 against Figure 2.7 to see the resemblance to the actual ship model.

2.3.4 A system of communicating agents

This section describes work completed by the author in support of extending early-stage ship design to include distributed system arrangements (Gillespie et al. 2010; Gillespie and Singer 2012). While the research direction discussed in this section is not the focus of the dissertation and is not specifically relevant to the studies contained in the remaining chapters, it provides a backdrop for the insights presented in Chapter 3, which underpin the analyses in Chapters 4-7.

The author's initial research centered on developing a method for generating feasible three-dimensional compartment, system, and component layouts in a reasonable timeframe to facilitate layout tradeoff studies. One of the challenges to conducting tradeoff studies for facility layouts is the exponential growth of computational time with the number of elements. This is due to the increasing number of interactions and potential configurations. As mentioned in Section 2.1.1, small layout problems can be solved exactly, but ship layouts are far from small. Increasing fidelity and decreasing runtime from their current state creates an inherent practical need to eliminate all unnecessary interactions (physically and computationally) and isolate and encapsulate elements to parallelize analyses.

The author developed a formulation and a prototype tool that combines and extends concepts found in existing approaches (Sections 2.3.2 and 2.3.3) while introducing several new ideas. The approach set out to address three major challenges:

- Constraint database development and maintenance is tedious and slow,
- The problem size is huge and grows exponentially,
- Optimization run-times are too long for effective early-stage tradeoff analyses.

The challenges were paired with the following goals:

- Automatically generate constraints on-the-fly based on component attributes,
- Build in flexible levels of detail and limit interaction evaluations when possible,
- Incorporate intelligence and facilitate parallelization.

The performance of ISA's intelligent hybrid agent-genetic algorithm over evolutionary algorithms alone led to the adoption of an agent-based approach. Selective communication amongst subsets of agents (Sections 2.3.4.1 and 2.3.4.2) was a novel approach to limiting information overload. From van Oers' packing approach, the "free space" block concept was extended to include a variety of interaction types (Section 2.3.4.3).

Figure 2.10 depicts a simplified version of the resultant method. The process minimizes the modeling effort required of a designer and exploits automation and intelligence where possible. Each system or component is encapsulated, meaning all attendant attributes, preference data, and interaction calculation engines are carried with it. By developing a library of such elements, designers can quickly select and swap the equipment to be included in a design study. At runtime, constraints between elements are automatically generated from a standardized hierarchy of taxonomic attributes that define the types of interactions that elements can have with other elements at varying levels of fidelity. Finally, intelligent agents operate within an optimization environment to make quality decisions (minimizing useless iteration) with minimal information about the rest of the current solution. The "minimal information" is limited to exactly the information required to assess one's current satisfaction with one's current state; this includes information regarding any component or system that might influence the preference of an element for a particular location in the ship. Agents know nothing else about the state of the design. Finally, parallelization across multiple processors and computers is facilitated by the encapsulation of the library's elements and the agents' ability to communicate.

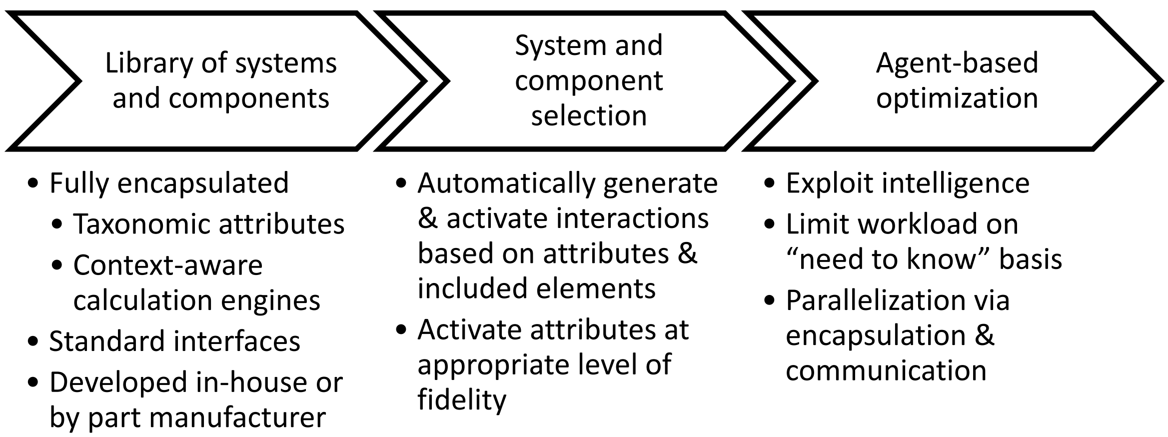


Figure 2.10: Process flow using automation and communicating agents.

Details for each of the major features will be discussed in the following three sections. Finally, Section 2.3.4.4 provides a brief overview of why this approach was abandoned in favor of a new track rooted in network science, which constitutes the core of this dissertation.

2.3.4.1 Concept of emissions and sensitivities

The constraints among elements are referred to as *emissions*. Emissions can represent broad characteristics that are physics-based (e.g., vibration, high-frequency sound/low-frequency sound, line-of-sight, etc.) or that may be hard to quantify in early-stage design (e.g., designated sanitary space, frequently accessed, contains contaminants, etc.). Emissions may be primary outputs or byproducts of a component. An item is said to be *sensitive* to an emission if that emission will affect its performance in some way. Sensitivities do not have to coincide with a component's primary function. An example is given in terms of a sonar array. In addition to sensing noise, a sonar array will also sense "heat" and "vibration" if those emissions alter the sonar array's performance.

Often in early-stage design, only preliminary estimates of a system's characteristics are known. Thus, emissions can be described with low specificity. For example, the vibration emissions from a main diesel engine could be described as "high intensity" and "low frequency." Degradation of a sensor from this vibration could be described as "full," "moderate," or "minimal" based on some measure of distance between the two components. Using its own internal calculation mechanism, the sensor can determine the impact on itself due to the diesel's emission using data about the diesel's location and the emission characteristics. The sensor can then make an informed decision regarding its preference for its current location and act accordingly.

2.3.4.2 Selective communication among agents

The ship layout is created using a system of communicating agents. The agent-based approach was developed with the perspective that the explosive growth in layout problem size is due in part to an increasing number of interactions and the time needed to assess potential interactions. The ability to restrict information to a need-to-know basis is fundamental to this approach. It assumes that the layout problem can be made more manageable by limiting the amount of information each element must process and by distributing the computational load to multiple computers. This section describes a communication tool, Lightweight Communications and Marshalling (LCM) (Huang et al. 2010), that was developed for use in real-time robotics applications. LCM's application as an agent communication mechanism is also described in this section. A more comprehensive description of LCM's role and benefits is provided in (Gillespie et al. 2010).

2.3.4.2.1 LCM and its application within an agent-based ship layout system

Agents in a ship layout need to communicate with a continually changing set of components. Components may be added or removed as a design evolves. For example, the number of fire suppression devices in a compartment or zone may change as the contents or configuration changes. Components may move in or out of a particular zone resulting in shifting spatial arrangement concerns within the zone. LCM provides a decentralized approach to message passing. LCM is a push-based messaging system that allows agents to subscribe to and publish to individual message *channels* identified simply by the channel's name. Messages sent to a channel are received only by agents subscribed to that channel. Figure 2.11 illustrates three cases where an agent sends a message to a channel. Standard Internet protocols provide the delivery mechanism to appropriate recipients. Agents subscribed to a given channel receive messages sent to the channel without a mediator and without the sender knowing the recipients. As a result, an agent need not maintain a list of agents with whom it communicates nor must it seek out new potential correspondents. This reduces the required computation. Furthermore, messages are not routed through a central server, which could result in a bottleneck. Agents can add or remove channels on the fly, giving them flexibility in communications without additional overhead. Finally, messages can be passed among agents across a network providing opportunities for parallelization using clustered computers.

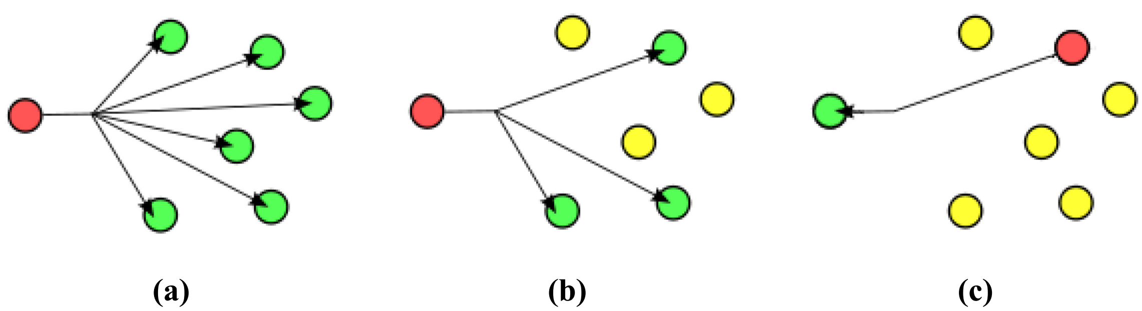


Figure 2.11: Diagram of a message (a) sent to all agents, (b) sent from agent *red* to channel *green*, and (c) a "direct" response from agent *red* to agent *green*.

2.3.4.2.2 Emissions as communication channels

The distributed system arrangements problem can be decomposed into sub-problems according to interaction types. This is done by limiting communication on a need-to-know basis related to interaction types. The use of channels to represent interactions permits global messaging capabilities that can be filtered to relevant parties so agents receive all relevant information, but are not overwhelmed with extraneous information. However, the decomposition of the full problem does not result in many independent sub-problems, but rather in many overlapping sub-problems. Agents that reside in overlap regions of the sub-problem space receive information from multiple channels and effectively tie the sub-problems back together.

Agents subscribe to and communicate along standardized channels corresponding to emissions and sensitivities. Agents alert others to changes in their status via their emission channels, and they continuously monitor their sensory channels for announcements from other agents. This is to minimize the number of messages passed and the amount of wasted computation. Each agent is always subscribed to at least one distinct channel: the agent's unique name. This response channel is included in all messages sent by the agent and facilitates responding "directly" to the sender (Figure 2.11c). In a more sophisticated implementation, agents could participate in a formal negotiation to collectively identify the best resolution to a conflict.

Channels can also represent logical aggregations, such as all the elements within a structural zone or on a specific deck. Passing messages along functional or logical lines is advantageous because it significantly reduces the quantity of information that an agent receives and must process, but without a loss of information quality. Agents can be aware of the actions of relevant agents throughout the ship without receiving information from all agents.

2.3.4.3 Interaction regions

Objects used in the packing approach (Section 2.3.2) can represent, for example, an occupied volume or a so-called "free space." By creating "free space" objects, designers are able to designate regions of the ship as interference regions between objects that require unobstructed space and those that occupy that space. The free space may designate a line-of-sight requirement, the firing arc of a weapon, or the open air space above helicopter landing pad. In this author's formulation, interference regions can be defined by any relationship that could affect the performance of a component in any way. In this manner, van Oers' "free space" blocks can be thought of as one type of interaction region. In fact, van Oers' use of "logical objects" to ensure separation of weapons systems (van Oers 2011) is another use of interaction regions. This extends the concept of "free space" objects to regions that represent multiple types of interactions.

In the framework presented, interaction regions are modeled using geometric primitives, though functionality for more complex shapes could be added. Components are assemblies of interaction regions, which are the geometric volumes that represent regions where interactions could occur. Potential conflicts exist where interaction regions overlap. Interaction regions can represent multiple emissions or sensitivities to emissions. Some emissions and sensitivities can be modeled using the part's physical geometry alone (e.g., spatial interactions or provision of services via physical connections).

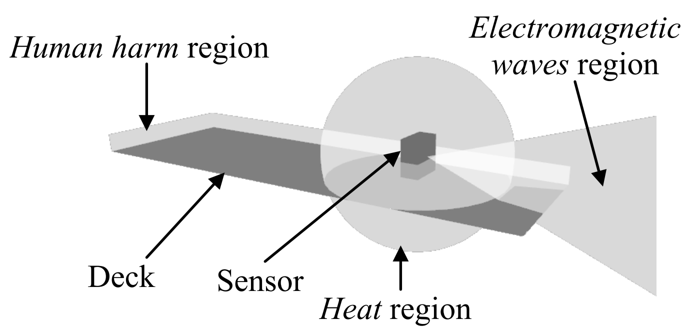


Figure 2.12: Notional components with multiple interaction regions.

Two notional components are shown in Figure 2.12. The first is a deck surface with a *Human harm* sensitivity region that represents the two to three meters above the deck where sailors typically conduct operations and where they would be affected by a component emitting something detrimental to human well-being. The second component is an idealized sensor box with a spherical *Heat* region and a conical *Electromagnetic* *waves* beam. The sensor component could also be used to simulate a weapon with *Noise* and *Firing arc* regions. If the sensor's electromagnetic waves are of a frequency and/or intensity that could harm a sailor, the beam would also be designated a region of *Human harm* so that an interaction would occur between the conical beam and the deck. When determining an acceptable location, the sensor considers the position of emission regions from which it requires services or to which it is sensitive, and then it evaluates its position accordingly.

Emissions, components, and compartments are created as objects in a part library and are self-contained; thus, after defining a part in the catalog, no additional configuration is needed beyond specifying that the part be included in a design concept. Each library entry represents a unique type of ship compartment or piece of equipment along with its associated geometry, attributes, definition of interaction regions, and calculation methods for determining interaction impacts.

2.3.4.4 Realization that a change of direction is necessary

The reason for abandoning this agent-based research direction centered on several realizations. Foremost among them were:

- **The approach remains modeling-intensive.**

  The effort required to develop and maintain constraint databases has been shifted to characterizing library parts and defining agent intelligence. This did not improve the problem; it simply transferred the workload.

- **The approach remains a brute-force means of developing arrangements.**

  The need for massive computing power is not significantly diminished (if at all) by using this technique. The computing requirements simply spread from one machine to multiple.

- **No specific insights into the nature of ship arrangements or fundamentally different design processes were foreseeable as a direct result of this technique.**

  Certainly, the ability to generate distributed system layouts would allow designers to evaluate tradeoffs at a higher level of fidelity in preliminary design. However, it was not certain whether the additional complexity would be helpful or overwhelming. In addition, the post-processing approach to design evaluation described in Section 2.2.1.3 would remain unchanged without new learning mechanisms to accompany this technique.

- **The true challenge of generating ship arrangements rests in the management of interactions.**

  Placing elements in a ship and evaluating candidate solutions is a comparatively simple task. Understanding the higher-order effects (Section 1.1.3, page 8) for informed decision-making is much more difficult, and this is precisely the area where advances are needed.

It is the last point that is taken up as the primary investigation in this dissertation. This concept is discussed in further detail in Chapter 3. Threads of this emissions-based approach can be found in the network approach to be presented. For example, a visual interpretation of the automated constraint generation process includes creating links between elements that produce emissions and elements that are sensitive to them – a directed network (Section 3.3.1). The emissions concept also forms the basis for investigations based on distinct relationship types (Chapter 7).

2.4 State of the art for early-stage ship arrangements

The most recent published review of ship arrangements in early-stage design is found in the International Marine Design Conference's Design for X State of the Art Report, which includes a section on Design for Layout (Andrews et al. 2012). The report describes the nature of the early stages of a ship design process and documents the importance of considering layout early in the process. It also provides a concise review of the three preeminent advanced approaches to early-stage ship arrangements already described (Sections 2.3.1-2.3.3). Therefore, this section is dedicated to discussing the common capabilities and challenges of these approaches and the recognized future directions for the ship arrangements research community.

2.4.1 Common capabilities and challenges

Though the advanced layout methods are fundamentally different in many respects due to different overall objectives and roles within existing naval design processes, each provides significant improvements over traditional 2-D manual drawing techniques. They successfully keep the designer "in the loop" while enabling the completion of tradeoff studies in less time. They do this by facilitating exploration of the design space through the generation of multiple diverse and feasible layouts in a moderate timeframe (hours to days) with reduced human effort.

The new developments are not without challenges of their own. The duration of analyses remains a quandary: as the size of ship and level of fidelity (number of elements) increases, the computational effort grows exponentially. At this point, none of the systems are capable of producing true system-level layouts in a reasonable amount of time. For the semi-automated approaches, the ability for a computer to generate hundreds or thousands of feasible designs has presented a new impediment: transferring knowledge to designers. The suggested a posteriori techniques (Section 2.3.2) are helpful, though certainly not sufficient as they only indirectly consider the relationship between input requirements and output solutions.

2.4.2 Recognized future directions in ship arrangements research

In developing the Design for Layout state of the art report, the authors of that report also identified critical needs for the field of ship arrangements research as part of a collaborative research endeavor (Singer et al. 2012, included as Appendix A). The following four overarching themes were identified:

- **Abstraction away from representations of physical geometry**

  The ability to view the requirements elucidation process, and the role of ship layouts in that process, as an overlay of multiple data types in order to preserve the richness of information that is lost when mapped in the domain of traditional general arrangements drawings.

- **Macro-level characteristics of ship layouts**

  The ability to understand the nature of ship arrangements on a macro-scale and to define appropriate metrics to provide insight into non-dominated solution sets and guidance for down-selecting designs.

- **User experience**

  The ability to provide users with efficient, natural tools for generating and evaluating general arrangements to promote designer exploration and learning and to reduce modeling demands on the designer.

- **Data and knowledge reuse**

  The ability to capture design data, knowledge, and intent in an unobtrusive, natural, and user-friendly manner to facilitate maintenance and reuse of that information.

The first three of these topics will be specifically addressed in this undertaking. Expanded descriptions of each topic are available in (Singer et al. 2012, included as Appendix A).

2.5 A continued need for designer learning

New naval architects enter the ship design ranks every year, and it is imperative that they be able to gain experience from and input experience into these arrangement approaches. The (semi-)automated systems (Sections 2.3.2 and 2.3.3) try to avoid "black box" implementations and encourage the user to be involved in the solution generation and selection process. Regrettably, they cannot eliminate the black box – they can only minimize it. Since an algorithm is used to generate feasible layouts, the designer does not undergo the full learning process of trying different configurations. There remains a need to understand the interplay of elements in the system as the candidate solution is considered in light of the design requirements or as it is moved forward toward detailed design. A lack of this knowledge could lead to unnecessary subsequent iteration or poor decisions that are counter to the "decisions" made by the algorithm.

Chapter 3
A new perspective

The greatest challenge today … is the accurate and complete description of complex systems. Scientists have broken down many kinds of systems. They think they know most of the elements and forces. The next task is to reassemble them, at least in mathematical models that capture the key properties of the entire ensembles.

– Edward O. Wilson (1998)

The arrangements research community recognizes that advanced methods and tools should enable designers to

> *do more designing and less modeling, meaning the designer spends more time learning about tradeoffs, challenging selection choices, and making decisions with less time drawing and maintaining models and setting up and running analyses.* (Singer et al. 2012, included as Appendix A)

The current trajectory toward developing more complex and higher fidelity 3-D geometric models is not consistent with this goal. Therefore, the methods presented in this thesis aim to uncover new information and create a richer understanding of the design space while requiring minimal user input.

New design methods and ways of conceptualizing the arrangements problem are needed to complete layouts during early-stage design without the explicit knowledge only available during detail design. This research endeavor aims to gain a better understanding of the nature of ship arrangements by focusing investigations on the set of underlying relationships. (In this thesis, the relationships are specified design constraints.) By building upon these foundational relationships, the author conjectures an increased likelihood of transitioning designs from preliminary layouts to detailed layouts without them becoming infeasible.

3.1 Focus on inputs instead of outputs

Chapter 2 described several (semi-)automated preliminary ship arrangements design methods and tools that are capable of generating sets of feasible designs. Each takes an indirect and ad hoc approach to understanding the relationship between the input design requirements and constraints and the output solution set. Inferences are made regarding the relationships among the ship's elements by analyzing the resultant designs. The focus is on the output designs. The approaches follow historical design processes in which designers are provided a set of systems to be integrated into the layout and designers proceed by generating traditional deck plans and spatial arrangements to determine the feasibility of a design (Figure 3.1a).

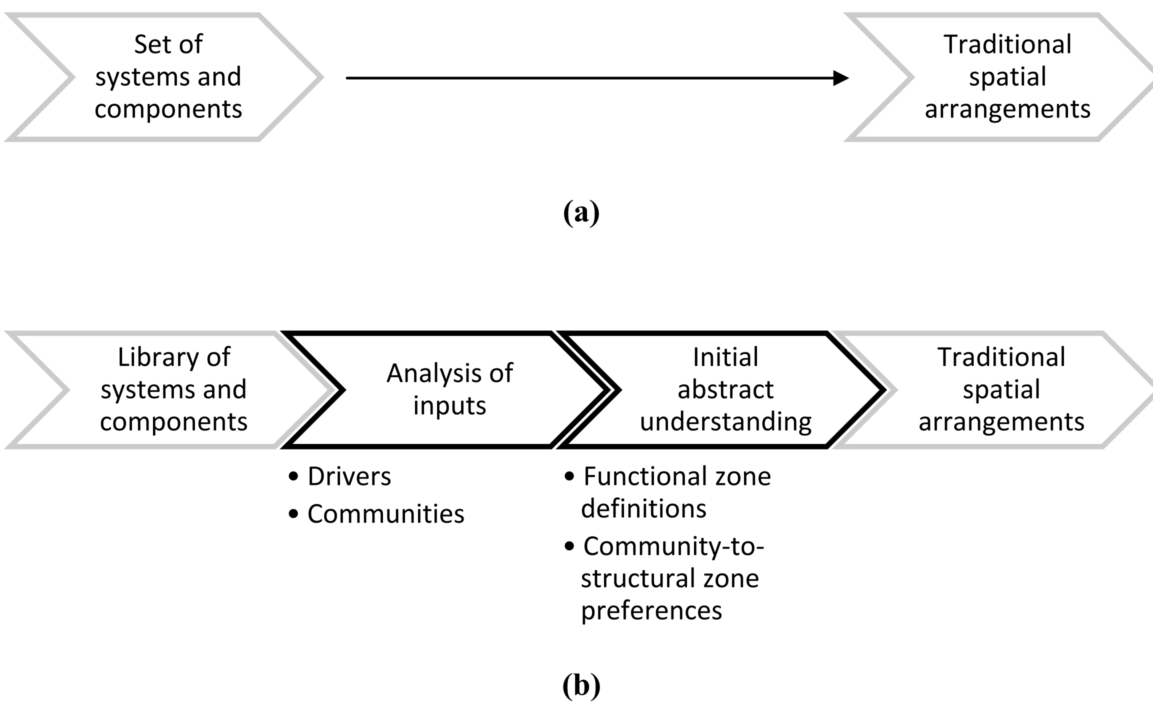


Figure 3.1: New focus on inputs.

This dissertation maintains that the inputs are important. As such, they should be analyzed directly, and the knowledge gained should form the basis for subsequent layouts. For the (semi-)automated approaches, the inputs dictate the solutions because they are shoved into a "black box" with a fixed algorithm and out pops a set of potential solutions. In a manual approach, a designer may traverse the design spiral several times while simply learning the basic dependencies and inter-element relationships. A designer may not learn the third- and fourth-order effects until the end of a design study (if at all) depending on the complexity and number of elements involved. By following a process such as that shown in Figure 3.1b, designers can gain a more complete understanding of the set of constraints prior to drawing layouts. With sufficient analysis of the inputs that drive a layout, more informed decisions regarding system selection could be made. The author presumes that feasible layouts can be generated with less iteration since more information is known up-front.

The author envisions a design process that includes analysis before, as well as after, creating layouts. The goal is to exploit the "richness of information that is lost when mapped in the domain of traditional general arrangements drawings" (Section 2.4.2). The approach to general arrangements presented in this thesis is summarized by Norman and Kuras (2006):

> *By focusing on the relationships among things, not just the state of the things as a result of the relationships, we can understand the reasons for the molar organization and perhaps understand the implications to change – even infer or deduce state elsewhere which may be out of view.*

Focusing on the inputs requires a new perspective of the information designers currently use. Ship layout constraints must be viewed as relationships among shipboard items. In that view, design data that was previously used for a posteriori design evaluation alone becomes an indispensible source of a priori information. Individual bits of information that were once evaluated in isolation can now be combined to draw a comprehensive picture, just as Wilson envisioned in this chapter's opening quote.

3.2 Abstracting the layout process

One tactic for focusing on the inputs to the ship arrangement process involves separating them from geometry generation. Section 2.2.1 noted that, for automated layout approaches, designer learning occurs during the post-processing of computer-generated layouts, at which point the inputs cannot be decoupled from influences of the spatial and physical domains. Clearly, the trajectory toward including system definitions in layouts, building more-detailed CAD models, and attempting to manage the growing development, modeling, and computational effort will not improve this situation (Section 2.3.4.4). A new perspective is needed that radically changes the way researchers and designers approach the layout problem.

Recognizing this, the arrangements community has identified a need for abstract representations, which minimize or remove the spatial considerations (Section 2.4.2). In accordance with these needs, this research effort utilizes network science to better understand ship arrangements and to approach their creation and analysis in a new light. The comprehensive picture of design data mentioned in the previous section will be manifested as a network of layout relationships.

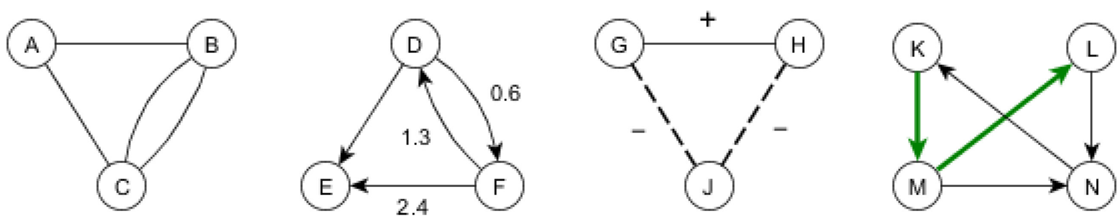
3.3 Network science

Network science is "the study of network representations of physical, biological, and social phenomena leading to predictive models of these phenomena" (NRCCNSFAA 2005). This field draws on diverse concepts, theories, and formulations from graph theory, statistical mechanics, data mining, stochastic processes, and sociology, to name a few sources of inspiration. Some network models correspond to physically connected systems, while others characterize conceptual relationships among various entities. In both cases, network science provides an efficient toolset for modeling these relationships. Under consideration in this work are the relational inputs of an arrangement process, in the desired abstract format, using the minimal information that is available in the earliest stages of design.

For the reader unfamiliar with networks, a brief description of relevant network terminology is provided next. Then, the value and use of networks in design and engineering is explained.

3.3.1 Network definitions and terminology

A *network*[4] is a set of points (called *vertices*) connected by lines (called *edges*)[5] (Figure 3.2). Network science builds upon graph theory; thus, graph theoretic concepts also apply to networks. Huang (2006) distinguishes between networks and *abstract graphs* noting that abstract graphs have no descriptive vertex or edge attributes such as labels, type indicators, or color codes. In this work, no differentiation is made and no descriptive attributes are used.



(a) (b) (c) (d)

Figure 3.2: Network types. (a) Undirected network with a multiedge $\overline{\text{BC}}$; (b) Directed network with weighted edges – unlabelled edges are assumed to have weight 1.0; (c) Signed network; (d) Directed multiplex network with heavy green edges and lighter black edges signifying different relationship types.

Networks are *directed* if they contain *directed edges*,[6] meaning edges have directionality such that $i \rightarrow j$ denotes an edge from vertex i to vertex j. In directed networks, $j \rightarrow i$ is unique from $i \rightarrow j$ if $i \neq j$. Networks are *weighted* if the edges are labeled with a value representing the strength, importance, or capacity of the connection. Networks may be both directed and weighted (Figure 3.2b). A *signed network* is one whose edges are

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[4] Some authors reserve the term *network* for weighted graphs. However, *network* will be used here in its broader sense, synonymous with *graph*. See Footnote 5.

[5] The terminology used differs by field. In the mathematical literature, *networks* are known as *graphs*. *Vertices* and *edges* may be referred to as *nodes* and *links* or *actors* and *ties*. These terms will be used interchangeably.

[6] Directed edges may also be called *arcs*.

designated as *positive* or *negative*; signed networks are commonly used in the social sciences to denote friendly or antagonistic interpersonal relationships. Positively weighted edges are drawn with solid lines and negatively weighted edges with dashed lines (Figure 3.2c). Networks with multiple edges between any pair of vertices, termed *multiedges*, are known as *multigraphs* (Newman 2004) (Figure 3.2a). *Multiplex networks*[7] have multiple types of links (Mucha et al. 2010) (Figure 3.2d). *Multislice networks* are "combinations of individual networks coupled through links that connect each node in one network slice to itself in other slices" (Mucha et al. 2010) (Figure 3.3). Nodes in any individual slice also connect to other nodes within that slice. Finally, all nodes with in a network need not be connected to all other nodes. Each subgroup of connected nodes is called a *component*. Components in the network sense will always be referred to as *network components* in this dissertation to distinguish them from shipboard components, meaning pieces of equipment. An example of a network with multiple network components can be seen in Figure 3.5 (page 55). Features from all the aforementioned network types will be used in this work and will be discussed in more detail next (see Table 3.1).

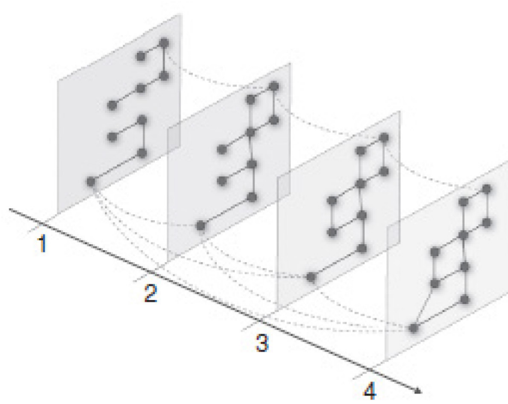

Figure 3.3: A multislice network representing four types of edges (interactions) as well as inter-slice edges representing the relationship of a node to itself. (Mucha et al. 2010)

[7] Multiplex networks may also be called *multi-relational networks*.

The *adjacency matrix* $\boldsymbol{A}$ is a common representation of a network. In a weighted, directed network, it has elements

$$A_{ij} = \begin{cases} w_{ij}, & \text{if there is an edge from } j \text{ to } i \\ 0, & \text{otherwise} \end{cases} \qquad 1$$

where w_{ij} is the weight or strength of edge $j \rightarrow i$. In unweighted networks, $w_{ij} = 1$ for all *i*,*j* given that an edge exists between i and j. The number of nodes in a network is typically denoted by the variable *n*. The number of edges (or total weight of edges) is given by $2m = \sum_{ij} A_{ij}$ for undirected networks and by $m = \sum_{ij} A_{ij}$ for directed networks.

In a ship layout relationship network, the vertices may represent individual compartments or components. Vertices may also represent aggregations of multiple compartments into functional complexes (food service, berthing, stores, etc.) or multiple components into pre-fabricated system subassemblies or machinery modules considered as a single, cohesive unit. Edges represent relationships or interactions between any two ship elements. These relationships may be conflicting. Naval architects and engineers often view these interactions as design constraints. Constraints can be categorized based on their function, impact, source, physical properties, etc., forming sub-networks within the full relationship network. These sub-networks could be viewed as different types of edges within a single multiplex network or as slices in a multislice network. Table 3.1 summarizes possible applications of various network types in the ship layout context.

3.3.2 Information encoded in (fundamental) relationships

Much of the network theory has roots in the social sciences for use in social network analysis. However, complex networks appear in many physical and non-physical domains. They are used in a variety of fields of study, including the analysis of biochemical and metabolic networks, neural networks, ecological networks, supply chains, power grids, transportation networks, communication networks, and the Internet (see Albert and Barabási 2002 or Newman 2003 and references therein). Refer to (Albert and Barabási 2002; Newman 2003) for a general survey of network applications and (Cui et al. 2010) for a survey specific to complex engineered systems. In these fields, network science has illuminated vast information encoded within the topology of relationships.

Table 3.1: Summary of network types and their application to ship layouts.

Network characteristic	Ship application
Directed edges	Element *A* may affect Element *B*, but *B* may be indifferent to *A*.
Weighted edges	Inter-element relationships may have varying intensities.
Signed edges	Relationships can be simplified into two basic types: *adjacency* and *separation*.
Multiedges	Element *A* may have multiple modes of influence on Element *B*, e.g., the noise and vibration of an engine room on the quality of life in berthing spaces.
Multiplexity	There are many relationship types among spaces and components: steam, electricity, communications, vibrations, heat, cleanliness, etc.
Multislice	Generations (iterations) of a ship design within an evolutionary design approach or multiple ship loading conditions.
Network components	Nodes within network components directly and indirectly affect elements within that component. Nodes in separate network components have no (direct or indirect) relationship to one other.

3.4 Networks in design and engineering

It is natural to look at complex design and engineering projects in terms of a network of relationships. By extension, it also makes sense to try to understand the structure of that network. Maier and Fadel (2006) state:

> *Since all of the details of a complex system can in principle never be totally understood, an essential tool for understanding complex systems is to study the system's organization, which is often relatively simple. Understanding the organization of the system can also lead to a better understanding of the system's behavior, since the behavior of a system is strongly affected by the system's internal organization.*

Braha and Bar-Yam (2006) take the next logical step, adding

> *Characterizing the real-world structure, and eventually the dynamics of complex [product development] networks, may lead to the development of guidelines for coping with complexity. It would also suggest ways for improving the decision making process, and the search for innovative design solutions.*

This is the goal of this investigation into the structure of ship layouts. The use of networks for ship arrangements provides a unique perspective relative to the traditional view of how ship arrangements must be created. Network theory helps us manage complexity by revealing underlying character and structure, and thereby providing insight into the function of a complex system. Existing methods assume that a physical layout must be generated in order to determine the characteristics of a design. Networks provide a means of abstracting the design so that underlying aspects of the set of relationships can be considered directly. Of particular relevance to facility layout problems is the abstraction out of the physical three-dimensional space in which the elements must eventually be located. Even so, some ship design analyses require spatial arrangements. Since there is no direct one-to-one mapping of a network to physical space, this topic will be considered in Chapter 6 in the context of ship layouts.

There have been a several recent investigations into complex systems related to design and engineering. Studies by Martin and Ishii (2002), Norman and Kuras (2006), Braha and Bar-Yam (2006; 2007a; 2007b), and Collins et al. (2009) centered on the *process* of engineering complex systems rather than the engineered system itself. Likewise, investigations by Braha and Bar-Yam (2007a) and Martin and Ishii (2002) focused on the *flow of information* within the design *process*, not on the output, as is desired here. Braha and Bar-Yam considered how one could improve strategic and operational decision-making, while Martin and Ishii looked at standardizing and modularizing product architectures, specifically for minimizing component coupling and its effect on redesign.

3.4.1 Use of graph theory for facility layout

Using graphs (networks) as a model for the facility layout problem (FLP) is not a new idea. In fact, graphs have been used as a modeling platform for FLPs for several decades. For example, Systematic Layout Planning (Muther 1973) has become a popular commercialized framework used in industrial management. The remainder of this section provides an overview of the application of graphs to the FLP. Hassan and Hogg (1987) provide a comprehensive, though now dated, review of graph theory applications to the FLP. Shouman et al. (2001) and Singh and Sharma (2006) provide general surveys of approaches to the FLP, and both include brief sections on graph-theoretic methods with accompanying references.

The graphs used for FLPs typically include adjacency relations among elements with edge weights indicating the desirability of two items to be adjacent. An underlying assumption is that the desirability of two elements to be adjacent is known. The graph-based model is not specifically restrictive, but edges in the graph often represent adjacency relations only (Foulds 1983). Likewise, negative weights are commonly disallowed. Pesch et al. (1999) is an exception; those authors do not enforce either of these two conditions and allow positive weights to represent material flows and negative weights to indicate a desire for machine separation.

Problems solved with graph-theoretic approaches tend to be small, a few tens of elements at most, because formulations often rely on the graph being *planar*. Planar graphs can be drawn on a planar surface without crossing edges (Hassan and Hogg 1987; Kusiak and Heragu 1987). As Figure 3.4 illustrates, a planar graph (drawn with dashed lines), and specifically its property of duality, allows a smooth transition from the set of relationships to a single-level floor plan. It may be obvious that as the number of interactions grows, the likelihood of a graph being planar diminishes. In this case, a maximal planar weighted graph can be used to create a planar graph that retains the strongest relationships and discards those that would make it nonplanar (Hassan and Hogg 1987).

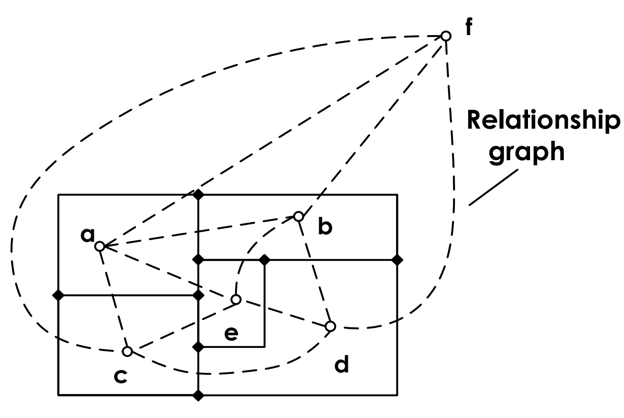

Figure 3.4: Planar relationship graph with block layout constructed around its dual. (Hassan and Hogg 1987)

Jayakumar and Reklaitis (1994) use the relationship graph differently. They attempt to minimize material flow costs among chemical plant units by partitioning the nodes of the relationship network into collections of items that represent regions of the overall facility that are cordoned off by aisles or corridors. In this single-floor approach, Jayakumar and Reklaitis identify the partitions in a graph-theoretic minimum cut-style problem by minimizing the total weight of the edges between nodes in subsets. In (Jayakumar and Reklaitis 1996), they extend their approach to multiple floor facilities, but they formulate the partitioning problem as an Integer Non-Linear Program rather than as a strict graph-theoretic problem. A variation on (Jayakumar and Reklaitis 1994) is considered in Chapter 5, while the multi-level assignment to ship structural zones in Chapter 6 takes a different direction.

3.4.2 Relationship between graph theory and network science

The graph-theoretic and network science-based approaches employ the same modeling framework (nodes connected by edges), but the perspective is substantially different. Architectural floor plans provide a similar challenge to ship arrangements, and Lobos and Donath (2010) note that graph-based formulations are rare. This may be due to the impracticality (or inappropriateness) of extending graph-theoretic approaches to larger problems. The field of network science provides new theories and methods for understanding the complex layout problem on a larger scale. In (Newman et al. 2006), the editors differentiate network science from graph theory based on its applicability to real-world networks and the manner in which the networks develop:

> *Pure graph theory is elegant and deep, but it is not especially relevant to networks arising in the real world. Applied graph theory, as its name suggests, is more concerned with real-world network problems, but its approach is oriented toward design and engineering. By contrast, [network science] … is focused on networks as they arise naturally, evolving in a manner that is typically unplanned and decentralized. Social networks and biological networks are naturally occurring networks of this kind, as are networks of information like citation networks and the World Wide Web. But the category is even broader, including networks – like transportation networks, power grids, and the physical Internet – that are intended to serve a single, coordinated purpose (transportation, power delivery, communications), but which are built over long periods of time by many independent agents and authorities.*

This last sentence in particular describes the development of design constraints for ship arrangements. Design constraints addressing everything from mission requirements to ship safety to habitability standards develop in stages, often on an irregular timeline and according to a singular focus by authorization-, acquisition-, operation-, or regulation-oriented authorities. Specific requirements may even be developed for a particular ship class or platform. Even so, this disparate and uncoordinated set of rules and guidelines must be merged into a coherent layout.

3.5 The Habitability Ship relationship network

Any analyses that depend on a network of ship relationships will require the network be defined. Developing this model will likely be a time-consuming endeavor. In fact, van Oers (2011) advocates for a process that avoids rule-based design decisions citing the

> *effort required to develop a set [of objectives and constraints] that can evaluate a ship design in a manner as comprehensive as an experienced naval architect [is] considered … prohibitive.*

In a different ship design culture, this knowledge capture effort is precisely what was desired of the Intelligent Ship Arrangements framework (Parsons et al. 2008). Regardless of whether the objectives and constraints are left to a designer to work though manually or are coded into a design system, the same goals must be satisfied. However, a methodical analysis will provide consistent and comparable results.

The Habitability Ship is a ship concept created to demonstrate the capabilities of the Intelligent Ship Arrangements (ISA) methods and computer program. The example ship is based on a non-US Navy notional corvette surface ship. Further details regarding the origin of the ship, its compartments, and its design constraints are provided in (Nick 2008; Parsons et al. 2008). The ship contains 103 compartments and 22 structural zones.

The Habitability Ship relationship network is derived from the relative location-based constraints stored in ISA's constraint database (Section 2.3.3.4, page 29) for the Habitability Ship. Each of ISA's information-rich 2-D fuzzy relative location constraints (Figure 2.9, page 30) has been simplified into a single edge in the network. When edge weights are used, they are not reflective of the preference values or locations of values within the fuzzy constraint; the presence of an edge in the network simply represents the existence of a relative location constraint. (ISA's global location constraints are not part of the network. The global location constraints are used only in Chapter 6 when compartment-to-zone allocations are created.)

The network is a directed graph. Each vertex v_i represents a unique compartment to be located within the ship arrangement, and each edge represents a relationship between vertices v_i and v_j, $i \neq j$. The compartments and relationships[8] are a modified set of (though very similar to) those used in (Nick 2008; Parsons et al. 2008). Edges run from the *influencing* node to the *influenced* node. For example, the galley (kitchen) v_g should be separated from the trash room v_t, thus the edge is $v_t \rightarrow v_g$. The weight of the edge is given by the weight w_{gt}, following the subscript convention set forth in Equation 1 (page 47). An unweighted network is used in Chapter 4, thus all $w_{ij} = 1$. A weighted, signed network is used in Chapters 5 and 6; adjacency links are modeled with positive weights and separation links are given negative weights. The weight w_{ij} is

$$\begin{aligned} w_{ij} > 0, &\quad \text{if } j \rightarrow i \text{ is an adjacency relationship} \\ w_{ij} < 0, &\quad \text{if } j \rightarrow i \text{ is a separation relationship} \end{aligned} \qquad \mathbf{2}$$

A discourse on the selection of edge weights can be found in Chapter 5 (Section 5.3.1, page 98).

3.5.1 Pre-layout and post-layout relationship network configurations

Two configurations of the relationship network are used in this thesis. The first is termed *pre-layout* and the second is termed *post-layout*. The pre-layout network is the primary network used throughout this thesis and is developed without generating arrangements; it is used in Chapters 4-7. The post-layout configuration, which relies on ISA-arranged layouts, is used only in Chapter 4. Both are directed networks. The pre-layout network is described first.

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[8] The relationships mentioned are referred to as *constraints* in other ISA literature.

3.5.1.1 Pre-layout network

The pre-layout network is a network representation of ISA's design constraint database.[9] Section 2.3.3.4 described a set of fuzzy design constraints used by ISA to specify relative location preferences among pairs of compartments. The design constraints are based on design rules, best practice, and experience. As stated above in the introduction to the Habitability Ship network (Section 3.5), each of these constraints has been simplified into a single edge between two nodes that represent ship compartments. The compilation of these design constraint-based edges into a network forms the *pre-layout network*.

A pre-layout network is dependent upon the ship concept being designed, just as the constraint database is. Destroyers, frigates, minesweepers, and submarines will all have different networks because the set of compartments and design constraints included in each is different. Furthermore, separate design concepts within a design study will have different networks. A cruiser concept with a diesel engine power plant will have a different network than a nuclear-powered concept. However, two diesel engine variants would have the same pre-layout network.

The pre-layout network is a desirable basis for analyses because it depends only on the ship design concept. The use and analysis of the pre-layout network provides direct access to the basic relationships that underlie each variant in a design concept exploration. The pre-layout network is a model that enables direct analysis of the inputs into design space exploration algorithms (Section 3.1). The abstract nature of the network is surmised to contain information that has heretofore only been considered through the lens of completed geometric layouts (Sections 2.4.2 and 3.1). Therefore, the use of the pre-layout network is expected to provide these insights without undergoing the time-consuming process of generating physical layouts.

The pre-layout Habitability Ship network used throughout this document is shown in Figure 3.5. It contains 103 nodes (compartments) and 1,017 edges (relative location

[9] More specifically, the pre-layout network models the portion of the constraint database concerned with the relative locations of compartments. The constraint database also contains, for example, global location constraints and constraints related to the geometric shape of compartments.

constraints/relationships). The network is composed of 15 network components, with sizes varying from 1 to 63 nodes. Each network component represents compartments that only have design relationships (constraints) with other compartments (nodes) within that network component. For example, in the center of Figure 3.5 is a network component with five nodes representing five fan rooms. The only design constraints on these fan rooms are relationships describing the mutual desired separation of these spaces. These fan rooms have no direct or indirect relationships to the remaining 98 compartments. In Chapter 4, no differentiation is made between edges that correspond to adjacency constraints versus separation constraints. In Chapters 5-7, this difference is exploited in the form of a signed, weighted network.

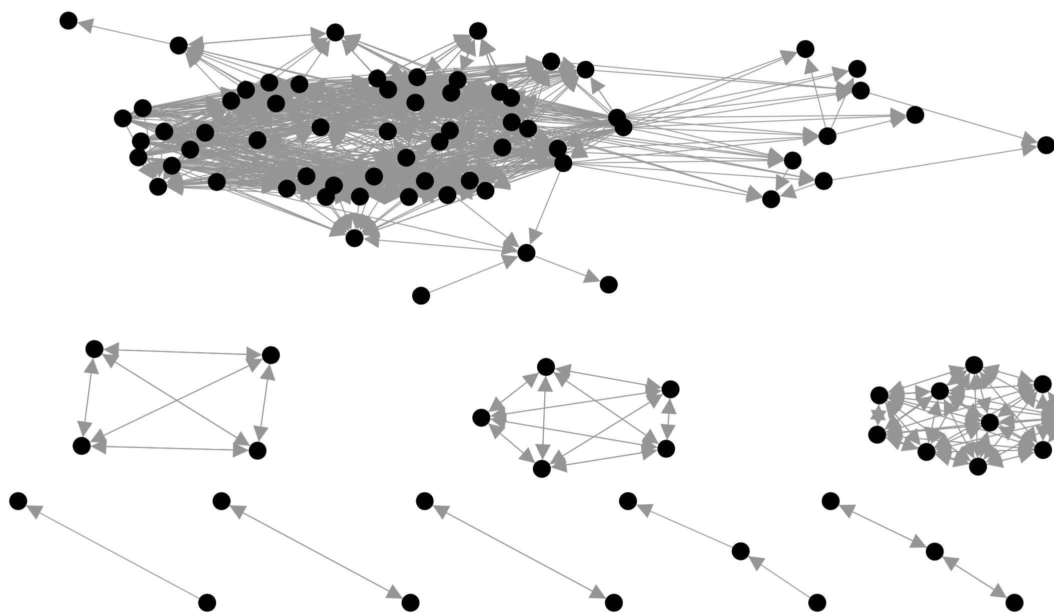


Figure 3.5: The pre-layout Habitability Ship relationship network.

3.5.1.2 Post-layout network

When a geometric arrangement (versus an allocation) is created, a set of constraints arises that did not exist at the beginning of the process, namely the spatial constraints that prevent compartments from existing in the same location. A post-layout network accounts for both the pre-layout design constraints and these additional spatial constraints. ISA is run only through the allocation phase, but the spatial constraints do not change between the allocation phase and the arrangement phase because the same compartments remain within each zone. The 103 compartments are always allocated to the 22 zones of the Habitability Ship.

A post-layout network is built upon the pre-layout network. Therefore, the post-layout network contains the same nodes and edges as the pre-layout network. In addition, a post-layout configuration adds a subset of edges intended to represent the inter-zonal spatial constraints that arise due to the interaction of geometrical compartment boundaries with a structural zone. These "spatial" edges are allocation-dependent. As such, this subset of edges is different for each layout.

Spatial edges are added to the pre-layout network after creating an allocation. This subset of edges is developed by creating reciprocal relationships among all compartments that are allocated to a single structural zone. If two nodes are already connected by an adjacency or separation constraint, a pair of edges will be added between the two nodes. When a post-layout network is used in Chapter 4, no differentiation is made between fixed pre-layout design constraints and variable post-layout spatial constraints. That is, a post-layout network is a multigraph, not a multiplex network (refer to Section 3.3.1). Figure 3.6 illustrates an example post-layout network, which includes the pre-layout network (gray edges) with an overlay of additional spatial edges (shown in blue). This example has 102 spatial edges, in addition to the 1,017 relationships from the pre-layout network. For different allocations, the configuration of, and likely the number of, the blue edges will change.

In Chapter 4, both pre-layout and post-layout network configurations are used in order to make comparisons between analyses that can be conducted before generating a single arrangement with those that employ a set of arranged designs. Chapters 5-7 use only the pre-layout network.

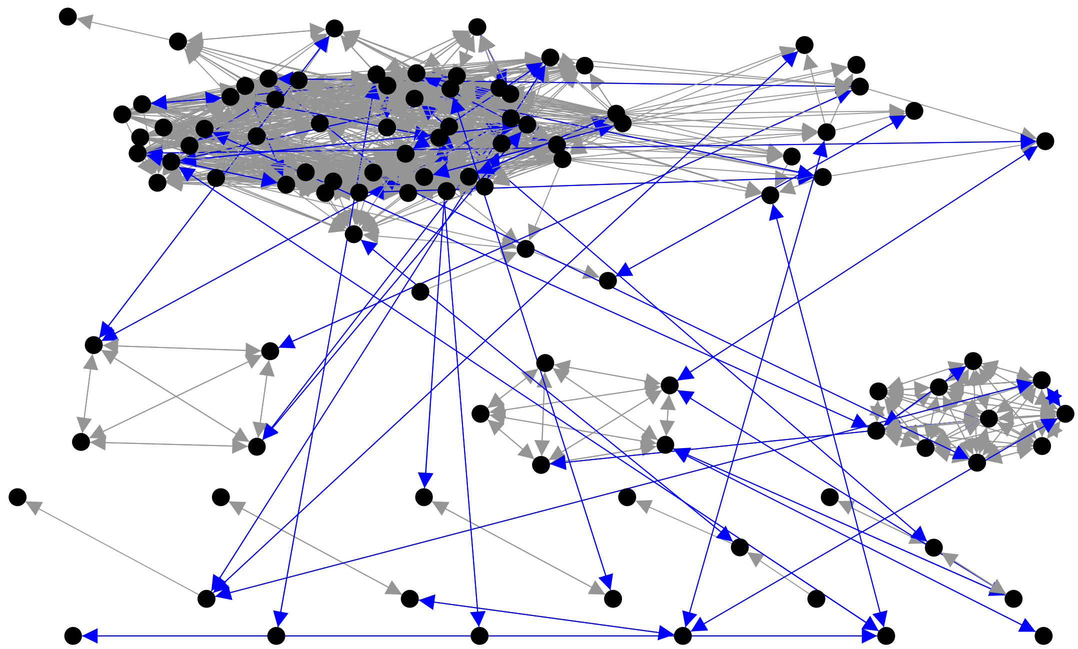


Figure 3.6: An example post-layout Habitability Ship relationship network.

3.6 Preliminary exploration of network relevance

Because network analyses are being introduced to understand and generate early-stage ship layouts, a preliminary exploratory analysis was conducted to demonstrate that a network perspective is indeed relevant and useful for interpreting ship arrangements via the relationship network. The belief was that if spaces connected by adjacency design constraints were co-located in the same structural zone, there would be overlaps of reciprocal spatial edges and adjacency relationships creating multiedges (Figure 3.7). Furthermore, one would expect a connection between the number of multiedges and the quality of the layout. In order to show that a network approach to early-stage arrangements may be feasible, the number of multiedges was investigated.

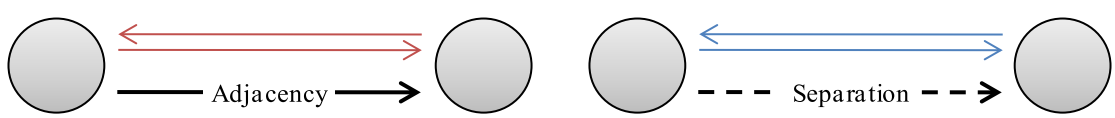


Figure 3.7: Adjacency and separation multiedges.

In the experiment, 1,478 allocations were created for the Habitability Ship using ISA. A post-layout network was developed for each design (Section 3.5.1.2). Therefore, all compartments within a structural zone have been given reciprocal relationships representing spatial constraints. The number of adjacency multiedges and separation multiedges was tallied for each design and plotted against an objective function value expressing the quality of the layout (ISA's overall allocation utility value, see (Parsons et al. 2008)).

Figure 3.8 shows that design quality increased with more adjacency multiedges and with fewer separation multiedges. The trend is appreciable at higher utility values, where the final placement of each compartment is more meaningful and less chaotic. These preliminary results suggest the number and type of multiedges may be used as a proxy for design quality. This introductory analysis confirmed the early belief in the usefulness of networks for understanding ship layouts.

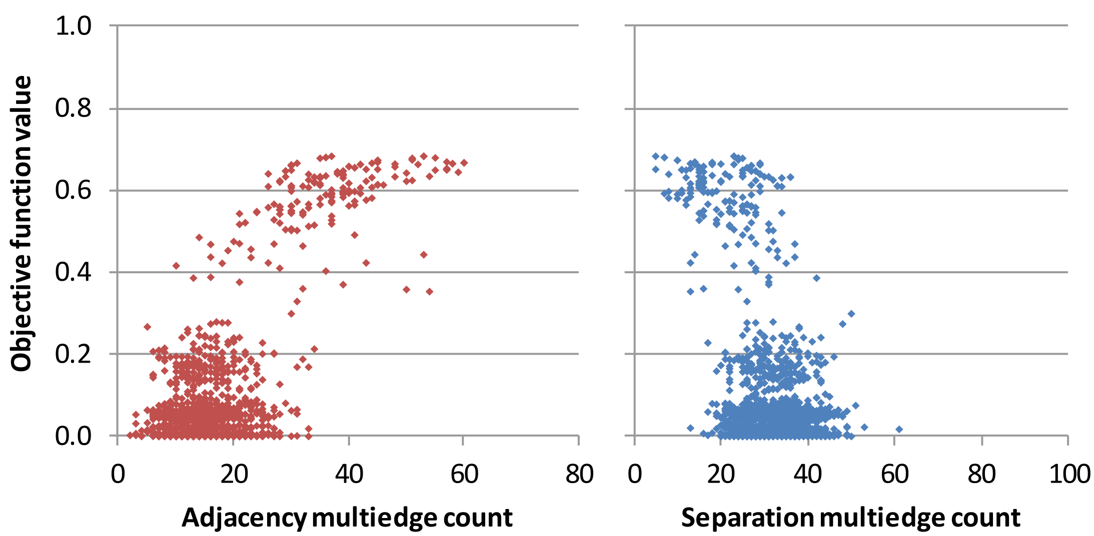


Figure 3.8: Correlation of design quality with number of multiedges.

Chapter 4
Identifying drivers of general arrangements

Naval ship design is a unique process in which designs are often created to understand requirements rather than to build ships (Section 1.1.2, page 4). If the goal is to understand the requirements placed on a design, then it makes sense to examine the requirements directly. The use of networks to represent design relationships allows naval architects to focus on the fundamental interactions that cause particular configurations instead of just the resultant layouts. For this to be successful, network-based concepts must be linked to traditional naval architecture concepts. If these links can be made by analyzing the design requirements alone, then traditional learning processes, such as the identification of drivers, can be conducted without enduring the time-consuming practice of generating geometric arrangements. Methods that provide this information would be particularly valuable for novel ship types, designs that contain emerging technologies, or densely outfitted vessels such as naval combatants and submersibles.

The goal of this chapter is to demonstrate how network analyses can identify items that drive or constrain an arrangement. Section 3.5.1.1 (page 54) describes the ship relationship network as a representation of ISA's constraint database. The database forms the core of ISA's design knowledge, and thus, the relationships contained within it dictate the character of the solutions produced from it. If one can appreciate the entirety of the picture illustrated in the constraint database, then one has a better chance of understanding the problem to be solved and its solutions. The network-based perspective is novel because it facilitates direct analysis of the relationships underlying a layout rather than requiring inference from a single layout or a set of layouts (Section 2.2.1.3). The results in this chapter were presented in (Gillespie and Singer 2011).

The network-based methods described in this chapter provide a mathematical formulation for an otherwise ad hoc process of identifying the drivers of general arrangements. As the quote opening Chapter 3 states, scientists need "mathematical models that capture the key properties of the entire [ensemble]". In a manual approach to driver identification, the set of interactions is limited to the items a designer can identify (correctly) and remember or document within the appropriate context. A network approach intrinsically addresses the entire set of relationships in methodical manner. Its systematic analysis allows a more fundamental and rational discussion than one based on intuition (Section 1.1.1, page 2). With a better understanding of the collective set of design relationships, designers can be more informed about the totality of impacts of system selections.

The existing ship layout methods (manual or automated) are essentially simulation-based tools. Many "design process" trials are conducted, and the results (designs) are analyzed. Learning from the output data (a set of designs) occurs in a haphazard manner, relative to scientific standards, partially because ship-level layout metrics are rare (Section 2.4.2, page 39). In the end, all existing layout design methods incorporate some level of human-driven a posteriori selection of a candidate design, and this is often where the "art" of ship design comes into play. As a result, the insights gained are dependent upon the complexity of the design, the naval architect's experience and astuteness, and the time allotted for the design study. A methodical approach, as called for by Leopold et al. (1972) (Section 1.1.1, page 2) and as advocated in this dissertation, should prove comprehensive and consistent.

Beyond the limited scope of drawing compartment boundaries and positioning equipment, the methods described in this chapter can be useful for concept-level explorations containing new systems or emerging technologies. System designers can begin to understand the breadth of influence and extent of disruption a new technology may have on the rest of a ship by viewing its position in a hierarchy of drivers. A converse view could shed light on potential system-level research avenues: by (re-)designing a piece of equipment or a system to increase its resilience to external influences, one could potentially change its position in the ranking of drivers.

4.1 Applicability to semi-automated and manual approaches

The existing (semi-)automated early-stage arrangements tools described in Sections 2.3.2 and 2.3.3 are capable of generating feasible layouts, but they remain a bit of a "black box" regarding why layouts are configured as they are. They lack efficient methods for highlighting the mechanisms that drive or limit the quality of resultant layouts. The network-based methods can be used in design processes that employ human designers or computer automation because the methods rely only on the relationships between shipboard elements, which are common inputs to both types of processes.

4.2 Analyses scope and focus

The focus of the analyses in this chapter is to highlight drivers embedded within the large and complex set of inter-compartment relative location relationships. The intent is to draw attention to elements that become important due to second and third order effects – that is, by having direct or indirect relationships with key elements (Section 1.1.3, page 8). The purpose of these analyses is not layout creation, though they may be useful for that by helping designers decide more judiciously when and where to position objects. These analyses do not aim to provide full guidance regarding placement of compartments or equipment because they do not contain global (ship) location information. For example, the analyses will not indicate that the flight deck and hangar bay for an aircraft carrier should be atop the hull or that the well deck of an amphibious assault ship should be positioned at the stern near the waterline. These "anchoring" facilities do in fact strongly influence the spatial arrangement of the vessel, but the importance of these features is likely to be known. These understood influences are not the primary interest here. The goal is to help structure an analysis framework that enables designers to see more clearly the hidden effects of indirect influences within the context of the entire set of relationships.

4.3 Network concepts, analyses, and metrics

Two concepts and three analyses will be described in this section. Two of the analyses are based on network measures of *centrality*, while the third is based on a notion of *hierarchy*. Each will be used to identify the drivers embedded in a set of design relationships. Only the measure of *degree centrality* can be used prior to allocating compartments to structural zones in all cases (pre-layout network, Section 3.5.1). If the network is *connected*[10], then all three analyses can be used without generating layouts. It is unlikely the network will be connected, thus the *hub/authority centrality* and *hierarchy* methods must be conducted after generating layouts. A fourth technique adds random edges to the network was developed to enable the use of the hierarchy method in a pre-layout stage. Table 4.1 provides a summary of the three analyses along with the point at which they can be used. All networks in this chapter are directed and unweighted.

Table 4.1: Summary of analyses for arrangement drivers.

Analysis	Pre-layout network	Post-layout network
Degree centrality	Yes	N/A
Hub/authority centrality	Yes, if network has one component	Yes
Hierarchy	Yes, if network has one component	Yes
	Yes, with random edge addition	N/A

Pre-layout and post-layout networks are described in Section 3.5.1 (page 53).

4.3.1 Centrality

It is often desirable to understand which nodes in a network are the most important, most central, or most highly connected. Within the field of network science, these nodes are identified using various measures of *centrality*. Centrality is a node-centric measure. A node's importance can be determined by, for example, the number of connections it has, the number of connections it has to other important nodes, or how close it is to other nodes. Related to ship arrangements, the placement of highly influential compartments

[10] A *connected* network is a network in which all nodes are connected to all other nodes by at least one edge. A connected ship relationship network represents a set of design constraints in which all elements influence or are influenced by, directly or indirectly, all other elements; that is, there is no subset of elements that can be positioned in the ship without (in-)directly affecting all other elements. By definition, a connected network has a single network component (Section 3.3.1, page 47).

may dictate or restrict the subsequent placement of other compartments. Highly influenced spaces may limit the quality of solutions; finding ways to increase their resilience to or decrease their dependence on external influences may reveal productive areas for additional component or subsystem design explorations.

Two types of centrality are considered. The first, degree centrality, is very simple, while the second, hubs and authorities, is more sophisticated. Both methods are shown to elicit similar results.

4.3.1.1 Degree

Degree centrality supposes that the most important nodes have the most connections. The simplest form of degree centrality is simply the degree of a node, meaning the number of connections it has. In directed networks, the total degree of a node is equal to the sum of the *in-degree* (the number of incoming edges) and the *out-degree* (the number of outgoing edges). Other variations consider edge weights (Newman 2004; Opsahl et al. 2010), but are not investigated here. Nodes with zero degree have no relationships with other nodes; these nodes represent compartments that have no expressed need to be near to or far from any other compartment in the ship.

4.3.1.2 Hubs/Authorities

Hub centrality and *authority centrality* (Kleinberg 1999) are a pair of measures that distinguish between *pointing to* important nodes and *being pointed at* by important nodes. Nodes often have both a nonzero in-degree and a nonzero out-degree leading to a coupling between these two concepts, and thus, they are mutually reinforcing. These centrality measures were developed in the context of webpage hyperlinks and web searches: *authorities* are web pages containing useful information relevant to the search topic and *hubs* are web pages that have links to multiple relevant authoritative pages. Equations 3 and 4 provide the pair of equations used to calculate authority scores x and hub scores y:

$$x_i = \alpha \sum_j A_{ij} y_j \quad \textbf{3}$$

$$y_i = \beta \sum_j A_{ji} x_j \quad \textbf{4}$$

where α and β are constants and *A* is the network's unweighted adjacency matrix (Section 3.3.1, page 45). In matrix notation, Equations 3 and 4 become

$$\bar{x} = \alpha \boldsymbol{A} \bar{y} \qquad \bar{y} = \beta \boldsymbol{A}^T \bar{x} \quad \textbf{5}$$

By combining these two matrix equations, we obtain

$$\boldsymbol{A}\boldsymbol{A}^T \bar{x} = \lambda \bar{x} \qquad \boldsymbol{A}^T \boldsymbol{A} \bar{y} = \lambda \bar{y} \quad \textbf{6}$$

where $\lambda = (\alpha\beta)^{-1}$. Now one can see that the eigenvectors of $\boldsymbol{A}\boldsymbol{A}^{\mathrm{T}}$ and $\boldsymbol{A}^{\mathrm{T}}\boldsymbol{A}$ having the same eigenvalue λ are the authority centralities and hub centralities, respectively. Calculation of these centrality values is known as the *hyperlink-induced topic search* (HITS) algorithm. The hub/authority values are presented on a [0,1] scale. In the design context, hubs are interpreted as design drivers, influencing multiple constrained items, while authorities are highly constrained elements, being influenced by multiple strong drivers.

4.3.2 A notion of hierarchy in directed networks

If one envisions a directed acyclic graph with drivers at the top and edge arrows pointing downward to each compartment influenced by that driver, a tree, or hierarchy, could be created full of paths of influence. Not surprisingly, in many real-world networks, the edges are sufficiently mixed so a perfect directed acyclic graph cannot be formed (Figure 4.1), but the concept can still be exploited.

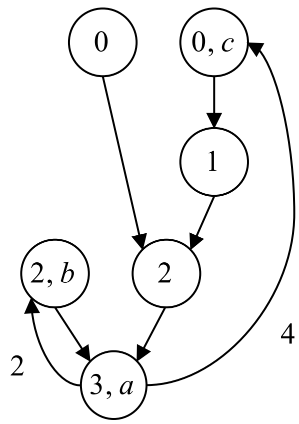


Figure 4.1: A hierarchy of drivers with paths of influence (generally) flowing downward. Adapted from (Gupte et al. 2011).

To address the convolution of relationships, the hierarchical ranking method in (Gupte et al. 2011) creates an integer ranking of nodes in a directed network that minimizes the number of edges pointing upward (against the downward flow of influence) by minimizing Equation 7:

$$SA(G,r) = \sum_{(u,v)\in E} \max[r(u) - r(v) + 1, 0] \qquad \textbf{7}$$

where *SA* is a measure of the quality of a ranking *r* of the nodes *u* and *v* in the network *G*, which is composed of the edge set *E*. According to this formulation, edge $b \rightarrow a$ in Figure 4.1, ranked $r(b) = 2 < r(a) = 3$ meaning *b* is higher than *a* in the hierarchy, does not increase *SA*; this is the desired configuration. In the case where $r(u) \geq r(v)$, *SA* is penalized by edge $u \rightarrow v$ according to the difference in their ranks. For example, edge $a \rightarrow b$ has a penalty of 3–2+1 = 2, while edge $a \rightarrow c$ has a larger penalty of 3–0+1 = 4 because it disrupts more extensively the downward-only flow of influence. The +1 term prevents a trivial solution where $r(u) = 1$ for all nodes *u*. The ranking *r* may not be unique for a minimum value *SA*.

4.4 Drivers by degree centrality (pre-layout)

If one agrees with the contention that quality three-dimensional distributed system layouts are difficult to generate, then the ability to evaluate the drivers prior to layout generation would be of value. With the convention that edges point from influencing node to influenced node (Section 3.5, page 52), a simple identifier of a driver is a node's out-degree: higher out-degree indicates influence over a greater number of spaces. Similarly, high in-degree indicates influence by many other spaces, thus possibly a highly constrained space. This metric has the advantage in that is easy and fast to calculate and can be done prior to the creation of any layouts. This test is conducted using only the pre-layout ship relationship network (Section 3.5.1.1, page 54) developed from ISA's constraint database; no designs are generated.

4.4.1 Method

The in- and out-degree are calculated for each node in the pre-layout Habitability Ship relationship network (Section 3.5.1.1, page 54). Then, each node is placed on a scatter plot having horizontal and vertical axes representing the in- and out-degree, respectively. Degree values are viewed on an absolute scale.

4.4.1.1 Assumptions & Limitations

First, this metric does not differentiate between stronger and weaker influences and assumes all relationships are of equal importance. Non-unity values could be used as edge weights to reflect the relative impact of relationships. It must be noted that the strength of a relationship is often dependent upon the locations of the elements, and thus determining the weight of a performance-based relationship is difficult to determine a priori (i.e., pre-layout). That said, a scale of relative importance or a metric based on expected degradation due to non-satisfaction of the constraint could be used as surrogates for true impacts.

Second, this measure of centrality intrinsically provides two unique values: drivers are measured on one scale (out-degree) and constrained items on another (in-degree). A measure that rates elements on a single continuum of strongest driver to most constrained is desirable.

4.4.2 Results

Figure 4.2 identifies many of the drivers and constraining elements that a naval architect might find intuitive. The reasons differ regarding why a particular compartment drives a solution. For example, the Sewage Treatment Machinery Room, Trash Room, petroleum/oil/lubricant (POL) and paint lockers drive solutions because they are unwelcome near or contain contaminants harmful to other spaces, notably food-related spaces and the crew's cabins. The Galley, on the other hand, drives layouts because it requires services from and provides services to a large number of spaces. Close proximity of the Galley to multiple dining rooms and provisions storage spaces is desirable. Separation of all these spaces from crew cabins is also preferred. Finally, many of the distributed systems' spaces (e.g., fan rooms, electrical equipment and switchboard rooms) have separation constraints only among other spaces of the same type resulting in both low in-degree and low out-degree. These spaces are interpreted as non-drivers because these spaces can be located in almost any structural zone without interfering with other spaces located there.

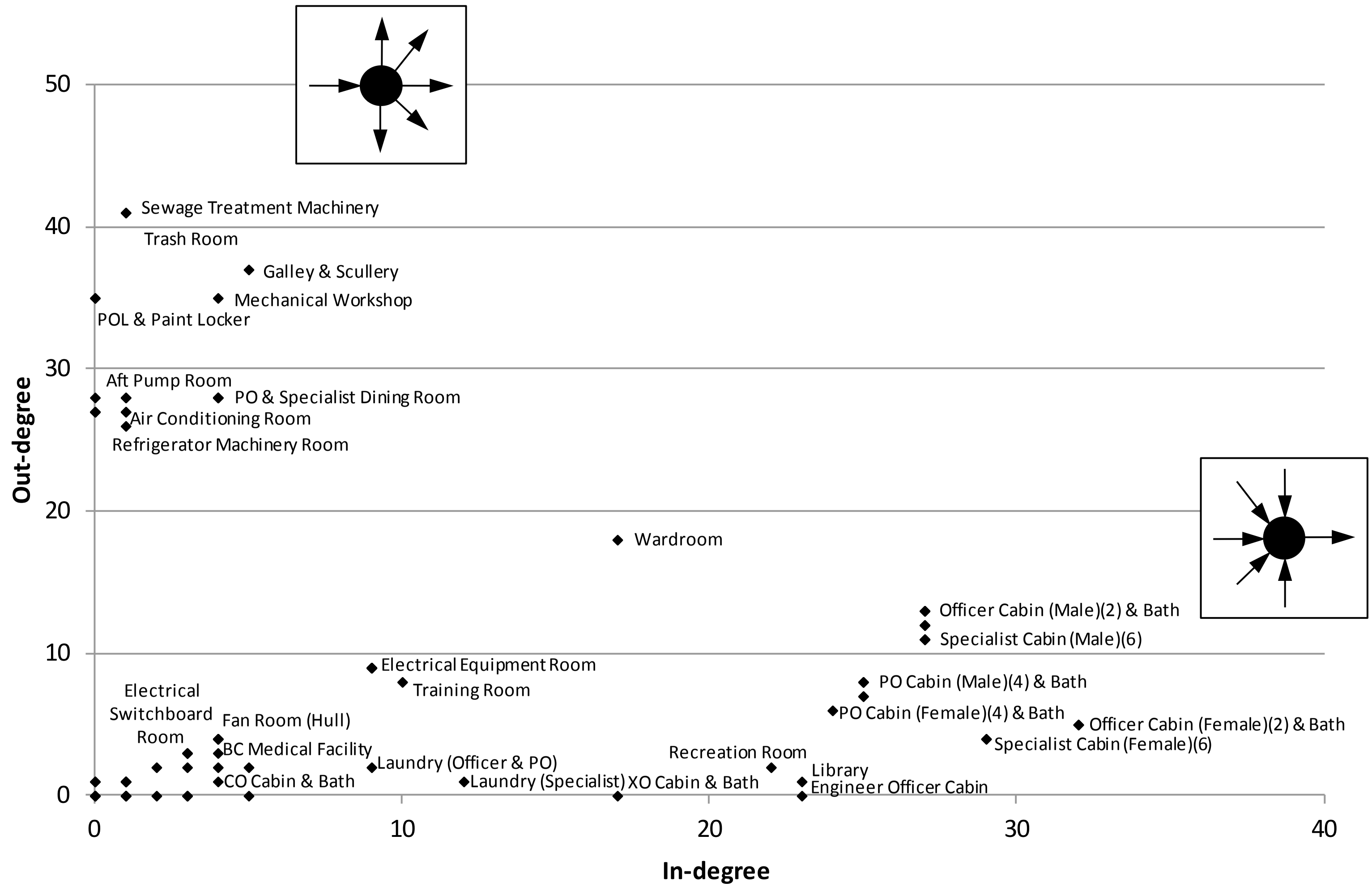


Figure 4.2: Identifying drivers and constrained spaces by out-degree and in-degree.

4.5 Drivers by hubs/authorities (post-layout)

A more sophisticated measure of centrality is the HITS algorithm (Section 4.3.1.2). Unlike degree centrality, the HITS algorithm incorporates an element of the directional connectivity for pairs of nodes as opposed to only the number of connections for an individual node. Another difference is that the HITS algorithm must be used after creating layouts (except in a limited case, see Section 4.5.1.1). The benefit of these two differences is that the post-layout HITS analysis will incorporate secondary and tertiary relationships that were not identified using the simple degree-based analysis, which is the goal (Section 4.2). The obvious drawback is that this information cannot be obtained before developing a set of compartment allocations.

The key concept is that a hub *points to* many authorities and an authority is *pointed at* by many hubs. Again, the edge convention used here is that edges point from influencing node to influenced node. Thus, in the design context, hubs are interpreted as drivers because they influence (point to) constrained items. Authorities, on the other hand, are influenced by (pointed at by) multiple drivers.

4.5.1 Method

This is a post-layout analysis; therefore, each ISA-generated design is converted to an individual post-layout relationship network (Section 3.5.1.2, page 55) for analysis. Each post-layout network corresponds to a unique ISA-generated allocation, and it includes the additional "spatial" relationships. In this test, 1,488 post-layout networks are analyzed. The number of edges varies by design; the size of the edge set ranges from m = 1,425-1,595. Of these edges, 1,017 represent the pre-layout network, which is common to all post-layout networks (Section 3.5.1.2, page 55). The remaining 408-578 edges represent "spatial" constraints. The number of edges varies with the distribution of compartments to zones.

The hub and authority scores were calculated for each of the 1,488 networks. Scores for each node were averaged, and compartments were separately ranked by decreasing hub score and by decreasing authority score.

4.5.1.1 Assumptions & Limitations

A connected network is needed for the HITS algorithm to produce good results. The hub and authority scores were calculated from post-layout networks, which include reciprocal spatial edges. The additional spatial edges are often sufficient to connect the 15 network components of the Habitability Ship pre-layout network (Section 3.5.1.1, page 54); as a result, most networks are composed of a single network component. A node will exist outside the largest network component if a compartment is allocated to a structural zone by itself and it has no relative location relationships with other compartments (in-degree = out-degree = 0). In this experiment, a node not connected to the largest network component is assigned a zero hub and authority score for that network since its isolated state makes it neither influencing nor constrained from a relationship standpoint.

Calculating the hub and authority scores from the pre-layout network alone is possible if the network is connected. If the network is not connected, isolated nodes and nodes in smaller network components receive scores of zero, resulting in little differentiation. This improper weighting effect is demonstrated and explained by Farahat et al. (2006).

4.5.2 Results

The rankings by descending average hub score and average authority score are given in Figure 4.3 and Figure 4.4, respectively. Error bars show ±1 standard deviation from the mean. The full rankings are listed in Appendix B. These two figures show that there are about 20 notable drivers and about 25~40 constrained compartments. In the hub score ranking, the top 20 compartments have markedly higher average scores than the rest of the compartments. These high-scoring hubs also tend to be found in the top left corner of Figure 4.2, signaling a common finding regarding the layout drivers. Unlike the degree centrality method that identified the crew's cabins as being predominantly constrained, the cabins are shown here to be stronger drivers than many other compartments. This is due to the large number of relationships these compartments have to top authorities (primarily other cabins). The Wardroom is ranked 21st and sits between the top ranked hubs and the lower-scoring set of cabins. The Wardroom is also the only space that exhibits a strong balance of outward and inward influences in Figure 4.2.

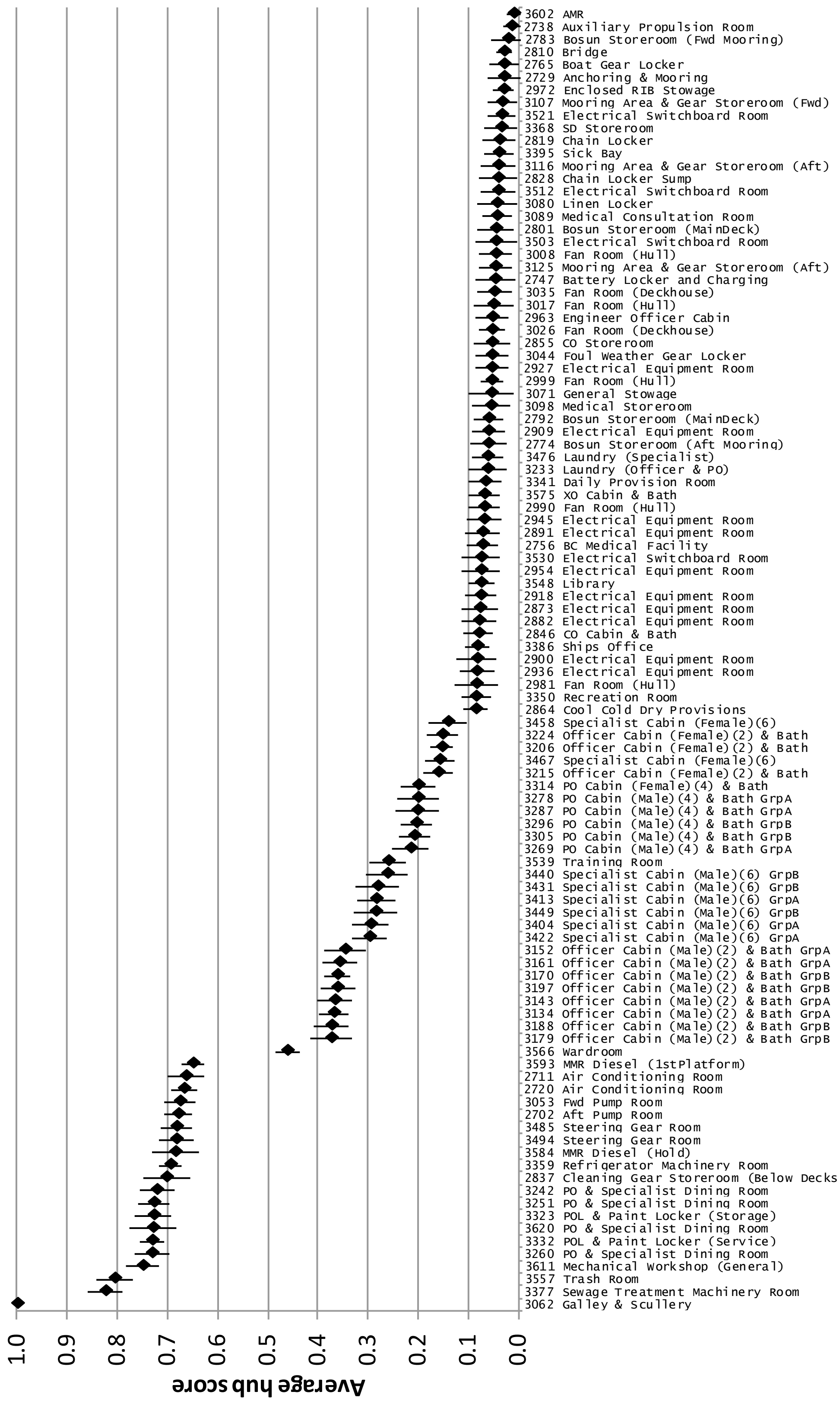


Figure 4.3: Ranking of drivers by average hub score.

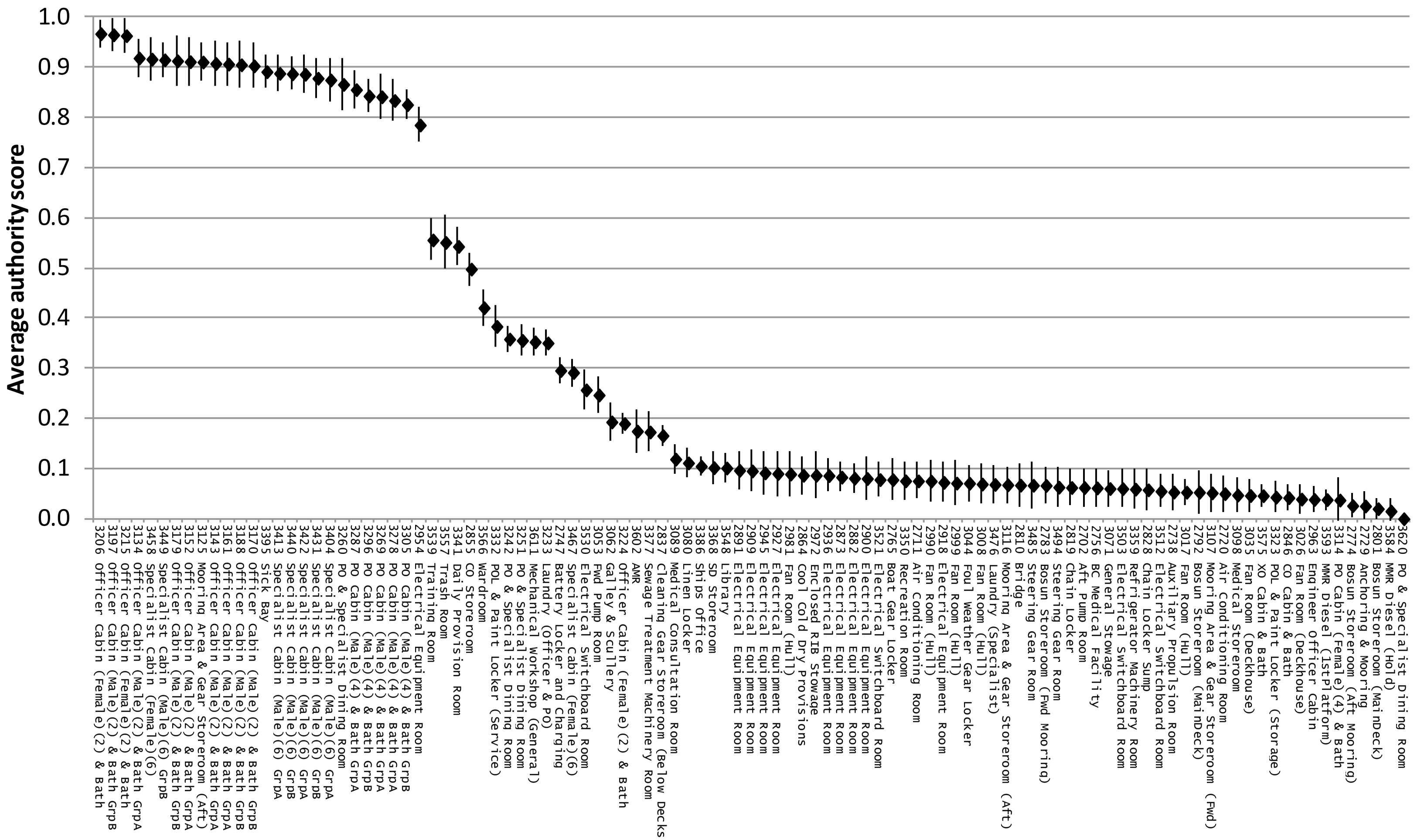


Figure 4.4: Ranking of most constrained compartments by average authority score.

4.6 Drivers by hierarchy (post-layout)

A hierarchical approach provides the node connectivity and degree-counting aspects of the HITS algorithm that were deemed beneficial in the previous section, although it, too, has the drawback of requiring a connected network (see Section 4.6.1.1). However, in addition to providing a different (non-centrality-based) perspective, the hierarchy permits the creation of a single continuum of least constrained (most influential) to most constrained (least influential) – a desirable insight.

In this section, each compartment is placed on the continuum according to its average hierarchy rank within a set of designs. This is a post-layout analysis; therefore, each ISA-generated design is converted into a post-layout relationship network (Section 3.5.1.2, page 55) for analysis. Since the drivers are identified from actual, balanced ship allocations, it is presumed that all influences (including spatial requirements and zone capacities) will be embedded in the network. This presumption will become important in Section 4.7 when the continuum of drivers identified here is compared to a similar continuum derived from the pre-layout network.

If both the centrality- and hierarchy-based methods are to be believed, then the drivers identified in this section should be similar to the top drivers identified using the other methods. That is, compartments with high out-degree or a high average hub score should be ranked high in the hierarchy (a low rank number) and the cabins and highly constrained compartments should be at the bottom of the hierarchy (higher rank numbers).

4.6.1 Method

Drivers are determined by hierarchy (Section 4.3.2) following the creation of unique allocations using ISA. As a result, most nodes are more connected than in the pre-layout network, resulting in fewer network components. In this section, only the largest network component is analyzed. The 1,488 post-layout networks created in Section 4.5.1 are used again.

4.6.1.1 Assumptions & Limitations

Each network component must be analyzed individually because no links exist between network components (see Figure 3.6). A single hierarchy must be formed for each network component, and the hierarchies are not directly comparable. Compartments with few or zero design constraints or that reside in a network component with few nodes may be artificially overestimated in their rank relative to the hierarchies of larger components. In this experiment, nodes not connected to the largest network component are ignored for that layout and are given no rank in the hierarchy for that network.

4.6.2 Results

The network was disconnected into multiple network components in 353 of the 1,488 trials. In total, 400 nodes were not part of the largest component; the corresponding compartments were primarily limited to the Auxiliary Machinery Room due to a lack of relationships with other spaces and a strong preference to be located in a single structural zone that is not preferred by other compartments. Figure 4.5 provides an example hierarchy of the ship's compartments; this particular hierarchy contains seven levels.

Two sets of rankings are given for a stark comparison: the first ranking was developed using all 1,488 designs regardless of quality, while the second ranking uses only high quality designs. The first ranking includes designs of varying quality, including poor quality designs and designs possessing fitness values of 0.0, which indicate that nearly every constraint is fully unsatisfied. Figure 4.6 shows the average hierarchy rank with error bars of ±1 standard deviation for each compartment. (The full ranking of compartments is listed in Appendix C.) Lower ranking values correspond to nodes higher in the hierarchy of drivers. The ranking generally matches the trend revealed in Sections 4.4.2 and 4.5.2, where nodes with a high out-degree or a high hub score can be found on the low-ranking end of the continuum, and nodes with high in-degree or a high authority score are located on the high-ranking end.

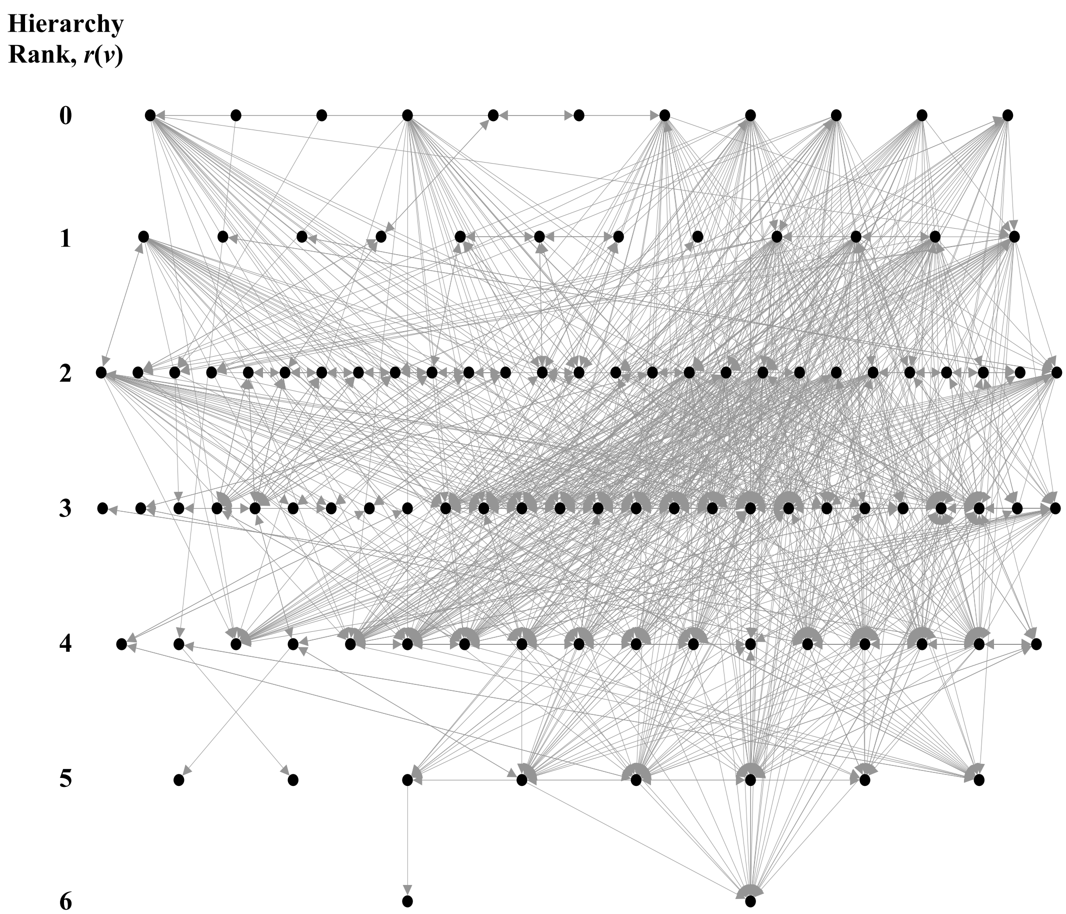


Figure 4.5: Example hierarchy of ship compartments.

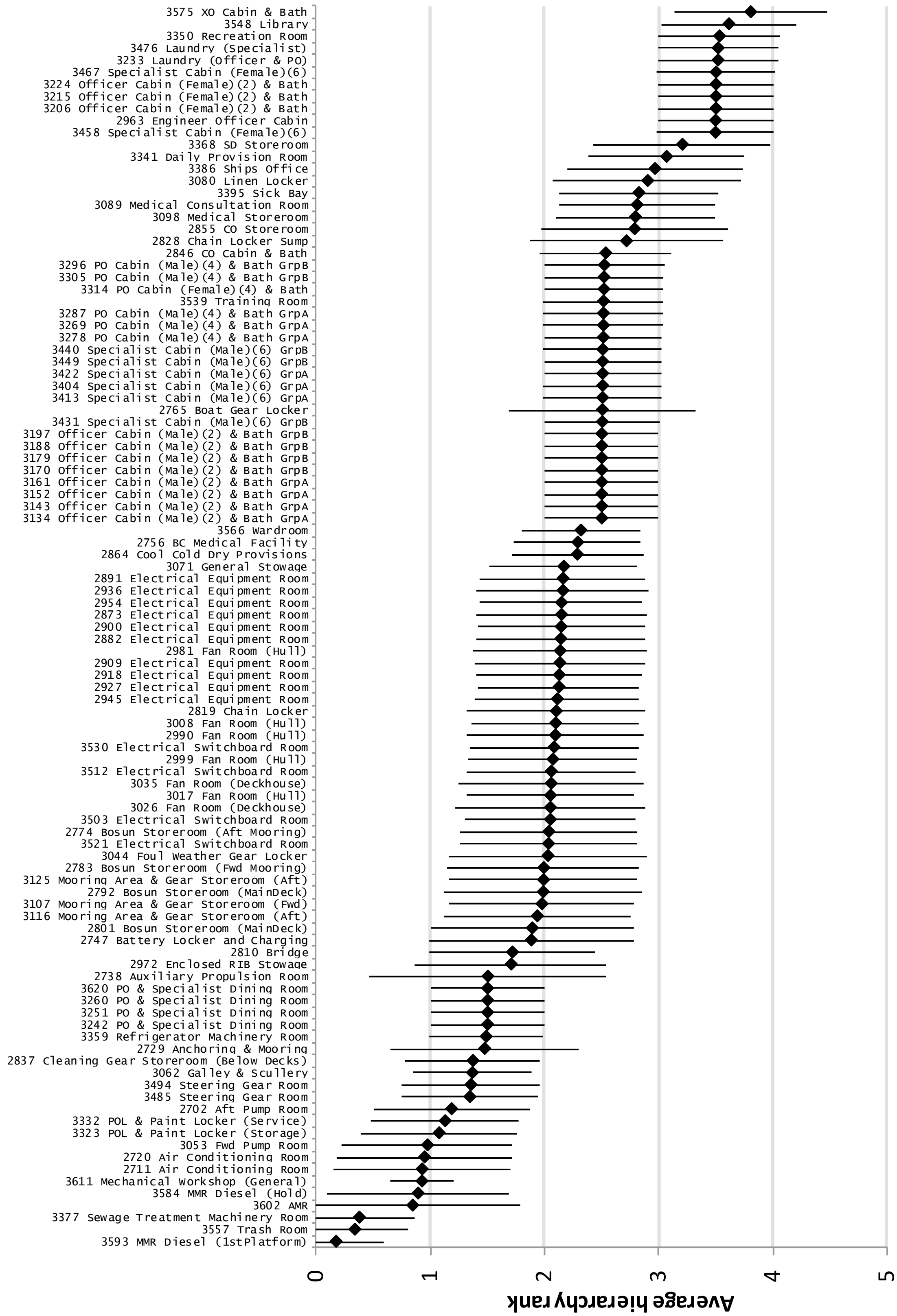


Figure 4.6: Ranking of drivers via hierarchy.

The second ranking was generated from only the best 11% of the 1,488 designs, as quantified using ISA's fitness function. In addition to providing the list of drivers, Figure 4.7 highlights the transition from heavy equipment/hazardous materials and food service as the primary drivers to compartments supporting ship operations, and finally the "sensitive" cabin and medical spaces. (The full ranking of compartments is listed in Appendix D.) This method has clearly revealed the intent of a Cold War designer and his guidelines, from which this set of design rules and constraints is derived. The primary importance was fighting the fight, keeping the crew fed, supporting the ship, and finally, supporting the crew. This is a powerful manifestation of how the set of constraints that are fed into a design tool's evaluation mechanism can direct the character of the generated layouts.

There is a great disparity in the quality of designs used to generate the rankings in Figures 4.6 and 4.7. However, the rankings are quite similar. The two rankings agree on 9 of the top 10 items, 23 of the top 25, and 46 of the top 50, for roughly 90% agreement. This is surprising because it suggests that the quality of the allocation, and hence the configuration of the compartments to zones (whether terrible or desirable), has little impact on the ability to expose the set of verified drivers and design intent. The edges of the pre-layout network seem to be driving the hierarchy, which would be consistent with the stance that a connected pre-layout network (without an arrangement) can illuminate the drivers. The unexpected agreement also suggests that adding a subset of randomly-assigned "spatial" edges to join the network's components may be sufficient for generating an accurate hierarchy of drivers without actually creating a physical arrangement. The next section tests this concept.

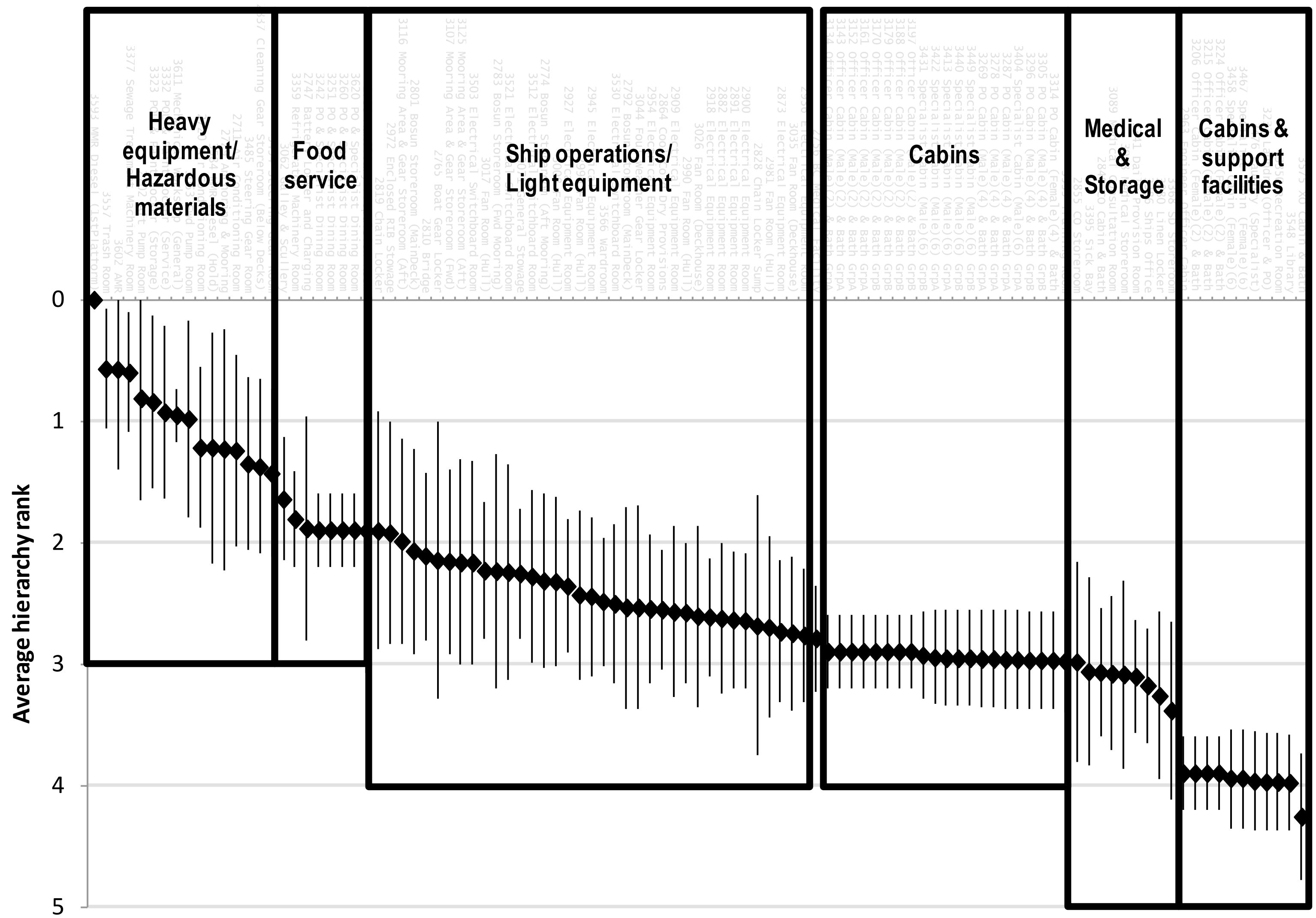


Figure 4.7: Ranking of drivers via hierarchy using only quality designs. Compartment categorization is highlighted.

4.7 Drivers by hierarchy (pre-layout)

One of the benefits of using degree centrality is the ability to identify arrangement drivers before creating spatial arrangements. When a pre-layout relationship network has only one network component (i.e., all spaces are linked to all other spaces through a series of design relationships), a hierarchy of drivers can be created prior to generating layouts because all nodes will be ranked on the same scale. Often, however, there are subsets of compartments that interact only with other compartments in that subset. This situation creates multiple network components. For instance, the Habitability Ship pre-layout network (Figure 3.5, page 55) has 15 network components. Electrical equipment rooms, for example, have only separation relationships with other electrical equipment rooms to encourage their distribution throughout the ship. A similar rule applies to fan rooms. There are also compartments having zero relationships to other compartments (e.g., the foul weather gear locker and several storerooms). Hierarchies and rankings for different network components are not comparable; thus, a network with a single network component is desirable.

In this section, random edges are added to the Habitability Ship pre-layout network to connect the 15 network components into a single network component to determine whether accurate hierarchy rankings can be obtained without assigning spaces to ship zones. Insertion of reciprocal edges between randomly selected nodes simulates the addition of "spatial" edges from an allocation (Section 3.5.1.2, page 55). ISA is not used for this pre-layout analysis. When ISA is mentioned, it is for comparison only, and the designs are the same as those generated for the post-layout analysis of Section 4.5.

The proposed method moves one step further away from identifying arrangements drivers through the time-intensive process of drawing general arrangements followed by qualitative analysis to a more rigorous method based on the fundamental underlying relationships. This concept is summarized in Figure 4.8, where the heavy line represents the current process for identifying drivers, the light solid line depicts the analysis processes described in the preceding sections, and the dashed line characterizes the new process tested in this section.

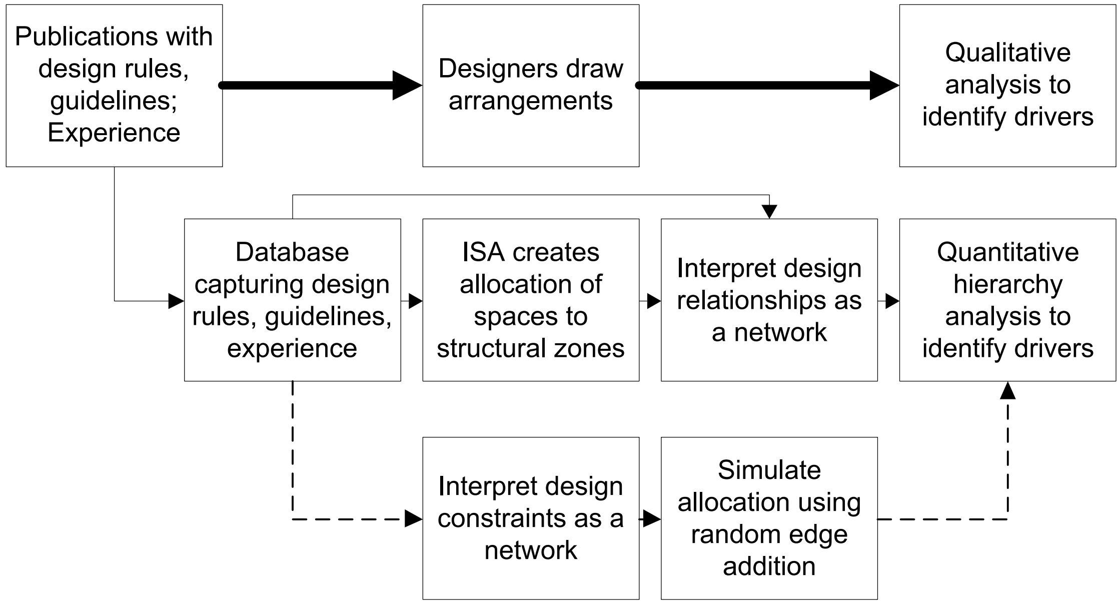


Figure 4.8: Existing and proposed processes for identifying arrangement drivers.

4.7.1 Method

The identification of drivers in the pre-layout stage will be described in three sections. First, an appropriate number of random edges to add to the pre-layout network must be determined (Section 4.7.1.1). Second, since the number of "spatial" relationships depends on the allocation of compartments to ship zones, the number of random edges will be varied to simulate a variety of potential compartment configurations (Section 4.7.1.2). Finally, Section 4.7.1.3 describes the methods and metrics used to compare the ranking of drivers identified from post-layout networks (derived from actual ship arrangements) to those from pre-layout networks (generated by simulating arrangements via random edge insertion).

This pre-layout hierarchy method will be deemed capable of identifying the drivers of a ship arrangement if it creates a continuum of drivers that matches the continuum derived from actual, balanced ship arrangements in the preceding section (Section 4.6).

4.7.1.1 Determining the number of random "spatial" edges to add

When simulating an arrangement using randomly added edges, one must choose how many edges to add. An appropriate number provides enough connections to create the necessary single network component and yet reflects the character of the "spatial" edges added in an actual arrangement. Prior to creating an arrangement, the number of edges that will model spatial constraints among spaces allocated to the same structural zone is unknown. In the networks described in Section 4.5, 408 to 578 spatial edges were added to the pre-layout network's edges after generating full layouts. It is important to remember that without completed arrangements, the appropriate number of edges to add remains unknown.

The first task, then, is to identify the appropriate number of random edges *E* to add to a pre-layout relationship network. Two methods are described. The first method estimates the expected number of spatial relationships in an actual arrangement given a uniform distribution of spaces to structural zones. The second tests how many randomly placed edges are necessary to connect all nodes into a single network component.

The first estimator is based on the notion that randomly placed edges can simulate an actual arrangement. Although real allocations are certainly not random, the results of the previous section suggest accurate rankings may still be possible due to the apparent strength of the underlying pre-layout network. Equation 8 is used to estimate the number of edges that can be expected in a uniform distribution (by count) of spaces to zones:

$$c = \text{Round}\left(\frac{s}{w}\right)$$

$$e = c(c-1)w \qquad \textbf{8}$$

where *s* is the number of spaces to be arranged, *w* is the number of available structural zones, and *e* is the number of directed "spatial" relationships (edges) one would expect to find in an actual arrangement. The term $c(c–1)$ in Equation 8 is the number of edges in a complete directed network. Rounding *c* up will overestimate the number of edges, while rounding down will underestimate.

Using the 103 spaces and 22 structural zones from the Habitability Ship, *e* ranges from 264~440, depending on whether *c* is rounded down or up. In contrast, the top 10% (by fitness value) of the 1,488 ISA designs generated averaged 503 spatial edges (Figure 4.9). ISA's attempt to use the deck area of each zone efficiently causes the distribution of spaces to zones to be non-uniform. The uniform distribution underestimates the actual number of edges of the high-quality allocations by at least 15% making it a seemingly poor estimator. For other ship types with different compartments, compartment area requirements, and zone capacities, the accuracy of this estimator may vary.

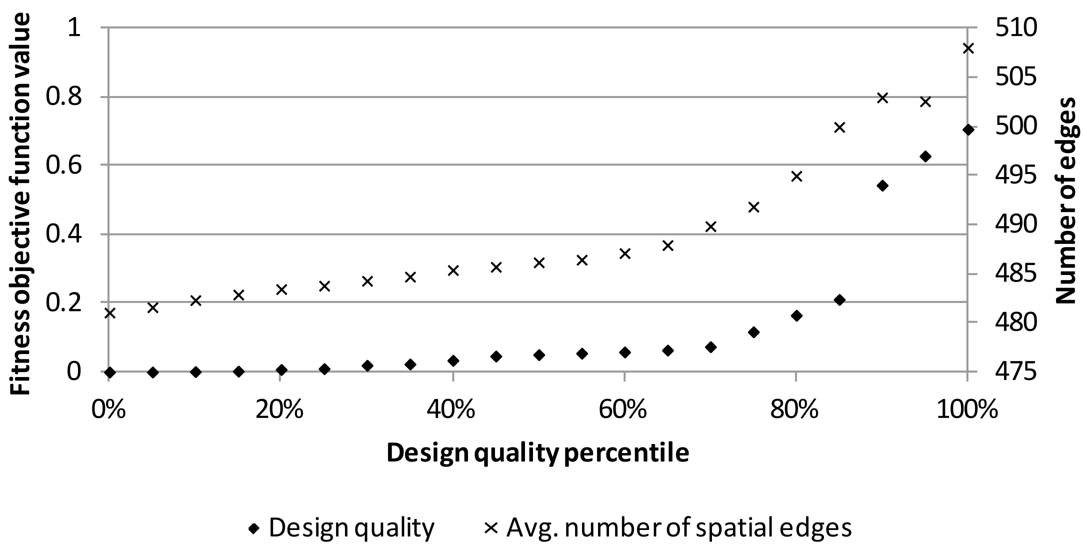


Figure 4.9: Design quality of ISA allocations and average number of spatial edges.

The second estimator is based on the belief that a hierarchy of arrangement drivers can be identified before creating any spatial arrangements when the pre-layout network has only one network component (Section 4.7). Therefore, a minimal number of edges should be added to create this connected network. This method identifies the appropriate number of edges by investigating how many random edges must be added to the pre-layout network to connect all nodes into a single network component. A range of values of was tested by adding *E* randomly-assigned edges to 100 pre-layout networks. Figure 4.10 shows the number of networks (out of 100) containing a single network component for a given number of random edges. Values close to zero are desirable because they indicate that the random edges consistently connected all subsets of nodes in the pre-layout network. For the Habitability Ship pre-layout network, a minimum of about 400~500 random edges are needed to connect all nodes into a single network component on a (roughly) consistent basis.

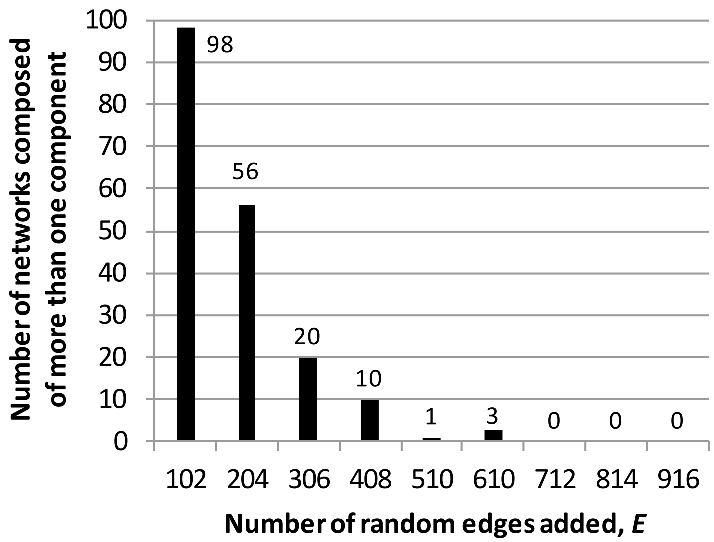


Figure 4.10: The number of random edges added and the number of networks with more than one component. One hundred networks were created for each value of *E*.

The number of edges suggested by the second approach (400~500) is more consistent with the actual number of spatial edges (408~578, above) and the average number of spatial edges in the top designs (503, Figure 4.9). For this reason, the second approach will be used in the subsequent comparison.

4.7.1.2 Evaluating an assortment of compartment configurations

Different layout configurations result in various numbers of spatial edges within structural zones. In this section, several combinations of random edge set sizes *E* are generated to simulate a collection of layout alternatives. Figure 4.10 shows that as few as about 100 randomly placed edges are capable of connecting the pre-layout network's components, albeit infrequently. Although 100 edges are far fewer than found in the actual ISA-generated allocations, a set of edges of that size is included in the trials below. Eleven combinations of the number of spatial edges *E* were used to simulate an assortment of potential allocations (Table 4.2). For each value of E, $k = 100$ independent networks were generated by adding randomly placed edges to the pre-layout network. Insertion of edges between any pair of nodes is completely random; node degree distributions are not specifically preserved under the supposition that any two compartments can be allocated to a zone regardless of the number of relationships each has to other compartments.

Table 4.2: Test matrix for the number of random edges added in each combination.

Combination	Number of random edges added E
A	102, 204
B	204, 306
C	306, 408
D	408, 510
E	104, 204, 306
F	104, 204, 306, 408
G	204, 306, 408
H	204, 306, 408, 510
I	408, 510, 610
J	712, 814, 916
K	104, 204, 306, 408, 510, 610, 712, 814, 916

Two types of rankings are used to identify the order of drivers. The first is the *r_1-ranking*. The r_1-ranking assigns a numerical rank $[1,n]$ to each node based on its hierarchy rank (from Equation 7) averaged across the k networks with E random edges. Spaces are sorted in ascending order in the r_1-ranking. The second is the *r_2-ranking*, which is used to combine r_1-rankings within a combination (Table 4.2). The r_2-ranking assigns a similar numerical rank to spaces according to some sorting policy, such as ascending minimum r_1-rank or ascending median r_1-rank.

The ranking process (summarized in Figure 4.11) begins with a pre-layout network composed of compartments (nodes) and design relationships (edges). Then:

Step 1. Add *E* random edges to the pre-layout network. Repeat this *k* times to create *k* networks containing *m* design constraint edges plus *E* random pseudo-allocation edges.

Step 2. Evaluate the hierarchy rank of each space for each of the *k* networks using the method described in Section 4.3.2 (page 64).

Step 3. Calculate the average hierarchy rank for each space across all *k* networks. Assign each space a rank r_1 according to its average hierarchy rank.

Step 4. Repeat Steps 1-3 for each value of *E* in a given combination (Table 4.2).

Step 5. Calculate the minimum and median r_1 rank for each space *type* using all r_1 ranks for spaces of that type.

Step 6. Assign each space a rank r_2 according to a sorting policy.

For example, in Combination A, k = 100 networks are created with E = 102 random edges and an additional 100 networks are created with 204 random edges (Step 1). Steps 2-4 result in two r_1-rankings: one for the E = 102 networks and one for the E = 204 networks. Finally, the r_2-ranking is developed from these two r_1-rankings according to the sorting policy.

4.7.1.3 Comparison methods and metrics

During the earliest stages of design, it may be unknown how many compartments of a given type will be included in the arrangement. Will there be six or seven Electrical Equipment Rooms? Are three, four, or five Fan Rooms required to achieve a desired level of performance? In addition, a designer would be interested in knowing the space *types* that influence a design rather than a specific instance of a space type, which is interchangeable with any other instance of that type. Thus, individual spaces are grouped by type for all ranking comparisons that follow. The 103 compartments have been distilled into 63 distinct space types.

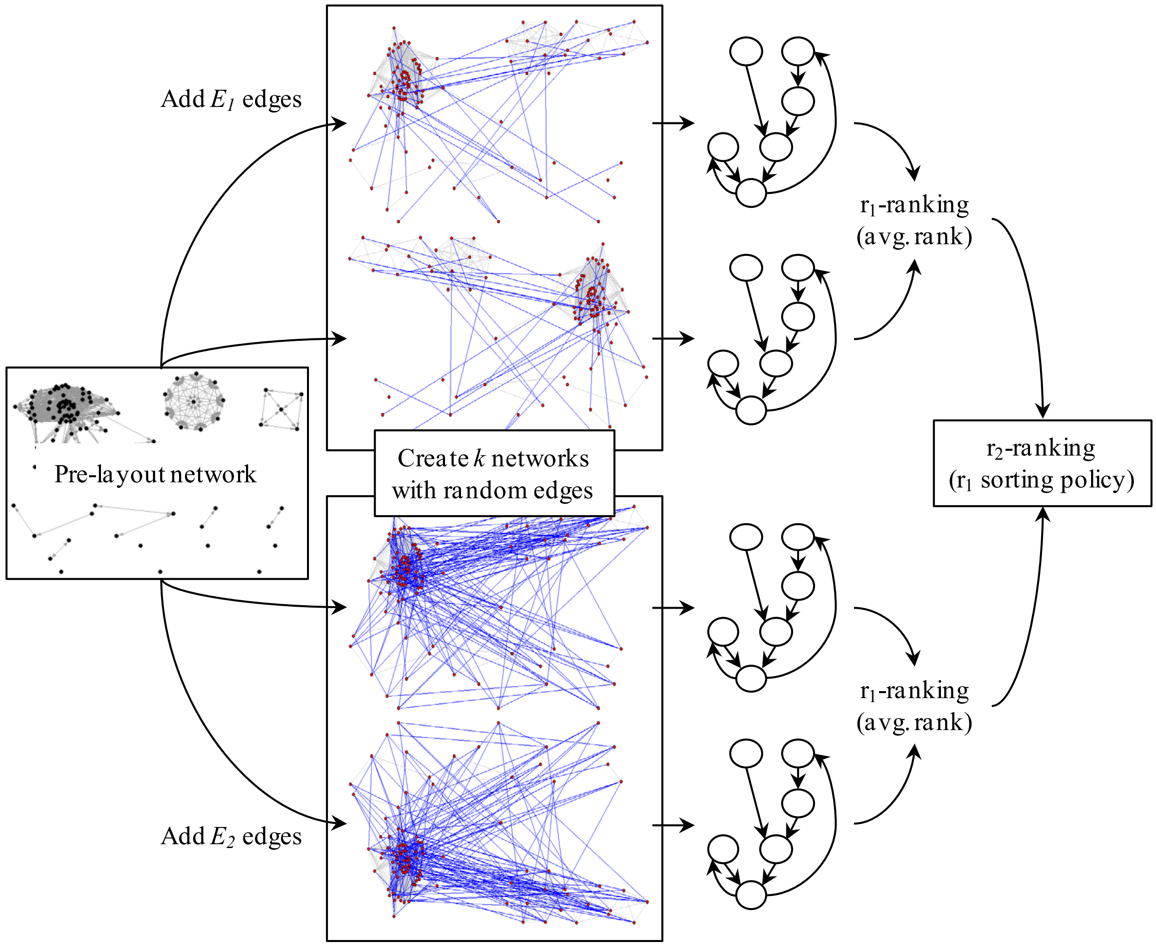


Figure 4.11: The r_2-ranking process.

Several methods and metrics were investigated for comparing an r_2-ranking from networks containing randomly added spatial edges with a baseline ranking of influential space types from the allocation of spaces to structural zones using ISA (termed *baseline* or *ISA ranking*). Baseline rankings were derived from the best arrangements (top ~11% by fitness value) generated by ISA in Section 4.5. The comparison was conducted to provide guidance for developing accurate r_2-rankings. In a true design scenario, designers typically would not have a baseline ranking available as a reference.

Four methods were used to compare r_2-rankings to the baseline ranking. The methods specify whether the sorting policy for the r_2-ranking is based on the minimum or the median r_1-rank of all instances of that space type. For example, the *min,median* method compares the ISA ranking based on the minimum rank of all instances of a given space type with an r_2-ranking based on the median r_1-rank of all instances of that space type. The four methods are min,min; min,median; median,min; and median,median.

Two metrics were used to quantify how closely each r_2-ranking matches the baseline ranking: the average number of correctly ranked compartments in the top 10, top 25, and top 50 ranks; and the *rank difference*. The rank difference assesses how closely two rankings match without imposing any artificial boundaries. The rank difference was calculated using Equation 9.

$$rank\ difference = \sum_{spaces} \left| \text{rank}_{space,r_2-ranking} - \text{rank}_{space,baseline} \right| \qquad 9$$

Each of these metrics can only be used as a comparison tool *after* a set of designs has been created since designers will not have the reference baseline ranking. Consequently, it is important to identify the appropriate number of random spatial edges *E* to add to the pre-layout network and the best sorting policy for an r_2-ranking.

4.7.1.4 Assumptions & Limitations

Both the baseline and the r_2-rankings assume a uniform level of influence. A modified version of the hierarchy ranking equation (Equation 7, page 65) that accounts for the strength of a relationship or the importance of a compartment could create a list of drivers that is based on relative levels of influence. The effect of a uniform level of influence can be seen in Figure 4.15 where the Cleaning Gear Storeroom is likely overestimated at rank 15 in the baseline and rank 12 in the r_2-ranking; Daniels et al. (2010) describe this compartment as a "filler" because of its low importance and small required area.

4.7.2 Results

4.7.2.1 Accuracy of compartment types ranked in the top 10, top 25, and top 50

Nine of the top ten space types in the baseline were identified correctly for all combinations in Table 4.2. The Galley & Scullery, Steering Gear Room, and Bridge tended to be overestimated in their rank by three to five places, incorrectly situating them in the top 10. In a comparison against the baseline top 25, combinations were again relatively indistinguishable. In most combinations, between 19 and 21 space types were correctly identified; two combinations achieved 22 matches and one matched 23. Overestimated space types often included the Bosun Storeroom, Electrical Switchboard Room, Electrical Equipment Room, Fan Room, Foul Weather Gear Locker, or Mooring Area & Gear Storeroom. Combinations A, B, and F scored highest with an average of 21.0 correct matches. Finally, 48 to 50 space types were correctly matched to the baseline top 50 for all combinations. Combinations F and G led in this category. Figure 4.12 shows the average number of space types correctly matched. According to this metric, the most accurate combinations included additions of 102 to 408 random edges.

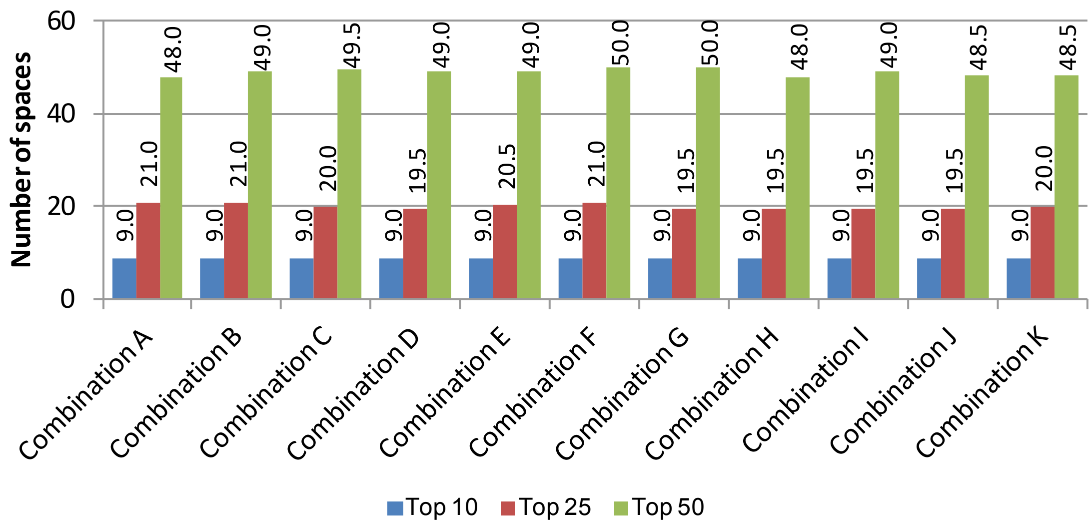


Figure 4.12: Average number of spaces correctly matched with various quantities of random edges added. Averages are across the four comparison methods.

4.7.2.2 Rank difference

Rank difference provided greater differentiation for determining an appropriate number of random edges to add. Combinations that included a moderate number of edges tended to perform best, that is, Combinations C, F, and B (Figure 4.13). These combinations correspond to the region in Figure 4.10 in which adding edges continued to connect isolated nodes; above approximately 400~500 edges, extra edges met diminishing returns. Combination A appears to insufficiently connect the nodes, while Combinations D, H, I, J, and K seem to reach saturation.

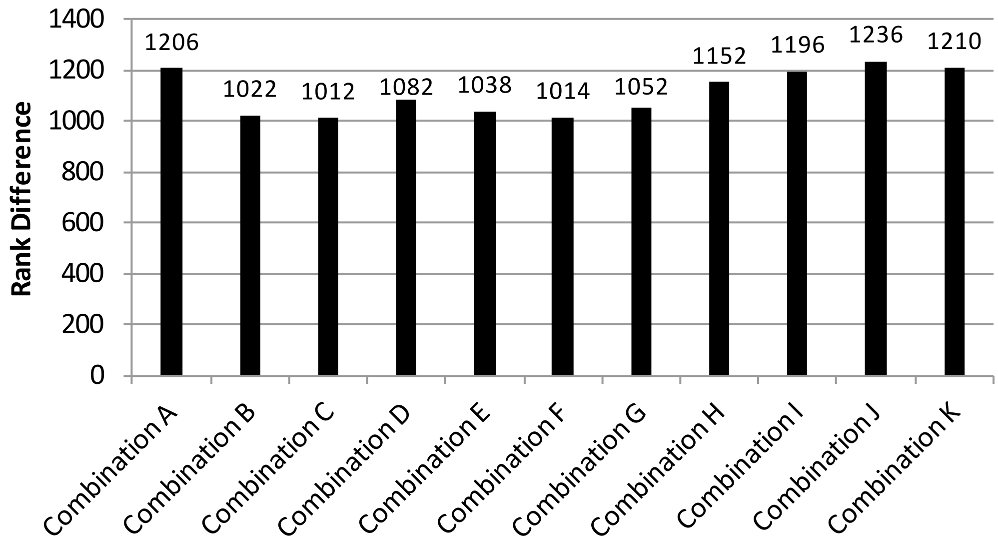


Figure 4.13: Rank difference for various quantities of random edges added.

The saturation theory is supported by Figure 4.14, which shows the hierarchy flattening with increasing numbers of random edges. This led to poor rankings that increased the rank difference. Recall the pre-layout network contains 1,017 edges (Section 3.5.1.1, page 54). Some networks in each of these five combinations (D, H, I, J, and K) contain up to one-third to one-half random edges when $E \geq 510$. For example, in the $E = 102$ networks, 798 (7.75%) of the nodes are ranked in the sixth level of the hierarchy (hierarchy rank 5). On the other hand, networks with $E \geq 510$ have exactly one node collectively at the fifth level of the hierarchy (hierarchy rank 4). These results are consistent with Gupte et al.'s (2011) findings that hierarchy in random graphs decreases with increasing network density.

In Figure 4.15, the ranges of r_1-ranks for each space type in Combination F are plotted along with the space type's baseline ranking. Space types are sorted left-to-right by ascending median r_1-rank. Table 4.3 lists the top ten drivers based on actual layouts (from Figure 4.7) and random pseudo-allocation layouts (from Figure 4.15) for comparison.

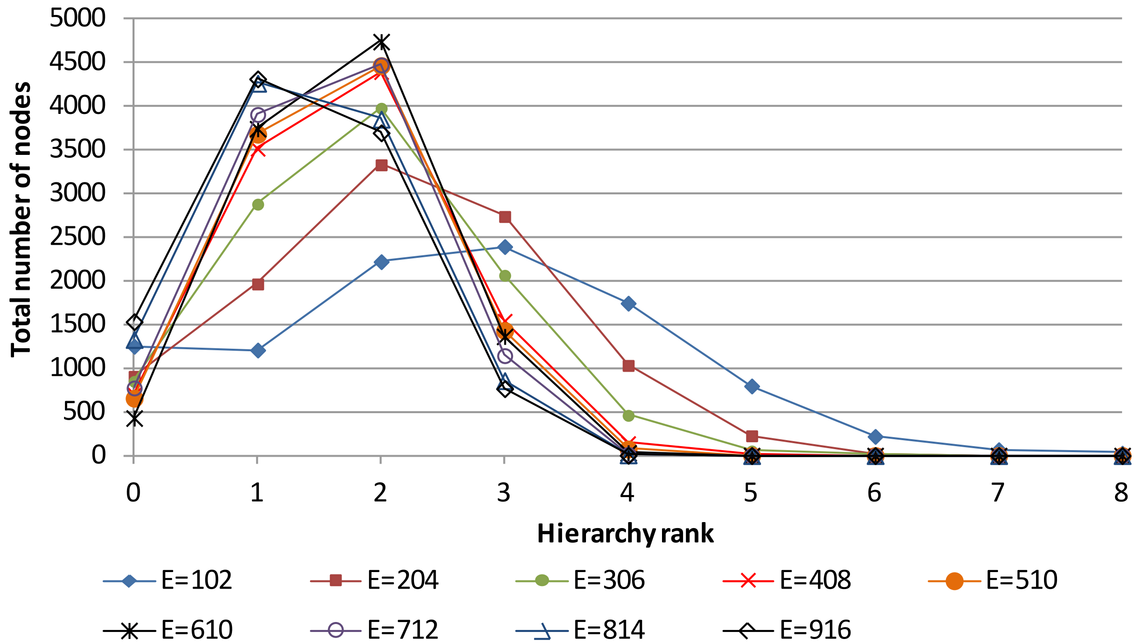


Figure 4.14: Flattening of the hierarchy with additional random edges.

Table 4.3: Comparison of top 10 drivers (min,median sorting policy).

Rank	Drivers via allocation (Figure 4.7)	Rank	Drivers via random edge addition (Figure 4.15)
1	Main Machinery Room (1st Platform)	1	Trash Room
2	Trash Room	2	Sewage Treatment Machinery Room
3	Auxiliary Machinery Room	3	Aft Pump Room
4	Sewage Treatment Machinery Room	3	Fwd Pump Room
5	Aft Pump Room	5	Main Machinery Room (Hold)
6	POL & Paint Locker (Storage)	5	POL & Paint Locker (Storage)
7	POL & Paint Locker (Service)	5	POL & Paint Locker (Service)
8	Mechanical Workshop (General)	8	Mechanical Workshop (General)
9	Fwd Pump Room	8	Main Machinery Room (1st Platform)
10	Air Conditioning Room	10	Galley & Scullery
10	Main Machinery Room (Hold)	10	Bridge

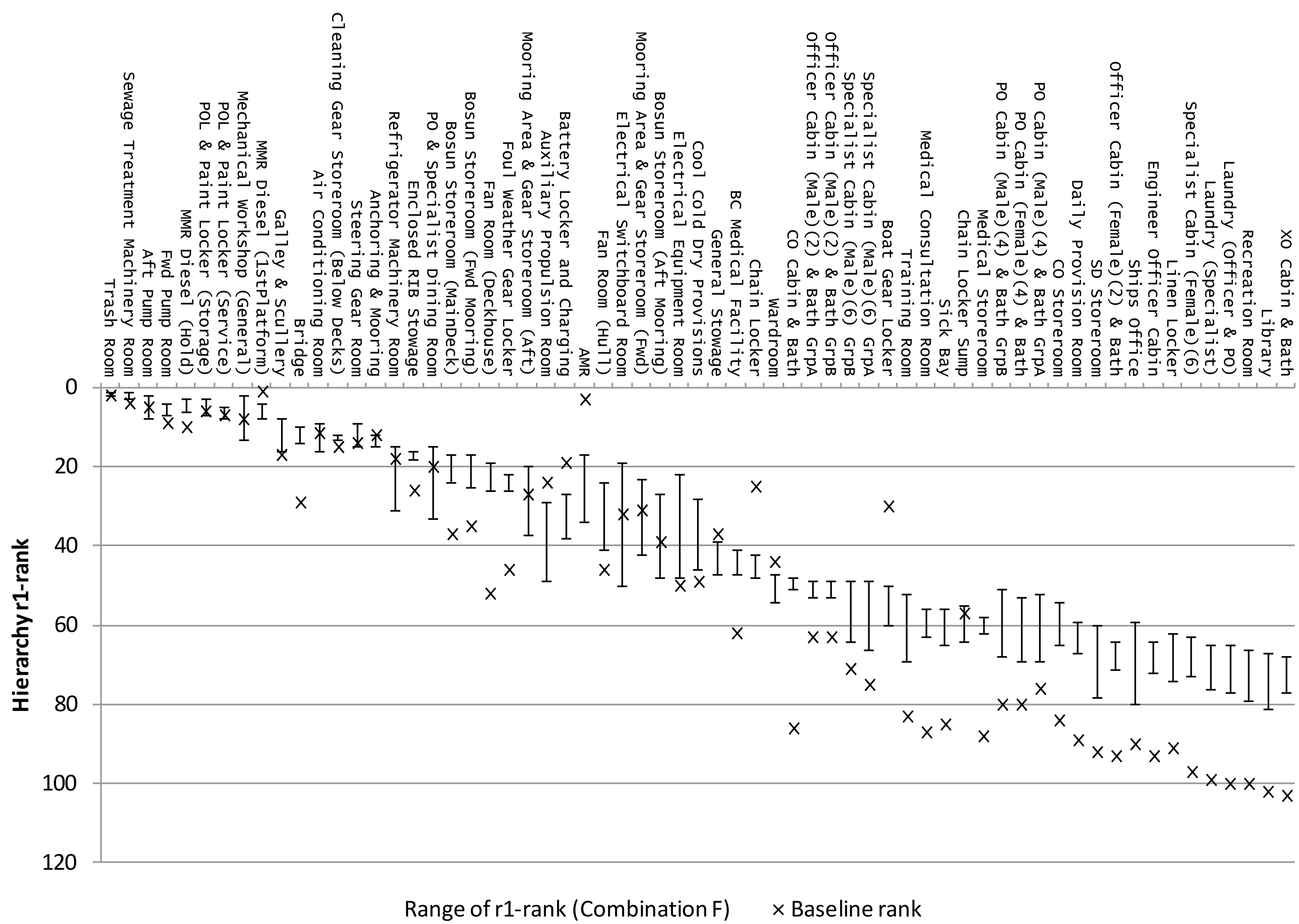


Figure 4.15: The range of r1-rankings for each space type in Combination F and the baseline hierarchy rank. Space types are sorted left-to-right by ascending median r1-rank.

4.7.2.3 Accuracy of comparison methods

The most accurate combinations (B, C, E, F, and G), as determined by rank difference, were used to evaluate the comparison methods. In all cases, the median-based r_2-ranking matched or exceeded the accuracy of the minimum-based r_2-ranking, when compared against the baseline. The min,median comparison yielded the closest match between the ISA-derived baseline ranking and the random pseudo-allocation ranking. Figure 4.16 shows the number of top 25 drivers from the baseline ranking that was correctly identified by each r_2-ranking; the order of the top 25 drivers is not considered in this comparison.

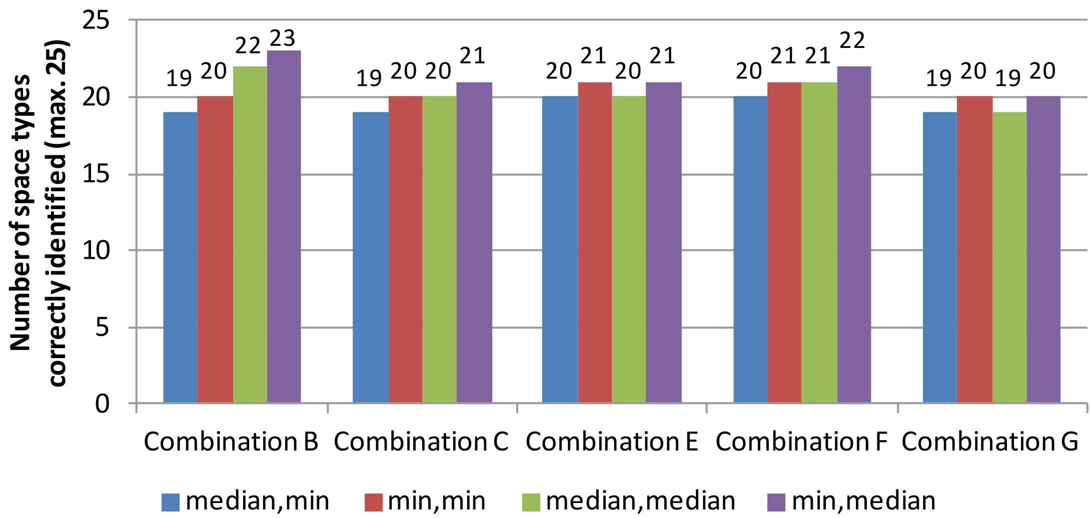


Figure 4.16: Comparison method performance for the most accurate combinations.

4.7.3 Analysis recommendation

When a pre-layout network has only one network component (i.e., all nodes are connected to all other nodes), a hierarchy of drivers can be created without adding any random edges. The addition of random edges to a connected network (a "saturated" network) will cause the hierarchy to flatten, and the rankings may change.

If the pre-layout network contains more than one component, it is recommended that the minimum number of random edges required to connect all nodes be used. This facilitates analysis of the drivers as a complete set without masking the underlying, fundamental relationship hierarchy. (For the Habitability Ship, this number also roughly coincided with the number of edges estimated under Section 4.7.1.1's assumption of a uniform distribution of compartments to zones.) Next, creating r_2-rankings using a sorting policy based on the space type's median r_1-rank is recommended for identifying the most realistic driver ranking, given the results shown here. An r_2-ranking based on minimum r_1-ranks also performed reasonably well and could be useful in certain situations for identifying compartment types that are on the borderline of becoming major arrangement drivers. Finally, the sensitivity of this method to the density of the underlying pre-layout network has not been investigated due to the absence of pre-layout networks for multiple ship types.

4.8 Summary

In this chapter, three methods based in network science were presented for identifying compartments and equipment likely to drive or constrain a ship arrangement, as dictated by the set of constraints entered into an automated arrangements tool. Two of the three methods were based on notions of centrality, and the third was rooted in the network's hierarchy. Each method provided consistent results from a slightly different perspective.

It was demonstrated that two of the methods could identify drivers of general arrangements prior to creating physical layouts while using only rudimentary information, namely pairwise separation and adjacency relationships. The importance of these findings is that designers now have a framework for analyzing the entire set of inter-compartment relationships, including secondary and tertiary influences, to highlight drivers.

Further study and comparison is warranted for other complex ship types, including different classes of military vessels, cruise ships, or offshore facilities. Additional investigations have been prohibited by the availability of data and the time investment required to generate the relationship networks.

Chapter 5
Identifying communities of mutually-compatible elements

5.1 A note on the use of Intelligent Ship Arrangements

Chapter 4 demonstrated the usefulness of network science to reveal the thought processes (design intent) embedded within a set of ship design relationships. The Intelligent Ship Arrangements (ISA) platform was relied upon to generate compartment allocations from which the layout drivers could be identified (in post-layout cases) and validated (in all cases). Moving forward, ISA will not be used for generating allocations. Only ISA's constraint database, from which the Habitability Ship network is derived, will continue to be used. All designs created in this and future chapters are constructed using existing network-based concepts and new methods developed by the author. (A single exception is provided in Chapter 7 as a counter example to contrast differences in a network-based design and an ISA-generated design.) In addition, all subsequent references to the Habitability Ship network will refer to the pre-layout Habitability Ship network, which is derived from the constraint database and is not reliant upon ISA or pre-existing layouts.

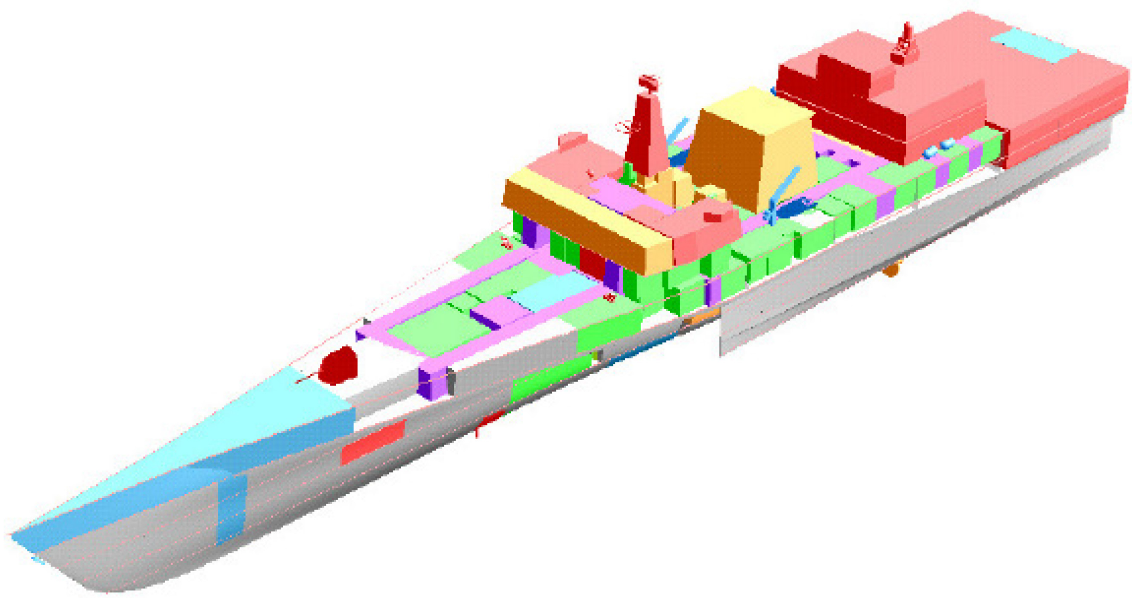
5.2 Introduction

This chapter presents a network-based partitioning approach for identifying groups of mutually-compatible ship elements (compartments, components, systems) such that they can be located in the same structural zone without degrading other items in the zone. These groups could be used as inputs into existing design considerations or as the sole basis for functional zone definitions. If components and systems were included in the network, this approach could also be used to relate equipment to compartments. The results presented in this chapter are included in (Gillespie et al. 2011).

The ship arrangements problem is largely one of managing relationships among components and systems and the compartments that house them. Developing three-dimensional compartment and component layouts for complex ships is a challenging and time-consuming task partially because the layouts include hundreds or thousands of elements with interconnecting relationships. The goal of early-stage design studies is to create a design to “a sufficient level of detail to satisfy the designer that he or she has sufficiently addressed the levels of risk and uncertainty appropriate to this point in the overall design process” (Andrews and Pawling 2008). Decreasing the number of elements could reduce the overall complexity of the arrangements problem and make it more manageable for both designers and computer algorithms.

At the earliest stages of a design, entire sections of a ship may be reserved at a very low level of fidelity and designated only by their intended function. Many systems have not yet been defined. UCL’s Design Building Block approach and TUD’s packing approach (Sections 2.3.1 and 2.3.2) exploit this reality. By aggregating compartments and systems into functional “boxes” the number of objects to be positioned is reduced resulting in a smaller search space. The assumption is that the top-level boxes are correctly sized initially or have enough flexibility to accommodate changes once a higher level of fidelity is desired. These approaches require the designer define a set of boxes or spatial objects representing (implicitly or explicitly) the volume to be occupied by a single compartment or system or a set of compartments and systems. These boxes can still be quite large during the earliest stages of design, and having a good understanding of the contents of each box is important because it influences the properties of the box (size, weight distribution, relationship to other boxes, etc.) and the ship as a whole.

Clustering approaches can be useful for estimating the number, type, and size of boxes. Wagner et al. (2010) and Wagner (2009) used manual clustering to reduce the overall complexity and time required to position objects. Their approach was rooted in experience and domain knowledge and based on functional breakdowns and process diagrams of a deepwater drill ship. The difficulty of using this approach for novel ship types is that system definitions may not be finalized or are subject to design changes. Multiple layers of constraints may also create secondary and tertiary effects that are not immediately discernible. As mentioned previously, managing the entire set of relationships manually can be overwhelming. Compartments for infrastructure and components of distributed systems may not need to be relegated to their own sections of the ship (Andrews 2003) as in Figure 2.4, but rather can be included within boxes possessing specific dedicated functions if it makes sense overall.



Reprint of Figure 2.4 (lower right): Example building block layout of a trimaran case study design.

5.3 Communities among shipboard elements

Many communities exist within a complex ship like a naval vessel. Communities may be related by mission function, proximity or access requirements, or required or provided services. Portions of the ship are dedicated to ship operations, mission operations, command and control, living quarters, medical facilities, fuel & oil tanks, and stores. From a Hull, Mechanical, and Electrical (HM&E) point of view, communities are composed of related components and subsystems of individual or complementary systems. These are the basis for the Design Building Blocks (Section 2.3.1, page 21). Different sizes of Design Building Blocks essentially represent views of communities of elements at different scales.

Communities often overlap and exist on multiple scales. For example, habitability spaces can be subdivided into communities for officers and crew, berthing and food service, or work and recreation. Many of these communities exist regardless of the physical layout of the constituent elements indicating networks may be able to provide insight prior to detail design phases. Understanding the ship's natural decomposition into communities can provide arrangement guidance earlier in the design cycle by enabling informed arrangements at a lower level of fidelity (community level rather than compartment or component levels) than is currently possible.

Regardless of the design tool or method, rational design prescribes placing the galley, dry and cold stores, and mess halls in the same structural zone to benefit from their co-location through minimized personnel movement and material handling. With thousands of adjacency and separation constraints among spaces and equipment, it would be helpful to have a method that identifies groups of items that can be located in the same structural zone without degrading other items in the zone. The aforementioned spaces should be able to be grouped together *based on their relationships* to one another, but without any knowledge that they relate to food preparation and consumption. These relationships relate to a need for shared resources, reduced materiel movement, or proximity. In a similar way, elements of distributed systems could be spread throughout the ship by specifying mutual separation relationships among them.

At the outset of a new design cycle, little design information is available. The analyses in this chapter build upon that limited, but fundamental, information. For the analyses that follow, a designer must only supply the following three items, which compose the ship relationship network:

- A list of items to be included in the design (compartments, components, etc.)
- A set of design relationships describing the strength of a compatible or a incompatible relationship between pairs of items
- The number of structural zones (or other subdivisions of the ship) into which the network should be partitioned.

5.3.1 Notes about relationship strength

The selection of edge weights (relationship strength) is not a simple task. Moreover, the definition for the weights is neither right nor wrong – it simply reflects the designer's values and objective. Jayakumar and Reklaitis (1994) suggest six categories of costs that could be incorporated into the edge weights among chemical plant units, and they observe there are others. Certainly, for a given definition, the weights can be more accurate or less accurate. In this chapter, edge weights have been assigned so that relationships influencing important spaces are more strongly respected. They could have been defined to emphasize ship producibility, human factors, or any number of other topics of interest. In the simplest case, all relationships can be given a strength value equal to +1 or –1 according to the compatibility of the two elements. The community-finding methods are agnostic to the values input,[11] though the communities formed may change when different values are used. Naturally, the use of more sophisticated edge weighting schemes should improve solutions.

Defining edge weights based on the expected performance of subsystems given their final spatial configuration is a desirable formulation. It is also a daunting task.[12] The strengths of the relationships likely will not be known in preliminary design because the systems are not yet defined or because the strength of the relationship depends on the relative or absolute spatial location of the two elements. Edge weights based on this definition will be dynamic. Jayakumar and Reklaitis (1996) implement a simplified approach by defining three unit-cost matrices for downward, upward, and horizontal flows that are multiplied by expected (average) distances. The advantages of using static values, as done in this chapter and the next, are the ease of selection in preliminary design and the elimination of complicated or time-intensive interaction calculations. In addition, the challenges of determining the costs of mission-based efficiencies or combining various performance scales can be mitigated by using values not based on cost or performance.

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[11] Community detection methods exist for a variety of number types (e.g., +1/–1, positive numbers, or integers). The type of numbers used as edge weights must still match the assumptions of the formulation.

[12] A few thoughts regarding how this might be achieved are given in Section 8.2.2 (page 154).

In the remainder of this chapter, each edge is given a weight proportional to the relative importance of the compartment influenced by the relationship as a proxy for the importance of the relationship strength. As an example, the Galley should be separated from the Trash Room. Therefore, the edge from the Trash Room to the Galley is given a weight proportional to the relative importance of the Galley. Relative importance values range from 1 to 20 and have been used throughout the development of ISA (Daniels et al. 2010).

5.4 Communities in networks

In real-world networks, edges tend to not be uniformly distributed among vertices; instead, high concentrations of edges are interspersed within a sparser matrix. Fortunato (2010) laments, however, there is no "theoretical framework that defines precisely what clustering algorithms are supposed to do." Thus, there is no universal quantitative definition for what constitutes a community in a network; the definition tends to depend on the system, context, and application that underlie the network.

Communities are typically identified using only the structure of the network itself while ignoring any characterizing attributes. Examples of communities include college football conferences (Girvan and Newman 2002; Yang et al. 2007), dormitory affiliations, and committees of the U.S. House of Representatives (Porter et al. 2009, and references therein). In the context of the ship relationship network, this means a community containing the food service compartments should be able to be identified based on its relationships alone and without any knowledge of the role the items.

A variety of formulations exists for identifying communities in networks containing edges that are weighted (Newman 2004), directed (Reichardt and Bornholdt 2006; Leicht and Newman 2008; Kim et al. 2010), and signed (Bansal et al. 2004; Yang et al. 2007; Doreian and Mrvar 2009; Gómez et al. 2009; Traag and Bruggeman 2009) networks. Optimizing clusters of nodes tends to be an NP-hard problem (Bansal et al. 2004), so many algorithms are based on heuristics. Fortunato (2010) provides a comprehensive review of community-related definitions, formulations, and algorithms. The following discussion is limited to signed, directed networks, which are of interest here due to the inherent ability to model adjacency and separation relationships.

5.4.1 Communities in signed networks

The basis for identifying clusters in signed networks is conceptually different from networks with only positive (or no) edge weights. Rather than defining communities as highly dense groups of edges with fewer edges between groups, signed network clustering algorithms attempt to partition the network in such a way that there are high concentrations of positive edges within groups and a high concentration of negative edges between groups (Yang and Liu 2007; Gómez et al. 2009).

In signed networks, there exists a theory of *structural balance* proved by Harary (1953) that is stated as:

> *A balanced network can be divided into connected groups of vertices such that all connections between members of the same group are positive and all connections between members of different groups are negative.*

A signed network is *clusterable* if it can be divided into k partitions as described. Thus, balanced networks are a subset of clusterable networks where $k = 2$. An algorithm for dividing such a network into two partitions is simple, though an explanation is left to Newman (2010).

5.4.1.1 Relevance to ship layouts

As noted in Table 3.1 (page 48), positively and negatively weighted edges can correspond to elements that should be adjacent to or separated from one another (Jayakumar and Reklaitis 1994; Pesch et al. 1999). Communities in a signed network could be used as a starting point for compartment-equipment pairings or the formation of functional complexes (food preparation, office space, medical ward, etc.). If a ship relationship network were clusterable, all spaces, systems, and components could be placed into structural zones so that no detrimental interactions occurred. Not surprisingly, ship relationship networks are messy and, like many real-world networks, are not likely balanced or perfectly clusterable. When a network is not clusterable (but possibly nearly so), additional community-formation methods are required.

5.5 Identifying communities in networks

Communities in networks can be identified by two broad classes of algorithms: those that specify a priori the number of (or size of) groups and those that do not. In the network science community, the first is referred to as *partitioning* while the latter is known as *community detection* (Newman 2010). Communities may also be known as partitions or clusters; the difference in terminology often signifies the type of algorithm used to identify them. *Graph partitioning* is a process in which nodes are separated into groups of predetermined number (or size) in an attempt to minimize the number of or total weight of edges lying between groups. For allocating compartments to the structural zones of a ship, the partitioning method is more appropriate due to the fixed number of structural zones of a given hull and structural configuration. *Community detection*, often referred to as *clustering*, is the process of identifying "naturally occurring" groups, or clusters, within a network. They are "naturally occurring" because no artificial constraints are placed on the number of (or size of) communities. Community detection methods are appropriate for gaining an understanding of how a set of shipboard items naturally clusters together when the number of groups is not restricted.

5.5.1 A facility layout application of graph partitioning

As mentioned in Section 3.4.1, Jayakumar and Reklaitis (1994) apply a graph partitioning approach for holistic, automated relationship management of a chemical plant. They divide processing units into groups representing regions of a facility separated by corridors. Their goal is to minimize the total cost (or flow magnitude) that crosses between regions. Their approach is amenable to both positive and negative edge weights, though it seems they only use positive edge weights in their study as the edge weights indicate the quantity or cost of material flow between two units. Negative edge weights would be used to separate units for safety or environmental reasons, for example.

Functionally, the method demonstrated in this chapter is similar to that of Jayakumar and Reklaitis. A notable difference between the two approaches is the rationale for the number of partitions. Jayakumar and Reklaitis specify the number of items to be included in each subset, while the approach used in this chapter specifies the number of subsets. Jayakumar and Reklaitis set the community sizes to be equal for a first approximation of a layout under the assumption that any solution would require subsequent adjustments to address concerns not incorporated into the edge weights. (It is not clear whether the locations of the corridors, and therefore the areas of the regions, are fixed.) For a fixed number of items, setting the sizes of partitions determines the number of partitions, though the opposite is not true.

Doreian and Mrvar (2009) argue that researchers generally should employ their familiarity with the system under investigation and specify the number of groups into which the network should be subdivided. In the compartment allocation problem, it is reasonable as a first approximation to specify the number of partitions if one intends to apply the resultant communities to a discrete number of fixed-size ship structural zones. Since neither method considers the area requirements of a subset as a feasibility criterion for a candidate partitioning, both options (fixed subset size or fixed number of subsets) will likely require post-processing. Therefore, a partitioning method that specifies the number of subsets is preferred. The partitioning algorithm used in this chapter is described in the next section.

5.5.2 Identifying communities in signed networks using partitioning

The goal of partitioning a signed network is to group nodes into a specified number of communities so that only positive relationships (or absent relationships) exist between each pair of nodes within each community and only negative relationships exist between communities (Figure 5.1). In many real-world networks, the nodes cannot be cleanly divided as desired. The goal then becomes to minimize the number of inconsistent edges. Doreian and Mrvar (2009) offer a simple and general objective function (Equation 10):

$$P(\boldsymbol{C}) = \alpha N + (1 - \alpha)P \qquad 10$$

where $\boldsymbol{C}$ is a vector of community assignments, N is the total number of negative edges within communities, P is the total number of positive edges between communities, and $0 \leq \alpha \leq 1$ is a weighting factor to adjust the relative penalty for positive and negative inconsistencies. Inputs to the algorithm include the weighted, signed network; the minimum partition size; the number of algorithm iterations; and the inconsistency weighting factor α.

Doreian and Mrvar's algorithm employs a local optimization technique to find the Pareto-optimal partitionings. Nodes are randomly assigned to partitions at the beginning of each iteration. The algorithm outputs a set of non-dominated partitions having equal (and minimum) $P(\boldsymbol{C})$. Since the algorithm is non-deterministic, the minimum may be a local minimum, and multiple runs may be needed to find a global minimum.

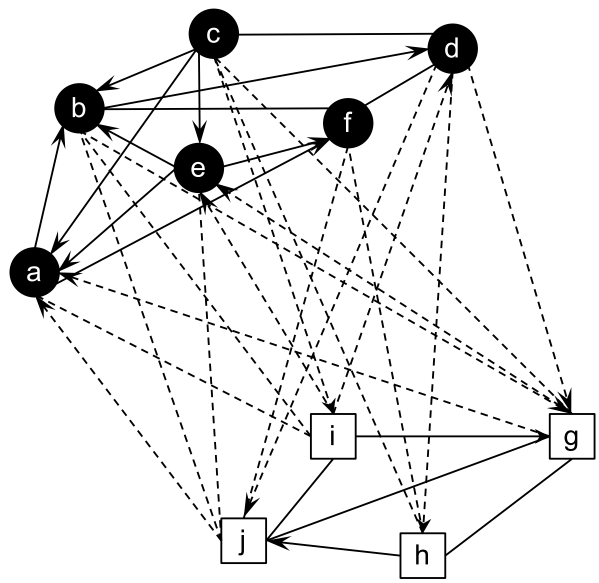


Figure 5.1: Partitions with positive inter-community relationships (solid lines) and negative inter-community relationships (dashed lines). (Doreian and Mrvar 2009)

5.6 Partitioning the Habitability Ship network

From a design standpoint, Doreian and Mrvar's partitioning algorithm is attractive because it requires only the ship relationship network and the minimum number of elements per community, yet allows the user to set the number of communities equal to the number of structural zones for eventual allocation. Therefore, the signed, weighted pre-layout Habitability Ship relationship network was analyzed using the method of

Doreian and Mrvar (Section 5.5.2) as implemented in the Balance command[13] of Pajek version 2.03 (Batagelj and Mrvar 2011). The analysis was conducted with k = 3, 4, 5, 6, 7, 15, and 22 partitions to gain an understanding of how the contents of partitions vary with the number of clusters. The value of k = 22 corresponds to the number of structural zones in the Habitability Ship.

The set of non-dominated solution partitions output by the Balance algorithm was combined using a co-occurrence frequency approach. For each value of k, a count was tallied of the number of times each pair of nodes was assigned to the same partition. This resulted in a symmetric matrix of non-negative values. The matrix was used as a similarity measure for a force directed layout algorithm (Kamada and Kawai 1989); larger numbers indicate stronger relationships and shorter proximity in the resultant co-occurrence network layout. Note that this layout is not a three-dimensional layout in ship space, but merely in a two-dimensional network space.

5.6.1 Assumptions and limitations

The minimum partition size was set to three nodes (compartments) with a weighting factor α = 0.75 to penalize errant separation constraints moderately more than errant adjacency constraints. The number of iterations varied from 200 for smaller values of k to 400 at higher k-values.

There is no accounting for area and volume requirements when creating partitions. The algorithm is only concerned with minimizing the number of inconsistent edges, and therefore, partitions may have unequal numbers of compartments or area capacity requirements. The primary focus is identifying groups of mutually-compatible spaces; the partitions' appropriateness for allocation is not of concern here (Pesch et al. 1999). Whether the partitions are truly acceptable for direct allocation to structural zones depends on additional factors like the total area and volume requirements of the partitions and the capacities of the various structural zones.

[13] The relaxed balance option was disregarded because it is not considered appropriate for this problem.

Finally, relationships between compartments (and therefore the partitioning algorithm) do not account for implied relationships from contextual information. For example, without an explicit separation constraint between the so-labeled "Forward Pump Room" and "Aft Pump Room," the compartments can be placed into the same community rather than into separate communities to be situated at the appropriate ends of the ship.

5.6.2 Communities at multiple scales

Figures 5.2-5.6 show the force-directed layouts based on the co-occurrence frequency matrices. Darker lines and shorter distances between nodes indicate higher co-occurrence values and more consistent placement in the same community. Distances and line colors are not comparable across different layouts since the sizes of the solution partition sets varied. Coloration of nodes was determined by visual inspection of proximity in the $k = 3$ case (Figure 5.2), though more rigorous methods could be used. In each figure, nodes retain the color and shape assigned in Figure 5.2. Figures 5.2-5.6 show only the combined co-occurrence networks; however, each unique solution partition is also an initial condition for subsequent analysis or refinement.

In Figure 5.2, three obvious dense communities emerge with an assortment of spaces lying between clusters. The main communities separate (generally) into:

- heavy machinery spaces and contaminants, including the main machinery room, steering gear rooms, pump rooms, trash room, and sewage treatment room (yellow squares),
- officer and crew cabins; galley, dining, and related spaces; and recreational spaces (red triangles),
- officer and crew cabins and medical facilities (green diamonds).

Officer and crew cabins are split across two communities due to separation constraints, just as they would be in an actual arrangement, to ensure continued operations in the event of a catastrophic event to one portion of the ship. The blue circles that lie between communities are generally spaces for distributed infrastructure systems (fan rooms, electrical equipment rooms) or support facilities (bosun's storeroom, foul weather gear locker, mooring gear area, etc.).

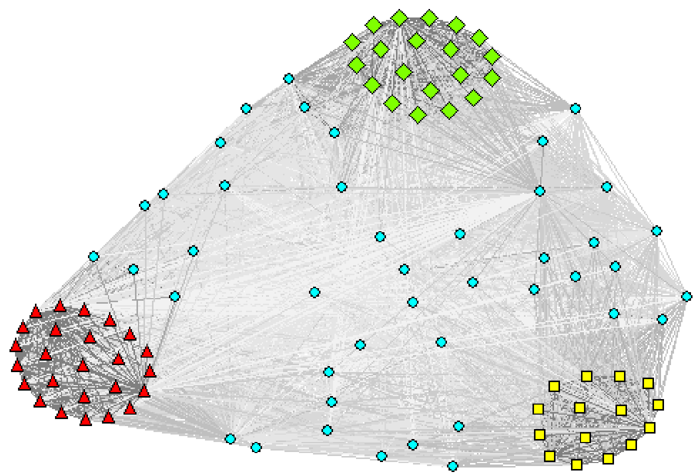


Figure 5.2: Co-occurrence network for *k* = 3 partitions. Node coloring is consistent in all networks shown.

Figures 5.3 and 5.4 show the division into four and seven partitions, respectively. In these layouts, some intermixing of the nodes colors occurs. In particular, distributed infrastructure nodes (blue) begin clustering with the machinery (yellow) and personnel (red and green) nodes indicating that, given the current design constraints, infrastructure-containing compartments can be co-located with other ship functions. This is in contrast to the Design Building Block approach, which isolates infrastructure into distinct regions of the ship (Section 2.3.1, page 21).

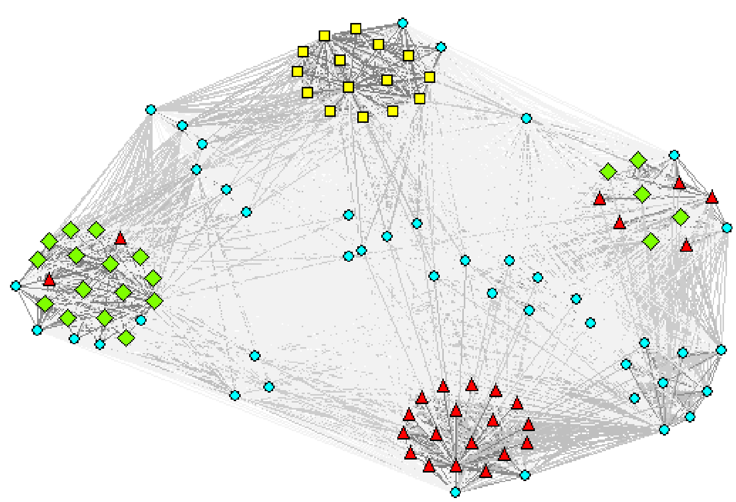


Figure 5.3: Co-occurrence network for *k* = 4 partitions.

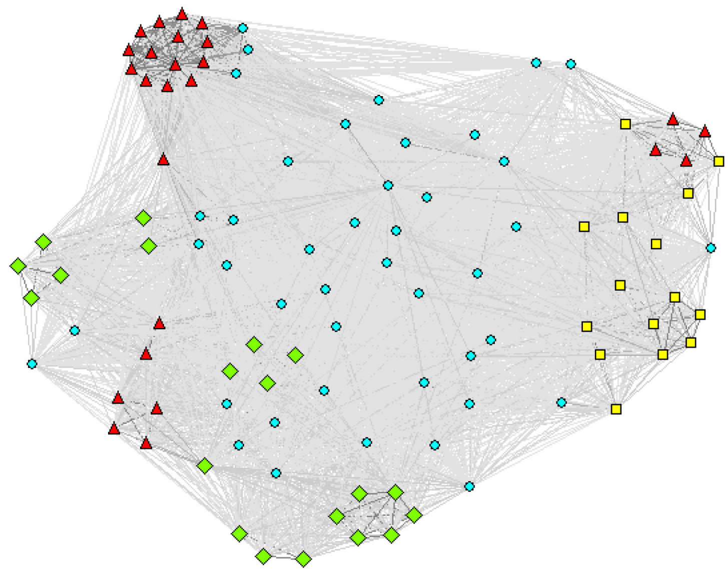


Figure 5.4: Co-occurrence network for *k* = 7 partitions.

The pre-layout network has been partitioned into 15 groups for Figure 5.5. The underlying co-occurrence matrix exhibits few dense communities and a uniform spatial dispersal of nodes indicating that the Pareto-optimal partitionings varied. Since communities are not clearly identifiable, a ship structural definition with 15 zones might not provide an obvious assignment of compartments to zones. This condition results from the existence of many partitions (to-be allocations) that score equally well (or poorly). This result informs designers early in the design process that this combination of shipboard elements, relationships, and number of zones may result in numerous alternatives requiring further investigation prior to down-selection.

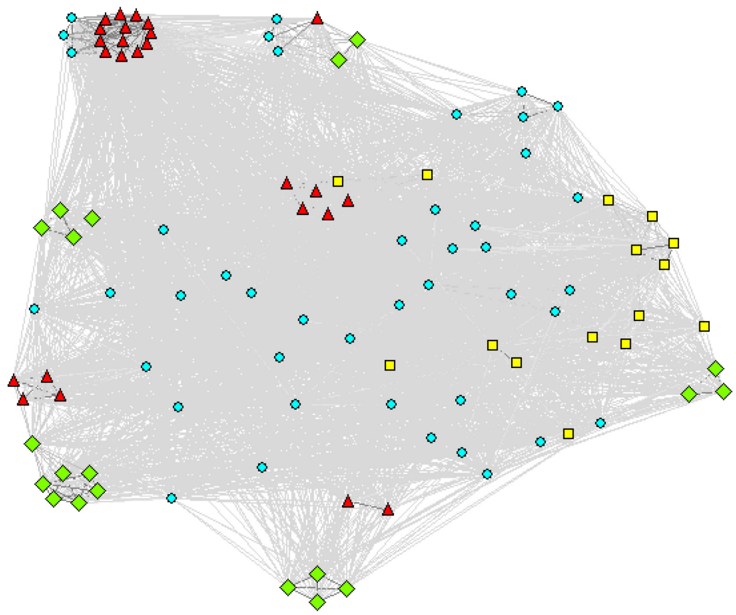


Figure 5.5: Co-occurrence network for *k* = 15 partitions.

In Figure 5.6, all nodes are grouped into one of 22 distinct communities representing the ship's 22 structural zones. The absence of very dark lines is due to the relative absence of node mixture across communities demonstrating many solution partitions possess similar partitioning patterns; the darkest lines are hidden by the node symbols themselves. Example communities include:

- Medical complex: medical facility, sick bay, medical consultation room, medical storeroom, an electrical equipment room, and a fan room,
- Food service complex: galley and scullery, daily provisions, cold provisions stores, refrigerator machinery room, general stowage, and an electrical equipment room,
- Main machinery spaces: main machinery room, forward pump room, general mechanical workshop, and an electrical switchboard room,
- "Officer country": officer cabins group A, engineer officer cabin, wardroom, and an electrical switchboard room. A second "officer country" is composed of officer cabins group B and the executive officer (XO) cabin,
- Berthing complex: petty officer cabins, specialist cabins, recreational facilities, laundry facilities, and the ship's office.

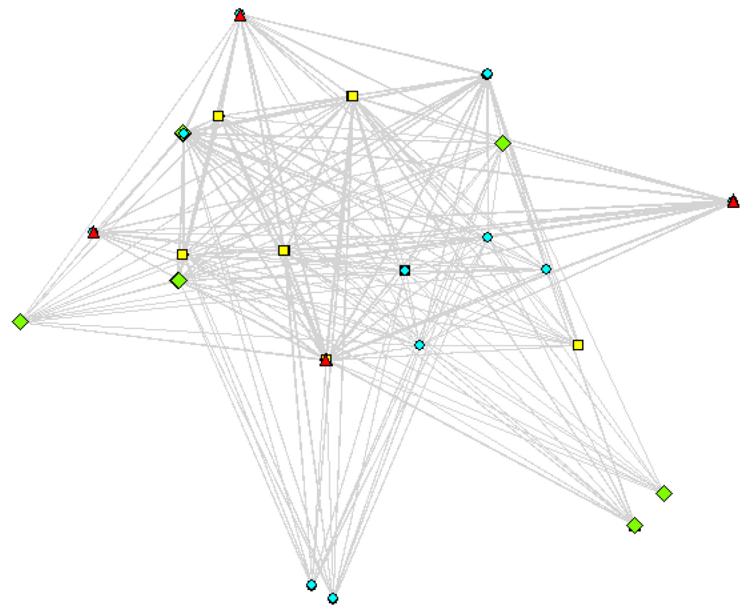


Figure 5.6: Co-occurrence network for *k* = 22 partitions.

5.7 Summary

This chapter demonstrated how signed network partitions can be used to identify groups of related compartments at multiple scales. The technique is particularly beneficial for early-stage design work because it requires only basic design-oriented information: the list of objects, the type of relationships among them (adjacency or separation), and the number of desired partitions. By its nature, the network contains very little designer-provided information for any pair of elements – simply the existence, directionality, and strength of the relationship. The partitioning approach does a respectable job dividing the set of compartments into communities representing plausible structural zone allocations based solely on rudimentary design knowledge. The relative importance values used as edge weights are not perfect, but their use as a proxy was successful.

Despite the aforementioned concerns in Sections 5.3.1 and 5.6.1 regarding edge weight selection and structural zone matching, the partitions generated are quite reasonable. This author's approach to the topic follows the observation of Jayakumar and Reklaitis (1994):

Theoretically, unit areas can be incorporated as weights assigned to vertices. Then, additional constraints would involve restrictions on the sum of the weights of the vertices in each subset. This leads to considerable additional complexity, and thus at this juncture, we defer consideration of areas to a later stage in the development of … layout.

The formulation presented does not attempt to balance the area required by a community nor does it attempt to match required areas to structural zone capacities. A modification to the objective function $P(\boldsymbol{C})$ could potentially address this issue.

The communities provide insight, guidance, and starting points for subsequent human or computer analyses. For example, if the number of partitions is set to the number of structural zones in the ship, the communities could provide a rough and fast means for generating initial allocations. Using the Habitability Ship network as an example, it was shown that partitioning the compartments into 22 communities based on a partition co-occurrence measure created reasonable sets of compartments for an initial direct allocation of compartments to structural zones. The communities may not a perfect allocation due to large differences in required area and area capacity. However, they do carve out functional zones that could be refined using more sophisticated and time-intensive methods. Initially, communities that are too large for a single zone could be split across adjacent zones, and smaller communities could be combined using guidance from larger communities at lower *k*-values. The task of assigning these communities to specific zones is taken up in the next chapter.

5.7.1 Potential application of communities to "sketching"

Section 2.4 describes a vision of ship arrangements that includes an improved user experience where designers spend less time modeling. Pawling and Andrews (2011) describe an approach to early-stage ship design that is akin to an architect's approach to building, bridge, and landscape design in which creativity is encouraged though rough sketching. Pawling and Andrews note that the Design Building Block Approach is amenable to sketching for preliminary ship design, though its implementation within the SURFCON module of PARAMARINE may not be "fast" or "fluid" enough to achieve the benefits of sketching due to the amount of modeling required for moderate and high levels of fidelity.

A potential use for the communities identified in this chapter is in a *recommender system* (Ricci et al. 2011). Recommender systems suggest items to users that are related to a particular item in which the user has expressed interest. Examples of recommender systems include suggestions of related products in online marketplaces or of potential friends in online social networks. As discussed in Section 5.3, communities at multiple scales are akin to Design Building Blocks (DBBs) at different levels of fidelity. Therefore, when a user desires to refine a DBB and increase the level of specificity of a model, a recommender system built upon these communities could be used to suggest elements that would be suitable for inclusion in the DBB. Rather than defining each new element individually, users could select an appropriate item from a list. In this way, designers would be assisted in managing the overwhelming number of (primary, secondary, and tertiary) constraints while increasing the pace at which one could determine mutually-compatible cohabitants for a Design Building Block.

Chapter 6

Allocating communities to structural zones

This chapter presents a new approach for positioning shipboard elements that begins with the non-spatial, network theory-based communities identified in the previous chapter and results in the traditional assignment of compartments to designated structural zones. Generating ship arrangements is inherently a problem of identifying the spatial regions to be occupied by compartments, systems, and components while balancing the impact on performance. Traditionally, each element is assigned a Cartesian coordinate location, and the arrangement problem is solved in three-dimensional space with each coordinate corresponding directly to a position within the final realized ship. The coordinates for each subsequent element are selected by considering the element's interactions (relationships) with elements that have been placed, or are expected to be placed, and in accordance with preferences for residency in specific regions of the ship.

The previous chapter provided a standalone analysis that enables the identification of communities of mutually compatible ship compartments. The communities themselves, and the non-spatial perspective they provide, are valuable to designers when learning about the complexities related to particular system selections. Nevertheless, some whole-ship design analyses require a geometric definition of the ship and its contents. Examples include crew egress during crises and materiel movement during underway replenishment. Thus, it is desirable to use communities as the basis for spatial layouts.

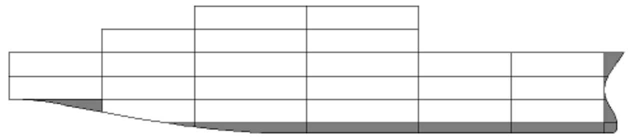
The method presented in this chapter is capable of generating designs that are as novel or creative as the input global location preferences allow them to be. If the crew's cabins, for example, highly prefer every zone in the ship, then the community containing them has the potential to be located anywhere in the ship. That community will be positioned in accordance with the preferences all the compartments included in the community, which may vary by partitioning. The method developed provides a robust way to manage the exploding number of unfamiliar relationships that are present when assimilating novel systems into familiar designs, combining uncommon sets of systems, or working within a novel hull form. A portion of the work in this chapter is included in (Gillespie et al. 2012).

6.1 Mapping communities to ship structural zones

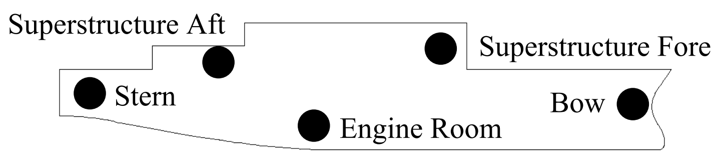
The process of mapping communities of compartments to regions of a ship involves several steps. First is the description of compartment preferences for particular regions of the ship (Section 6.1.1). Second, individual compartment preferences must be combined to form a joint preference for the entire community (Section 6.1.2). Finally, the communities are assigned to zones based on the communal preferences (Section 6.2).

6.1.1 Global location preferences for individual compartments

Many compartments and pieces of equipment work more effectively when they are placed in particular regions of the ship, thus we say they have a preference to be located in those regions. Regions may be defined regularly and grid-like or irregularly and dependent specifically upon the items of interest (Figure 6.1). The advantage of an irregular definition is that it permits the generation of layouts using minimal information enabling the development of feasible arrangements in the earliest stages of design, a cornerstone of the network-based arrangement methods being presented here. That said, the grid-based global location preference maps for each compartment are adopted from existing data developed for ISA (Figure 6.2) in order to compare more accurately the final allocations. The global location preference map specifies a compartment's preference from zero to one for being allocated to a corresponding structural zone.



(a)



(b)

Figure 6.1: Examples of (a) regular and (b) irregular region definitions.

		0.05	0.05			
	1	1	1			
0.50	1	1	1	0.50	0.20	0
0.20	0.50	0.50	0.50	0.50	0.20	0
0	0.05	0.05	0.05	0.05	0.05	0
	0	0	0	0	0	0

Figure 6.2: Example global location preference map for the Ship's Office indicating a preference to be located near the lower portion of the superstructure.

6.1.2 Global location preferences for communities

A metric was developed to express the collective preference for a community of compartments to be positioned in a particular structural zone. For the discrete grid shown in Figure 6.2, a community's cumulative preference to be located in any zone is calculated as a weighted sum of the constituent compartments' preferences (Equation 11).

$$P_{n,z} = \sum_{s \in n, p_{s,z} \geq t} I_s G_s \frac{p_{s,z}}{z_s{}'} \qquad 11$$

This equation states that the preference $P_{n,z}$ of a community n to be located in zone z is equal to the weighted sum of the preference of each space s in n to be allocated to z.

Each compartment's contribution is a function of the importance of the space I_s, the importance of the global location relationship to s G_s, and the preference of s to be in z $p_{s,z}$ discounted by the number of zones s prefers to be in z_s' given a preference level threshold t. Zones having preference levels below t contribute zero to the cumulative preference. The values of $p_{s,z}$ are provided by the global location preference maps. The analyses in this chapter use a preference threshold of $t = 1.0$ so that compartments only prefer a zone if they will be fully satisfied being placed there. Setting $0 < t < 1$ will expand the range of preferred zones for a given community.

For example, consider a community $n = 1$ containing two spaces, the Bridge and the Medical Facility, that have the global location preferences shown in Figure 6.3. The Bridge is one of the most important compartments and has a relative space importance value $I_{Bridge} = 20$ (out of 20), while the Medical Facility has $I_{MedFac} = 9$. If it is assumed that all global location preferences carry equal weight, then $G_{Bridge} = G_{MedFac} = 5$ is a viable statement. As described above, the global location preference threshold is set to $t = 1.0$; thus, the number of zones for which each space has an individual preference of at least 1.0 is $z'_{Bridge} = 2$ and $z'_{MedFac} = 3$. Each relevant zone is denoted by a character in its cell of Figure 6.3; that is, the preference for the Medical Facility to be located in the forward-most zone on the uppermost deck of the deckhouse is denoted $p_{MedFac,\S} = 0.50$. The calculation of the community's cumulative preference for each zone is provided in Table 6.1. The calculation reveals that the community has greatest cumulative preference for zone ° because of the overlap of the two individual preference regions. The second-most preferable zone for the community as a whole is zone § because the Bridge is a more important space and it has fewer zones overall that will satisfy its individual preference at the given threshold.

Bridge

		0.05	§ 1			
	+ 0.05	x 0.05	° 1			
0.05	0.05	0.05	0.05	0.05	0.05	0
0.05	0.05	0.05	0.05	0.05	0.05	0
0	0.05	0.05	0.05	0.05	0.05	0
	0	0	0	0	0	0

Medical Facility

		0.50	§ 0.50			
	+ 1	x 1	° 1			
0.05	0.50	0.50	0.50	0.05	0.05	0
0.05	0.05	0.05	0.05	0.05	0.05	0
0	0.05	0.05	0.05	0.05	0.05	0
	0	0	0	0	0	0

Figure 6.3: Global location preference maps for two compartments.

Table 6.1: Calculation of a community's cumulative zone preference values.

$P_{n,z}$	Bridge	Medical Facility	Cumulative Preference, $P_{n,z}$
$P_{1,\S}$:	20 * 5 * 1.0 / 2 = 50	0.5 < (t = 1.0) → 0	$P_{1,\S}$ = 50 + 0 = 50
$P_{1,\circ}$:	20 * 5 * 1.0 / 2 = 50	9 * 5 * 1.0 / 3 = 15	$P_{1,\circ}$ = 50 + 15 = 65
$P_{1,\mathrm{x}}$:	0.05 < (t = 1.0) → 0	9 * 5 * 1.0 / 3 = 15	$P_{1,\mathrm{x}}$ = 0 + 15 = 15
$P_{1,+}$:	0.05 < (t = 1.0) → 0	9 * 5 * 1.0 / 3 = 15	$P_{1,+}$ = 0 + 15 = 15

6.1.3 An example partitioning

Communities, as defined in Chapter 5, contain compartments or components that, to the greatest extent possible, do not have separation relationships among themselves indicating they all can be allocated to the same structural zone. When the partitioning algorithm (Section 5.6, page 103) is used, multiple partition solutions are created; compartments that are tightly connected (as measured by the strength of the relationship) may remain in the same group in all solutions while other less-tightly connected spaces may be assigned to a few or many different groups. The partitioning algorithm was run with a minimum cluster size of three nodes and an inconsistency weighting factor $\alpha = 0.5$. One representative partition is drawn in Figure 6.4; darker lines signify stronger relationships, solid lines adjacency relationships, and dashed lines separation relationships. Figure 6.5 shows the same set of relationships, but from a community viewpoint. (Note that line weight does not represent relationship strength in Figure 6.5). The relationship strength from any community *A* to any other community *B* is the sum of the strengths of the edges that start at a compartment in *A* and end at a compartment in *B*. The dashed lines between nodes indicate that the connected communities, in the aggregate, prefer separation.

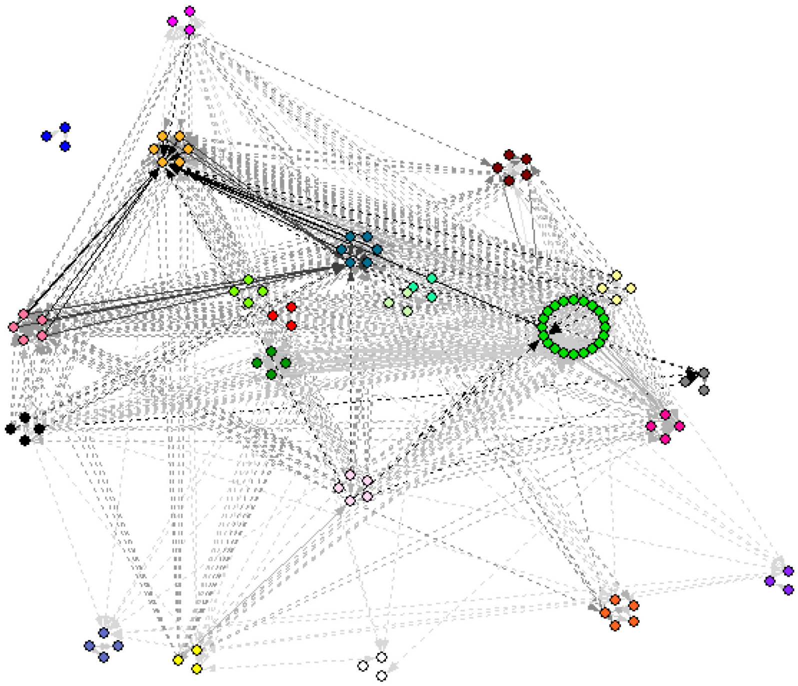


Figure 6.4: Example of the 103 Habitability Ship compartments split into 22 partitions.

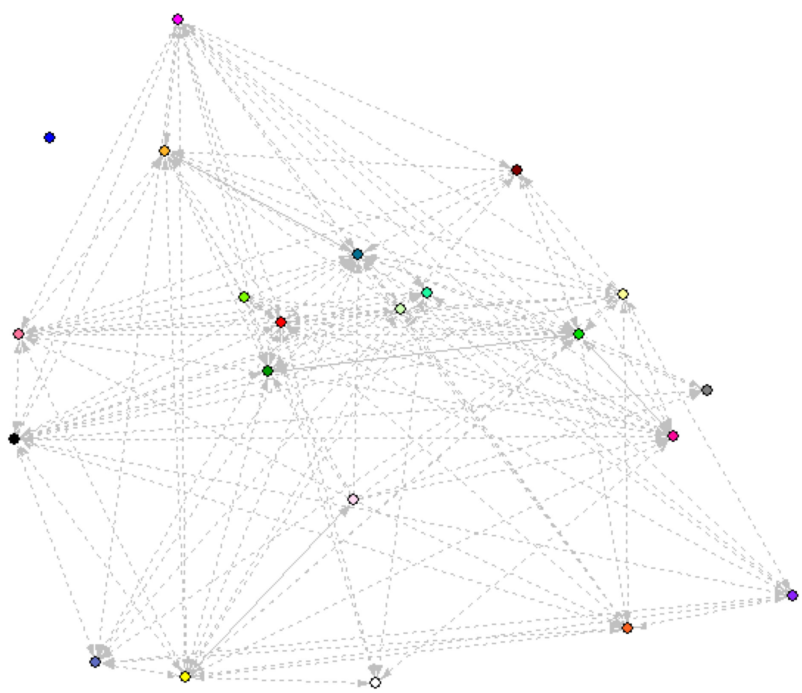


Figure 6.5: The network in Figure 6.4 reduced to 22 nodes that represent communities.

When partitions are formed, there is no accounting of the area requirements for the constituent spaces and no consideration for structural zone capacities or global location preferences. As a result, partitions as a whole contain no guidance regarding whether they will fit in the ship's zones or where they should be located within the ship. The required area for the communities in Figure 6.4 ranges from 20 m^2 to 443 m^2. Table 6.2 lists the compartments in the largest partition (C21), which has a total area requirement equal to about three large structural zones in the Habitability Ship model. Figure 6.6 shows C21's community-to-zone preference values $P_{21,z}$, with the colors representing a scale of preference points from 3.3 to 137.5. The community, which contains the galley, petty officer dining rooms, and specialist cabins, has a clear preference to be on the damage control deck, just below the deckhouse.

Table 6.2: Compartments in partition C21 in a single network partitioning solution.

Galley & Scullery	PO Cabin (Male)(4) & Bath GroupA (x3)
Laundry (Officer & PO)	Recreation Room
Laundry (Specialist)	Ship's Office
Library	Specialist Cabin (Male)(6) GroupB (x3)
Linen Locker	Specialist Cabin (Female)(6) (x2)
PO & Specialist Dining Room (x4)	Training Room

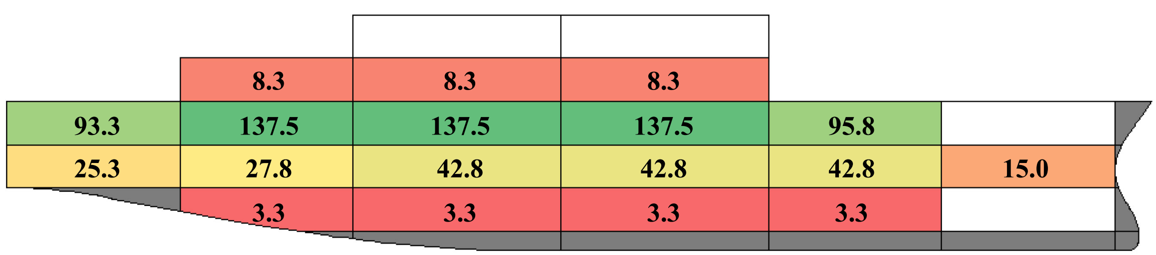


Figure 6.6: Preference values $P_{21,z}$ for community C21. $P_{21,z}$ = 0 for unlabeled zones.

6.2 Assigning communities to ship structural zones

The next step in creating an arrangement is determining where compartments will be located in the ship. A direct assignment procedure is investigated whereby entire communities are assigned to a single preferred structural zone. The quality, or fitness, for all allocations will be evaluated using Equation 12. This is the same ISA allocation objective function developed and used in (Parsons et al. 2008; Parker et al. 2011). This objective function is not specific to ISA, but rather a generic formulation for measuring the quality of a design.

$$U(\mathbf{x}) = U_1 \times U_2 \times U_3 \leq 1 \qquad 12$$

Equation 12 states that the fitness of the allocation $U(\mathbf{x})$ is the product of the minimum structural zone satisfaction U_1, the average structural zone satisfaction U_2, and the weighted average space satisfaction U_3. All of the multiplicands are [0,1] utilities.

In the direct seeding method, communities are individually assigned to structural zones in descending order of cumulative zone preference $P_{n,z}$ (Figure 6.7). This is done to be partial to “weighty” communities, which indicates the presence of important spaces, many spaces, or spaces that prefer few zones. The assignment process is a sequential procedure in which the unassigned community possessing the highest overall cumulative zone preference is assigned first. If a zone is already occupied by another community, then the current community is skipped since its preference for that zone cannot be satisfied. The community will have an opportunity to be placed into a different preferred zone, if available, once its next-highest preference value equals the maximum preference value of all unplaced communities. Since 137.5 is the highest zone preference value of all the communities in the example partitioning (Section 6.1.3), C21 is assigned first. The area utilization of zones is not considered.

A fixed set of compartments (with accompanying relationships) and a single network partitioning result in a deterministic set of preferences values $P_{n,z}$. This is because the compartments in each partition and all the values on the right hand side of the cumulative zone preference equation (Equation 11) are specified. Variation is introduced into the allocation process to increase the number of designs created from a single partitioning. If a community has equal preference for multiple zones, it is assigned to a randomly-selected equally-preferred zone. For example, in Figure 6.6, C21 prefers three zones with preference $P_{n,z}$ = 137.5; therefore, C21 is assigned to one of those three zones with equal probability. If each community prefers exactly one zone at its maximum preference level, then the allocation for that partitioning will be deterministic.

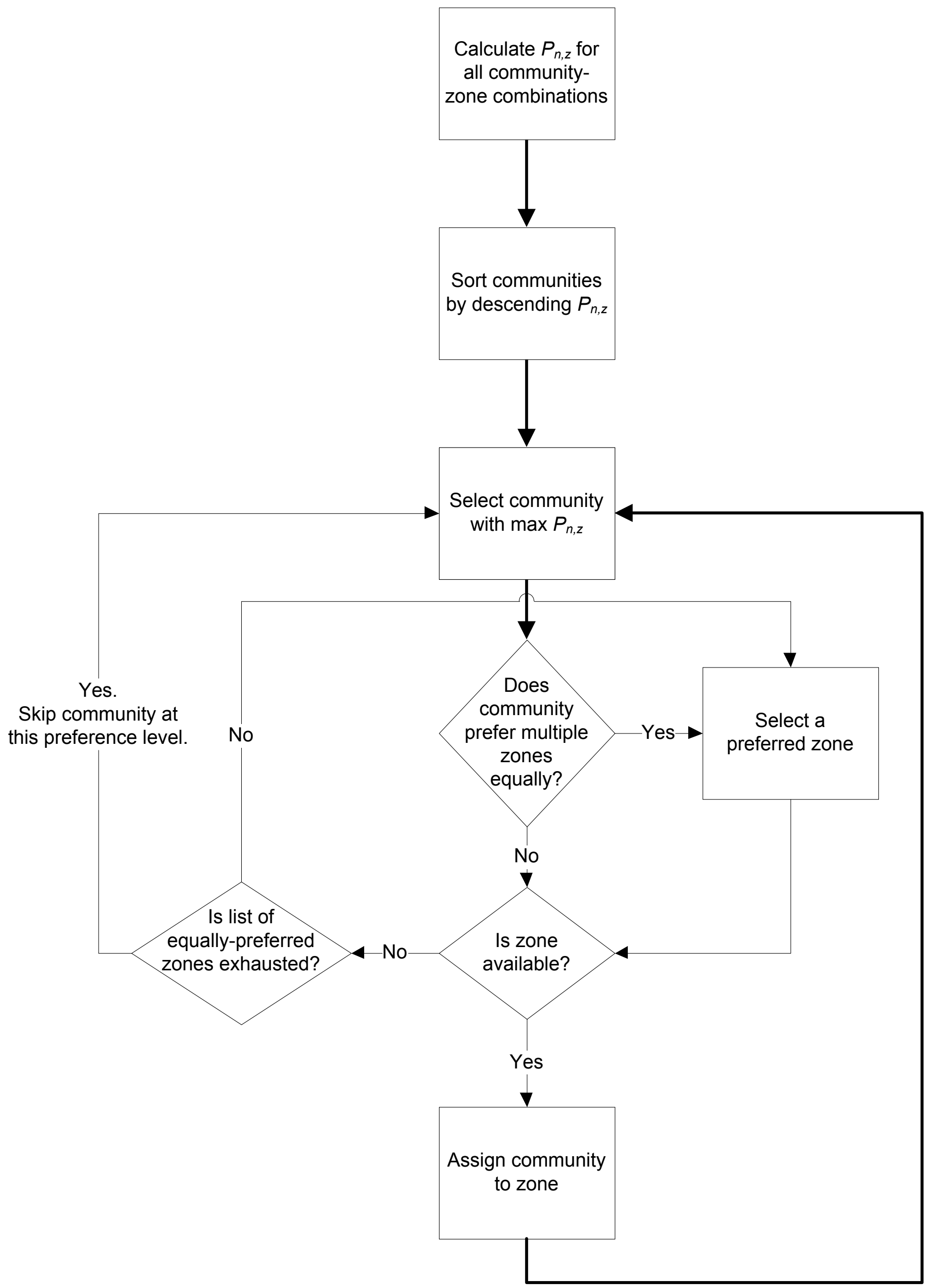


Figure 6.7: Procedure for assigning communities to structural zones.

6.2.1 Sensitivity to the number of communities

In Chapter 5, it was presumed that the proper number of network partitions for a direct allocation procedure would be equal to the number of structural zones to be arranged. This subsection is dedicated to testing that assumption and identifying an appropriate number of communities to use when partitioning the network for the purpose of structural zone allocations. If fewer communities than zones are used, zones will necessarily be left unfilled. The maximum number of partitions has been limited to the number of structural zones. If more communities than zones are created, then a mechanism would be needed for combining compatible communities or determining a community's compatibility with other communities already assigned to a zone. Also, if one were to move toward many partitions, the approach would become less community-oriented and more individual compartment-oriented.

6.2.1.1 Method

The Habitability Ship pre-layout network was partitioned into multiple numbers of partitions ranging from k = 16 to 22 using the approach described in Chapter 5. One hundred of the unique partitionings for each k were used as the basis for direct seed allocations (Figure 6.7). Each partitioning was used to create three unique allocations; the multiplicity originates from the random assignment of communities to one of several equally-preferred zones. The resultant allocation has k zones containing compartments and 22-k zones remaining empty.

The quality of each allocation was calculated using Equation 12. The average structural zone satisfaction value U_2 was calculated using only the zones containing compartments. The 22-k empty zones were not included in the calculation of U_2 in order to reflect the true satisfaction of the zones in use; assigning the unused zones a score of 0 (no satisfaction) or 1 (full satisfaction) would have under- or over-inflated the average. This is a slight departure from the previous definition of U_2 used within ISA, wherein all empty zones receive a utility of unity.

6.2.1.2 Results

Figure 6.8 shows that the overall quality $U(\mathbf{x})$ remains constant at zero due to the influence of the minimum structural zone satisfaction U_1. The limiting value is the minimum structural zone satisfaction due to several zones being over-utilized. The tendency of U_1 to dominate solutions is a known issue of this objective function formulation (Daniels et al. 2009) and is not specific to this allocation method.

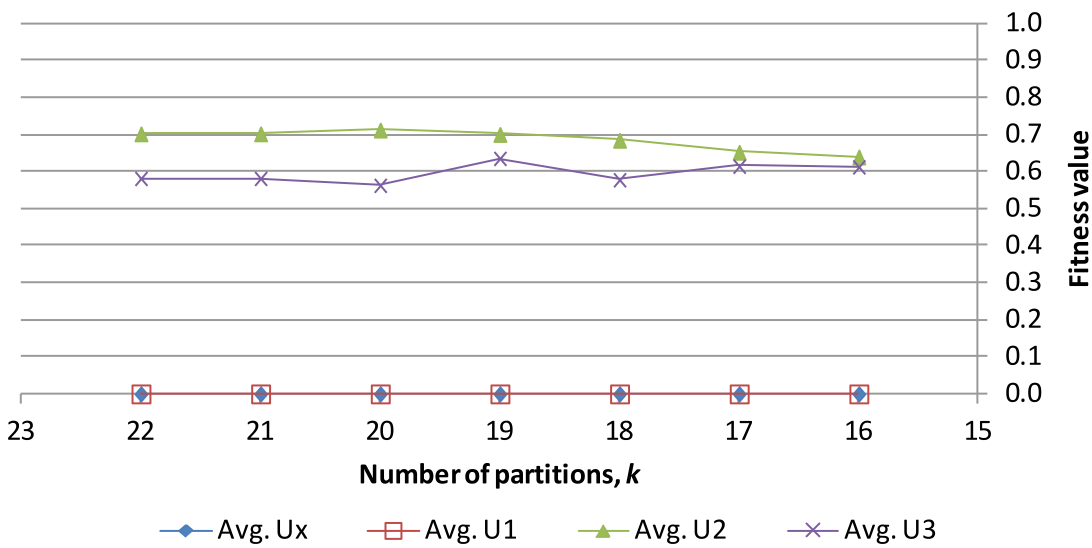


Figure 6.8: Change of fitness value components with number of partitions.

Figure 6.8 also shows that the weighted average space satisfaction U_3 remains relatively steady around ~0.60 as the number of partitions decreases and compartments are redistributed among other communities. This indicates a sort of balance between satisfied adjacency relationships, unsatisfied separation relationships, and global location preferences for this design. This is positive news in that it demonstrates a bit of flexibility in selecting the number of partitions. This facilitates matching communities to ship variants with slightly different structural zone configurations with 21 or 20 zones, for example.

The self-balancing is only expected up to a point. As the number of communities becomes smaller, more compartments are assigned to a single zone. With fewer partitions, more adjacency relationships will be satisfied and fewer separation relationships will be respected. The value of this will depend on the balance of adjacency and separation relationships. However, as the number of communities decreases and the area requirements of each community increases, zones that are used will become less satisfied as their area utilization rises. The average structural zone satisfaction U_2 remained nearly constant when using 19 or more partitions (zones), but declined when using fewer than 19 partitions.

6.2.2 Example allocations using 22 and 19 communities

The stability of the curves in Figure 6.8 between 22 and 19 communities provide little clear guidance for identifying a single appropriate number of zones. However, the stability also showed that setting the number of partitions equal to the number of zones provides a reasonable assumption.

An example allocation of 22 communities is given in Figure 6.9 and the compartments in each zone are listed in Appendix F. The compartments allocated to each zone represent a complete community. This allocation obtained utility scores of $U_x = 0$, $U_1 = 0$, $U_2 = 0.769$, and $U_3 = 0.656$. While these fitness values are lower than those reported elsewhere (e.g., Daniels et al. 2010) for designs created using ISA's agents, the network-based method uses substantially less information.

A second example allocation uses 19 communities (Figure 6.10; listing of compartments in Appendix F). The three unfilled zones are 14, 20, and 25. The objective function scores are similar to those of the 22-community allocation ($U_x = 0$, $U_1 = 0$, $U_2 = 0.747$, and $U_3 = 0.679$). This allocation is as expected; the average utility is slightly lower for the zones and a bit higher for the compartments.

		SUBZONEDECK 23: Zone_Deck_023: RESIDENT SPACES: SPACE 35: Fan Room (Hull) SPACE 36: Fan Room (Deckhouse) SPACE 91: Electrical Switchboard Room	SUBZONEDECK 17: Zone_Deck_017: RESIDENT SPACES: SPACE 52: Officer Cabin (Male)(2) & Bath GrpB SPACE 53: Officer Cabin (Male)(2) & Bath GrpB SPACE 54: Officer Cabin (Male)(2) & Bath GrpB SPACE 55: Officer Cabin (Male)(2) & Bath GrpB		
	SUBZONEDECK 28: Zone_Deck_028: RESIDENT SPACES: SPACE 29: Engineer Officer Cabin SPACE 48: Officer Cabin (Male)(2) & Bath GrpA SPACE 49: Officer Cabin (Male)(2) & Bath GrpA SPACE 50: Officer Cabin (Male)(2) & Bath GrpA SPACE 51: Officer Cabin (Male)(2) & Bath GrpA SPACE 56: Officer Cabin (Female)(2) & Bath SPACE 57: Officer Cabin (Female)(2) & Bath SPACE 58: Officer Cabin (Female)(2) & Bath SPACE 68: PO Cabin (Female)(4) & Bath SPACE 96: Wardroom SPACE 97: XO Cabin & Bath	SUBZONEDECK 22: Zone_Deck_022: RESIDENT SPACES: SPACE 7: Boat Gear Locker SPACE 22: Electrical Equipment Room SPACE 30: Enclosed RIB Stowage	SUBZONEDECK 16: Zone_Deck_016: RESIDENT SPACES: SPACE 6: BC Medical Facility SPACE 12: Bridge SPACE 16: CO Cabin & Bath SPACE 17: CO Storeroom SPACE 37: Fan Room (Deckhouse) SPACE 43: Medical Consultation Room SPACE 44: Medical Storeroom SPACE 77: Sick Bay		
SUBZONEDECK 31: Zone_Deck_031: RESIDENT SPACES: SPACE 8: Bosun Storeroom (Aft Mooring) SPACE 46: Mooring Area & Gear Storeroom (Aft) SPACE 66: PO Cabin (Male)(4) & Bath GrpB SPACE 67: PO Cabin (Male)(4) & Bath GrpB	SUBZONEDECK 27: Zone_Deck_027: RESIDENT SPACES: SPACE 18: Cool Cold Dry Provisions SPACE 40: Galley & Scullery SPACE 59: Laundry (Officer & PO) SPACE 60: PO & Specialist Dining Room SPACE 61: PO & Specialist Dining Room SPACE 62: PO & Specialist Dining Room SPACE 63: PO Cabin (Male)(4) & Bath GrpA SPACE 64: PO Cabin (Male)(4) & Bath GrpA SPACE 65: PO Cabin (Male)(4) & Bath GrpA SPACE 71: Daily Provision Room SPACE 72: Recreation Room SPACE 76: Ships Office SPACE 81: Specialist Cabin (Male)(6) GrpB SPACE 82: Specialist Cabin (Male)(6) GrpB SPACE 83: Specialist Cabin (Male)(6) GrpB SPACE 84: Specialist Cabin (Female)(6) SPACE 85: Specialist Cabin (Female)(6) SPACE 86: Laundry (Specialist) SPACE 93: Training Room SPACE 94: Library SPACE 102: PO & Specialist Dining Room	SUBZONEDECK 21: Zone_Deck_021: RESIDENT SPACES: SPACE 20: Electrical Equipment Room SPACE 38: Foul Weather Gear Locker SPACE 90: Electrical Switchboard Room	SUBZONEDECK 15: Zone_Deck_015: RESIDENT SPACES: SPACE 15: Cleaning Gear Storeroom (Below Decks) SPACE 27: Electrical Equipment Room SPACE 31: Fan Room (Hull) SPACE 75: Sewage Treatment Machinery Room SPACE 95: Trash Room	SUBZONEDECK 11: Zone_Deck_011: RESIDENT SPACES: SPACE 9: Bosun Storeroom (Fwd Mooring) SPACE 23: Electrical Equipment Room SPACE 45: Mooring Area & Gear Storeroom (Fwd)	SUBZONEDECK 7: Zone_Deck_007: RESIDENT SPACES: SPACE 3: Anchoring & Mooring SPACE 13: Chain Locker SPACE 14: Chain Locker Sump
SUBZONEDECK 30: Zone_Deck_030: RESIDENT SPACES: SPACE 1: Air Conditioning Room SPACE 24: Electrical Equipment Room SPACE 87: Steering Gear Room	SUBZONEDECK 26: Zone_Deck_026: RESIDENT SPACES: SPACE 21: Electrical Equipment Room SPACE 41: General Stowage SPACE 74: SD Storeroom	SUBZONEDECK 20: Zone_Deck_020: RESIDENT SPACES: SPACE 5: Battery Locker and Charging SPACE 47: Mooring Area & Gear Storeroom (Aft) SPACE 73: Refrigerator Machinery Room	SUBZONEDECK 14: Zone_Deck_014: RESIDENT SPACES: SPACE 78: Specialist Cabin (Male)(6) GrpA SPACE 79: Specialist Cabin (Male)(6) GrpA SPACE 80: Specialist Cabin (Male)(6) GrpA	SUBZONEDECK 10: Zone_Deck_010: RESIDENT SPACES: SPACE 28: Electrical Equipment Room SPACE 34: Fan Room (Hull) SPACE 39: Fwd Pump Room	SUBZONEDECK 6: Zone_Deck_006: RESIDENT SPACES: SPACE 19: Electrical Equipment Room SPACE 69: POL & Paint Locker (Storage) SPACE 70: POL & Paint Locker (Service)
SUBZONEDECK 29: Zone_Deck_029: RESIDENT SPACES:	SUBZONEDECK 25: Zone_Deck_025: RESIDENT SPACES: SPACE 2: Air Conditioning Room SPACE 10: Bosun Storeroom (MainDeck) SPACE 26: Electrical Equipment Room SPACE 88: Steering Gear Room	SUBZONEDECK 19: Zone_Deck_019: RESIDENT SPACES: SPACE 0: Aft Pump Room SPACE 98: MMR Diesel (Hold) SPACE 99: MMR Diesel (1stPlatform) SPACE 101: Mechanical Workshop (General)	SUBZONEDECK 13: Zone_Deck_013: RESIDENT SPACES: SPACE 11: Bosun Storeroom (MainDeck) SPACE 89: Electrical Switchboard Room SPACE 100: AMR	SUBZONEDECK 9: Zone_Deck_009: RESIDENT SPACES: SPACE 4: Auxiliary Propulsion Room SPACE 25: Electrical Equipment Room SPACE 33: Fan Room (Hull)	SUBZONEDECK 5: Zone_Deck_005: RESIDENT SPACES: SPACE 32: Fan Room (Hull) SPACE 42: Linen Locker SPACE 92: Electrical Switchboard Room

Figure 6.9: Sample allocation via direct seeding using 22 communities.

		SUBZONEDECK 23: Zone_Deck_023: RESIDENT SPACES: SPACE 24: Electrical Equipment Room SPACE 37: Fan Room (Deckhouse) SPACE 52: Officer Cabin (Male)(2) & Bath GrpB SPACE 53: Officer Cabin (Male)(2) & Bath GrpB SPACE 54: Officer Cabin (Male)(2) & Bath GrpB SPACE 55: Officer Cabin (Male)(2) & Bath GrpB SPACE 66: PO Cabin (Male)(4) & Bath GrpB SPACE 67: PO Cabin (Male)(4) & Bath GrpB	SUBZONEDECK 17: Zone_Deck_017: RESIDENT SPACES: SPACE 12: Bridge SPACE 16: CO Cabin & Bath SPACE 17: CO Storeroom SPACE 31: Fan Room (Hull)		
	SUBZONEDECK 28: Zone_Deck_028: RESIDENT SPACES: SPACE 29: Engineer Officer Cabin SPACE 48: Officer Cabin (Male)(2) & Bath GrpA SPACE 49: Officer Cabin (Male)(2) & Bath GrpA SPACE 50: Officer Cabin (Male)(2) & Bath GrpA SPACE 51: Officer Cabin (Male)(2) & Bath GrpA SPACE 56: Officer Cabin (Female)(2) & Bath SPACE 57: Officer Cabin (Female)(2) & Bath SPACE 58: Officer Cabin (Female)(2) & Bath SPACE 68: PO Cabin (Female)(4) & Bath SPACE 96: Wardroom SPACE 97: XO Cabin & Bath	SUBZONEDECK 22: Zone_Deck_022: RESIDENT SPACES: SPACE 7: Boat Gear Locker SPACE 30: Enclosed RIB Stowage SPACE 38: Foul Weather Gear Locker	SUBZONEDECK 16: Zone_Deck_016: RESIDENT SPACES: SPACE 6: BC Medical Facility SPACE 28: Electrical Equipment Room SPACE 43: Medical Consultation Room SPACE 44: Medical Storeroom SPACE 77: Sick Bay		
SUBZONEDECK 31: Zone_Deck_031: RESIDENT SPACES: SPACE 8: Bosun Storeroom (Aft Mooring) SPACE 27: Electrical Equipment Room SPACE 46: Mooring Area & Gear Storeroom (Aft) SPACE 47: Mooring Area & Gear Storeroom (Aft)	SUBZONEDECK 27: Zone_Deck_027: RESIDENT SPACES: SPACE 26: Electrical Equipment Room SPACE 36: Fan Room (Deckhouse) SPACE 89: Electrical Switchboard Room	SUBZONEDECK 21: Zone_Deck_021: RESIDENT SPACES: SPACE 15: Cleaning Gear Storeroom (Below Decks) SPACE 23: Electrical Equipment Room SPACE 32: Fan Room (Hull) SPACE 87: Steering Gear Room	SUBZONEDECK 15: Zone_Deck_015: RESIDENT SPACES: SPACE 18: Cool Cold Dry Provisions SPACE 40: Galley & Scullery SPACE 41: General Stowage SPACE 42: Linen Locker SPACE 59: Laundry (Officer & PO) SPACE 60: PO & Specialist Dining Room SPACE 61: PO & Specialist Dining Room SPACE 62: PO & Specialist Dining Room SPACE 63: PO Cabin (Male)(4) & Bath GrpA SPACE 64: PO Cabin (Male)(4) & Bath GrpA SPACE 65: PO Cabin (Male)(4) & Bath GrpA SPACE 71: Daily Provision Room SPACE 72: Recreation Room SPACE 74: SD Storeroom SPACE 76: Ships Office SPACE 81: Specialist Cabin (Male)(6) GrpB SPACE 82: Specialist Cabin (Male)(6) GrpB SPACE 83: Specialist Cabin (Male)(6) GrpB SPACE 84: Specialist Cabin (Female)(6) SPACE 85: Specialist Cabin (Female)(6) SPACE 86: Laundry (Specialist) SPACE 93: Training Room SPACE 94: Library SPACE 100: AMR SPACE 102: PO & Specialist Dining Room	SUBZONEDECK 11: Zone_Deck_011: RESIDENT SPACES: SPACE 9: Bosun Storeroom (Fwd Mooring) SPACE 45: Mooring Area & Gear Storeroom (Fwd) SPACE 75: Sewage Treatment Machinery Room SPACE 95: Trash Room	SUBZONEDECK 7: Zone_Deck_007: RESIDENT SPACES: SPACE 2: Air Conditioning Room SPACE 3: Anchoring & Mooring SPACE 13: Chain Locker SPACE 14: Chain Locker Sump SPACE 35: Fan Room (Hull)
SUBZONEDECK 30: Zone_Deck_030: RESIDENT SPACES: SPACE 34: Fan Room (Hull) SPACE 73: Refrigerator Machinery Room SPACE 88: Steering Gear Room	SUBZONEDECK 26: Zone_Deck_026: RESIDENT SPACES: SPACE 20: Electrical Equipment Room SPACE 78: Specialist Cabin (Male)(6) GrpA SPACE 79: Specialist Cabin (Male)(6) GrpA SPACE 80: Specialist Cabin (Male)(6) GrpA	SUBZONEDECK 20: Zone_Deck_020: RESIDENT SPACES:	SUBZONEDECK 14: Zone_Deck_014: RESIDENT SPACES:	SUBZONEDECK 10: Zone_Deck_010: RESIDENT SPACES: SPACE 5: Battery Locker and Charging SPACE 11: Bosun Storeroom (MainDeck) SPACE 33: Fan Room (Hull)	SUBZONEDECK 6: Zone_Deck_006: RESIDENT SPACES: SPACE 22: Electrical Equipment Room SPACE 69: POL & Paint Locker (Storage) SPACE 70: POL & Paint Locker (Service)
SUBZONEDECK 29: Zone_Deck_029: RESIDENT SPACES:	SUBZONEDECK 25: Zone_Deck_025: RESIDENT SPACES:	SUBZONEDECK 19: Zone_Deck_019: RESIDENT SPACES: SPACE 0: Aft Pump Room SPACE 21: Electrical Equipment Room SPACE 98: MMR Diesel (Hold) SPACE 99: MMR Diesel (1stPlatform) SPACE 101: Mechanical Workshop (General)	SUBZONEDECK 13: Zone_Deck_013: RESIDENT SPACES: SPACE 1: Air Conditioning Room SPACE 39: Fwd Pump Room SPACE 90: Electrical Switchboard Room	SUBZONEDECK 9: Zone_Deck_009: RESIDENT SPACES: SPACE 4: Auxiliary Propulsion Room SPACE 25: Electrical Equipment Room SPACE 92: Electrical Switchboard Room	SUBZONEDECK 5: Zone_Deck_005: RESIDENT SPACES: SPACE 10: Bosun Storeroom (MainDeck) SPACE 19: Electrical Equipment Room SPACE 91: Electrical Switchboard Room

Figure 6.10: Sample allocation via direct seeding using 19 communities.

6.3 Collective community preferences

When looking at a polar plot of speed and sea state for a seakeeping analysis (Figure 6.11), a naval architect quickly comprehends what pages of data would hide. The arrangements community needs similar ways of visualizing the mechanisms that steer layouts besides traditional deck plans. Like a polar plot that illustrates the response of a ship in all headings and at all speeds for a given sea state, arrangements visualizations are needed that portray the *tendency* of the set of spaces for all configurations.

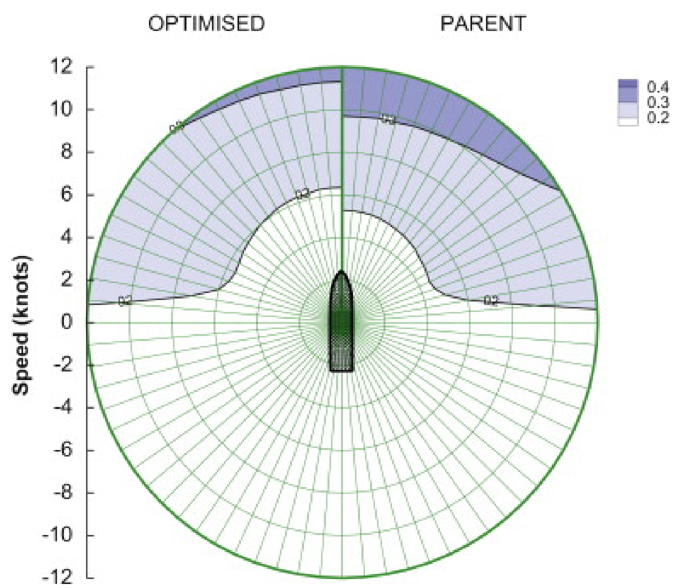


Figure 6.11: Example seakeeping polar plot. (Sarıöz 2009)

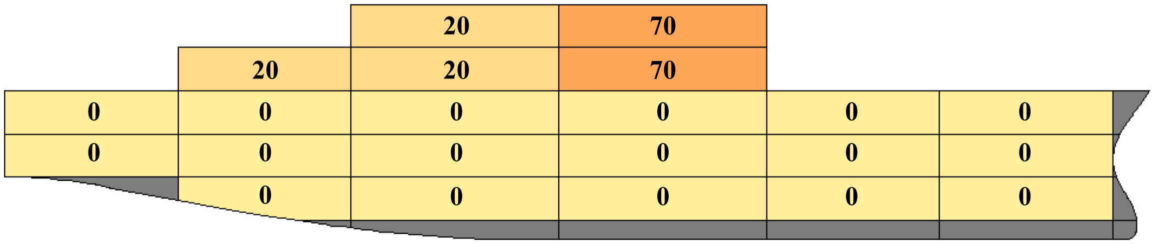
A heat map is used to illustrate the structural zones that are desired most among a set of communities. This map is a visual representation of the compartments' preferences for a particular zone – jointly with associated compartments. The resulting diagram provides insight into regions of potential interdisciplinary conflict, limited space or volume, or that require specific attention when assigning compartments and communities or managing routings.

The cumulative zone preference $P_{n,z}$ (Section 6.1.2) describes a community's preference to be located in any individual zone. Many communities prefer multiple zones, and therefore, there will likely be numerous overlapping preferences. By summing the $P_{n,z}$

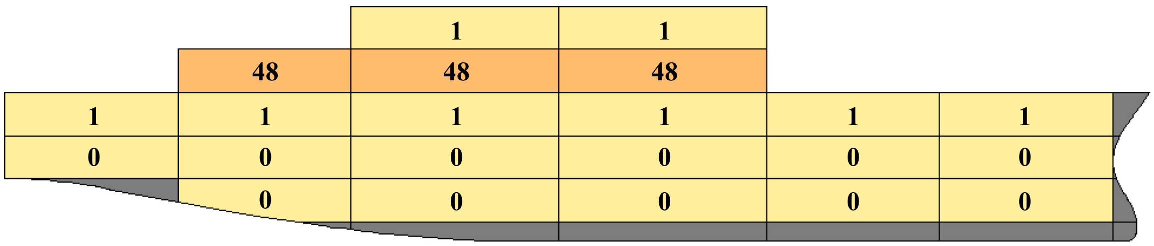
preference values over various partitions and zones, the collective preferences of multiple communities can be revealed. Each structural zone in the heat map is colored according to the collective community preference; darker shades are more highly desired.

In the deckhouse example that follows, two important communities share this region of the Habitability Ship. They are the Bridge community and the Medical Complex. The Bridge community includes the bridge and the commanding officer (CO)'s cabin and storeroom, and the Medical Complex community includes four medical spaces and an electrical equipment room. Figure 6.12(a) and (b) show the cumulative zone preference values (Section 6.1.2) for these two communities. Figure 6.12(c) shows the overlap of these two communities' preferences – from a joint compartment and community viewpoint. The community-based perspective provides a more nuanced view of the compartments' preferences than simply overlaying the global location preference maps of the bridge and medical facility (Figure 6.3). In this simple example, an electrical equipment room has been included. This viewpoint considers how the bridge and medical complex share the deckhouse while taking into account any other coupled compartments.

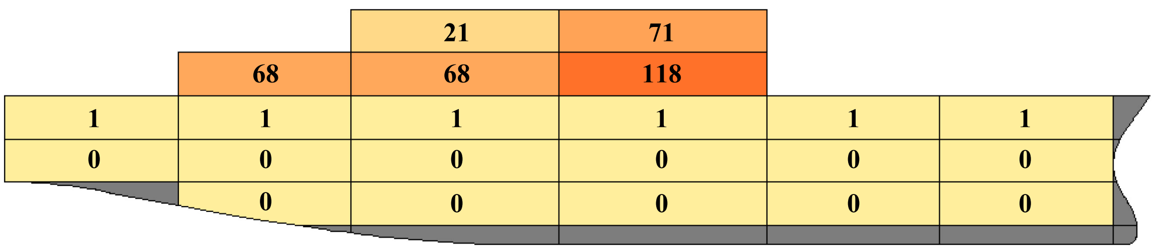
The overlap of communities is easy to identify for pairwise comparisons, but larger sets of communities are more difficult to envision. The result of summing the cumulative zone preferences for all communities of the Habitability Ship is shown in Figure 6.13. The colors represent a range of preferences from 34 to 264 points. (The point scales for Figure 6.12 and Figure 6.13 are the same, though the color scales differ.) Zones in the forward deckhouse and on the main deck near the superstructure are the most coveted zones. This simple, natural format for viewing potential conflict zones can help designers understand the propensity of the chosen systems (Section 2.4.2, page 39). If estimates for compartment weights were used as the basis for the coloring scheme, a weight-based heat map could be generated that would help designers understand potentially risky configurations more than a single value of the center of gravity does. This visualization provides designers the equivalent of a probability distribution versus a single expected value.



(a) Bridge community cumulative zone preference



(b) Medical Complex cumulative zone preference



(c) Collective community preferences

Figure 6.12: Joint compartment and community preferences for structural zones.

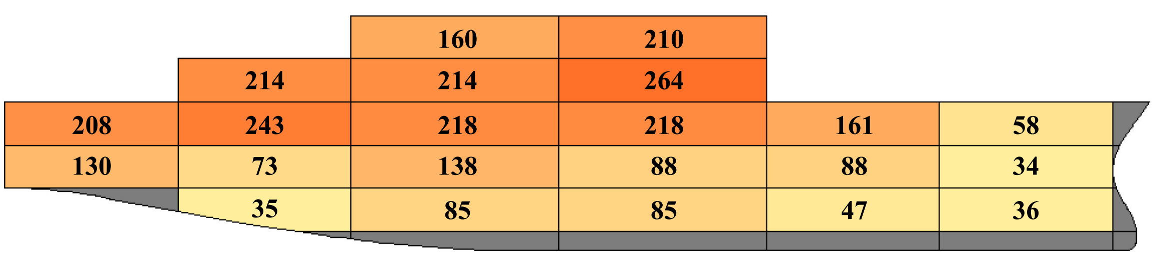


Figure 6.13: Heat map of collective community preference for the Habitability Ship.

6.4 Summary

Though traditional methods for generating ship arrangements have been effective in the past, there is an emerging need for new design methods that stem from a different perspective of general arrangements, particularly as higher fidelity arrangements and analyses are introduced into early-stage design. A network theory-based partitioning method has been paired with simple global location-based relationships to create a new method for allocating ship compartments (or equipment) to structural zones. The concept of a community of compartments from Chapter 5 was used with a new metric that expresses the collective preference of a set of compartments for various regions of the ship. The partitioning method enables the identification of collections of spaces that minimizes the number of detrimental relationships within each zone. This allocation method can be used for standalone design processes or as a seeding algorithm within ISA.

A distinct advantage over existing methods is the speed at which rough designs can be generated. The network-based algorithm shows promise as it is capable of generating allocations with very respectable average structural zone and weighted average space satisfaction values in a fraction of the time required by other methods. This is achieved through the elimination of an evolutionary design algorithm.

In a manual or semi-automated process, the network of communities (Figure 6.5) can provide guidance for community compatibility – nodes with positive or absent edges represent communities which are, on the whole, mutually compatible (the rare exception being when the positively- and negatively-weighted inter-compartment relationships from one community to another sum to zero). In the event that a net positive relationship between two communities conceals a less weighty negative relationship, designers have the opportunity to make adjustments accordingly.

Chapter 7

Visualizing multiple types of relationships

Section 2.4.2 identified a need to understand the nature of ship arrangements on a macro-scale in order to gain insight into non-dominated solution sets while offering guidance for down-selecting designs. It also mentioned a need for efficient, natural tools that facilitate designer learning and exploration. This chapter explores a new way to visualize the myriad types of relationships underlying an allocation or arrangement to begin achieving these goals. It does not attempt to measure the value of or impact of a design's characteristics, as ascertained from its relationships. Instead, the focus here is on creating a visual, qualitative assessment mechanism for human designers.

One challenge of using computer-generated designs is the tendency of designers to rely on overall design quality metrics for decision-making (van Oers et al. 2008). By their very nature, fitness functions distill complex information or a large amount of information into a single value. Thus, the richness and complexity contained in the design are hidden from the decision maker. There is currently little middle ground between the granular individual constraint and the aggregated whole-ship fitness value. Intelligent Ship Arrangements does have intermediate objective function values that can be assessed individually (Parsons et al. 2008; Daniels et al. 2009). The goal of this work is to aggregate the constraints (relationships) into a simple, understandable form that enables much of the richness to be retained. The visualization method described is not intended as a replacement for objective function values, but rather as a complementary source of information.

This chapter consists of three sections. The first describes a network that is built from multiple types of relationships. The second section describes a method for visualizing the network in the compartment allocation context. The final section illustrates the use of the visualization method and provides a few insights that can be learned from comparing two different designs and six types of relationships.

7.1 Multiple types of relationships

To this point, the set of ship design relationships (constraints) has consisted of two basic types: adjacency and separation. In Chapters 5 and 6, the two types were modeled using a signed network of positive and negative edges. (In Chapter 4, relationship types were not differentiated because both types represent some type of "influence" on another compartment.) Networks that model multiple types of relationships are called multiplex, multirelational, or multislice networks, depending on the mathematical representation.

The adjacency and separation relationship types are themselves aggregations of various relationship types; that is, there are multiple reasons *why* a compartment needs to be adjacent to or separated from another compartment. The possible reasons are numerous, and may be driven by, for example, ship production processes, operational necessities, or habitability standards. In this demonstration, adjacency constraints and separation constraints from the pre-layout Habitability Ship relationship network (Figure 3.6, page 57) have been divided into three sub-types each. The six sub-types represent different major underlying reasons for the existence of each adjacency or separation constraint. The breakdown is given in Table 7.1. The sub-types were identified by a naval architect and the author. Certainly, other relationship types and sub-types are conceivable and would be appropriate for investigations of different characteristics.

Table 7.1: Adjacency and separation relationships sub-types.

Adjacency	Separation
Distance/Proximity	Human factors
Ship producibility	Survivability or Distributed system
Functional group or Complex	Hazardous materials

Adjacency or separation constraints may represent more than one sub-type. For example, the Daily Provisions Storeroom should be near the Galley to minimize the distance that goods must be transported and because they both are involved in daily food preparation and service (functional group). Likewise, the dining rooms should be separated from mechanical workshops to reduce noise and traffic concerns (human factors) and to minimize the risk of contamination due to hazardous materials in the workshops.

7.2 Visualization of layout relationships

Visualizing the network of ship design relationships can help reveal important characteristics that would be difficult to highlight by analyzing constraints individually or by considering compartments on a pairwise basis (Newman 2010). Numerous visualization algorithms exist for laying out the nodes of a network in visually appealing or information-revealing ways. Most attempt to directly or indirectly minimize the number of edge crossings, place pairs of nodes with reasonable spacing across the entire drawing space, or maintain equal edge lengths to encourage readability (Kamada and Kawai 1989; Fruchterman and Reingold 1991; Battista et al. 1994). The concept of this new visualization is to display the nodes in a way that establishes connections between the relationship network and the completed ship arrangement. The nodes are positioned on a 2-D canvas so they reflect their respective element's location in a ship profile view.

The visualization requires an allocated (or arranged) ship (Section 2.3.3.1) and a pre-layout ship relationship network (Figure 3.6, page 57). Each element (compartment) in the ship is represented by a node in the network. Nodes are placed in such a manner so as to form a rough depiction of the zonal layout of the ship (Figure 7.1; compare to the zonal description of the ship in Figure 2.7, page 28). Edges are overlaid onto Figure 7.1 to show the overall structure of the relationship set relative to the elements' locations. Relationships can be viewed at multiple levels of specificity: all relationships, adjacency or separation relationships, or any combination of the relationship sub-types listed in Table 7.1. In general, the lengths of edges representing adjacency relationships should be minimized, and ideally, start and end in a single zone. Ideally, separation constraints should only exist only between zones.

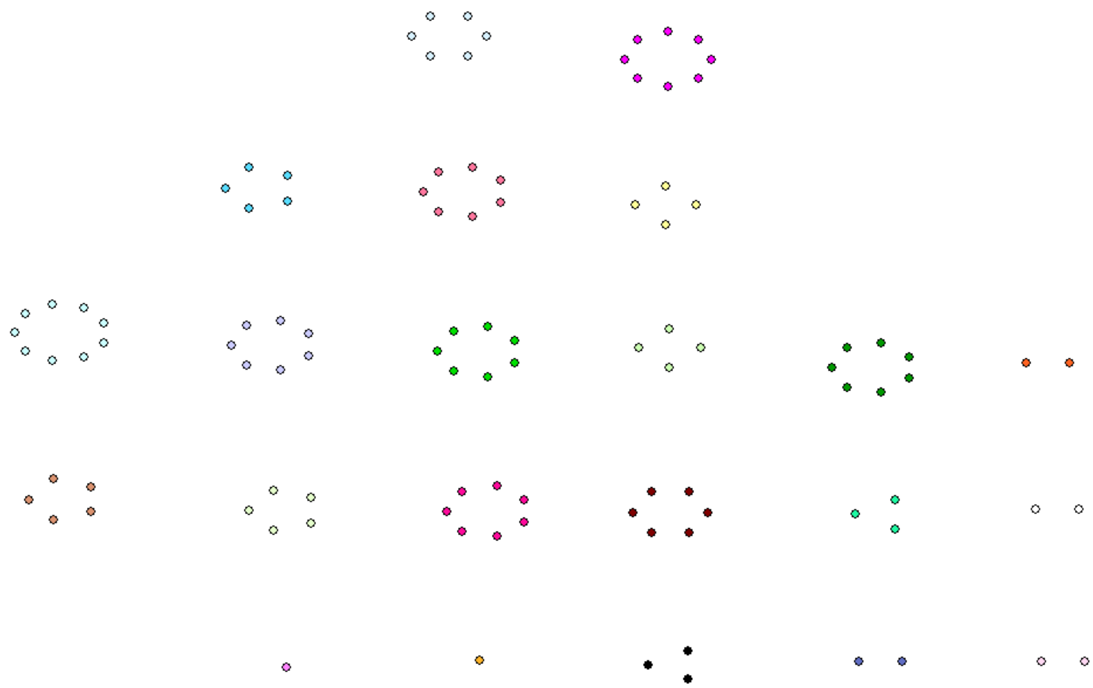


Figure 7.1: Compartment nodes arranged in a rough depiction of the zonal layout.

7.3 Visual comparison of relationship structure

The next six sections are divided into two halves. The first three sections present the three adjacency relationships sub-types, and the second three walk through separation sub-types. In Figures 7.2-7.4, edges represent adjacency relationships, and thus, starting and ending in the same zone is desirable. In Figures 7.5-7.7, as separation relationships, edges should lie between zones.

Two different ship allocations are compared: one was created using the community-based direct seeding method described in Section 6.2 (page 119), while the other was created using ISA's hybrid genetic algorithm and multi-agent intelligent system (HGA-MAS) (Section 2.3.3). The network-based allocation is the same as that shown in Figure 6.9 (page 124). One way to judge the quality of the designs is using ISA's allocation objective function (Equation 12, page 119). As a reminder, the allocation quality $U(\mathbf{x})$ is the product of the minimum structural zone satisfaction U_1, the average structural zone satisfaction U_2, and the weighted average space satisfaction U_3. Table 7.2 provides a comparison of the objective function values. From an objective function perspective, the ISA-generated design is clearly more desirable. Presumably, it represents a more balanced design due to ISA's built-in intelligence and detail in modeling fuzzy constraints. The value in the network-based approach is that it is extremely simple and is far more extensible to the necessary scale (number of and variety of items) that are needed for 3-D compartment and component layouts. Development of ISA agents would take significantly more modeling effort, a recognized limiting factor of all existing approaches (Section 2.4).

Table 7.2: Objective function value comparison.

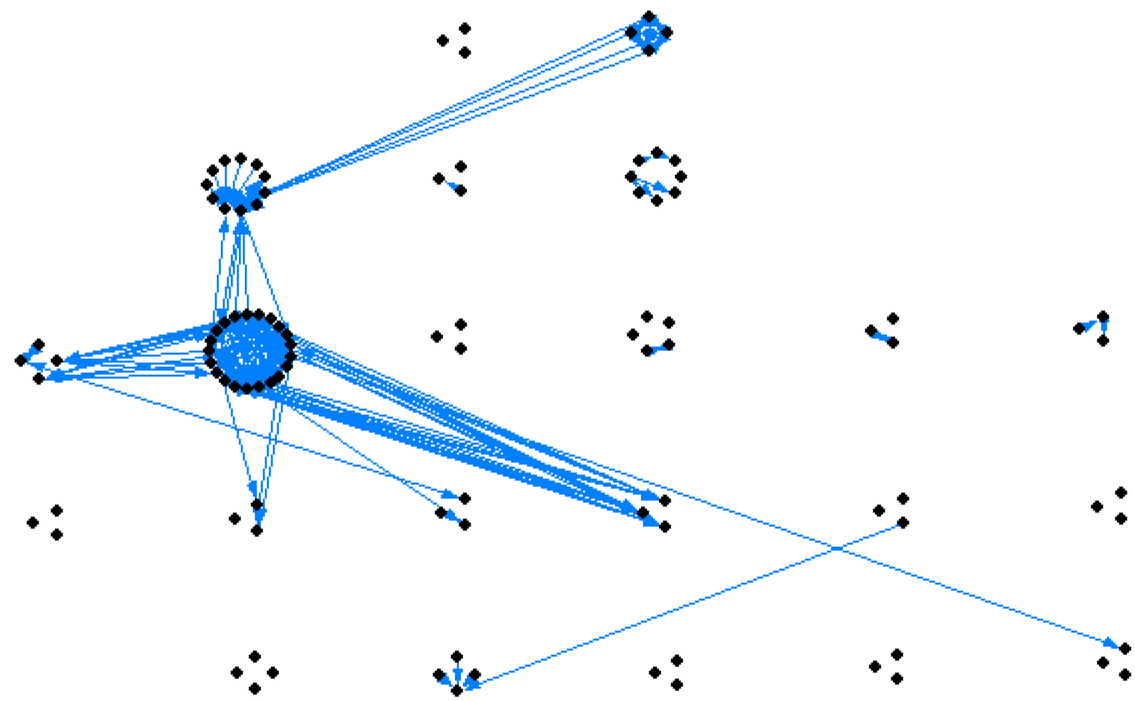
Objective function value	Network communities	ISA HGA-MAS
U_x	0.0	0.874
U_1	0.0	0.998
U_2	0.841	1.0
U_3	0.656	0.877

7.3.1 Distance/Proximity

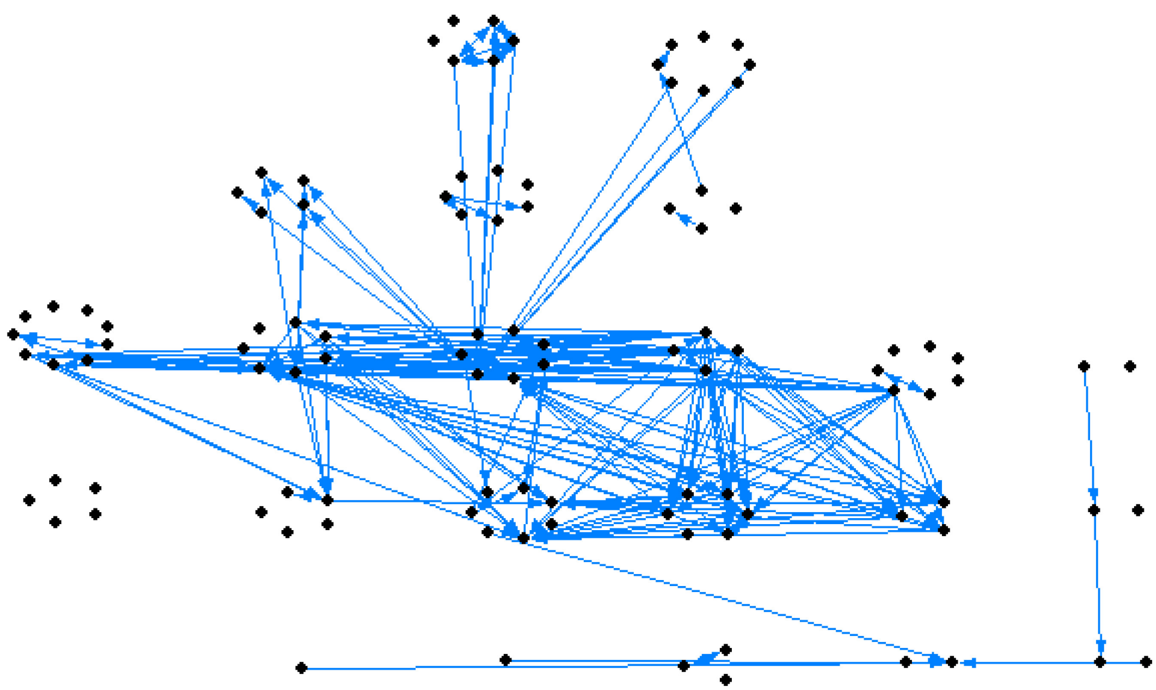
Designers always experience a tradeoff between satisfaction of distance-based constraints, compartment size, and zone density. If the relationships in Figure 7.2 represent personnel or materiel movement, the designer can gain a basic appreciation for potential access bottlenecks early in the design process without configuring and running simulations.

The lack of attention to zone capacities in the network community-based allocation scheme results in a configuration that supports minimum distance goals. The network-based configuration in Figure 7.2a yields a very tight concentration of relationships in the after portion of the ship. This is due to a large number of compartments located in a single zone. The network-based design possesses multiple zones meeting distance-based goals among a majority of the spaces in the zone.

The presumed overall balance of the ISA design is achieved by sacrificing Distance/Proximity constraints. The ISA-based design exhibits a more diverse and distributed mix of vertical and horizontal separation between compartments that prefer to be co-located within a single zone. The ISA-based design has horizontal relationships concentrated across the entire main deck. If a designer wanted to avoid violating the Distance/Proximity constraints, the network-based figure shows how to do it. This gives early guidance to the designer that a bulkhead configuration is needed that allows for a large open zone in the aft part of the ship while also meeting floodable length requirements. Possibly this leads one to a catamaran configuration so this upper deck is not submerged, or to a novel system of automatic doors that secure regions during flooding situations.



(a) Network-based



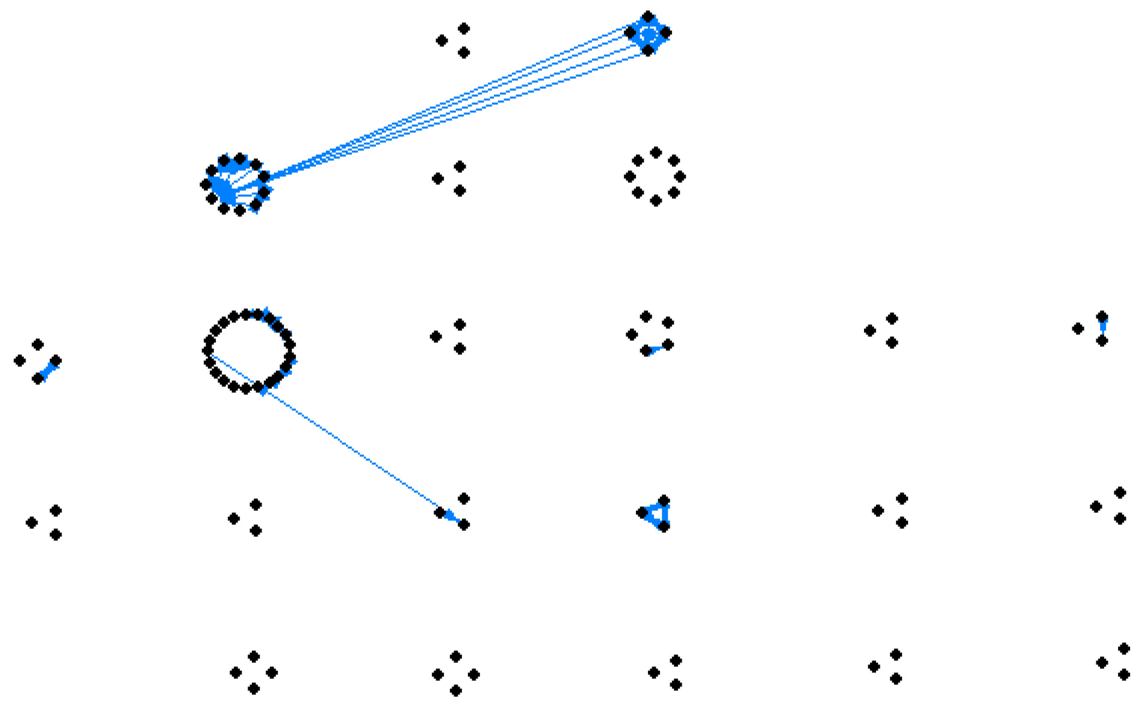
(b) ISA-based

Figure 7.2: Visualization of Distance/Proximity relationships.

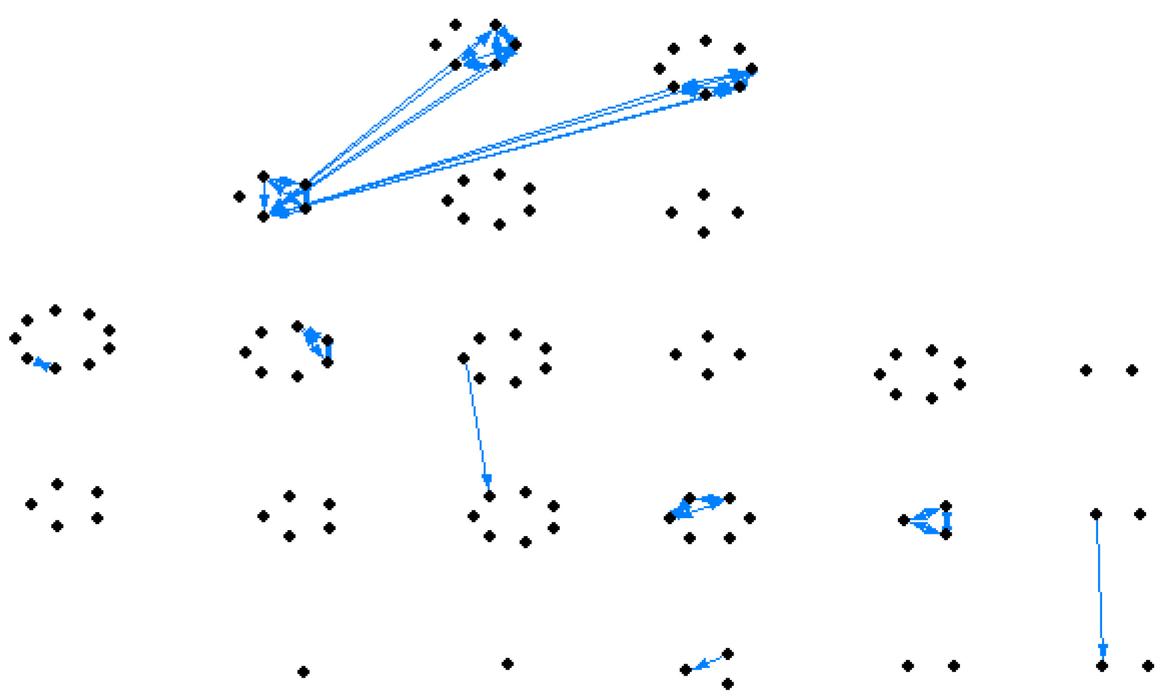
7.3.2 Producibility

In an ideal arrangement, producibility-related relationships should not cross zonal boundaries. If a relationship cannot be contained within a single zone, it should connect to a node in a neighboring zone. This arrangement would maximize the ability to do pre-outfitting and exploit production efficiencies. In Figure 7.3, the deckhouse region of both allocations demonstrates the challenge of positioning together compartments that should be co-located. In this case, subgroups of officer cabins have been separated for survivability reasons (Section 7.3.5) despite the advantages that could be achieved through mass installation of prefabricated berthing units. To see this tradeoff, compare the three affected zones with the density of separation edges in Figure 7.6.

As shown in Chapter 4, the relationships input into an arrangement algorithm can reveal the intent of the design (Section 4.6.2). The relatively small set of edges illustrates the constraint database's low emphasis on producibility-related constraints. As a result, one can expect solutions that do not specifically accentuate producibility. That being said, the combination of relationships has allowed many compartments to be co-located as desired. By comparing Figure 7.3 to Figure 7.2, one can identify duplicated edges; the adjacency constraints exist for multiple reasons. Furthermore, this visualization technique provides a quick, simple, and intuitive way to gauge the satisfaction of these constraints.



(a) Network-based

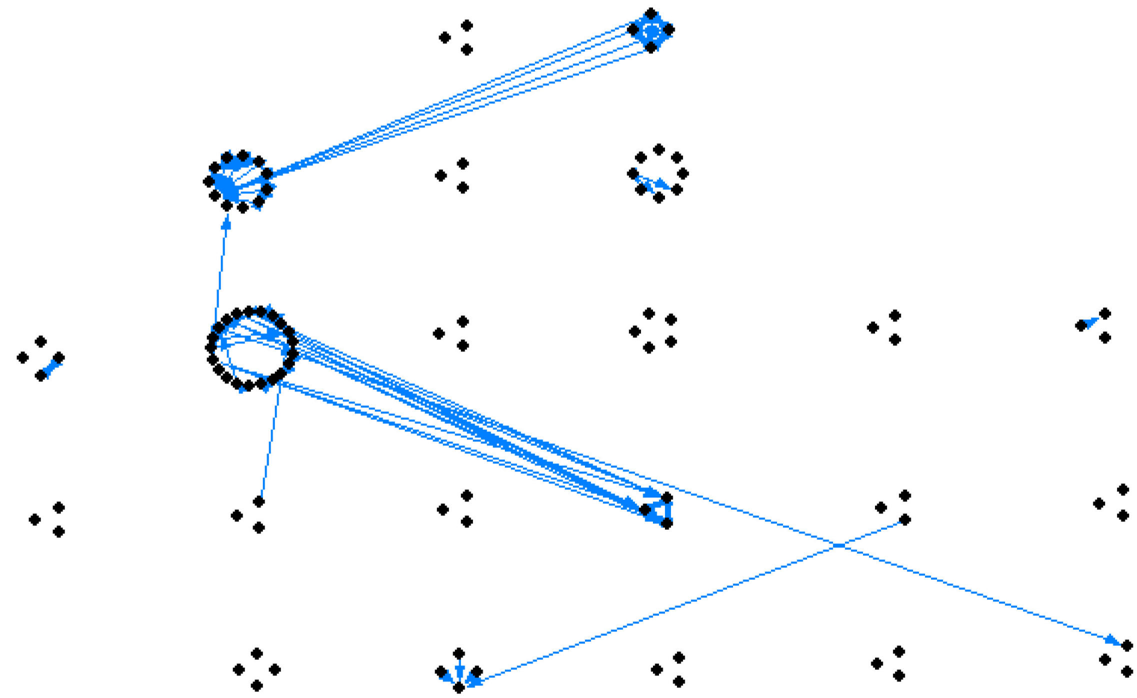


(b) ISA-based

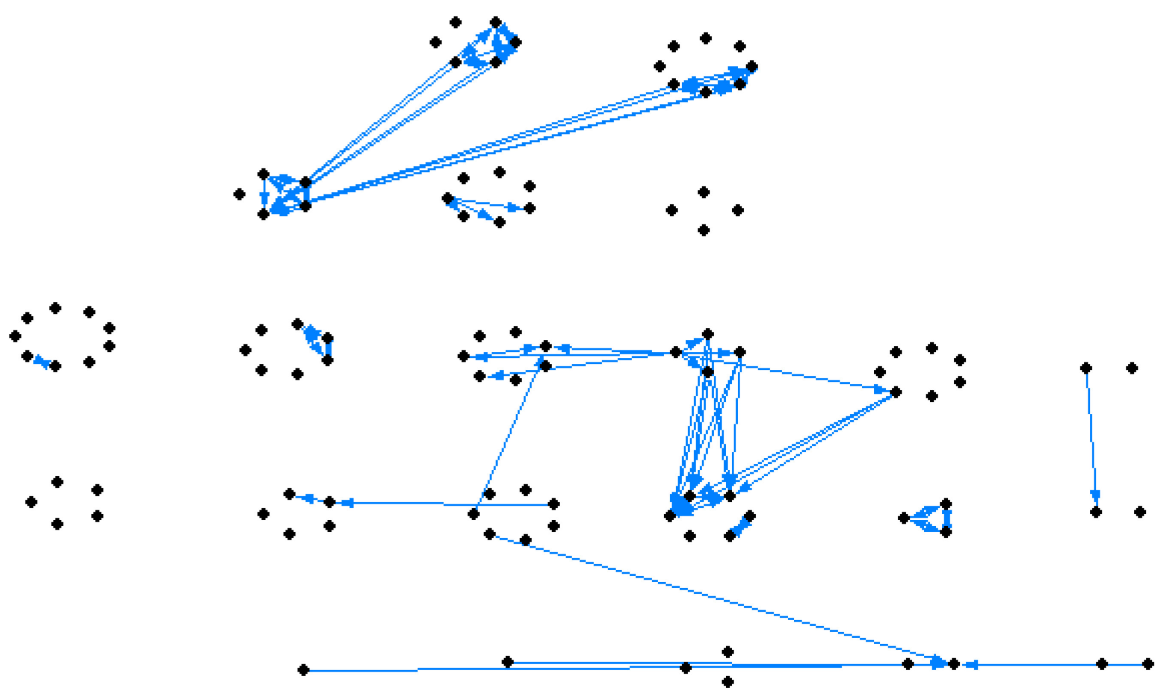
Figure 7.3: Visualization of Producibility relationships.

7.3.3 Functional group/Complex

A functional group is composed of compartments or systems that operate in service of a larger goal. Examples include aviation support, propulsion plant equipment and facilities, food preparation and service, or medical aid. Figure 7.4 shows the relationships that define functional groups. The network-based design has very concentrated sets of relationships, highlighting the importance of access corridors between certain regions. The ISA-based allocation has better vertical alignment of compartments in a complex, possibly necessitating additional or dedicated lifts. The intuitive presentation of the information make it easy to see that various edges straying across watertight zone boundaries low in the ship may hinder efficient access.



(a) Network-based



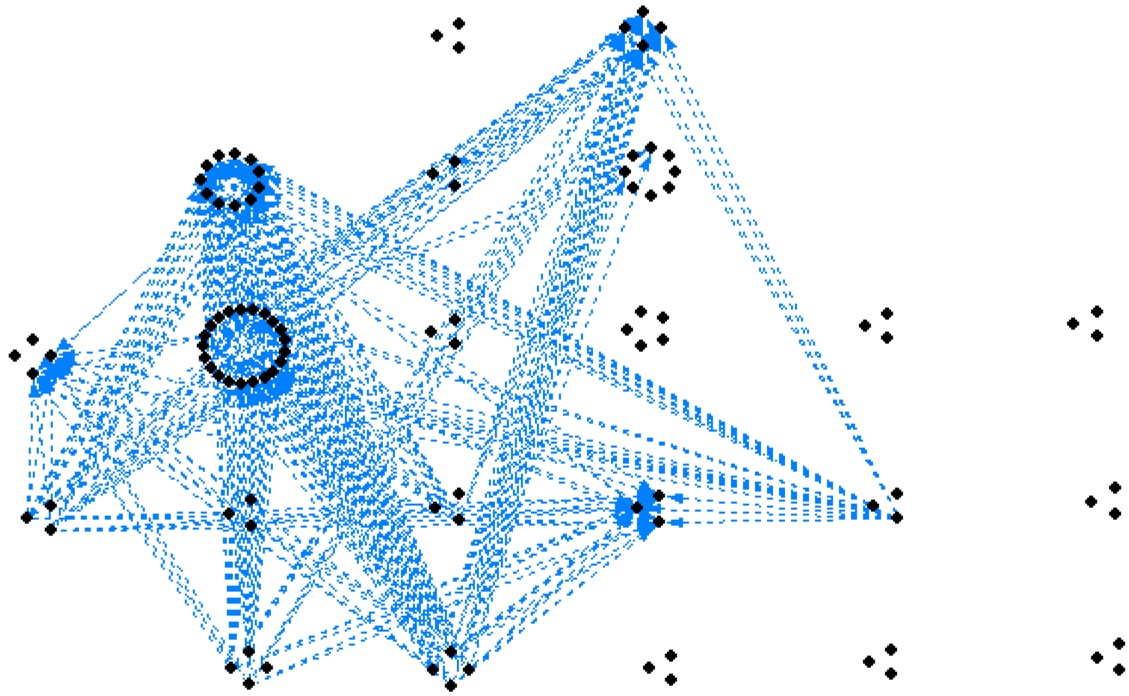
(b) ISA-based

Figure 7.4: Visualization of Functional group/Complex relationships.

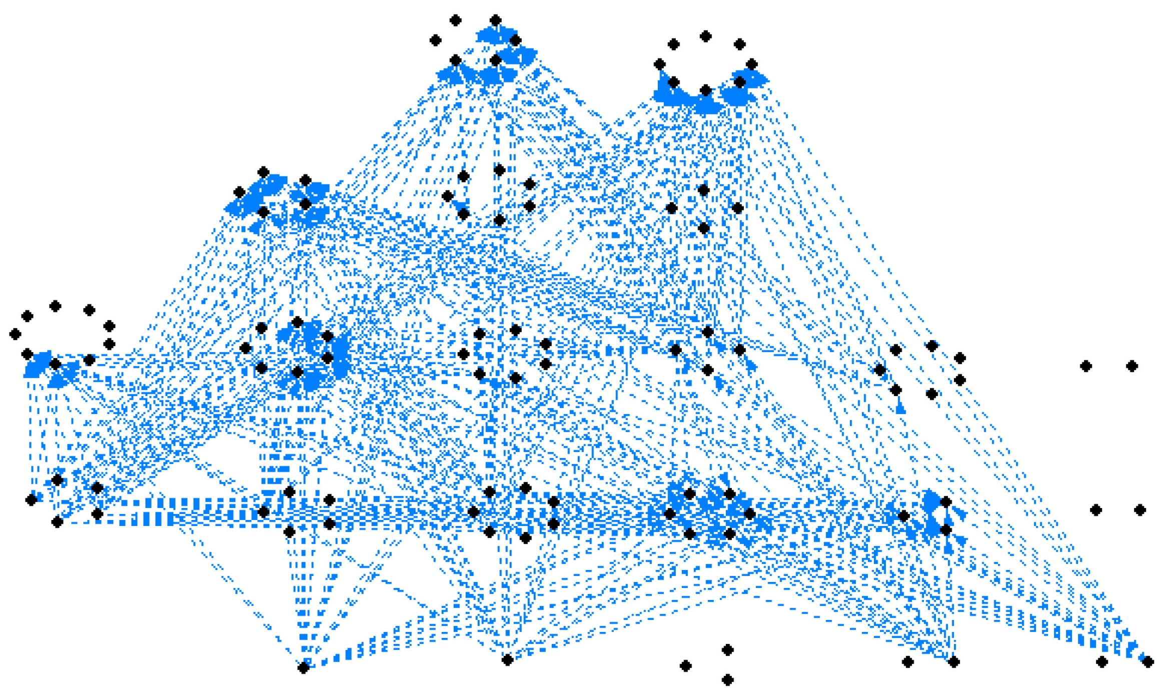
7.3.4 Human factors

The first separation constraint sub-type to be examined is Human factors. Since this is a separation relationship, the majority of edges should lie between zones.

In Figure 7.5, Human factors relationships affect a compartment in nearly every zone in the ISA-based design. The limited number of zones affected in the network-based design is partially due to a high concentration of compartments in two zones in the after part of the ship. However, dispersing the spaces to the surrounding zones would leave the forward half of the ship relatively unaffected. Another takeaway from Figure 7.5 is the locations of the point sources. The network-based allocation has several concentrated zones of emitters, particularly in the lower stern region. Zones containing an edge's tail tend to have multiple tails originating from that zone. This is in contrast to the ISA-based configuration in which many zones have a single compartment causing Human factors concerns. Again, each configuration defines a design methodology (concentrating vs. distributing influences) that is easily identified by viewing the diagrams.



(a) Network-based



(b) ISA-based

Figure 7.5: Visualization of Human factors relationships.

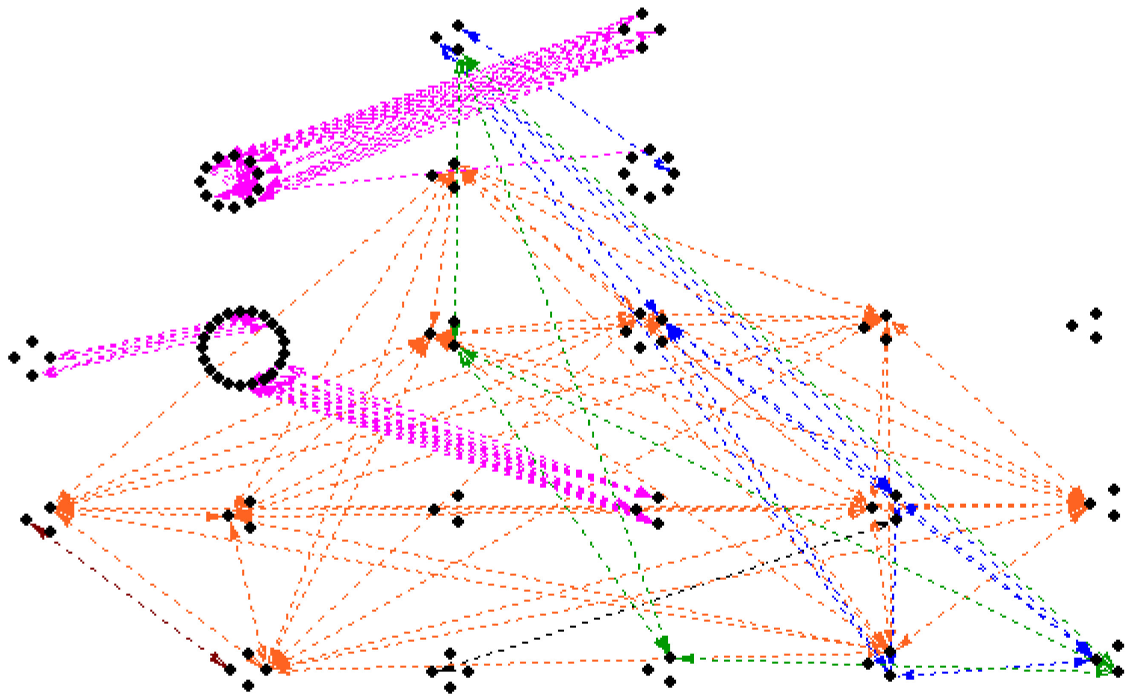
7.3.5 Survivability/Distributed system

Ships, particularly naval vessels, are designed with redundancy in mind to maximize the ship's ability to return home safely in the event of an emergency. Compartments and systems are distributed throughout the ship to maintain operational capabilities at all times. Other systems, such as ventilation rooms, are distributed throughout the ship to maximize performance and minimize wasted space and losses due to unnecessarily long piping or ducting runs. Distributed system elements in the ship relationship network have separation constraints among them to disperse them throughout the ship.

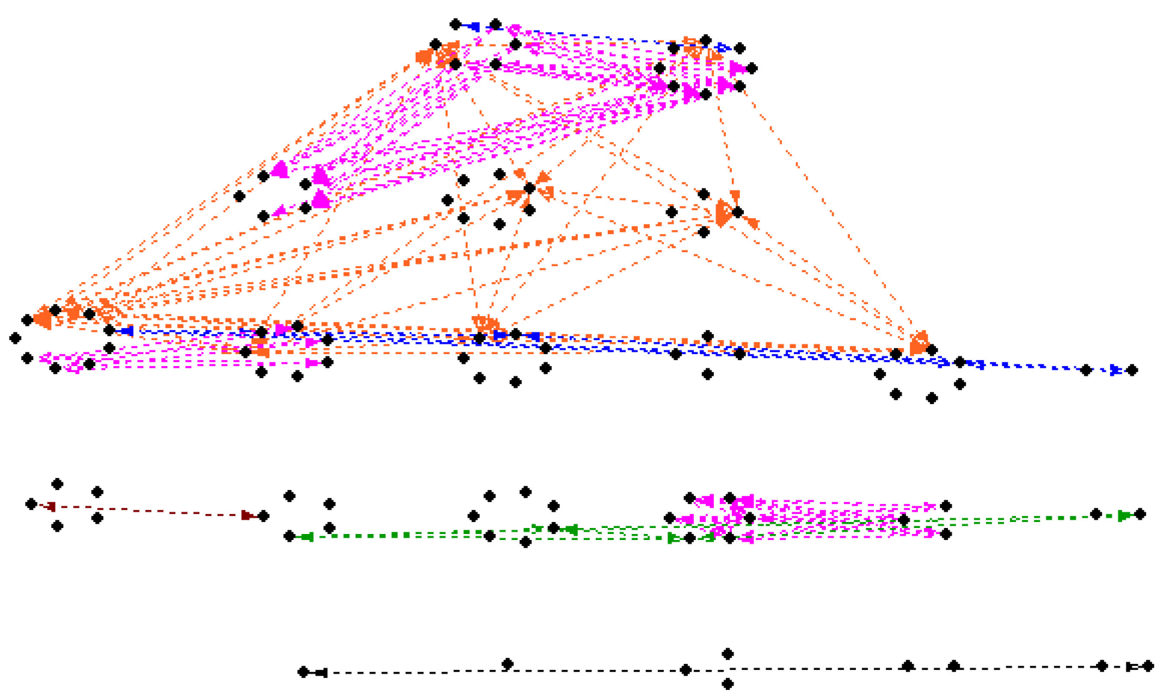
In this case, additional clarity is provided by breaking down the Survivability/Distributed system sub-type into its own sub-categories and by color coding edges according to system type. The diagrams in Figure 7.6 include four major Survivability/Distributed systems sub-categories: two electrical systems (green and orange lines), one ventilation system (blue), and officer/petty officer/specialist cabin groupings (magenta). The network-derived design has elements from each system scattered across the entire ship. ISA exemplifies an across-deck, rather than a vertical, approach to distributing systems. Neither approach is necessarily right or wrong; each reflects a different design philosophy.

It should be noted that some results in the network-based approach are poor decisions. The ventilation rooms (blue) located deep in the hull below the waterline is an example. These compartments would be more appropriately positioned along upper decks as in the ISA layout. A designer could quickly determine a new position for the lowest ventilation room by viewing the layers of relationships in which this element is included. From the overlays, alternative zones could be identified intuitively through visual inspection. For a first pass inspection, the designer would not have to identify the contents of each zone and subsequently conduct a pairwise comparison for possible negative impacts. The relational information is already provided in these diagrams in an easy-to-interpret format.

Regardless of the actual feasibility of an individual network-based layout, it provides a reality check for the set of constraints (the constraint database) in minimal time. The network-based approach contains no damage control logic, but the network-based configuration demonstrates that the database respects this concept. For example, if the string of blue edges that connect ventilation rooms were rotated 45° counterclockwise, it would lie along the Damage Control Deck as in the ISA-based layout. The existence of the line of ventilation rooms illustrates the design intent; it simply lacks the logic of where to put it. Thus, if the set of constraints were used in a more sophisticated and time-consuming algorithm, one can have confidence that designs with good survivability characteristics would result. The network-based approach gives assurance that more intelligent and complicated algorithms can provide feasible designs according to the input relationships.



(a) Network-based

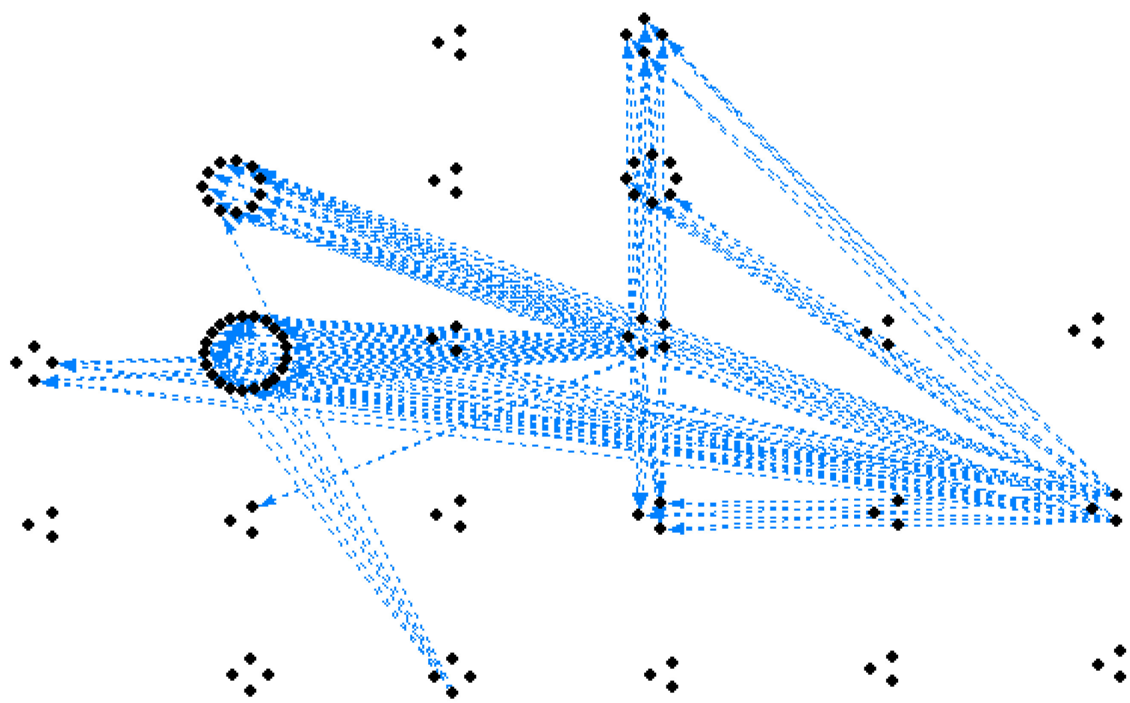


(b) ISA-based

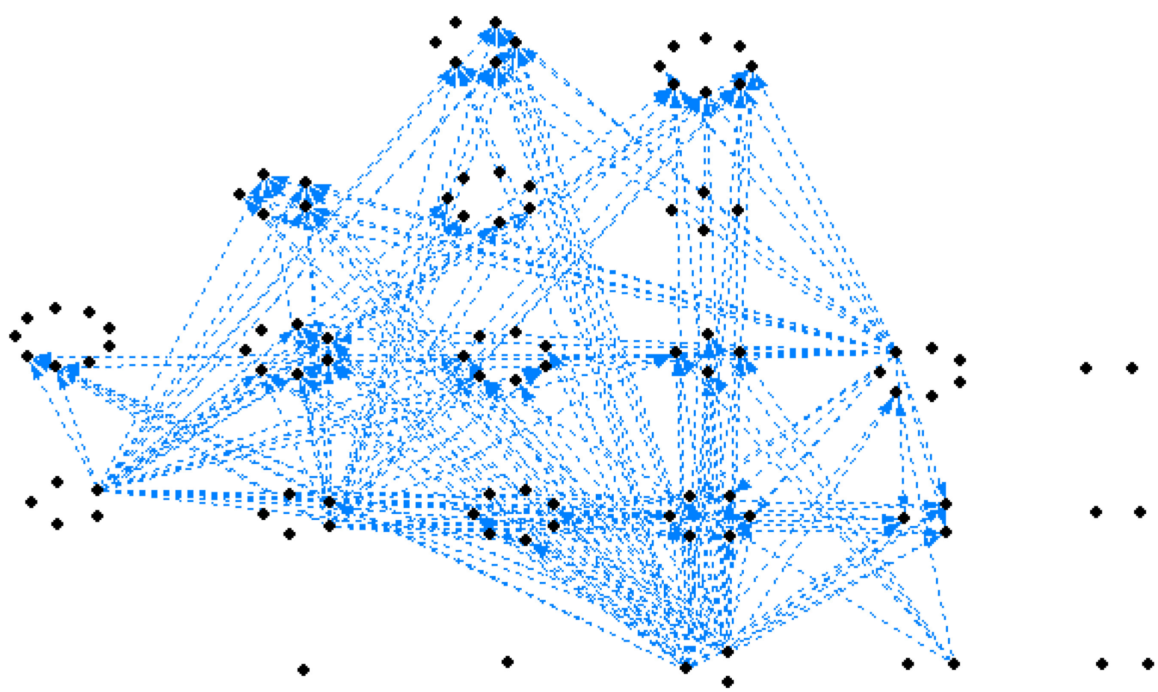
Figure 7.6: Visualization of Survivability/Distributed system relationships.

7.3.6 Hazardous materials

Ships are often self sufficient for weeks at a time, and therefore must carry a variety of hazardous materials and wastes that support and result from ship and mission operations. These materials may include petroleum-based oils and lubricants; paints; toxic, corrosive, or flammable chemicals; and solid waste. In Figure 7.7, both designs have compartments spread throughout the ship that are sensitive to hazardous materials. The designs differ in the location of the hazardous material storage facilities. The network-based design has a more concentrated set of sources (the engine room, one zone amidships, and one zone in the bow), meaning there are fewer point-sources to monitor as design progresses. The concentration could also represent an environmental risk should damage be sustained to one of those regions of the ship. In either case, visualizing the entire set of relationships within the context of the ship layout provides a designer with a concise yet comprehensive picture of the arrangement of compartments that are concerned with hazardous materials.



(a) Network-based



(b) ISA-based

Figure 7.7: Visualization of Hazardous materials relationships.

7.4 Summary

The new visualization concept presented is based on a network layout scheme that mimics a ship arrangement. Nodes are placed in a 2-D space that models a ship's zones as viewed on an inboard profile drawing. A basic classification scheme was developed to describe the ship's constraints in six different types. The relationships for each type were individually overlaid onto the nodes to present a macro-level perspective of the design relationships within the ship arrangement context.

As more elements are included in the network, these diagrams will become more involved and dense. Information could be conveyed clearly and simply by adding color or line thickness to the edges to contextualize relationships. Further subdivision of categories like Human Factors could reduce the number of edges displayed at any one time. In addition, the compartments in each zone could be collapsed into a single node, as was done in Figure 6.5 (page 117), with edges signifying aggregated relationships between entire zones.

This visualization method is certainly not perfect because it relies on a network representation. Some relationships are complex, and cannot be defined with a simple edge direction. An example was shown in Figure 2.9a (page 30) where an adjacency constraint is defined to be "close, but not too close." However, when used at an appropriate stage in the preliminary design process, this new visualization technique can provide a more holistic view of the constraints being placed on a ship than is currently available.

Chapter 8
Conclusions

This final chapter is divided into two sections. The first recaps the contributions asserted in Section 1.2.3 and reviews the work completed in support of those claims. The second section provides the author's thoughts on potential future extensions for network-based ship arrangements research.

8.1 Review of intellectual contributions and work completed

This dissertation has confirmed the relevance and value of network science to the understanding and generation of ship arrangements. The results provided in the preceding chapters are the product of a combination of the innovative application of network science concepts to ship general arrangements and the development of new methods. The following paragraphs recount the novel contributions enumerated in Section 1.2.3 (page 13) while providing additional support for the stated claims.

Recognizing a need to shift from the current trajectory toward higher-fidelity 3-D layout models and re-vectoring toward a perspective that focuses on understanding and respecting the fundamental underlying relationships among elements within those models.

Section 2.3.4 describes the author's attempt at developing a system for generating 3-D component layouts using communicating agents. In the end, that research prompted several realizations that incited the author's change of direction. Attempts at increasing model fidelity along the current track only create a higher modeling demand on the designer, which is an undesirable consequence. Geometrically-based approaches remain brute-force tactics for solving a difficult problem because the mechanisms do not work with the fundamental relationships that define the problem. However, the network-based approach outlined in this dissertation enables naval architects to approach the arrangements problem in a radically different manner. Rather than generating layouts as a means of learning about the design, the author adopts an innovative methodology that emphasizes analysis of the design relationships themselves in order to understand better the nature of the arrangement problem to be solved. Network science furnishes an appropriate means for abstracting the analysis away from geometric representations.

Re-conceptualizing the traditional set of design constraints used for concept evaluation as a network of design relationships to be used as an information source input for analyses.

The new focus on direct analysis of design relationships presented by the author requires an atypical perspective of the information designers currently use. The opening sections of Chapter 3 describe the author's translation of traditional, post-layout evaluative design constraints into pre-layout sources of information. Specifically, the constraints become relationships. This is an important distinction because it facilitates direct study of the requirements and constraints input into ship layout processes. Knowledge that a designer would typically not obtain until the end of a design study is now made available at the beginning, giving designers a more complete understanding of the set of constraints prior to drawing layouts.

Identifying and applying methods for highlighting and ranking the embedded drivers of an early-stage arrangement prior to developing spatial layouts by directly analyzing the network of design relationships (constraints) in a methodical and holistic manner.

Existing ship arrangement processes rely on inference-based investigations guided by designers in an ad hoc manner to build a limited picture of the interplay among the relationships that dictate ship layouts. This dissertation presents a systematic analysis framework that lays the foundation for more fundamental and rational discussions than those based on intuition. The introduction of these mathematically-centered methods to the field of ship arrangements endows researchers and practitioners with methodical analyses that yield consistent and comparable results. Unlike existing methods that consider individual constraints sequentially, the methods introduced in this thesis examine the entire ensemble of relationships concurrently. These new concurrent procedures provide the ability to elucidate drivers based on higher-order effects. Obtaining this information is now not dependent upon the ability of the designer to extract it, the complexity of the design, or the time allotted for the design study.

Degree centrality, hub/authority centrality, and hierarchical analyses are shown to provide consistent rankings of ship layout drivers embedded within a set of relative location relationships. The results would be deemed intuitive by naval architects familiar with the design concept demonstrating the suitability of the analyses to early-stage arrangements. Furthermore, the hierarchical approach revealed the ship designer's original intent, as expressed through a set of design relationships, highlighting the method's ability to decipher information encoded in the ship relationship network. Degree centrality and a version of the hierarchical approach that employs random edges identified drivers prior to generating arrangements, a radical deviation from the current process of pouring over sets of designs to infer the ranking of relationships. The true utility of these methods can be exposed by applying them to ship concepts containing emerging technologies and unfamiliar combinations of systems.

Clustering shipboard elements (compartments, components, systems) into collections of mutually-compatible elements with the intent to minimize the degradation of other items located in the same region of the ship.

The ship arrangements problem is largely one of managing relationships among compartments and systems so it makes sense to systematically identify sets of mutually-compatible elements. This dissertation builds a case for a rational approach to grouping shipboard items based on their relationships to one another. The partitioning method proposed in this thesis accounts for the secondary and tertiary relationships that make the design process iterative and that are often not discernible in the earliest stages of design. The author introduces a methodical and holistic approach for aggregating shipboard items in Chapter 5; the mathematical formulation diverges from previous approaches based on functional decompositions and experience. The new method is compatible with existing approaches that consolidate compartments and systems into functional zones or blocks for preliminary assessments. The communities are identifiable using only the network of relationships giving designers the opportunity to estimate more accurately the properties of each block before initiating the geometric modeling process.

The signed Habitability Ship relationship network was divided into multiple numbers of partitions exposing a multi-scale picture of the set of ship compartments. The resultant communities contain (to the greatest extent possible) mutually-compatible elements so they can be co-located within the ship without causing detriment to other elements. The compatibility is determined by partitioning the signed relationship network. Dividing the network into four or more partitions provided a noteworthy result: infrastructure and distributed systems compartments were located in communities with other ship functions providing a contrast to the dedicated infrastructure regions prescribed by other methodologies.

Allocating communities of ship compartments to ship structural zones in a manner that respects each community's aggregate global location preferences to the greatest extent possible.

Eventually ship layouts must be geometrically defined to conduct analyses in various domains making it necessary to design a spatial arrangement plan. Designers do not randomly place shipboard elements in isolation, but instead continually keep related items in the back of their mind to inform placement decisions. Chapter 6 describes a new community-based (or functional complex-based) seeding mechanism for compartment allocations that follows the human thought processes more closely than existing single-element routines do. The communities discussed above respect the inter-element relationships as desired, and therefore they form the basis of the seeding mechanism. The author suggests and demonstrates one potential domain-specific function and algorithm for mapping network space to ship space. The process for assigning communities to structural zones utilizes a new metric expressing the collective preference of a community of elements to be positioned in a particular zone. Reasonable allocations are created rapidly and without iteration.

Mapping and visualizing compartments' preferences – jointly with their associated compartments – for particular regions of the ship, providing insight into areas that may require specific attention when creating layouts.

The two visualization techniques developed in this thesis provide "efficient, natural tools for … evaluating general arrangements to promote designer exploration and learning" (Section 2.4.2). The first is a heat map of the collective preference of communities to be located in structural zones. The map highlights regions that are likely to need additional deliberation when allocating resources due to the high value placed on them by numerous shipboard elements. This joint perspective is novel because it provides a more nuanced view of the compartments' preferences than simply overlaying global location preference maps. It considers how functional complexes share regions of the ship while also taking into account items that are not always coupled. Two examples demonstrated the ease of identifying coveted zones.

Developing a visualization technique that helps designers establish connections between networks of inter-element relationships and the completed ship arrangement.

Chapter 7 introduces an innovative technique for visualizing the relationships among shipboard elements once they have been positioned with the hull. This new method for assessing layout relationships provides designers the ability to interpret and understand the structure and patterns of relationships as manifested in various spatial configurations. Differing layout philosophies and styles are readily apparent by contrasting images from alternative arrangements. The unique, domain-specific configuration of the network's nodes and edges helps designers establish connections between the relationship network and the completed ship plan to gain a holistic view of the constraints placed on a ship layout. The technique's straightforward nature provides designers an intuitive appraisal of multiple relationship types.

8.2 Potential future directions

This dissertation began with the following challenge: *Develop a method to generate and analyze 3-D distributed system and compartment arrangements without designing a ship* (Section 1.2.1). The methods and results presented in this dissertation have laid the foundation for further investigations in line with this challenge. The fundamentals underlying all analyses presented in this dissertation are general enough to permit extension to compartments *and* components. In fact, the compartments of the Habitability Ship are nothing but generic ship "components." Both compartments and equipment have underlying relationships with other elements for various reasons. In this sense, both can be modeled as nodes in the same network. Another view follows the relationship of compartments and structural zones: communities of components form compartments just as communities of compartments form zones. In this way, a multi-scale or hierarchical clustering scheme could be used to represent compartments and zones in the same network.

As this dissertation was an introduction of network science to the field of ship arrangements, much remains to be studied. This section covers four potential topics the author believes would be worthy of future investigation.

8.2.1 Verifying additional ship types

The most obvious need is to validate these results with additional classes of naval vessels and ship types. The more data points one has, the stronger conclusions one can make. One of the goals of this work and others is to reduce modeling demands and the workload of designers. Therefore, reliability of information and analyses is critical so time is not wasted using improper assumptions or misleading information. Though the process of analyzing the relationship networks is straightforward, generating the set of relationships remains a tedious endeavor.

8.2.2 Varying edge weights

Some challenges exist when attempting to incorporate components into the layout scheme. Along with them comes an inherent desire to base edge weights on performance measures. When positioning components, the challenges of determining edge weights become more pronounced and one must be attentive to carefully crafting appropriate edge weight definitions. Section 5.3.1 discusses a few of the challenges of selecting appropriate edge weights.

Insights could be gained from comparing Chapter 5's results with those generated from different edge weightings as discussed in Section 5.3.1. The effect of alternative edge weight definitions could lead to interesting comparisons. A few additional example definitions include the percent of component degradation or overall mission degradation due to non-satisfaction of the constraint or a probabilistic performance value. In early-stage design, these alternate values may be difficult to determine. One potential a work-around is to use a machine learning process in which edge weight probability distributions are continually updated based on generated allocations. This would form a closed loop of spatial layouts informing edge weight distributions for future design concepts. Following this idea, the stability and variance of edge weights could be studied to learn which relationships are sensitive to final relative spatial positions.

The idea of varying edge weights also leads one to consider the sensitivity and significance of communities. Portions of communities likely will change as different edge weightings emphasize different values and objectives. Designers would need to consider carefully the tradeoffs of splitting highly significant communities.

8.2.3 Exploiting multiplex and multislice networks

Multiplex and multislice networks were only briefly touched on in Chapter 7, however, they show great potential for integrating a variety of ship layout aspects into a single, cohesive framework. A few potential applications include:

- multiple types of physical and logical relationships (as in Chapter 7),
- passageways and egress routes on multiple decks,
- cable, pipe, and ducting runs,
- generations (iterations) of solutions within an evolutionary design algorithm, or
- multiple ship loading conditions or operational conditions (cruising, battle, etc.).

Since all of these alternatives can be modeled using variations of a relationship network, they theoretically could be combined into a unified analysis. With sufficient understanding of the relationship network, designers may be able to emphasize specific attributes in layouts according to the designer's strategy and goals.

Regardless of which directions future researchers take, it is clear that network-based analyses possess great potential to assist naval architects continue learning about the fascinating intricacies of early-stage general arrangements.

Appendix A: NICOP Project Year 1 Report

Preliminary Ship Design General Arrangements Naval International Cooperative Opportunities in Science & Technology Program (NICOP) Project

Year 1 Report 2011-2012

June 2012

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1 INTRODUCTION

This is a new section under "Design for X" State of Art reports, however some of the background has been addressed in previous IMDC SoA reports particularly those addressing Design Methodology (Andrews et al 1997, 2006, 2009). Given that there is a new initiative underway that is combining research in three major marine design centres it was considered worthwhile both taking stock of the State of the Art in ship layout design particularly in regard to initial or preliminary ship design, where the new initiative is directed.

This section of this D for X report commences with two review sections, firstly on preliminary ship design process and why it can benefit from an architecturally based approach, and secondly, a review of ship design approaches and research on layout methods applied to various ship types. This then provides a basis for the three current research programmes, now being brought together under a project funded by the US Navy Office of Naval Research (ONR). The separate research activities into ship architecture and layout undertaken to date by the three universities of University of Michigan (UM), University College London (UCL) and Technical University Delft (TUDelft) are then described inorder to appreciate how these might be developed to improve the preliminary design of future naval vessels by incorporating layout design early in the ship design process.

2 PRELIMINARY SHIP DESIGN

2.1 The Preliminary Ship Design Context

It might seem there have been a lot of papers on preliminary ship design, however generally they are either describing a specific ship design or talking in general about different ways in which ships may be designed. In the former case, especially when the design may only have been completed at that stage to a preliminary design or concept level, then it is usually just the final design outcome, rather than a detailed step-by-step description of the evolution of the design, for which a level of technical description is provided (Eddison & Summers 1995, Eddison & Groom 1997). If the description is of a completed design for a built ship then some detail of the early evolution is usually provided, as this is crucial and records major design choices, but these details are not sufficiently comprehensive to understand how the preliminary design itself evolved. (See for example Honnor & Andrews (1982) for the Royal Navy's INVINCIBLE Class, Bryson (1984) for R.N. Type 23 Frigate and Leopold & Reuter (1971) for the U.S. Navy SPURANCE and TAIWAN Classes.) When it comes to generic expositions on ship design, if covering the whole ship design process, insufficient detail is provided to outline the preliminary steps beyond, at best, a few technical examples of the concept design effort (Gale (2003), Ferreiro & Stonehouse (1994).

Most discussion of ship design in general and preliminary design in particular has focused on what might be considered to be design managerial, organisational and process perspectives. An example of this is Andrews' (1994) paper on preliminary warship design, which spelt out the stages in preliminary design that had been adopted by the UK Ministry of Defence's Future Projects Design Group that he headed up in the early 1990s. In particular it laid down a graduated process, appropriate to a major new warship concept, with three overlapping stages within the overall concept phase. Example projects that were being addressed were the next escort (which subsequently became the R.N. Future Surface Combatant (Andrews 2000)) and the Future Carrier (CVF) (Eddison & Groom 1997), both of which were commencing concept consideration at that time. The three stages were denoted as:

- Concept exploration;
- Concept studies;
- Concept design.

Each stage had a distinct objective in ensuring by the end of the overall concept phase, what the UK MoD now denotes as Initial Gate (MoD 1999), that a comprehensive exploration of the solution space, a comprehensive study of the main parameters and style issues, and a comprehensive investigated trade off study have been preformed. This approach was intended to result in a single preferred option, which matched the emergent (and affordable) operational requirements and was the basis for proceeding into

Feasibility (now designated Assessment by UK MoD (MoD 1999)), This exposition was done with design examples but not showing the intermediate steps to each of those concept designs, described in the Andrews & Pawling (2008) paper.

Two earlier papers by Andrews (1986, 1987) described the overall and the preliminary ship design process as part of that author's particular approach to ship design that culminated in the general exposition of his "Architectural" approach to ship design in (Andrews 2003a). Several examples of applying this approach to preliminary design tasks, for actual "real world" design investigations, are summarised in Andrews & Pawling (2006) and these outputs can be compared to purely academic exercises using the approach, such as those early cases described in Andrews (1986, 1987).

It has been acknowledged, by many eminent practitioners, that Preliminary Ship Design (PSD) is a complex process (see Turner 1994, Graham 1982, Rydill 2003). Andrews (1998) at Table 4 in that paper distinguished between a range of types of ship design in terms of their degree of novelty, from a stretch version of an existing design to the extreme of a radically new technology, typified by the U.S. Navy's 1970s 3KSES combatant (Lavis et al 1990). Neither the least or the most novel of this design spectrum would be appropriate examples on which to base consideration of the PSD process, nor, indeed, would the type ship or evolutionary design approaches, since they are heavily constrained by the specific designs they draw upon. We are thus left with essentially new or *ab initio* designs, which might be designs conventionally produced by the methods discussed below, or designs produced by such as the "architecturally integrated approach" (see (Andrews 2003a) and (Andrews & Pawling 2006) and outlined further in the later parts of this section on Design for Layout.

It is taken as axiomatic that the main motivation for preliminary ship design should be the elucidation of the initial requirement perception of the operational or naval staff and to thus inform that dialogue between the naval staff and the concept designer with a trade off process that balances the operational needs with what is perceived to be affordable (Andrews 2003b). Thus presentation of case studies, such as that in Andrews & Pawling (2008), is primarily to provide a detailed sequencing of the technical evolution of what would (probably) be just one option among several. In that instance a trimaran solution to a U.S. Littoral Combatant Ship requirement was the example chosen. Furthermore any requirement for a new ship concept would be far less clear at design commencement than this specific case, with the eventual "preferred option" at Initial Gate usually emerging from a difficult and often protracted trade off exercise, where affordability looms large. So the lack of the "requirement elucidation" element in this 2008 case study had the advantage of not complicating the main objective of that paper in presenting a technical case study showing a preliminary ship design evolution. With this proviso it is now appropriate to briefly review the general process of preliminary design.

2.2 The Preliminary Ship Design Process

Given the overriding importance of the initial ship design process in creating a new ship design by setting the "skeleton" on which the subsequent design is built, it can be considered surprising that there has been little direct discussion, over the years, on the specifically technical nature of that process. This is considered to be due, at least in part, to the fact that the vast majority of ships are evolved directly from specific previous designs. However, it is also in part due to the sensitivity of individual preliminary design organisations in not revealing the commercial or security aspects of their "Intellectual Property". The clearest exposition on the preliminary design of mercantile ships is that by Watson & Gilfallin (1977), now more than 30 years old. Perhaps the nearest equivalent from the naval ship design field is, surprisingly, from the highly sensitive world of submarine design. This is the three page "submarine design procedure" presented by Burcher & Rydill (1990) in their classic text book on concepts in submarine design. Unlike Watson & Gilfallin this does not give specific algorithms, though much of the book provides the basis for populating the various steps in the sizing procedure. However neither of these submarine or mercantile expositions takes a particular example and shows its stepwise development through the initial design process, hence the intention behind Andrews & Pawling (2006) was to provide such a description.

Lest it be thought there have been few publications on the nature of preliminary ship design, attention is specifically directed to the first State of the Art Report on Design Methodology (Andrews et al 1997) which included sections on Preliminary Ship Design Methodology and on Naval Ships and Submarine Design Methodology. These two sections are considered, with their 33 and 64 references respectively, to provide a comprehensive review to that date of the literature in the field. An update on the mercantile and naval ship design methodology was provided in the 2006 IMDC SoA report on Design Methodology (Andrews et al 2006). A further "state of the art" overview was provided by Gale in Chapter 5 of "Ship Design and Construction" and which is entitled "Ship Design Process" (Gale 2003). However, like most of the publications reviewed in these IMDC State of Art reports, this focuses largely on procedures and issues related to the environment in which ship design is practiced, rather than specifically on the progressive technical steps.

The use of computers to undertake a range of design explorations has also been characterised by presentations of a general nature with usually one or two example design outputs from the end of the concept process, rather than detailed expositions of the technical process including specific intermediate design solutions, as is presented in Andrews & Pawling (2008). An early naval ship design example of the general type, somewhat akin to Watson & Gilfallin (1977), was due to Eames & Drummond (1977). There have also been examples of a range of comparative design studies being presented, notably by Garske & Kerr (1981) and Mistree et al (1990), which give insights into the nature of concept exploration through altering various input parameters. An early computer supported investigation by Andrews (1984) varied both inputs and hull form parameters and this has been greatly extended by more recent work at UCL by MacDonald et al (2004) and, specifically using genetic algorithms, by Vasudevan & Rusling (2007). What all these studies reveal is the nature of specific worked up and balanced design studies as options or variants in exploring, either specific requirement impacts (e.g. speed, margins, payload) or form or dimension choices, in terms of ship performance or affordability. What they do not specifically reveal is the manner in which a given design option is both chosen and then developed to a given level of definition through a set sequence of intermediate balanced design steps, as presented in Andrews & Pawling (2008).

Because so many real designs evolve in response to the dialogue with the requirements owner, the technical nature of the preliminary design development is often obscured, or at best the major design choices are recorded for posterity. Thus for example, Bryson (1984) shows three intermediate design studies in the case of the Type 23 Frigate evolution from a 100 m light frigate to the 123 m final medium sized frigate design. However, aside from the completed design, little in the way of detail is given for each intermediate study, apart from profile drawings. In this case of the Type 23, significantly more information is provided in a Ministry of Defence produced schedule history of the full process of that design's development from 1979 to 1983 in a four page bar chart, which has been reproduced in a UCL internal publication handed out to the Naval Architecture MSc Course students (Brown 1984). However even this comprehensive design history only records major design decisions and specific design related activities rather than comprehensive technical descriptions of the intermediate design steps.

The most comprehensive design evolution description provided in open literature on a US Navy design, at an equivalent level to this Type 23 design history, was provided by Leopold & Reuter (1971). This largely describes the specific separate design processes for the SPRUANCE Class Destroyers in terms of the general arrangement, envelope definition, subdivision (and stability), structural design and subsystem design to a level more appropriate to the UK definition of the Feasibility phase than just initial concept design. That is to say at a level that is normally required at the conclusion of preliminary design leading up to contract definition. Leopold and Reuter do show four alternative cut away profiles from what are said to be at least nine "alternative (configurational) concepts" that the Littons team examined. However, again no technical detail is given on these alternative design studies or, indeed, any earlier concept studies that led to these configurational design options from which the final design was developed.

Before Section 3 outlines the issue of ship layout in preliminary ship design, it is considered sensible to spell out, in a little more detail, the overall concept process in terms of three initial design stages listed at the beginning of this section. These were comprehensively presented in Andrews (1994) considering the preliminary design of warships:-

a) Concept Exploration
This initial design phase can be said to comprise a wide ranging exploration, which starts at the initiation of investigations for a new ship design. It should be an extensive investigation of all possible options and typically include modernising existing ships, modifying existing designs and exploring the full range of, for example:

(i) packaging of the primary function (e.g. aircraft, weapons or sensors for a combatant; cargo/passengers for auxiliaries or merchant ship equivalents);
(ii) capability of the ship to deliver the functions (e.g. speed, endurance, standards);
(iii) technology options to achieve the functions and capability (e.g. existing technologies, enhanced materials and systems, enhanced technological/ configurational options, reduced technology levels).

These explorations may well be cursory or may show the need to pursue several distinct options and may require research programmes or revisiting (not for the last time) the operational concept.

b) Concept Studies
Assuming only one or two options are to be taken forward, the wide ranging but cursory nature of the initial exploratory stage is unlikely to have investigated in any depth the perceived design drivers and the impact of various choices on function, capability and technology. This stage is dependent on the type of vessel (i.e. combatant, aircraft carrier) and degree of novelty (e.g. conventional monohull, unconventional configuration), as well as a range of issues to be addressed from payload demands through speed and endurance to style issues, such as those associated with design life, signatures, survivability and complement standards. All these issues normally merit investigation before the design is too fixed. They can also significantly influence the downstream design but, more importantly, they need to be debated with the requirements owner, since their impact on the ship's performance and affordability should be part of the requirements elucidation dialogue before the form and style of the solution is too precisely fixed.

c) Concept Design
This final stage prior to approval to commit to a more substantial design effort (i.e. in UK MoD terms, prior to Initial Gate decision) is primarily focused on the design (and costing) information necessary to ensure that the approval to proceed is based on sufficient information and the process beyond that approval can proceed coherently. Typically the stage is dominated by cost capability tradeoff studies and the interaction with any associated operational analysis. It can be appreciated that to enter into this last concept stage with inadequate exploration of the solution space or of the style and performance issues, is unwise as any submission to proceed is likely to be vulnerable to probing by approval authorities of the decisions on such issues. This just emphasises the inherently "political" nature of naval ship acquisition at the front end of the process and why it is often protracted and seen to be unsuccessful and apparently costly, as is well addressed in US Navy organisational papers (such as Tibbitts & Keane (1995)).

Alongside the specific technical design development task in preliminary ship design is the political and process procedure. The wider procedural issues, which have been addressed in numerous generic papers (see Andrews (1994), Tibbitts and Keane (1995)) and indeed in papers on specific ship designs, should be seen together with the detailed technical design evolution, as they strongly interact.

2.3 The Need for the PSD Process to be Architectural

Betts (2000) in a keynote paper to the 2000 IMDC discussed, in terms of warship design, the needs for tools to be used in preliminary design. These were listed at Table 5.2 of Andrews (2003a) (and reproduced at Table 1) where Betts "Needs" are compared to a summary of the types of CAD tools available for Preliminary Warship Design.

Table 1: A listing of Betts (2000) analysis of preliminary warship design tools needs with the current range of types of tools available (Andrews 2003a)

Needs for Preliminary Warship Design Tools	Current Types of Preliminary Warship Design CAD Tools
1. Utilise data for assessment of performance, risk and Through Life cost. 2. Useable by knowledgeable design team. 3. Deal comparably with conventional and unconventional ship concepts. 4. Provide reasonable (preliminary) solutions. 5. Assist communications with design team and all stakeholders, especially those evolving the operational requirement.	1. Optimisation – black box, fuzzy methods, Genetic algorithms, neural networks. 2. Expert systems, knowledge based. 3. Decision Based Design and MCDM. 4. Configuration based, including Design Building Block approach. 5. Simulation Based Design and Virtual Prototyping.

In justifying the adoption of a configuration based approach (item 4 of Table 1) (Andrews 2003) went on to list the features required of a preliminary ship design approach. Thus these should provide:

- Believable solutions, i.e. solutions which are both technically balanced (Hyde & Andrews 1992) and sufficiently descriptive (Andrews & Pawling 2003);
- Coherent solutions, which mean that the dialogue with the customer should be more than merely a focus on numerical measures of performance and cost, by including a comprehensive visual representation.
- Open methods, in other words the opposite of a 'black box' or a rigid/mechanistic decision system, which means that the description is responsive to those issues that matter to the customer, or are capable of being elucidated from customer/user teams;
- Revelatory insights, in particular those identifying, early in the design process, likely design drivers to aid design exploration in initial design and beyond;
- A creative approach, not just as a "clear box" but actually encouraging "outside the envelope" radical solutions and a wide design exploration.

3 THE ARCHITECTURALLY BASED APPROACH TO SHIP DESCRIPTION

3.1 Motivation for an Architecturally Based Approach to Ship Description

A 1980 paper entitled "Creative Ship Design" (Andrews 1980) concluded that creativity in ship design would be fostered by an approach to the initial ship synthesis which placed greater emphasis on the physical description of the ship's layout. A subsequent justification for, and initial demonstration of this approach to initial ship sizing was given in 'An Integrated Approach to Ship Synthesis' (Andrews 1986). That contrasted the sequential process of gross ship sizing, followed by hull parameter determination and then architectural and engineering development, summarised in Figure 1, - with the all in one or concurrent synthesis - summarised in Figure 2. That paper showed that this combination of the architectural and balanced numerical description enabled the ship designer to develop *ab initio* design options, which through the architectural representation could take into account many of the ship's main requirement drivers.

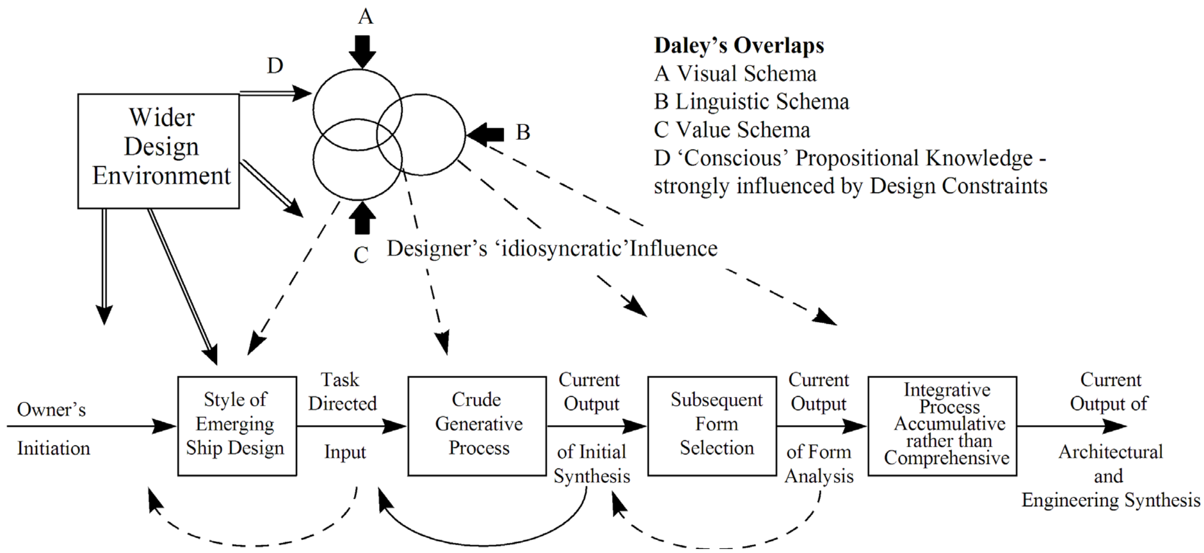


Figure 1: A summary representation of current sequential synthesis (Andrews 1986)

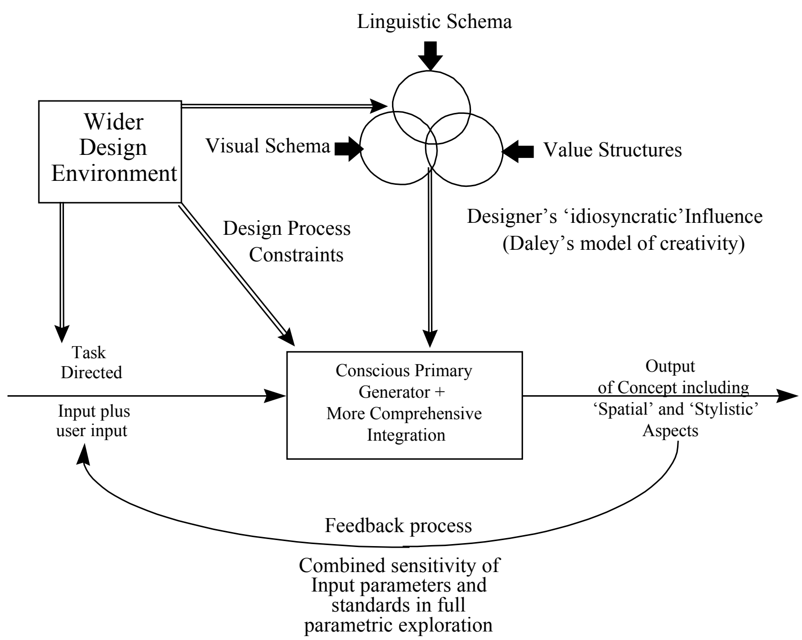


Figure 2: A summary representation of a more "holistic" approach to a fully integrated ship synthesis (Andrews 1986)

With an architecturally based description at the preliminary stage of a design it becomes possible to explore many of the issues which are of direct interest to the naval staff. Such issues - ranging from those concerned with the ship's fighting capabilities and crew evolutions on board, to the sustainability and supportability of the vessel on mission - are best investigated for their impact on the overall design at the earliest exploratory stages of the design. Thus, for example, layout for weapons effectiveness is a function of topside disposition (Andrews & Bayliss 1998) and also of internal arrangement and zone logic (Andrews, Piperakis & Pawling 2012), both of which are more readily explored through the ship's architecture. The logic adopted for routeing ship systems also affect producibility and constructional building block considerations. Also the initial configuration is able to reflect not just the traditional focus of the naval architect on the aspects of Speed, Seakeeping, Stability and Strength as performance drivers but also Style issues (Andrews 2012), including through life supportability considerations and adaptability for changing roles and technology upgrading. Without this architecturally based approach, the alternative of a simple recourse to the use of margins on the numerical values of space, weight and mass centres would not adequately reflect the configurational and associated ship service demands so as to provide genuine adaptability through the life of a given design.

3.2 A Review of Ship Architectural Design

A major aspect of ship design, that of ship architecture and how it is produced as part of the evolution of a new ship design, has in general been somewhat neglected by the profession of naval architecture. The 1980 vision (Andrews 1980) was justified since:

- Many of the features and aspects of design could not be properly addressed with the traditional sizing approach but could be incorporated in initial design with the better design methods and tools becoming available;
- The enormous recent advances in computer aided graphical design, in its infancy in 1980, are available to every personal computer user.

The current section considers how the architectural aspects of ship concept design have been dealt with prior to approaches, such as the UCL DBB approach, reached their current maturity. Also summarised below are examples of research in ship and terrestrial architectural approaches to designing the internal configuration of large, complex constructions. Three ship layout types are now summarised:

3.2.1 The Example of a Frigate Architecture

A paper entitled "The Architecture of Frigates" (Brown 1987) drew on that author's experience of preliminary warship design and on research undertaken by Andrews (1984) with various post graduate students at University College London (Hutchinson 1981, King 1985). Brown's paper was largely a comprehensive survey of many of the aspects and constraints impinging on frigate layout design through the various phases of design (termed levels by Brown), from initial design concept (Level 1) through to detailed General Arrangement (Level 3). The design constraints were indicated in his Figure 4, where an outer ring showed "problem areas" directly affecting a frigate's architecture (e.g. access, noise, vibration, hydrodynamics, structural continuity, survivability, stealth, aesthetics and through life issues), while his inner ring showed elements of the material solution (e.g. accommodation, decks & bulkheads, shape & proportions, passages, ladders, services & machinery seatings). In keeping with the last of the Brown and Andrews' (1980) "S^5" aspects in ship design, namely that of 'Style', Brown discussed the range of style-related issues relevant to the layout of a given design (i.e. ship role, modular/cellular features, margins, zoning). He emphasised how, for his Level 1 (for a frigate and similar combatant vessels), the key to the internal layout is the design of the upper or weatherdeck disposition of weapons, helicopter arrangements, radars, communications, bridge, boats, seamanship features, machinery uptakes and downtakes, and the access over the deck and into the ship and superstructure. Figure 3 shows Andrews' (2003) updated version of Brown's frigate configuration.

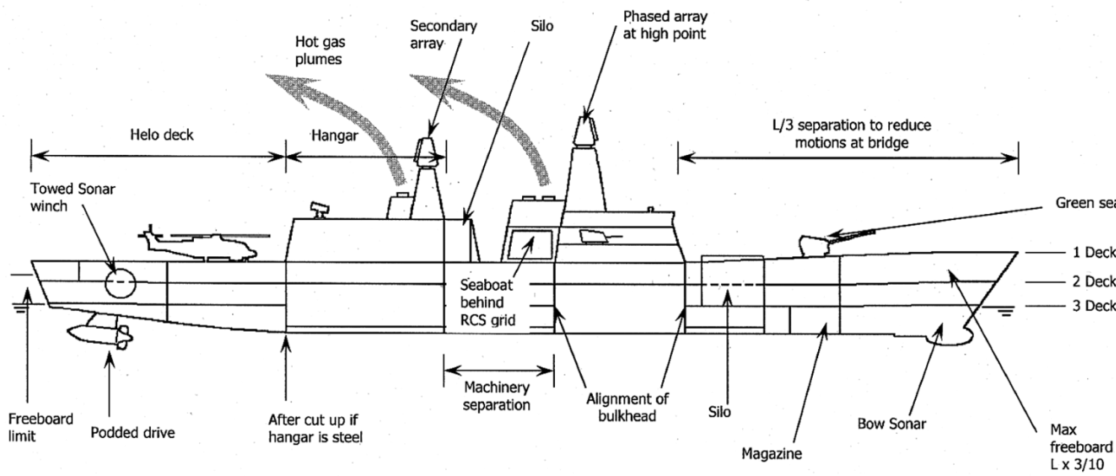


Figure 3: Frigate layout considerations (updated by Andrews (2003) from Brown (1987))

When considering Level 2 of layout evolution Brown discussed various numerical techniques under two categories, namely those intended to quantify the need for the layout feature and those used to analyse the performance of a stated function. This is shown in Table 2, where other techniques are also included beyond those taken into account in the 1980s UCL research programme (Andrews 1984).

Table 2: Numerical techniques for warship layout (Andrews 2003)

Category	Technique	Application	Source
Needs Elucidation	Association matrix Circles of Influence	Frigate layout preference Frigate Compartment relationship	Andrews (1984) Andrews (1986)
Layout Performance	Circulation	Adapted from CAAD	Buffa(1966), Hutchinson(1981)
	Multi criteria knowledge based	Ship layout to minimize size	Graves (1980), Hills (1993)
	Contact diagram	Merchant ship superstructure	Cain (1979)
	Mission evaluation	Overall layout	Hope (1981)
	Numerical analysis of spatial structure	Architecture applied to frigate Layout	Hillier (1984), Andrews (1984)

Some of the techniques listed in Table 2 have been proposed for some time as a means of evaluating the layouts of buildings and ships but they have failed to be adopted in general design practice, largely because of the difficulty in assigning numerical values to layout options which provide valid bases for assessment. For example, the method used to investigate the circulation of personnel in frigate layouts, for watch changes in cruise and action states (Hutchinson 1981), did not constitute a believable measure because:

- The most "efficient" configuration (i.e. smallest value of circulation) in the designs investigated was actually the peacetime layout;
- Circulation did not take into account the fact that layouts are driven by cultural aspects (e.g. officers, petty officers and ratings are not accorded equal status);
- While personnel flow is readily quantifiable, it is not as important in determining a ship's layout as the juxtaposition of vital compartments driven by the need to fight the ship, survivability, maintenance etc.

Another approach proposed for looking at layout design is that of expert systems. These have been applied to layout design by Helvacioğlu and Insel (2003), who outline a container ship design tool where the ship is described at three levels of detail, with different rules bases and expert system engines applied to each level of decomposition. Of interest in this SoA report is the so-called “third level” of decomposition, representing the layout of individual decks of the container ship’s accommodation block. In common with most expert systems, this approach is primarily suited to “type ship” designs, where the overall topology and style are specified, and a relatively simple performance function can be used to determine the preferred arrangement – in this case the estimated evacuation time. Expert systems require a well-structured and populated rules database to function, and Helvacioğlu and Insel describe the methods they used to obtain layout preference information from human designers and the structures used to store this in a manner allowing it to be applied in new designs.

There would seem to be some difficulty in separately conducting a range of evaluations, beyond personnel circulation (because that is relatively easy to compute) and then additionally adding them together, when the aspects are so disparate that it makes it questionable that a layout can be “optimised”. However, this is not an excuse for the designer to revert to making arbitrary choices, rather to use numerical analysis where appropriate, so as to properly inform decisions, rather than questionable numbers being the sole basis for making a design decision.

3.2.2 Configuration Driven Design

Although it has been argued that the design of all warships (and most commercial service vessels) should be driven in large measure by their internal (and upper deck) configuration, it will be recognised that the concept design of certain ship types has to be approached by firstly configuring the spaces required to achieve the primary function(s) of that vessel. Thus, the physical description of a passenger, cruise or ferry ship can only be produced by commencing with the arrangement of the public spaces and cabins (Levander 2003). Similarly the configuration of certain large naval vessels, such as aircraft carriers and amphibious warfare vessels, are driven by the spaces required to accommodate the primary “cargo”, whether the hangar and flight deck or the well dock and vehicles decks in those specific cases. See Figure 4, which schematically shows personnel routes, equipment removal routes and stores routes around and directly below the primary decks, i.e. the flight deck and hangar deck. Honnor & Andrews (1981) discussed the need for access from the main through deck, below the hangar, and around the side of the hangar, taking into account the other needs for machinery inlets, outlets and removal routes, as well as features such as boat arrangements and ventilation. The paper also pointed out, however, that some important military features were deliberately omitted from this figure, such as:

- Magazines and weapon movement routes;
- Other important aircraft support spaces and stores;
- The location of ship and force command, control and communications;
- Damage control features.

Although these would need to be included in order that the evolution of such a complex ship configuration could be properly appreciated, this example - and the previous frigate case – are considered to leave no doubt as to the centrality of a ship’s architecture in the design process.

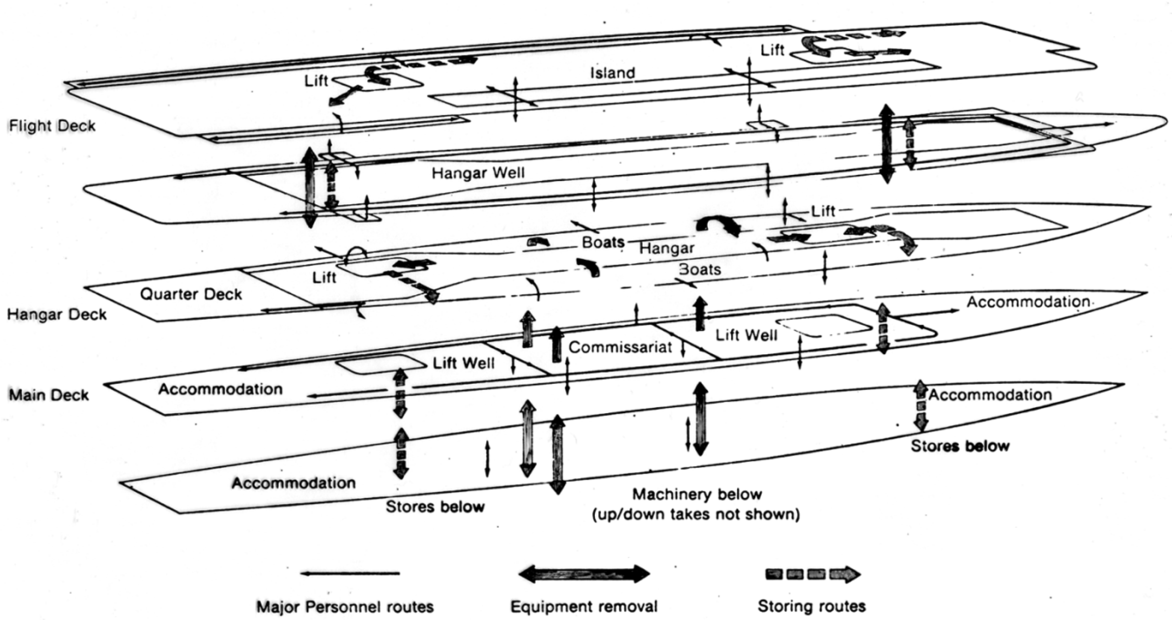


Figure 4: Schematic of INVINCIBLE Class internal arrangement (Honnor & Andrews 1981)

3.2.3 Unconventional Hull Configurations

Unconventionally hulled vessels require a significantly distinct ship design process. In the case of displacement-borne multi-hulled configurations - like the catamaran, SWATH and trimaran - the architectural design is highly significant. The high speed advanced vehicles, like the ACV, hydrofoil, SES and various hybrid forms, on the other hand, are governed by a technology akin to aerospace, which has been the industry behind most of the current fast (coastally operated) craft in service. When the initial sizing of the larger multi-hulled vessels is considered, in terms of dimensions and form parameters, it is apparent that their sizing is not circumscribed by the relatively narrow range of parameters typical of monohulls. Consequently the designer, of say a SWATH or trimaran, has to size these vessels on the basis that it is the configuration of their major spaces which constitutes the main driver for determining the vessel's dimensions and principal form parameters (Andrews 2003). As can be seen from Figure 5, the size and shape of the trimaran ship shown are determined by the arrangement of the major operational and habitable spaces.

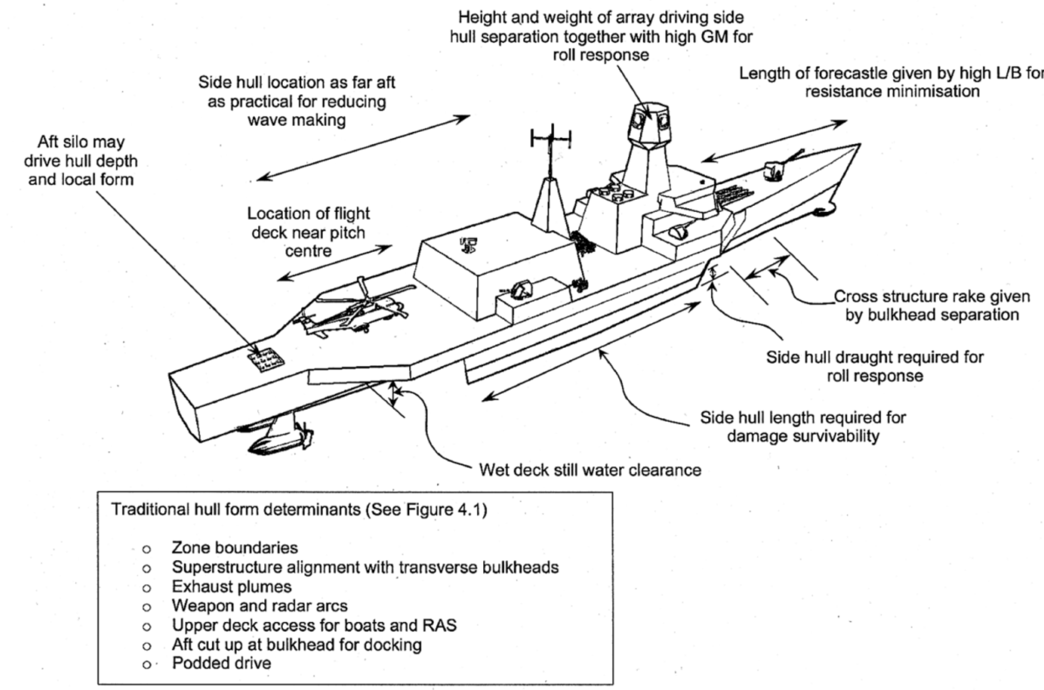


Figure 5: Trimaran combatant configuration drivers (Andrews 2003)

3.3 Architectural Design Methods for Ships

While the advent of computer aided design systems to naval ship design has led, specifically in US Navy practice, to formalised procedures for General Arrangement Design, the broad principles predate CAD technology in ship design (Carlson & Fireman 1987). The need for the naval architect, at the formative preliminary design stages of a ship design, to have a clear understanding of the issues affecting configuration has become more important, because of the risk that the readily available design tools enable the novice ship designer at his/her personal computer all-to-readily to produce what appear to be worked up ship design solutions.

An early approach to 'Functional Arrangement Design' was due to Barry (1961), for both large passenger ship conversions to troop ships and on cruiser gun disposition, while providing insights relevant to current ship design practice. For example, Barry proposed the juxtaposition of what were drafting tables, so that those designers working up the upper decks and superstructure could better interface with the outboard profile designer, while those responsible for the lower deck arrangements interfaced with the inboard profile design. In modern practice this approach translates to the necessity for the ship designer to ensure that 3-D models of compartment locations are considered not just in terms of a given deck arrangement but also of the relationships with adjacent decks and the topside, as indicated by Figures 3, 4 and 5. The second example, of a similar vintage (Baker 1956), was produced as a means of maintaining coherence in ship layout. Baker's 'stylised layout', designated areas of his ‘St LAURENT’ Canadian Destroyer design to the specific functions of machinery, living, working, payload (weapons), services and liquids, with the object of avoiding excessive interaction between functional areas which could lead subsequently to loss of design control. Leopold and Reuter (1972), in their comprehensive design history of the DD963, LHA and FDL classes for the US Navy, outlined, for their designations of five 'ship systems' (i.e. containment, mobility, ship support, mission support and human support), a basis for “logical selection of design configurations within boundaries of the feasibility envelope”. Each arrangement was then individually evaluated for a range of parameters, such as ease of modernisation and conversion, modularity and minimisation of vulnerability and topside clutter.

Even when the move to computerisation of the ship design process was gathering momentum (see Carlson & Cebulski 1974, Holmes 1981), manual general arrangement procedures were still adopted and the computer used to present compartment attributes and to manage the auditing process. The allocation of space then took place within the defined overall ship envelope at what was termed, in UK practice of the day, the Feasibility Stage and involved an initial assignment of compartments to decks and watertight subdivision locations which was rarely changed subsequently – or, if so, in a minimal manner to avoid wholescale redesign- an approach which could result in the loss of the original layout logic. Carlson & Fireman (1987) stated that architectural layout programs were examined for their potential for application to ship layout, but could not deal with ship shape and space limitations; also, optimisation techniques were infeasible because of the large number of independent variables involved in ship layout. They provided an update of the US Navy's General Arrangement CAD system with an 'Arrangement Design Methodology', summarised in Figure 6, which shows a sequential approach constrained by the initial concept design output and hull form plus subdivision of the decks and bulkheads.

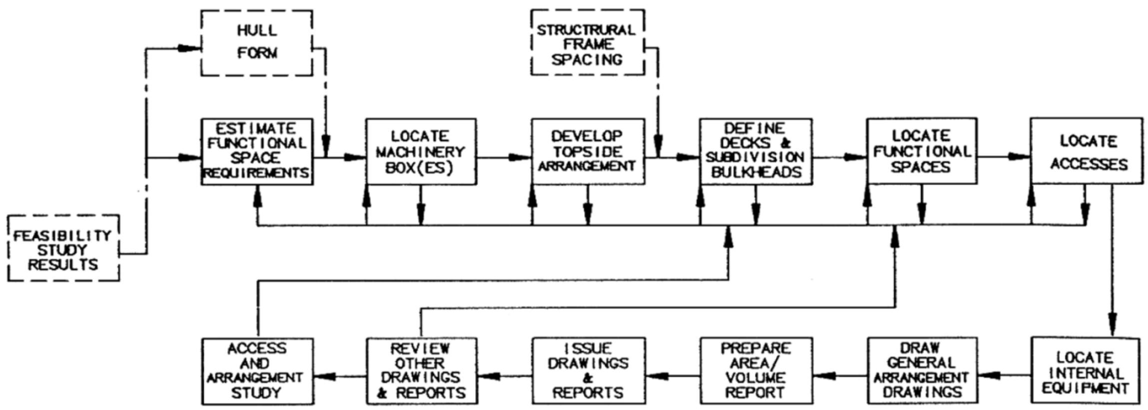


Figure 6: US Navy's general arrangement task sequence (Carlson & Fireman 1987)

This background serves to demonstrate that General Arrangement design has continued to be a deliberately constrained process, and that decisions which constrain the architectural design are made at the preliminary or concept stage, where there is an apparently unavoidable and insufficient consideration of the consequences of the constraints being imposed on the layout. Furthermore, when the arrangement is subsequently developed, there is a momentum in evolving the total ship design, which massively inhibits any significant exploration of the constraints and any possibility of a radical readjustment of the architecture of the ship. This downstream tyranny of the schedule virtually eliminates any real ability to meet the aspirations of Concurrent Engineering.

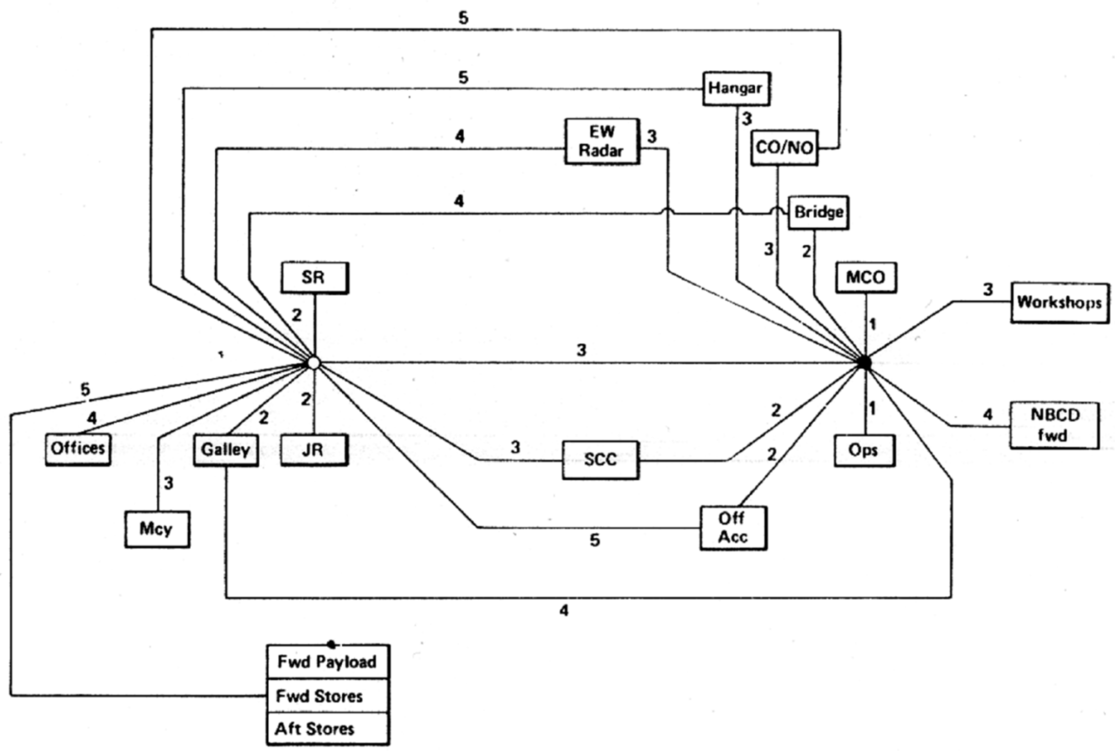
3.4 An Integrated Architectural Synthesis

The approaches described in the foregoing contribute to, but also constrain, the challenging design problem of producing the general arrangement of a complex ship design. This is done by the well-established method of using damage stability and structural continuity considerations to determine main transverse bulkhead disposition and thereby controlling the evolution of the general arrangement, within a previously determined envelope of the hull form. An alternative logic, that of using the disposition of the principal spaces in the ship to determine both the initial sizing of the ship and the selection of hull dimensions and form parameters was proposed in Andrews (1980). The aim was to have a means of fostering 'creative ship design', which was then demonstrated in what was termed an 'integrated synthesis' (Andrews 1986). This gave an example of a sequence for allocating the various compartments in a frigate design. This sequence was not suggested as the recommended way of obtaining the layout, but rather as a suitable start point for an integrated synthesis to take and to utilise the ship arrangement, produced by such a sequence, to size, dimensionalise and select form parameters. It was also argued that with integration of the ship architecture with weight, space and form parameters, a better initial design solution could be achieved, since a more comprehensive initial design description:

- Would provide a better basis for initial cost tradeoffs and parametric selection;
- Could be used to explore alternative layouts, while the hull form and dimensions were still fluid;

- Could be readily altered, both as regards layout disposition and the consequent hull dimensions and form impact.

The latter advantage was also justified the initial adoption of a conventional layout sequence, but only provided the ability to readily alter the layout and the initial sizing could then be exploited (rather than this layout being adopted and closing down the option of configuration exploration). Andrews (1986) also proposed that a layout could be synthesised by a progressive design approach of 'circles of influence' to address compartment relationships and thereby yield a 3-D block layout, around which a hull form could be "wrapped" (see Figure 7).



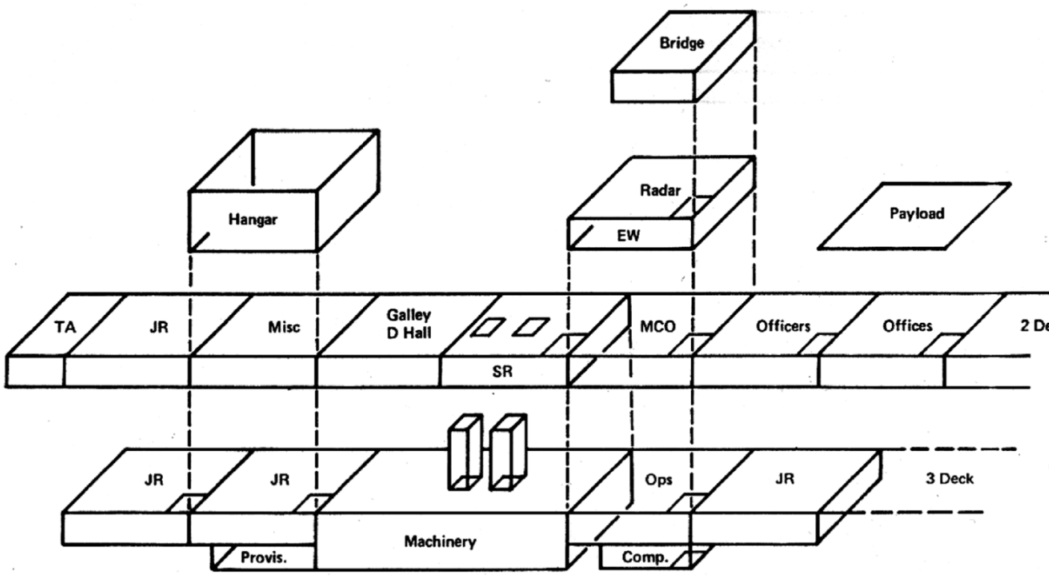


Figure 7: ***Ab initio*** **frigate compartment block synthesis (Andrews 1986)**

While the integrated synthesis approach was demonstrated in the 1980s, it was not until computer graphics had advanced sufficiently in the early 1990s that the methodology outlined above could be adopted in a working design tool for submarines and then in 2001 for surface ships via the PARAMARINE ship design system (Andrews & Pawling 2003).

4 UNIVERSITY OF MICHIGAN (U-M)

The research of U-M called "Intelligent Ship Arrangement (ISA)" published in Daniels and Parsons (2008), Daniels et al. (2008, 2009) , Nick et al. (2006), Nick and Parsons (2007), Nick (2008), Parsons et al. (2008), focuses on arranging spaces into pre-defined structural zones. ISA was developed in the context of the U.S. Navy's design process, which has influenced the scope, direction, and intended use of the method. The overarching objective is "to provide an optimization technology and design tool to assist the arrangements designer to create effective, rationally based surface ship arrangements with the maximum amount of intelligent decision making support" (Parsons et al. 2008). Secondary goals relate to the capture and application of Navy requirements and best practices and to the objective comparison of alternative layout configurations. ISA was developed to assist designers in creating layouts at the end of the conceptual design phase (Analysis of Alternatives, AoA) and at the beginning of preliminary ship design phase.

Due to the existing capabilities of U.S. Navy design tools and processes, ISA solves only the space arrangement part of the total ship design problem. ISA takes as key inputs: 1) a ship hull including structural subdivisions, 2) a list of spaces to be arranged, and 3) a collection of relative and absolute space location constraints and space-centric geometric constraints. These inputs can be specified beforehand using automated or manual synthesis tools. Currently, the U.S. Navy's Advanced Ship Synthesis and Evaluation Tool (ASSET) (Beyer et al.(1990)) is the conceptual ship design synthesis tool used to determine, among other items, the main dimensions of a hull with its major structural subdivisions, a list of ship spaces appropriate for the given ship type, and the placement of major machinery. The automated/semi-automated approach employed by ISA was developed, in part, with the goal of incorporating general arrangements quantification into the larger ASSET synthesis, enabling a feedback loop of layout quality into total ship design at an early stage.

The ISA method works with a two-step process, Figure 8. The first step allocates the list of spaces to the structural zones of the vessel whilst the second step creates multiple arrangement (geometric) solutions for the allocation of the first step. This follows the methodology that each space allocation can have multiple geometrical arrangements, whilst each geometrical arrangement can be traced back to one unique space allocation. Thus multiple arrangements are needed for each allocation to find the "optimal" allocation/arrangement combination.

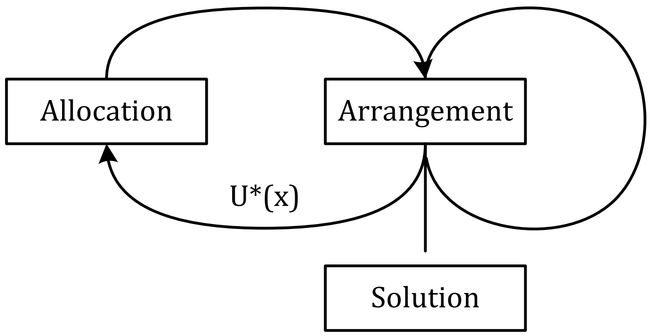


Figure 8: ISA two step allocation/arrangement schematic, (Daniels et al. 2009)

4.1 Step 1: Allocation

The first step of the ISA method is the allocation of a pre-defined list of spaces to structural zones of the vessel. Each structural zone is subdivided by major bulkheads and decks and is fixed (i.e. the structural zone arrangement does not change during the ISA steps), see Figure 9. The spaces are allocated to the available structural zones by a Hybrid Genetic Algorithm - Multi Agent System (HGA-MAS). In this optimization scheme, the genetic algorithm is used to explore the design space by encouraging solution diversity, while the agents are used to provide intelligent search capabilities. Genetic algorithms are robust when used on highly multimodal problems with flat solution spaces, of which general arrangements is a prime example. The intelligence provided by the agents enables significant performance improvements over genetic algorithms alone.

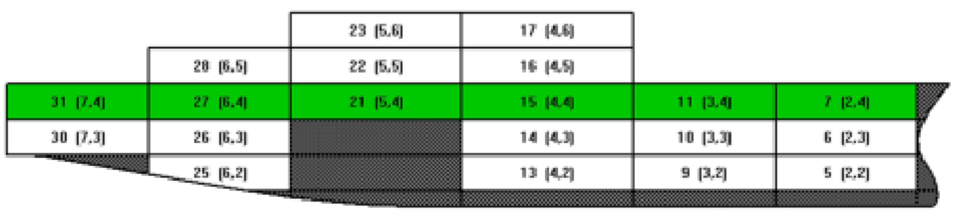


Figure 9: ISA structural zone definition, (Daniels et al. 2009)

The allocation of the spaces to the structural zones is driven by an optimizer employing fuzzy constraints (Nehrling 1985). Fuzzy optimization has been used by others for ship arrangements, including Cort and Hills (1987), Slapnicar and Grubisic (2003) and Ölçer et al. (2006), The structural zones have a built in fuzzy constraint that tracks their area utilization. Spaces have built in global location preference and geometry constraints (required area, aspect ratio, etc.) as well as a collection of relational constraints with other spaces (adjacency, separation, etc.). The use of fuzzy logic to define the constraints allows the modelling of constraints such as; "close to", "separated from", or "more-or-less square". These types of constraints are often encountered in the arrangement design rules.

4.2 Step 2: Arrangement

After the space allocation to each structural zone has been defined the second step of the ISA method is activated. The arrangement algorithm maps the centroids of each space assigned to the current structural zone to an orthogonal grid which is a 2D description of the structural zone plan. This is done to ensure that each space has sufficient area available around it to achieve its final size. As shown in Figure 8, the arrangement algorithm is called several times to find the "optimal" arrangement of the current space allocation.

The arrangement step is also driven by fuzzy constraints. Spaces here have built in geometry constraints that address required area, aspect ratio, minimum dimensions, minimum segment width, and perimeter length. In addition they have the same collection of relational constraints between themselves and other spaces (adjacency, separation, etc.). The space geometry related criteria ensure that each space has its minimum required dimensions and that no unwanted irregular shapes are created whilst the other constraints control basic topology between spaces. The final result is a space arrangement of each structural zone according to their assigned topology, see Figure 10.

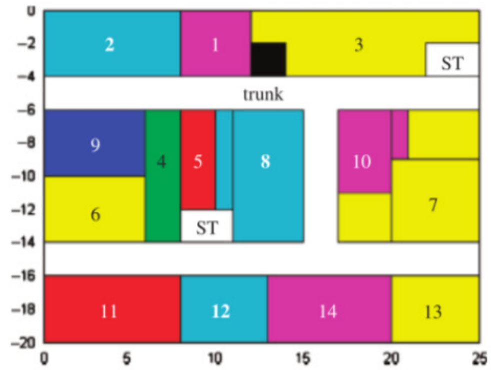


Figure 10: ISA structural zone arrangement, (Parsons et al. 2008)

The ISA tool is a 2D area driven design tool, this makes it suitable for arranging spaces/areas into a fixed positioning space (structural zone). Arrangement of weapon systems, sensors and the propulsion system, although theoretically possible, are not part of the arrangement process and are fixed prior to the ISA arrangement tool. As such ISA focuses on the arrangement design within the fixed envelope of the hull and topside.

4.3 Unique Features

- The Hybrid Genetic Algorithm - Multi Agent System (HGA-MAS) enables diversification of designs while the intelligent agents identify high quality regions of the design space.
- The use of a Fuzzy Optimizer creates a design tool and that naturally mimics the thought processes of human designers. Designers are provided a method for modelling constraints that is consistent with the language and terminology commonly used in layout design.
- The flexible fuzzy logic constraint system with customizable calculation objects allows for modularity to facilitate information reuse and for user-defined alterations to, for example, space types and attributes, utility functions, and calculation methods. The flexibility lets researchers test multiple hypotheses and gives industry users the ability to tailor the analysis methods to their specific needs, helping reduce the size of the "black box."

4.4 Recent and Ongoing Developments

There have been a number of improvements to the current working version of ISA. They include:

- Development of the ISA design tool is still under way, recently new studies have been made to improving the compartment and access networks. The new Passage Variable Lattice Network methodology (PVLN) allows for the generation of more complicated passage network configurations to better suit the access needs of all spaces in a zone-deck. In addition, passage, stair tower, and deck templates can be applied in commonly used compartment and access network patterns.

- Design Agent intelligence has been increased, allowing for more complicated design change requests. The objective functions have also been rewritten to increase performance of the search algorithm. Finally, algorithms now use the ship's actual geometry to improve accuracy over a bounding-box approach.
- A new space projection system has been implemented to dramatically speed up compartment geometry generation. Spaces no longer have to take many iterations to "grow" to their final geometries.
- Research is currently underway to find ways to use networks and the relations between spaces to cluster spaces and identify functional groups and allow for complex (group) moves (Gillespie et al. 2011, 2012). A related goal is to use this information to determine "hot spots" of possible design conflict due to overlapping preferences.

5 UNIVERSITY COLLEGE LONDON (UCL)

The first paper on the UCL originated Design Building Block (DBB) approach to preliminary ship design was presented to IMDC in 1997 (Andrews & Dicks 1997). However that methodology for preliminary ship design originated in 1981 (Andrews 1981) and was then developed in the subsequent few years (Andrews 1986 and Andrews 1987) achieving its first working realisation, produced for the UK Ministry of Defence (MoD) in a classified version, for UK submarine design (Andrews et al 1996). This has since been developed in an unclassified form known as ESSD by GRC (http://www2.quinetiq.com/home_grc.html).

The 1997 IMDC paper, on SURFCON, outlined the procedure for preliminary ship design using the DBB approach, which was subsequently adopted in the working version of SURFCON as part of the GRC preliminary ship design tool PARAMARINE (see Munoz & Forrest 2003), and included the use of a functional breakdown.. That 1997 paper also showed an early application of the approach to both monohull and multihull (SWATH and Trimaran) design studies of frigate-sized combatants. The overall DBB methodology was presented to a wider technical audience in 1998 (Andrews 1998) when it was suggested that this constituted a new paradigm for the preliminary design of large complex products.

The 2003 IMDC paper (Andrews & Pawling 2003) spelt out the development of the practical PARAMARINE based DBB capability developed from the 1997 specification and the research demonstration presented to IMDC in 1997. A subsequent IMDC paper (Andrews & Pawling 2006) showed that in the intervening three years a considerable range of ship design studies were undertaken by the UCL Design Research Centre (DRC). Following the outlines of the design applications of the DBB approach to ship design research, design for production, novel concept studies and simulation based design that paper concluded with a range of further issues that the computer aided graphical design approach to preliminary ship design could readily and usefully open up for consideration, while the design solution is still malleable. Thus, while ensuring the traditional naval architectural issues, such as stability, powering, weight and space balance, are still prominent in initial ship design, the designer can now give due weight to other aspects of major importance to potential owners and operators, which are best addressed through their interaction with ship layout and furthermore encourage creatively exploring innovation in ship design.

5.1 Summary of Design Building Block approach to preliminary ship design

The combination of modern computer graphics and interactive computer aided ship design tools was required to achieve an integrated CAD system readily available to practicing ship designers, since the design examples reported in the 1997 IMDC paper (Andrews & Dicks 1997) had only been achieved using a research "breadboard" demonstrator. With the setting up of the UCL Design Research Centre (DRC), within the UCL Marine Research Group, in 2001 the Design Building Block approach to integrating ship architecture into the initial ship synthesis could then be achieved at a practical level, as opposed to one restricted to a research level. This was done through its incorporation within an existing and established computer aided ship design system.

The PARAMARINE ship design system was produced by Graphics Research Corporation, a company initially set up to provide the UK Ministry of Defence naval ship design agency with a support and exploitation agent for its longstanding GODDESS ship design computer system (Barratt et al 1994). PARAMARINE took the essential naval architectural capabilities of the GODDESS system and reconfigured them into an object-oriented configuration, executable on modern personal computers (Munoz and Forrest 2002). This system was then able to accept a new module, known as SURFCON, which implemented the Design Building Block approach in a fully integrated manner. Thus the methodology, outlined in Andrews (1998) and summarised by Figure 11, can be said to be fully incorporated within a practical and available CAD system. The manner in which the SURFCON tool (as part of GRC's PARAMARINE system) is structured and the demonstration of that, through the UCL DRC's beta testing, was outlined at the 2003 IMDC (Andrews & Pawling 2003), detailed in (Pawling 2007) and summarised below.

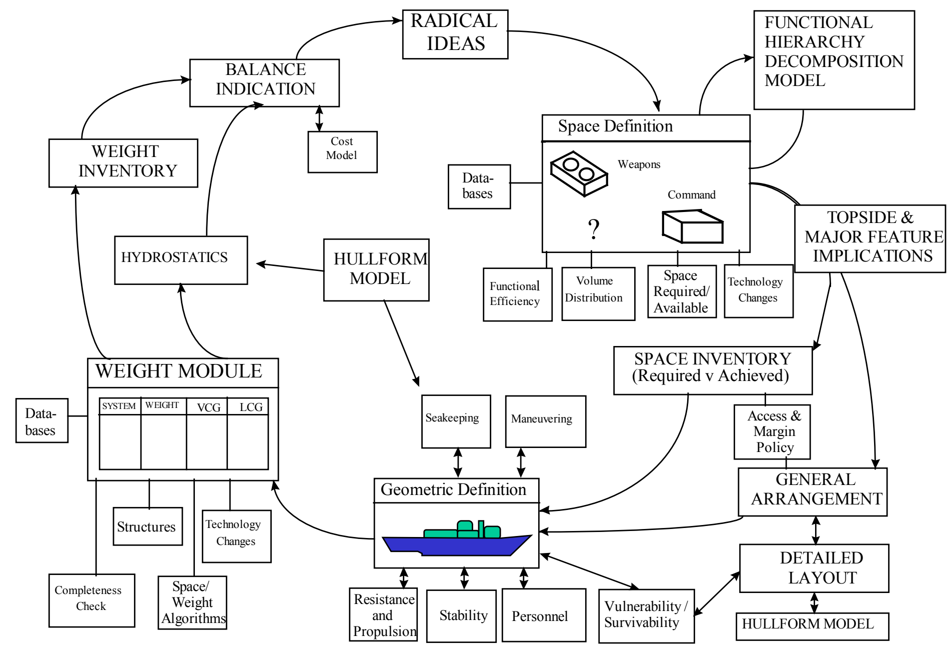


Figure 11: The Design Building Block approach applied to surface ship design synthesis

Two features incorporated in the PARAMARINE version of SURFCON that were part of the UCL prototype were:-

(1) A "Functional" breakdown of the design building blocks adopted for ship description. The categories of the building blocks (i.e. float, move, fight/operation and infrastructure) can be distinguished by their four characteristic colours in the example screen shot of the SURFCON system in Figure 12 and the subsequent examples. This breakdown of the DBBs was designed to foster the exploration of more innovative configurations and also to show the impact of additions or deletions of capability as part of the elucidation of requirements highlighted in the paper of that title to the 2003 IMDC (Andrews 2003).

(2) The term Master Building Block denotes how the overall aggregated attributes of the Design Building Blocks are brought together to provide the numerical description of the resultant ship design. The advantage of providing the Design Building Block capability of SURFCON as an adjunct to the already established ship design suite of PARAMARINE, means the audited building block attributes within the Master Building Block could be directly used by PARAMARINE. Thus the necessary naval architectural calculations can then be performed to ascertain the balance, or otherwise, of the architecturally based configuration just produced by the designer.

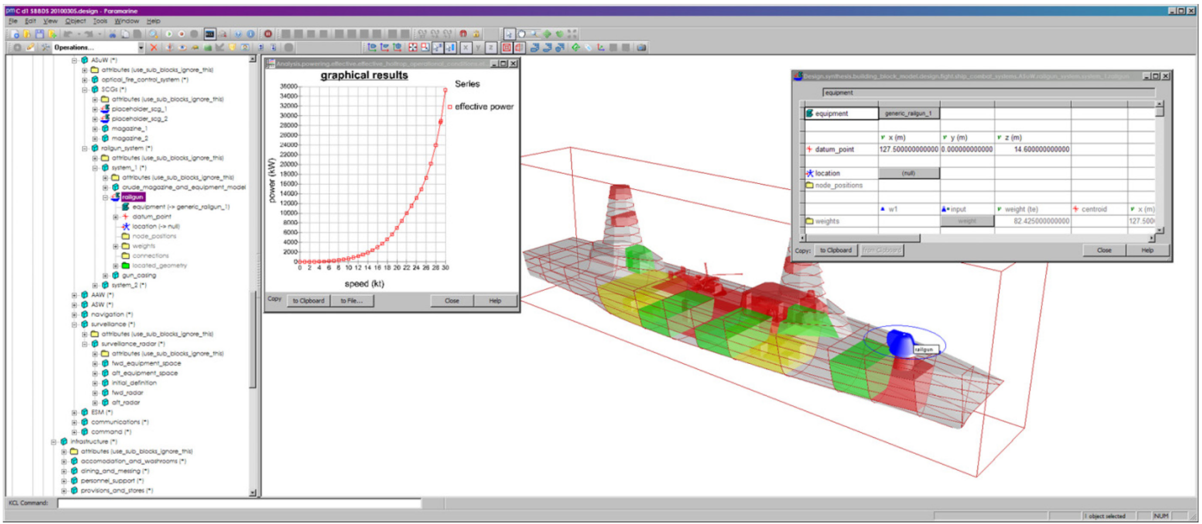


Figure 12: An example DBB ship description using SURFCON and showing the graphical screen, the object-oriented hierarchy and an example PARAMARINE analysis

5.2 The Design Building block

The Design Building Block approach is both intended to foster innovative design solutions and is not "hard wired" or has set routines to achieve naval architecturally balanced ship solutions. It is required to be used by a capable ship designer, who can exploit the capabilities of the system and also produce coherent and balanced ship design studies. The system, in auditing a new configuration of design building blocks, will report to the designer the state of the design. Rather than automatically changing the dimensions and or the hull parameters, which might be the case in a "black box" system, SURFCON-PARAMARINE will tell the designer where the design is no longer balanced and the designer can make the decision that he or she considers appropriate to the design at that point in time, drawing on what are perceived to be the imperatives for the given study at that juncture.

Each Design Building Block, as the fundamental component of the SURFCON approach, can be regarded as an object in the design space and as a "placeholder" or "folder" containing all the information relating to a particular function within the functional hierarchy. The manner in which the design can be manipulated on the screen is spelt out in the 2003 IMDC SURFCON paper (Andrews & Pawling 2003). Importantly, the "block definition" object permits the designer to add whole ship margins and characteristics, such as accommodation demands, once the “block summary” object has summarised all the information in the top level block in the DBB hierarchy. In effect this is the Master Building Block object. The "design audit" object then allows the design description to be audited for any of the characteristics entered. Results can be displayed using the Functional Group hierarchy. This "design audit" object is then assessed both for a range of design infringements, by other objects in the design space, and for the balance of the overall ship design from the whole ship characteristics given by the Master Building Block.

5.3 The General Procedure used in the DBB Approach

The general procedure to be adopted in producing a new ship design study can be summarised as follows:

(1) A very broad intent or “outline requirement” is identified and a design style proposed;

(2) A series of Design Building Blocks are defined or selected (from a library or newly created), containing geometric and technical attributes;

(3) The Design Building Blocks are located as required within a prospective or speculative configurational space;

(4) An initial sizing and overall weight and space balance and performance (e.g. stability, powering) of the design is made, using the PARAMARINE naval architectural analysis routines;

(5) The configuration is then manipulated until the designer is satisfied with both the configuration and the naval architectural balance;

(6) Decomposition of the DBBs to ever greater levels of detail is undertaken as required, and balance / performance maintained at the required the level that is seen to be appropriate for the particular study at its current level of definition.

Table 3 shows the five main design stages for a typical DBB concept design study. The table also shows the main design decisions that were undertaken and indicates the number of DBBs at each of these stages, for a frigate example (Andrews & Pawling 2008). Thus an initial "super building block" definition of the principal architectural spaces finally works up to over three hundred DBBs for the fully naval architecturally balanced definition at the end of this particular concept design. Figure 13 shows each of the architectural definitions at the end of each stage in Table 3.

Table 3: DBB design stages with granularities for each stage for the LCS study (Andrews & Pawling 2008)

Design Preparation
Selection of Design Style
Topside and Major Feature Design Phase (18-47)
Design Space Creation
Weapons and Sensor Placement
Engine and Machinery Compartment Placement
Aircraft Systems Sizing and Placement
Superstructure Sizing and Placement
Super Building Block Based Design Phase (110)
Composition of Functional Super Building Blocks
Selection of Design Algorithms
Assessment of Margin Requirements
Placement of Super Building Blocks
Design Balance & Audit
Initial Performance Analysis for Master B.B.
Building Block Based Design Phase (343)
Decomposition of Super Building Blocks by function
Selection of Design Algorithms
Assessment of Margins and Access Policy
Placement of Building Blocks
Design Balance & Audit
Further Performance Analysis for Master B.B.
General Arrangement Phase
Drawing Preparation

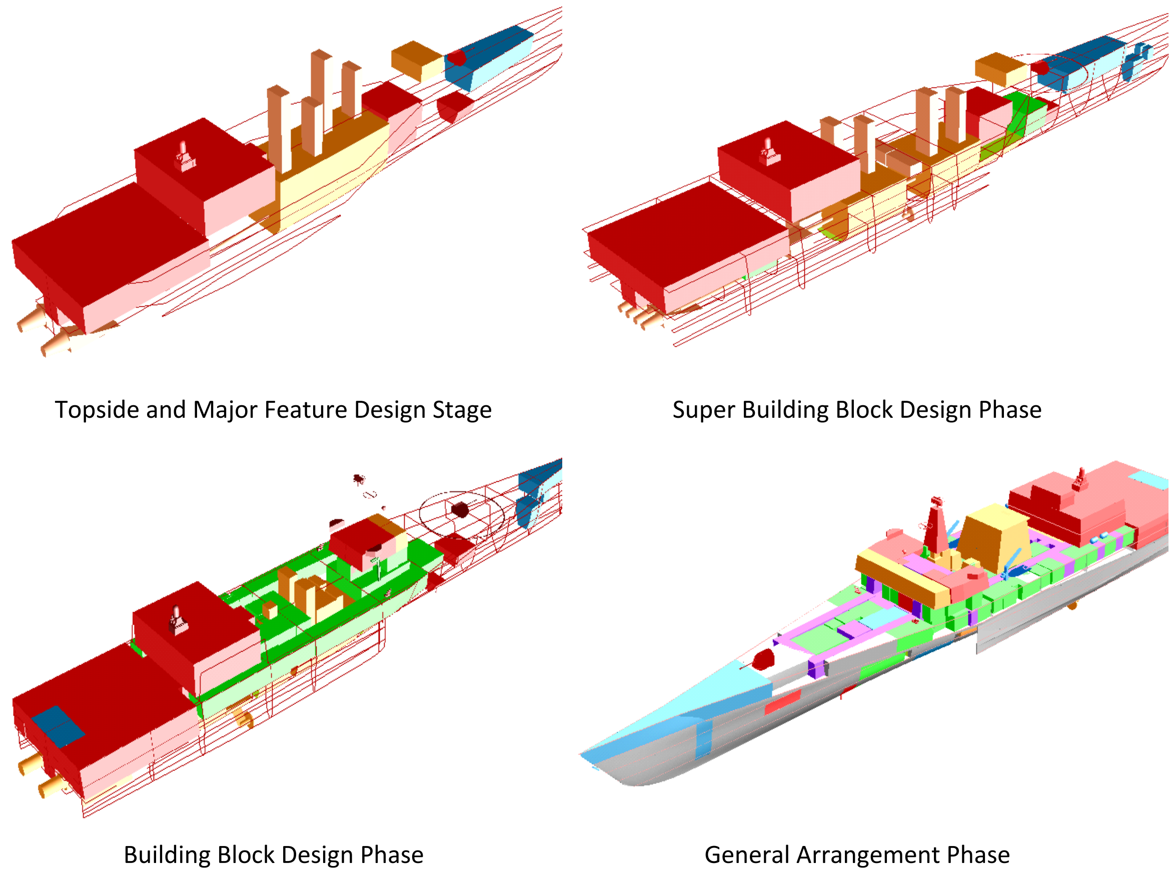


Figure 13: Architectural representations for the LCS study at the end of each design stage in Table 3 (Andrews & Pawling 2008)

5.4 Application of the Design Building Block Approach to Ship Design

While the instances of the use of SURFCON to date have largely, but not exclusively, been confined to warship design, the areas of design to which this manifestation of the DBB approach has been applied have been extensive. The following lists the four main areas of design studies undertaken by the DRC and detailed further in (Andrews & Pawling 2008).

a) Studies related to ship design research, including a task for the UK MoD which looked at the impact of certain requirement drivers on the ship concept with regard to size, cost and configuration. The other two sets of research investigations were specific studies within the DRC; the first into the impact of the adoption of all electric machinery fit on a combatant and the second two discrete preliminary studies into naval aviation features on aviation capable vessels.

b) Use of the DBB approach to investigate Design for Production (DfP) from the commencement of the design process for three distinct (naval and commercial) ship types, one of which explored DfP implications of adopting unconventional hull forms.

c) Use of the DBB approach for the design of novel ship concepts under contracted design tasks for two major navies: one concept being that of a high speed and adaptable littoral combatant; the second a series of options for the fast transport of small fast combatants for littoral operations.

d) Use of the DBB approach to facilitate exploration by simulation tools in preliminary ship design; the first a funded research programme into personnel movement on naval combatants and the second exploring the ship design implications of freight loading and unloading on to high speed short sea shipping.

5.5 Design Drivers and Issues Addressed by the Approach

As remarked in IMDC papers on SURFCON, the facility of an information rich three dimensional representation of a new ship concept, when integrated with a proper naval architectural numerical description, means the ship designer is able to explore many issues that traditionally were difficult to consider with a purely numerical description and, possibly, a separate sketch or profile. With this integrated representation, the concept designer is able to undertake a greater range of studies, better address innovative and novel options and investigate issues previously left until later in the design process. With such a tool the designer can produce concept descriptions that are able to move more smoothly into the later design phases when much more detailed graphical representations, such as Integrated Product Models (IPM) drive the design and production process.

Due to its three dimensional representation SURFCON was said to be capable of investigating a large number of issues that are related to the ship's configuration, as was spelt out in the 2003 IMDC paper (Andrews & Pawling 2003).:-

- Human factors. The simulation example was motivated by the pressures to reduce the number of people onboard. This can be facilitated by reconfiguring in preliminary design the arrangement of compartments and the main access routes, both through the ship and to the upper decks (Andrews et al 2008).
- Safety is a particular concern in modern ship design both for the crew and any passengers carried. Again the internal layout, not just to ease escape in emergencies but also for damage and fire fighting evolutions, can be reconfigured whilst the design is still fluid.
- Particular evolutions, specific to a given ship usage, such as helicopter operations from medium sized naval combatants or off shore support vessels right up to large scale aircraft or vehicle operations, from aircraft carriers or amphibious warfare vessels, can be investigated to make these critical evolutions more effective, as the two aircraft carrying studies referred to in item (a) above indicate
- For a naval vessel the topside configuration with launchers, directors, radar aerials, communications antenna, guns, helicopters, sonar gantries as well as the usual ship features of boats, access, navigation, anchors and cables etc, is a major design driver which is very hard to incorporate into usual ship concept studies. The graphical nature of SURFCON, because it is integrated into the numerical sizing, means that this aspect can be more readily influence the initial ship synthesis and earlier work on this could be readily incorporated in SURFCON (Andrews and Bayliss 1998).

6 DELFT UNIVERSITY OF TECHNOLOGY

The method of the Delft University of Technology, published by (van Oers 2011; van Oers et al. 2008, 2009, 2010), is based on the Design Building Block approach, similar to UCL's SURFCON. The intention of the tool is to increase the detail of a design in the conceptual design phase whilst maintaining a high level of design flexibility. This allows for more prediction tools to be used in this early stage increasing the knowledge about the concept designs.

In the tool objects and clusters of objects (systems, spaces, and components) are defined as building blocks which can be placed into a positioning space. By using different object types (i.e. envelope, subdivision, hard, soft, connection, and logical) van Oers is able to make a detailed parametric description of the vessel which a search algorithm can alter. The parametric model allows for large changes to the entire design (e.g. hull, superstructure, decks, bulkheads, object positions, etc.) thus maintaining the desired flexibility within the design.

The tools methodology is based on two simple steps; first create a large set of designs which are all feasible on a basic naval architectural level. Secondly have the designer (user) display and select designs out of this set based on characteristics and information which he/she deems important. The intent of this approach is to provide the naval architect with a diverse set of conceptual designs which all have sufficient detail to make relevant performance prediction. These performance predictions can be on the entire set of generated designs or only on those selected by the user as interesting subjects. The predictions can then support the further selection process of the "final" design.

Searching for alternatives is performed in a basic loop, see Figure 14. A search algorithm provides input to generate a parametric ship description which is then used to perform performance predictions. These provide a basis for rating the current ship arrangement and thereby direct the search algorithm towards better arrangements. A more detailed description of the TU Delft packing-based ship description is explained in the following subsections.

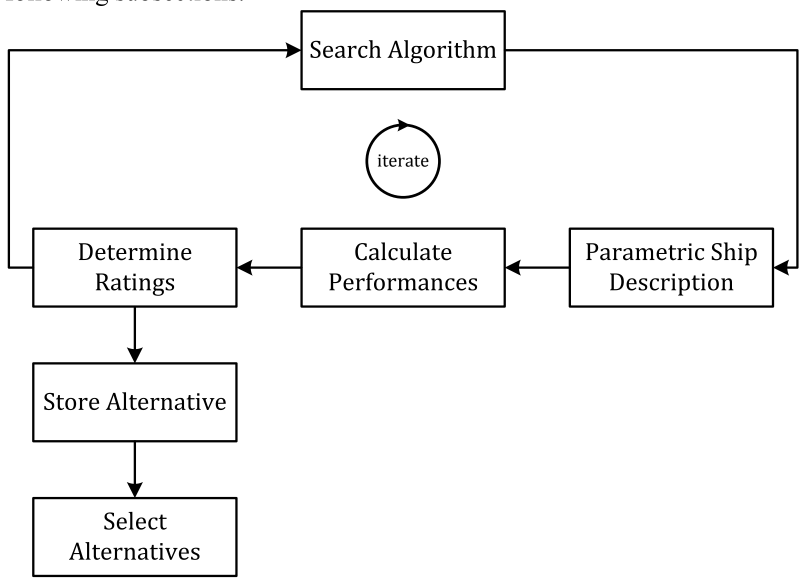


Figure 14: Searching, storing and selecting alternative ship arrangements

6.1 Parametric Ship Description

In order for a computer algorithm to be able to change the description of the ship, a parametric ship model is needed. This model allows the algorithm to change the entire arrangement of the ship by altering simple numerical values. The parametric model contains different object types represented by so called voxels (with the exception of the hull, decks, and bulkheads which are surfaces). The voxels are 3D blocks with a user defined dimensions (e.g. 1x1x1 meter) they can be placed on an orthogonal 3 dimensional grid. Clustering voxels into object allows the designer to create any type of system, space, or object (e.g. diesel engine, fuel tank, and bridge).

The parametric model takes the packing sequence (i.e. the order in which the systems are placed on/in the ship) and vectors with initial positions for each object as input. By using overlap management and different object types the placement, shape, and size of objects is regulated. The result is a fully packed and detailed 3D configuration of the concept design which can be easily changed in subsequent designs by a search algorithm, see Figure 15. Searching for alternative design configurations is covered in the next section.

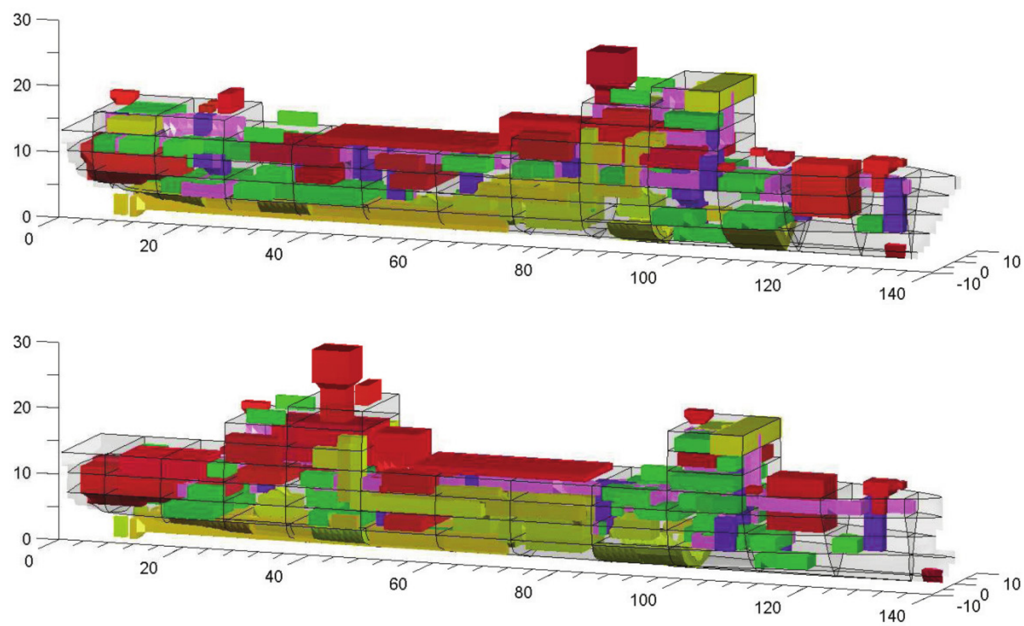


Figure 15: Example of a parametric model of a frigate with two different arrangements, (van Oers 2011)

6.2 Searching for Alternatives

Searching for alternative ship arrangements is done by a NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm), see (Deb et al. 2002). The algorithm provides new input parameters to alter the parametric ship description (e.g. hull main dimensions, and object initial positions), see Figure 14. Using several performance prediction tools the search process is directed and constrained ensuring the generation of feasible designs. In this application feasible refers to compliancy with non-negotiable requirements such as the ability to float, sufficient initial (and damage) stability, and sufficient space to place all the objects. Included performance predictions are; ship weight, centre of gravity, hydrostatics, intact stability, reserve buoyancy, ballasting, resistance & propulsion (endurance), packing density, and diversity of the configuration. Depending on the ship type other performance measures can be added or removed, refer to (Wagner et al. 2010) for a drillship application.

The packing density (i.e. the ratio between the sum volume of objects and total volume enclosed by the hull) is used as the objective function in the algorithm to be maximised. Other objective functions can be used to suit the needs of the ship type under consideration or the preferences of the user/designer. The goal however is to keep the number of objective functions used in the algorithm to a minimal to maintain the generation of diverse designs which gives the possibility to identify and study tradeoffs. The selection of the final design(s) is thus left to a later stage where extra criteria are used to select the most promising alternatives.

6.3 Selecting Alternatives

The results of the search algorithm are a large number of feasible designs which are stored into a database. Using a selection process the user selects/discards designs according to decisions. This selection approach is meant to increase the designers' acceptance of the resulting configuration and to find out why this configuration is preferred. The approach follows a few simple steps:

1. Determine which characteristics are important for selecting the design, these follow from design requirements which can be negotiable or non-negotiable. The characteristics selected are then ordered according to their importance.

2. The configurations generated by the search and packing algorithm are filtered and visualised according to the characteristic under consideration in a 2D scatter plot (e.g. position of the bridge relative to the envelope hull).
3. Selection of the relevant configuration is made "by hand" by drawing a selection polygon enclosing the desired configurations in the scatter plot, see Figure 16. The non-selected configurations are discarded from further selection in subsequent characteristic decisions/selections.
4. By changing the sequence of analysing characteristics tradeoff decisions can be made by visualising the influence of two different sequences on the final configuration.

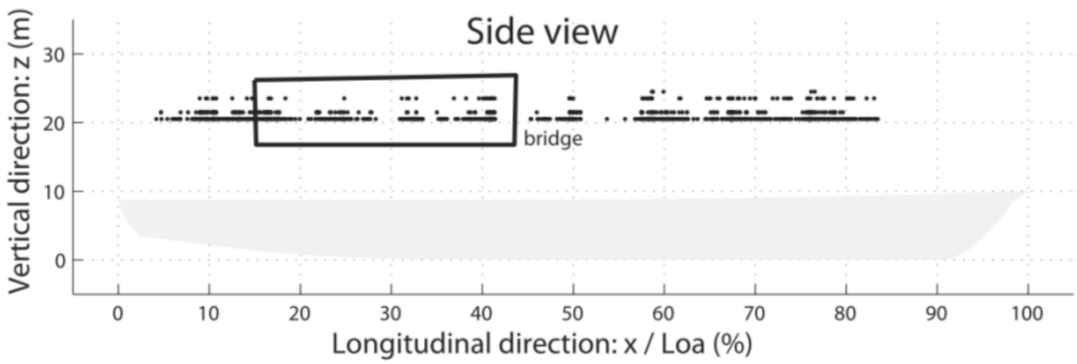


Figure 16: Selection of preferred bridge positions (van Oers 2011)

The novel feature of the selection approach is that visualization is used to trigger the expression of human engineering judgement, rather than having an algorithm select the "best" design based on a numerical value (e.g. objective function).

6.4 Unique Features

The packing approach used by van Oers, allows for large changes within the parametric ship description. Objects are placed sequentially according to an initial position. After each object is placed at its initial position overlap between the current object and all previous objects is removed. The large changes are possible by changing the initial position of each object by an algorithm. The result is a detailed but flexible parametric ship description which can be used to explore the design space.

As mentioned the selection of ship configuration is done in a post-processing step, by interactively confronting the user with choices for certain characteristics. This approach is meant to increase the sense of acceptance for the final selected design (i.e. the user is in control for important decisions made) and to allow for expression of human engineering judgement in the design.

6.5 Practical Applications

The TU Delft emphasizes that its tool is not limited to naval applications. Research into practical non-naval applications by (den Hamer 2011; van Bruinessen 2010; Wagner 2009; Wagner et al. 2010) show that the configuration optimization routine can be used for different types of complex vessels. Examples are the application for the general arrangement of a deepwater drillship design (see Figure 17), and the deck layout of an offshore wind turbine installation jack-up.

During these practical applications the tool's input was modified to incorporate ship type and problem type specific performance predictions, objects and constraints. This show the value of the generic parametric model set up by *van Oers*. By defining a library of ship specific systems and objects, using the generic object types, the arrangements of multiple vessel types can be explored.

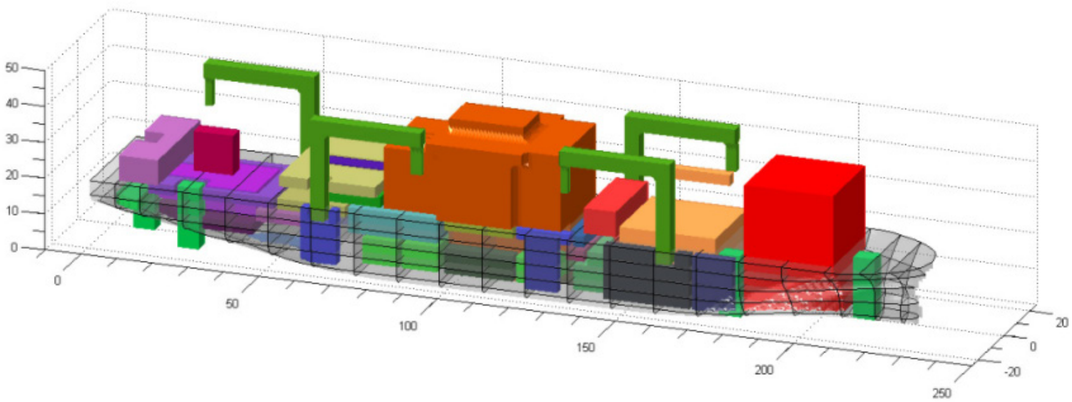


Figure 17: Application of the TU Delft tool to the configuration of a deepwater drilling vessel design (Wagner 2009; Wagner et al. 2010)

6.6 Recent and Ongoing Developments

Recent research, by (DeNucci 2012; DeNucci et al. 2009), focuses on the capture of design rationale, i.e., implicit reasoning and justification, behind configuration decisions, see Section 6.3. In their research, an integrated Rationale Capture Tool is presented which includes a novel elicitation approach (Reactive Knowledge Capturing), dedicated ontology for the structure of configuration rationale and an optimization-based feedback mechanism designed to increase the breadth of the database and improve the efficiency of the capture process. Analysis and results of a comprehensive test case performed with this tool are presented in this conference. The rationale database supports the decision-making process inherent in configuration design and shows promise in complementing any of the arrangement approaches described previously.

Feedback of captured knowledge during the design process is essential. This calls for a more dynamic and interactive design approach in which the user is constantly interacting with the design tool to identify and select promising design features and alternatives. This allows for gradual decision making regarding tradeoffs throughout the design process. In this interactive approach a search algorithm would first generate an initial set of designs using only few systems and constraints. From this set the user identifies and selects promising designs for use in the next iteration. This process should give designers the opportunity to immediately see the effect of adding, removing or changing; systems, constraints, and requirements.

Current research being performed by Peter de Vos focuses on component selection, system functioning and matching steps for energy systems in the preliminary design stage. Due to limited resources (e.g. time, money, adequate personnel), these steps are often taken at a later stage in the ship design process when actual system selection has already taken place, often based on re-used information from previous similar designs. This may results in ill-estimated system dimension, sub-optimal system functioning and component matching, and limited creativity in the system design. The proposed solution is to automatically generate system (topology) models which can be used to analyse system dimensions, matching, operational modes, redundancy, and performance through simulation. This gives valuable information and input for use in the configuration optimization model, in which currently the systems are assumed available and decided upon.

The generic design and engineering process can be visualised by a Vee model, based on the model used in systems engineering, as shown in Figure 18. The developments by van Oers and DeNucci focus both on the design of ship configurations at the right side of this Vee model and assume that initial decisions on required systems and components have been made. However, these decisions also require a design process to select the most promising system solutions and are very much dependent on the knowledge available within the design team. In addition, the selection of system solutions is based on the required functions and related performance requirements which themselves are a result of a selection process to fulfil stakeholder's needs to execute a mission in an effective way. New developments will focus on additional tools to support these decision making processes and the capturing of the related knowledge in the left side of this Vee model.

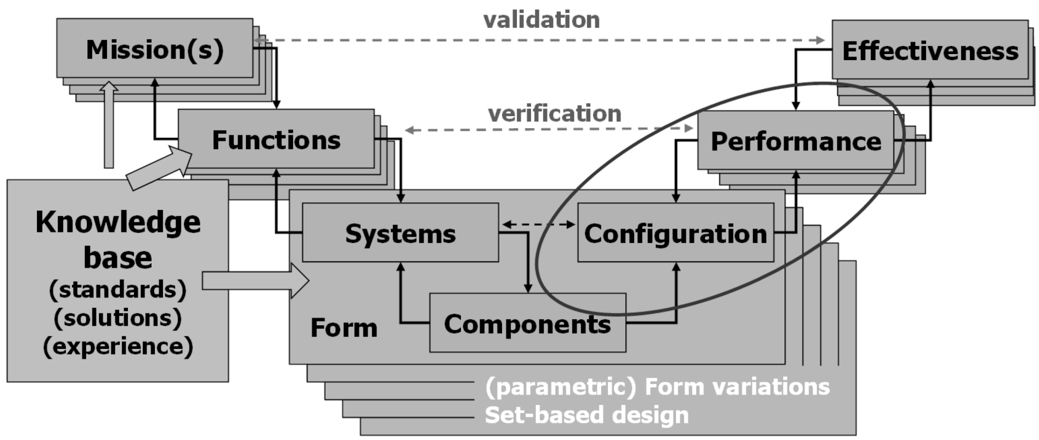


Figure 18: Vee model of generic design and engineering process (based on *Systems Engineering*)

7 SUMMARY OF METHODS

From Sections 4, 5, and 6 of the IMDC 2012 Design for Layout State of the Art Report included above, it is clear that each presented method has its own unique way of tackling the ship system arrangement and configuration problem. University College London has produced a design approach which synthesizes a new ship design by an architecturally driven philosophy (the Design Building Block approach) and had this incorporated in a state-of-art commercial preliminary ship CAD system (Paramarine) through a specifically produced module (SURFCON). The University of Michigan has focused on space allocation and geometry inside a fixed ship hull via optimization using embedded intelligence. Delft University of Technology has developed a design tool that automatically generates a large number of feasible designs by packing systems into a positioning space. A general comparison of the major important features is given in Table 4.

Table 4: Comparison of features

	UM	UCL	TU Delft
Driver	Area	Volume (DBB)	Volume (DBB)
Full ship design[14]	Deck arrangements only	Yes	Yes
N dimensions[15]	2.5D	3D	2.5D or 3D
Computer-generated layouts	Yes	User drag-and-drop	Yes
Optimization scheme	HGA-MAS	Manual	GA
# feasible concepts	Hundreds	Few	Hundreds
Adaptable hull shape	No, fixed from ASSET	Yes, can be wrapped	Yes, between designs

8 GAP ANALYSIS

The papers previously referenced in this report document the increase in general arrangements research and early-stage design capabilities, particularly during the last decade. In order to continue pushing the field of

[14] Ability of the design tool to provide a full ship arrangement and analysis (e.g., weights, centers, stability, etc.) independent of other tools.

[15] For UM and UCL, 2.5D is defined as 2D deck plans on multiple decks with consideration for vertical connectivity from deck to deck. For TUD, 2.5D is defined as a limited level of detail in the y-direction (breadth), refer to IMDC paper of Van Oers 2012.

general arrangements forward, we identify areas of the ship general arrangements process that are insufficiently addressed or not addressed at all.

We have identified four core areas in which advancements are needed:

1) **Data and knowledge reuse:** The ability to capture design data, knowledge, and intent in an unobtrusive, natural, and user-friendly manner to facilitate maintenance and reuse of that information.
2) **Macro-level characteristics of ship layouts:** The ability to understand the nature of ship arrangements on a macro-scale and to define appropriate metrics to provide insight into non-dominated solution sets and guidance for down-selecting designs.
3) **Abstraction away from representations of physical geometry:** The ability to view the requirements elucidation process, and the role of ship layouts in that process, as an overlay of multiple data types in order to preserve the richness of information that is lost when mapped in the domain of traditional general arrangements drawings.
4) **User experience:** The ability to provide users with efficient, natural tools for generating and evaluating general arrangements to promote designer exploration and learning and to reduce modeling demands on the designer.

Each topic is discussed in the following sections. Where a specific application of a need is mentioned, it is followed by the appropriate research center's initials (i.e., UCL, UM, TUD).

8.1 Data and knowledge reuse

Need: The ability to capture design data, knowledge, and intent in an unobtrusive, natural, and user-friendly manner to facilitate maintenance and reuse of that information.

Much of the time spent conducting tradeoff studies for general arrangements is related to the modeling process. Each of the existing ship arrangements methods requires a data or knowledge source, which is the repository for design specifications, rules of thumb, and best practices. Significant manual effort is required for dataset development and maintenance (UCL, UM, TUD). In addition, the ship model description itself (without arranged spaces and systems) requires a similar commitment of resources. The ability to re-use data and knowledge is critical for efficient design processes and extensive tradeoff analyses.

Currently, each ship type or ship concept requires its own, specific dataset of spaces, systems, and design constraints (UCL, UM, TUD). Though ship-class templates can be used, this dataset may change with differing concepts within a trade study and each dataset must be adjusted manually. The automatic generation of constraints or topology models for systems depends on the ability to capture information and knowledge from existing sources. Learnings from the test and integration (right-hand) side of the systems engineering Vee diagram (Figure 18) should be relayed back to the requirements definition (left-hand) side (TUD). However, none of the existing methods have the ability to capture the information, experience, and designer intent embedded within resultant arrangements so they can be incorporated into future designs. One vision of such an information capture and reuse system is one that learns design constraints, relationships, intent, and style by observing an experienced designer creating a layout and then provides suggestions to future, possibly less-experienced, designers.

8.2 Macro-level characteristics

Need: The ability to understand the nature of ship arrangements on a macro-scale and to define appropriate metrics to provide insight into non-dominated solution sets and guidance for down-selecting designs.

The design space for ship layouts is huge, highly multimodal, and generally flat, resulting in large sets of non-dominated solutions (by existing metrics). TUD has developed guidelines and tools for selecting from Pareto optimal solution sets (van Oers, 2008), but specific, quantifiable metrics are lacking. Methods and metrics are needed which can differentiate solutions that are visually different, but receive the same overall quality score using existing objective functions. These metrics could be the general arrangements equivalent to non-dimensional parameters, for example, Froude and Reynolds numbers.

Existing arrangements tools for assisting in design provide the capability to query individual design constraints to determine their level of satisfaction, but they cannot describe ship-level characteristics. It would be beneficial to be able to describe the performance of a layout in early-stage design, for example, the relative producibility or whether and why a design is more habitable to sailors than another. Macro-level descriptors could be used as intelligence mechanisms for optimization engines (UM, TUD) or for providing feedback to designers regarding how closely an arrangement meets the intent of a specified design style (UCL). Further, describing the sensitivity of hull shape, configuration, and size on the internal arrangement requires these types of macro-level metrics (TUD).

8.3 Abstraction

Need: The ability to view the requirements elucidation process, and the role of ship layouts in that process, as an overlay of multiple data types in order to preserve the richness of information that is lost when mapped in the domain of traditional general arrangements drawings.

Arrangements research efforts thus far have primarily focused on creating feasible ship and space layouts of the traditional variety in shorter timeframes. The purpose of generating layouts rapidly is to enable the comparison of many designs in tradeoff studies. Often, the tradeoff studies are conducted in order to gain a more complete understanding of the impacts of requirements on individual designs and on the design space. This process can be described using Figure 19, where the primary feedback loop is conducted to identify a well-balanced set of requirements and diverse set of designs to match. However, when using automated approaches where designers do not directly participate in the iterative process, the impacts of requirements must be inferred from the resultant geometric and spatial layouts (UM, TUD). Another option is to use a semi-automated interactive approach where the user is constantly identifying emerging requirement impacts and trends within a generated set of designs (TUD).

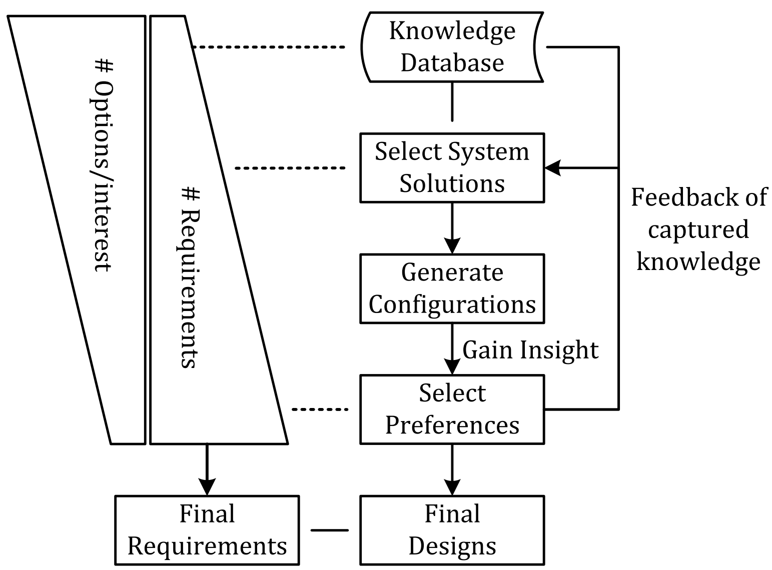


Figure 19: Simultaneous development of both layouts and requirements

The ship arrangements community needs to be able to see the impact of requirements and system selections without the lens of the resultant geometry. General arrangements are more than just geometry, but regardless of the nature of the design decision or option being considered, all layout-related information is currently reduced to the domain of a general arrangement drawing. Underlying each spatial layout decision and position of a shipboard element is an array of information strongly influenced by the designer's 'idiosyncratic' influences etc. Much of this information can be modeled abstractly, using, for example, system topologies, networks representing physical and logical relationships, and parametric models. Integrating different conceptual domains and conducting joint analyses directly on these information sources could provide a more direct way of examining and elucidating requirements.

8.4 User experience

Need: The ability to provide users with efficient, natural tools for generating and evaluating general arrangements to promote designer exploration and learning and to reduce modeling demands on the designer.

Well-developed methods and tools are of no use without a committed user base, and developing a user base requires gaining acceptance of the design community. Providing designers a satisfactory experience requires more than developing attractive and easy-to-use graphical interfaces, though that is an important aspect. As mentioned previously, much of the user's time and effort is related to model development and maintenance. The vision is to possess tools for improving the ship layout process by letting designers do more designing and less modeling, meaning the designer spends more time learning about tradeoffs, challenging selection choices, and making decisions with less time drawing and maintaining models and setting up and running analyses. User experience issues have been subdivided into two categories: efficient, natural model interaction and shortened runtimes.

8.4.1 Efficient, natural model interaction

For tasks such as visualization and model editing, CAD-style interfaces are a common need (UCL, UM, TUD). While these tools exist in commercial applications and do not represent a new area for research, additional features could build upon the existing foundation. For example, when a building block or space is added to a layout, intelligent mechanisms could assist the designer in automatically sizing it based on the ship type (UCL), suggesting related elements (UCL, UM), or even placing related elements according to style guidelines or specified requirements in a manual or automated process (UCL, UM, TUD). The mechanisms for building intelligence, as well as the ability to assess and change a design's "style" as the design progresses, must be developed.

Visualization of a design in new ways is also needed. Designers need new cognitive aids for managing the large amount of information embodied in a ship arrangement. For example, overlays of different types of relationships, linkages, and patterns onto the traditional geometric representation could help a designer realize and modify the nature of an emerging design. An example of this sort of image is provided in Figure 20. Graphical methods for combining the myriad information abstractions previously described (e.g., networks, topologies, etc.) would give designers a more complete visual description of the full arrangement.

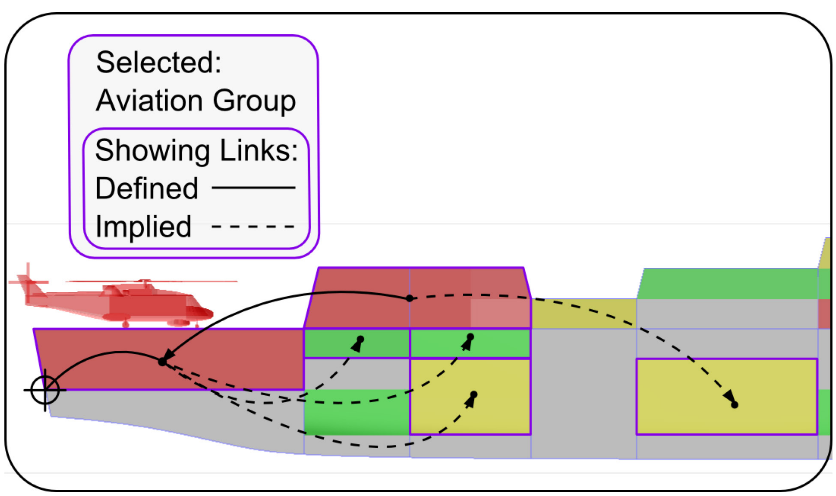


Figure 20: Example overlay of different types of relationships and patterns in an emerging design (Pawling & Andrews, 2011)

8.4.2 Shortened runtimes

Whether designs are created using manual (UCL) or automated (UM, TUD) means, the design cycle time needs to be reduced. The automated methods may take a few hours to a full day to run, while expert users of Paramarine can create tens of designs in a few weeks. Feasible candidate solutions are often eliminated and the number of variants reduced in the later stages of a design processes simply because the effort required to represent secondary and tertiary concerns exceeds available manpower (Figure 21). This reduction of variants is shown in the UCL LCS (Andrews & Pawling, 2008) and JSS (Andrews & Pawling, 2007) studies. Additional automated methods and associated enabling technologies are needed to move in the right direction.

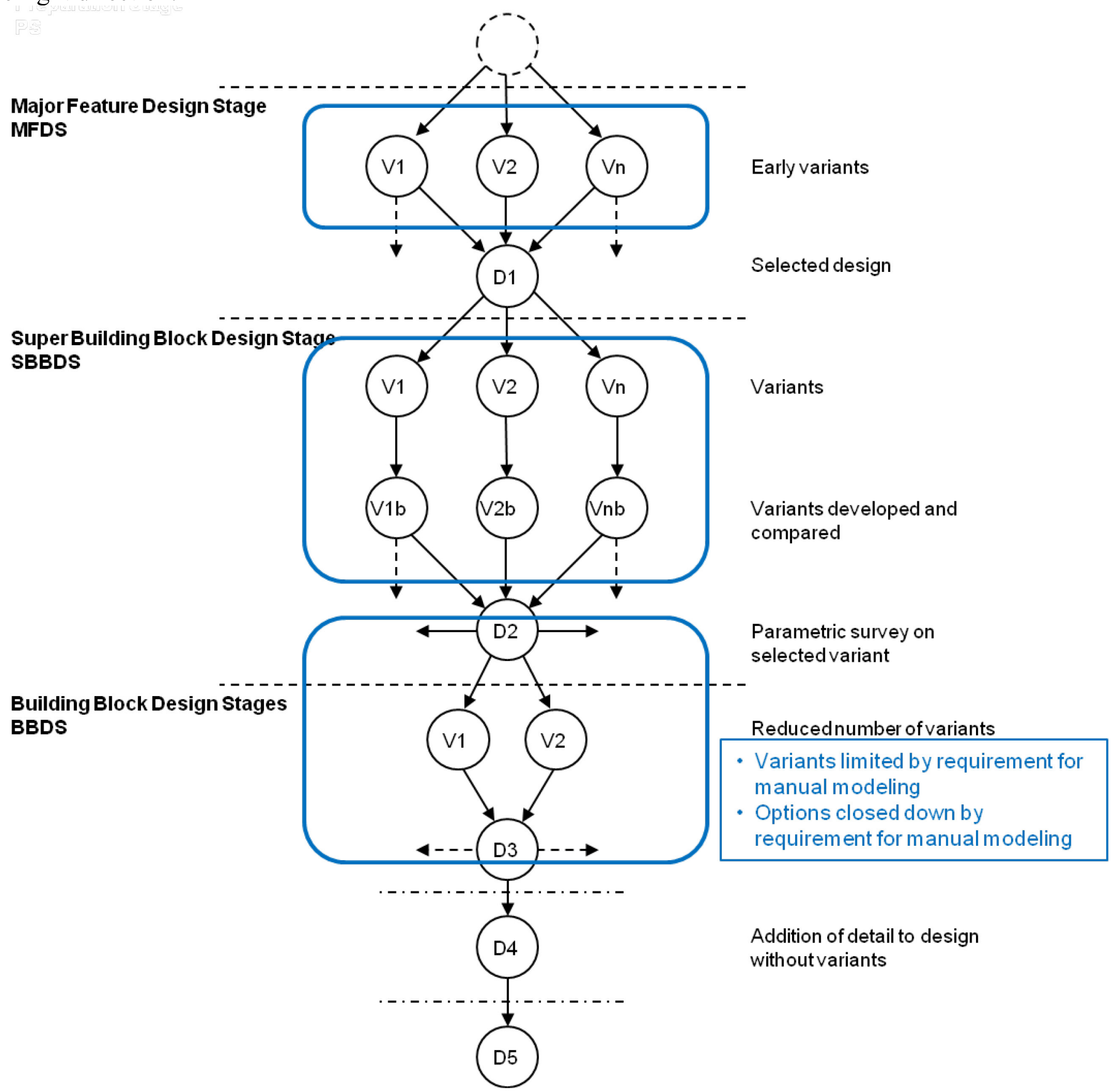


Figure 21: Reduction in the number of variants in later design stages due to manual modeling requirements

One current vision of the design process includes the user actively interacting with a population of designs as new variants are created and analyzed in real-time. Extremely quick optimization runs, automated suggestion routines, and intuitive information presentation are just a few areas where innovations are needed. Implementing these changes is not trivial. Optimizations could be done in shorter time through a combination of, for example, algorithm parallelization, enhanced intelligence, high performance computing hardware, or reformulations of the model description. A clear basis must be defined for optimization with the ability to alter criteria readily and conduct multi-criteria sensitivity analyses.

9 OPPORTUNITIES FOR COLLABORATION AND FUTURE RESEARCH

This document has identified four core needs for continued development in the field of ship layout research, namely related to data and knowledge reuse, macro-level characteristics of ship layouts, abstraction away from representations of physical geometry, and user experience. Fortunately, there is much overlap in the needs of UCL, UM, and TUD for developing methods that can address the broad goals of navy clients while providing appropriate approaches, tools, and guidance to the individuals creating the designs.

Each design center also has a set of needs specific to its approach to generating and evaluating ship layouts within the context of its sponsor's own overall ship design process. These unique challenges are detailed in the following sections.

10 UCL DESIGN BUILDING BLOCK APPROACH CHALLENGES

- Remembering that the approach could be more appropriately described as a CAD paradigm rather than an approach to preliminary arrangements;
- And also noting that the intended use case for the DBBA is in the development of style (i.e. solution type) and capability variants (i.e. problem type) as part of an exploratory dialectic process of requirements elucidation

10.1 Encouraging the Sketching Approach

The exploratory approach used in concept ship design, particularly in architecturally centred methods, Figure 21 is seen to be equivalent to a sketching approach to ship design, where the designs are developed as part of a dialectic process of investigation, discussion and the gaining of understanding about the problem. This was introduced in Pawling (2007) and has been discussed more extensively in Pawling & Andrews (2011). There are two areas where the application of such approaches could be enhanced. One is the overall design process supported by the toolset and DBB approach. The other is the technical detail of the user interface.

10.2 User Interfaces

The user interface and imbedded modelling paradigm in PARAMARINE are a reflection of the origins of the kernel as a general purpose product modelling tool. Some of the other developmental areas described here have associated UI developments. In terms of the general interface approach, specific gaps have been identified; the general modelling interface could be enhanced with "natural" modelling methods similar to other 3D modelling tools. For example the ability to reflect objects port to starboard, snap objects, and assign object relationships is key to the modelling and sketching process. Additional methods of interacting with the 3D model could be provided, such as interactive 2D deck plans, customisable 2D views (sections), which allow the 3D model to be interrogated in different ways. A general interest is in replacing the CLI dialogues with more GUI methods, using both direct representations (3D and 3D rendering of geometry) and abstract representations (e.g. nodal editor renderings of systems and interconnections)

10.3 Overall Design Process Issues

10.3.1 The Requirement to Model all Solutions, All the Time

Currently, there is no automation of modelling or generation of any layout features. A major feature, such as an operations room, consisting of a single cuboid, can be placed much more rapidly that a minor one, such as a set of ATUs, as the latter consist of several cuboids. Yet the designer is not carrying out the same level of mental tradeoff with the ATU as with the Ops room – they are usually placed in a mechanistic way. In a given design, usually only a small number of spaces, objects or features are of explicit interest to the designer, with the majority being placed "like a frigate" or "like a trimaran". The time difference is due to the requirement to model everything by hand. There is a capability gap in that these established, and in many cases explicitly recorded layout types and location preferences are only implemented in the designers head. This requires the designer to manually model every feature of the design in a bespoke fashion, even if they can describe the rules to be applied universally and generically. As a result, the designer must spend more time implementing the consequences of decisions (e.g. central ops room or battery system) than they do in defining those decisions themselves.

10.3.2 Integrating Different Conceptual Domains in the Design

The "general arrangement" of the ship encompasses more than just the geometry. It (usually implicitly) includes topological networks, organisational networks (flow) etc., styles like "zoning" and system networks. In the current implementation of the DBBa, regardless of the nature of the design decision or option being considered, it is always reduced to the domain of manually generating a general arrangement. The integration of the different possible topological descriptions of the design into a single geometric description is currently a very human centric process – employing the dialectic sketching process, where the geometry is used as an external aid to the internal discussion and subsequent reviewing.

10.3.3 Extraction of (Emergent) Knowledge from the Developing Design

Although past studies have shown that the designer and design teams gain a great deal of knowledge about the interactions and other emergent properties of the design - from the physical layout perspective - by performing the arrangement manually, this requires the designer to model, analyse, categorise and describe simultaneously. Improvements need to be developed in the ability for the designer to alter properties of the design to asses multiple 'what if" scenarios. Implementations of the 'rules of thumb' in design are inherently difficult to represent as emergent properties as they are solution specific, often require extensive elemental design tradeoffs as they develop and are representative of accumulated knowledge for the basis of design decisions. Better methods of extracting both emergent (problem-solution specific) and generic (usually DBB properties) and applying them in new designs are desired. Currently all designs start from a standard dataset that can only be maintained with significant manual effort.

10.3.4 Understanding Connections in the Design

Although the current tool contains a method for interrogating the connections explicitly defined between objects in the design, it is very simple and requires significant cognitive effort to visualise and internalise the connections represented. This is also restricted to the explicitly defined connections between objects in the design model (e.g. parametric links used to control positions of bulkheads etc. This could be improved through a better GUI, perhaps a "node editor" concept, which could then be extended to allow direct editing of the connections through a GUI as opposed to the current CLI type dialogue.

10.3.5 Incorporation of Design Logic and Style

There is currently no way to directly represent design decisions, logic or design style in the PARAMARINE implementation of the DBBa. All that can be modelled is the solution adopted. In some cases the perceived need is for recording and logging tools, to act as a design "diary". More radically, there is a need for methods of generating solutions based on style choices and rules, not on modelling of complete solutions.

10.3.6 Incorporation of Additional Analysis Tools and Approaches

By incorporating architectural aspects into the early stages of design, the DBBa should assist in the application of simulation based performance analysis methods. These may be full simulation or knowledge based approaches.

11 UM INTELLIGENT SHIP ARRANGEMENTS CHALLENGES

11.1 Constraint database

Developing the constraint database, which specifies the requirements for each space and the relationships among spaces, is a tedious and error-prone process. In a frigate-sized ship, there may be several thousand constraints. If components and systems were included, the numbers would grow exponentially. Ensuring these are input correctly is essential. ISA currently does not provide a smooth process for identifying errors or inconsistent relationships.

Due to the immense time required to develop a new database, the ability to reuse constraint information is needed. Currently, constraint information is developed for a ship of a given type (frigate, cruiser, etc.) and stored in a database. Methods are needed to split and merge portions of databases to facilitate the reuse of information for new or hybrid ship types.

Additional research is needed on auto generation of constraints. The vision is an intelligent AI system that can auto generate not only the list of constraints but also the function values of those constraints. Boundaries for each individual constraint must be able to be explored for their impact on the overall integrated design.

11.2 Agents

The agents developed for ISA are intelligent and very effective. However, they are also task-specific. Individualized logic is required for agents that represent spaces, passages, and stair towers. In a scenario involving distributed systems, components and systems may require their own specialized decision-making rules. Identifying the rules agents should follow in order to replicate a designer's thought process as a nontrivial and time-consuming task.

11.3 Solution representation

When a solution is presented in ISA it is difficult to trace the drivers of the solution. One can evaluate each constraint and utility function to see its final values, but there are no methods to analyze the results in a "macro" sense. The ability to quickly analyze the solution against design driving criteria and develop queries is needed.

11.4 High performance computing

An overarching need for extending general arrangements tools to include distributed systems is the need to exploit high performance computing advances. ISA currently runs on a single processor. Taking advantage of multiple processors on a single computer or of multiple networked computers would enable shorter runtimes through increased simultaneous constraint evaluations. Increased processing power would also facilitate evaluation of larger populations, enabling thorough exploration of the design space and likely better solutions. However, parallelizing and coordinating the agents in a coherent design optimization is nontrivial.

11.5 Graphics & GUIs

Recent improvements to ISA have included an enhanced GUI and graphics. Additional capabilities are needed, however, to support additional use cases. One example is the ability to draw an arrangement manually and rapidly in order to support traditional design processes with the added benefit of rational, rigorous, and consistent grading mechanisms. Currently, drawing a new passage network takes about a day; a more CAD-like interface that is easier to use would help decrease the time required to generate a configuration.

11.6 Support for different use cases

A desire has been expressed to use full functional complexes, rather than spaces, as the base unit for an arrangement. In this use case, designers would need the ability to identify and designate spaces belonging to complexes. Then, each complex would be assigned to a structural zone or multiple structural zones, and spaces would be given a shape in an arrangement phase. Methods for identifying the appropriate contents of a complex are being developed at the University of Michigan, but refinements are needed.

12 TUD PACKING APPROACH AND SYSTEM DESIGN CHALLENGES

12.1 System design and selection

Current research (2012) being performed by de Vos, focuses on component selection, system functioning and matching steps for energy systems in the preliminary design stage (van Es, 2012). Due to limited resources (e.g. time, money, adequate personnel), these steps are often taken at a later stage in the ship design process when actual system selection has already taken place, often based on re-used information from previous similar designs. This may result in poorly estimated system dimension, sub-optimal system functioning and component matching, and limited creativity in the system design. The proposed solution is to automatically generate system (topology) models, which can be used to analyze system dimensions, matching, operational modes, redundancy, and performance through simulation. This gives valuable information and input for use in the configuration optimization model, in which currently the systems are assumed available, static, and decided upon.

12.2 Knowledge capturing

The generic design and engineering process can be visualized by a Vee model, based on the model used in systems engineering. The developments by (van Oers 2011) and (DeNucci 2012) focus both on the design of ship configurations at the base where detailed sub-system design is accomplished and approach the right side of this Vee model, assuming that initial decisions on required systems and components have been made. However, these decisions also require a design process to select the most promising system solutions and are very much dependent on the knowledge available within the design team. In addition, the selection of system solutions through PSD tools is based on the required functions and related performance requirements which themselves are a result of a selection process where preferences are chosen *a posteriori* by the designer sequentially based on criteria. New developments should focus on additional tools to support these decision making processes and the capturing of the related knowledge (e.g. system selection knowledge and requirement elucidation knowledge) in the left side of this Vee model.

12.3 Interactive steering

Feedback of captured knowledge during the design process is essential. There is no use in capturing knowledge if it is not (re)used. This calls for a more dynamic and interactive design approach in which the user is constantly interacting with the design tool to identify and select promising design features and alternatives. This allows for gradual decision making, tradeoff selection, visualization, and increase of detail throughout the design process, see Figure 19.

In this interactive approach a search algorithm would first generate an initial set using only a few systems, and constraints (e.g. positions) starting with a super building block, designed for one complete ship function. From this set the user can identify and select the most promising and “freeze” their desirable features temporarily, and increase the number of systems and constraints for the next run or to revisit downstream in the design. This iterative process gradually increases the number of systems and constraints (and even objectives) during the search process. All developed systems, constrains and objectives need to be managed through the use of visualization.

The interactive process also allows the designer to gain insight into the relations between posed requirements and resulting designs. This is done by adding systems, removing systems, changing systems positions, changing whole ship style and investigating the added constraints.

The result of the entire exercise should be a well-balanced set of requirements including a well-balanced, diverse set of ship designs that fit the requirements in the most optimal way.

12.4 Weight and centroids

Several non-negotiable requirements concern buoyancy, stability and trim whose prediction relies heavily on the accurate estimation of both weight and center of gravity. Early layout of the design can help development of accurate centers of gravity, which are key drivers in the design requirements. Development of a more accurate and sensitive weight estimate is necessary to ensure better practical application of the tool.

A difficulty in developing a more accurate weight estimate is the dependency of the weight of an object on the global location in the ship. A passageway object might weight less if located low in the ship. The reason for this is the additional equipment that might be present when located higher in the ship for reasons of damage control or additional cabling and ducting.

Ideally, one should be able to distinguish between systems that do not change weight according to location, and systems that do change weight. This may require a higher level of detail of the ship description.

12.5 Center of gravity related constraints

Currently the requirements related to stability and trim are considered after the packing of the ship configuration has taken place. These constraints can be incorporated into the packing process. This could prevent heavy systems from taking unwanted positions that have a negative effect on the COG, which finally could result in a non-feasible design with insufficient stability. As part of a sequential and iterative process, the initial estimate of the COG can not be accurately determined until packing is complete.

12.6 Reusability

A reusable parametric ship description can improve the practical applicability of the tool. Applications to parts of a vessel design or even to the arrangement of cargo are also possible. This does however call for a need to keep the parametric ship parameters generic.

12.7 Different hull shapes

The approach has only been applied to mono-hull type vessels. Further application to ship and offshore structures with more unconventional envelope shapes, e.g., jack-ups, semi-submersibles, catamarans, trimarans and SWATHs, is considered both possible and worthwhile. Among other things, it would provide more insight in the interaction between envelope shape and size and the interior arrangement.

Still, application to unconventional envelope shapes will require considerable effort as one has to update weight and center of gravity predictions (difficult enough for a mono-hull), as well as adjust numerous other performance prediction tools, e.g. stability, resistance, propulsion.

12.8 Prediction tools

The number of prediction tools integrated with the packing approach should increase. Even though the results do not have to be used by objectives or constraints, this will increase the information available to the naval architect to identify and resolve tradeoffs during the selection process. Moreover, integrating more advanced prediction tools, e.g., RAPID (Raven 1996) will help predict performances for a broader range of designs and, as a result, will improve the ability of the naval architect to further increase the competitiveness of service vessels.

Additional prediction tools should, for warships at least, include sea-keeping (already investigated and used by van Bruinessen (2010)) and vulnerability (investigated by van Ingen, (2011)) as a stand-alone interface to use designs generated by the packing approach).

12.9 Implementation, graphics and GUI

Currently the program uses a slow but user-friendly higher level programming language in MATLAB, this allows for easier alteration and modification of the code. However, when deemed appropriate the program can be rewritten in a faster lower level programming language such as FORTRAN, C++ or C#.

Construction (currently based on text files) and visualization of a parametric ship description should improve ease of use and increase speed with which a suitable parametric ship description could be developed.

A CAD type viewer should improve the ease with which generated designs can be explored. Selecting systems and displaying relevant information such as relations to other objects (much like the UCL approach by Andrews et al (2008)) can visualize impacts of decisions, captured and used configuration knowledge, etc.

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Appendix B: List of compartments by hub, authority ranking

From Figure 4.3: Ranking of drivers by average hub score.

3062 Galley & Scullery
3377 Sewage Treatment Machinery Room
3557 Trash Room
3611 Mechanical Workshop (General)
3260 PO & Specialist Dining Room
3332 POL & Paint Locker (Service)
3620 PO & Specialist Dining Room
3323 POL & Paint Locker (Storage)
3251 PO & Specialist Dining Room
3242 PO & Specialist Dining Room
2837 Cleaning Gear Storeroom (Below Decks)
3359 Refrigerator Machinery Room
3584 Main Machinery Room Diesel (Hold)
3494 Steering Gear Room
3485 Steering Gear Room
2702 Aft Pump Room
3053 Fwd Pump Room
2720 Air Conditioning Room
2711 Air Conditioning Room
3593 Main Machinery Rm. Diesel (1stPlatform)
3566 Wardroom
3179 Officer Cabin (Male)(2) & Bath GrpB
3188 Officer Cabin (Male)(2) & Bath GrpB
3134 Officer Cabin (Male)(2) & Bath GrpA
3143 Officer Cabin (Male)(2) & Bath GrpA
3197 Officer Cabin (Male)(2) & Bath GrpB
3170 Officer Cabin (Male)(2) & Bath GrpB
3161 Officer Cabin (Male)(2) & Bath GrpA
3152 Officer Cabin (Male)(2) & Bath GrpA
3422 Specialist Cabin (Male)(6) GrpA
3404 Specialist Cabin (Male)(6) GrpA
3449 Specialist Cabin (Male)(6) GrpB
3413 Specialist Cabin (Male)(6) GrpA
3431 Specialist Cabin (Male)(6) GrpB
3440 Specialist Cabin (Male)(6) GrpB
3539 Training Room
3269 PO Cabin (Male)(4) & Bath GrpA
3305 PO Cabin (Male)(4) & Bath GrpB
3296 PO Cabin (Male)(4) & Bath GrpB
3287 PO Cabin (Male)(4) & Bath GrpA
3278 PO Cabin (Male)(4) & Bath GrpA
3314 PO Cabin (Female)(4) & Bath
3215 Officer Cabin (Female)(2) & Bath
3467 Specialist Cabin (Female)(6)
3206 Officer Cabin (Female)(2) & Bath
3224 Officer Cabin (Female)(2) & Bath
3458 Specialist Cabin (Female)(6)
2864 Cool Cold Dry Provisions
3350 Recreation Room
2981 Fan Room (Hull)
2936 Electrical Equipment Room
2900 Electrical Equipment Room
3386 Ships Office
2846 CO Cabin & Bath
2882 Electrical Equipment Room
2873 Electrical Equipment Room
2918 Electrical Equipment Room
3548 Library
2954 Electrical Equipment Room
3530 Electrical Switchboard Room
2756 BC Medical Facility
2891 Electrical Equipment Room
2945 Electrical Equipment Room
2990 Fan Room (Hull)
3575 XO Cabin & Bath
3341 Daily Provision Room
3233 Laundry (Officer & PO)
3476 Laundry (Specialist)
2774 Bosun Storeroom (Aft Mooring)
2909 Electrical Equipment Room
2792 Bosun Storeroom (MainDeck)
3098 Medical Storeroom
3071 General Stowage
2999 Fan Room (Hull)
2927 Electrical Equipment Room
3044 Foul Weather Gear Locker
2855 CO Storeroom
3026 Fan Room (Deckhouse)

2963 Engineer Officer Cabin
3017 Fan Room (Hull)
3035 Fan Room (Deckhouse)
2747 Battery Locker and Charging
3125 Mooring Area & Gear Storeroom (Aft)
3008 Fan Room (Hull)
3503 Electrical Switchboard Room
2801 Bosun Storeroom (MainDeck)
3089 Medical Consultation Room
3080 Linen Locker
3512 Electrical Switchboard Room
2828 Chain Locker Sump
3116 Mooring Area & Gear Storeroom (Aft)
3395 Sick Bay
2819 Chain Locker
3368 SD Storeroom
3521 Electrical Switchboard Room
3107 Mooring Area & Gear Storeroom (Fwd)
2972 Enclosed RIB Stowage
2729 Anchoring & Mooring
2765 Boat Gear Locker
2810 Bridge
2783 Bosun Storeroom (Fwd Mooring)
2738 Auxiliary Propulsion Room
3602 Auxiliary Machinery Room (AMR)

From Figure 4.4: Ranking of most constrained compartments by average authority score.

3206 Officer Cabin (Female)(2) & Bath
3197 Officer Cabin (Male)(2) & Bath GrpB
3215 Officer Cabin (Female)(2) & Bath
3134 Officer Cabin (Male)(2) & Bath GrpA
3458 Specialist Cabin (Female)(6)
3449 Specialist Cabin (Male)(6) GrpB
3179 Officer Cabin (Male)(2) & Bath GrpB
3152 Officer Cabin (Male)(2) & Bath GrpA
3125 Mooring Area & Gear Storeroom (Aft)
3143 Officer Cabin (Male)(2) & Bath GrpA
3161 Officer Cabin (Male)(2) & Bath GrpA
3188 Officer Cabin (Male)(2) & Bath GrpB
3170 Officer Cabin (Male)(2) & Bath GrpB
3395 Sick Bay
3413 Specialist Cabin (Male)(6) GrpA
3440 Specialist Cabin (Male)(6) GrpB
3422 Specialist Cabin (Male)(6) GrpA
3431 Specialist Cabin (Male)(6) GrpB
3404 Specialist Cabin (Male)(6) GrpA
3260 PO & Specialist Dining Room
3287 PO Cabin (Male)(4) & Bath GrpA
3296 PO Cabin (Male)(4) & Bath GrpB
3269 PO Cabin (Male)(4) & Bath GrpA
3278 PO Cabin (Male)(4) & Bath GrpA
3305 PO Cabin (Male)(4) & Bath GrpB
2954 Electrical Equipment Room
3539 Training Room
3557 Trash Room
3341 Daily Provision Room
2855 CO Storeroom
3566 Wardroom
3332 POL & Paint Locker (Service)
3242 PO & Specialist Dining Room
3251 PO & Specialist Dining Room
3611 Mechanical Workshop (General)
3233 Laundry (Officer & PO)
2747 Battery Locker and Charging
3467 Specialist Cabin (Female)(6)
3530 Electrical Switchboard Room
3053 Fwd Pump Room
3062 Galley & Scullery
3224 Officer Cabin (Female)(2) & Bath
3602 Auxiliary Machinery Room (AMR)
3377 Sewage Treatment Machinery Room
2837 Cleaning Gear Storeroom (Below Decks)
3089 Medical Consultation Room
3080 Linen Locker
3386 Ships Office
3368 SD Storeroom
3548 Library
2891 Electrical Equipment Room
2909 Electrical Equipment Room
2945 Electrical Equipment Room
2927 Electrical Equipment Room
2981 Fan Room (Hull)
2864 Cool Cold Dry Provisions
2972 Enclosed RIB Stowage
2936 Electrical Equipment Room
2873 Electrical Equipment Room
2882 Electrical Equipment Room
2900 Electrical Equipment Room
3521 Electrical Switchboard Room
2765 Boat Gear Locker
3350 Recreation Room
2711 Air Conditioning Room
2990 Fan Room (Hull)

2918 Electrical Equipment Room
2999 Fan Room (Hull)
3044 Foul Weather Gear Locker
3008 Fan Room (Hull)
3476 Laundry (Specialist)
3116 Mooring Area & Gear Storeroom (Aft)
2810 Bridge
3485 Steering Gear Room
2783 Bosun Storeroom (Fwd Mooring)
3494 Steering Gear Room
2819 Chain Locker
2702 Aft Pump Room
2756 BC Medical Facility
3071 General Stowage
3503 Electrical Switchboard Room
3359 Refrigerator Machinery Room
2828 Chain Locker Sump
3512 Electrical Switchboard Room
2738 Auxiliary Propulsion Room
3017 Fan Room (Hull)
2792 Bosun Storeroom (MainDeck)
3107 Mooring Area & Gear Storeroom (Fwd)
2720 Air Conditioning Room
3098 Medical Storeroom
3035 Fan Room (Deckhouse)
3575 XO Cabin & Bath
3323 POL & Paint Locker (Storage)
2846 CO Cabin & Bath
3026 Fan Room (Deckhouse)
2963 Engineer Officer Cabin
3593 Main Machinery Rm. Diesel (1stPlatform)
3314 PO Cabin (Female)(4) & Bath
2774 Bosun Storeroom (Aft Mooring)
2729 Anchoring & Mooring
2801 Bosun Storeroom (MainDeck)
3584 Main Machinery Room Diesel (Hold)
3620 PO & Specialist Dining Room

Appendix C: List of compartment drivers by hierarchy

From Figure 4.6: Ranking of drivers via hierarchy.

3593 Main Machinery Rm. Diesel (1stPlatform)
3557 Trash Room
3377 Sewage Treatment Machinery Room
3602 Auxiliary Machinery Room (AMR)
3584 Main Machinery Room Diesel (Hold)
3611 Mechanical Workshop (General)
2711 Air Conditioning Room
2720 Air Conditioning Room
3053 Fwd Pump Room
3323 POL & Paint Locker (Storage)
3332 POL & Paint Locker (Service)
2702 Aft Pump Room
3485 Steering Gear Room
3494 Steering Gear Room
3062 Galley & Scullery
2837 Cleaning Gear Storeroom (Below Decks)
2729 Anchoring & Mooring
3359 Refrigerator Machinery Room
3242 PO & Specialist Dining Room
3251 PO & Specialist Dining Room
3260 PO & Specialist Dining Room
3620 PO & Specialist Dining Room
2738 Auxiliary Propulsion Room
2972 Enclosed RIB Stowage
2810 Bridge
2747 Battery Locker and Charging
2801 Bosun Storeroom (MainDeck)
3116 Mooring Area & Gear Storeroom (Aft)
3107 Mooring Area & Gear Storeroom (Fwd)
2792 Bosun Storeroom (MainDeck)
3125 Mooring Area & Gear Storeroom (Aft)
2783 Bosun Storeroom (Fwd Mooring)
3044 Foul Weather Gear Locker
3521 Electrical Switchboard Room
2774 Bosun Storeroom (Aft Mooring)
3503 Electrical Switchboard Room
3026 Fan Room (Deckhouse)
3017 Fan Room (Hull)
3035 Fan Room (Deckhouse)
3512 Electrical Switchboard Room
2999 Fan Room (Hull)
3530 Electrical Switchboard Room
2990 Fan Room (Hull)
3008 Fan Room (Hull)
2819 Chain Locker
2945 Electrical Equipment Room
2927 Electrical Equipment Room
2918 Electrical Equipment Room
2909 Electrical Equipment Room
2981 Fan Room (Hull)
2882 Electrical Equipment Room
2900 Electrical Equipment Room
2873 Electrical Equipment Room
2954 Electrical Equipment Room
2936 Electrical Equipment Room
2891 Electrical Equipment Room
3071 General Stowage
2864 Cool Cold Dry Provisions
2756 BC Medical Facility
3566 Wardroom
3134 Officer Cabin (Male)(2) & Bath GrpA
3143 Officer Cabin (Male)(2) & Bath GrpA
3152 Officer Cabin (Male)(2) & Bath GrpA
3161 Officer Cabin (Male)(2) & Bath GrpA
3170 Officer Cabin (Male)(2) & Bath GrpB
3179 Officer Cabin (Male)(2) & Bath GrpB
3188 Officer Cabin (Male)(2) & Bath GrpB
3197 Officer Cabin (Male)(2) & Bath GrpB
3431 Specialist Cabin (Male)(6) GrpB
2765 Boat Gear Locker
3413 Specialist Cabin (Male)(6) GrpA
3404 Specialist Cabin (Male)(6) GrpA
3422 Specialist Cabin (Male)(6) GrpA
3449 Specialist Cabin (Male)(6) GrpB
3440 Specialist Cabin (Male)(6) GrpB
3278 PO Cabin (Male)(4) & Bath GrpA
3269 PO Cabin (Male)(4) & Bath GrpA
3287 PO Cabin (Male)(4) & Bath GrpA
3539 Training Room
3314 PO Cabin (Female)(4) & Bath

3305 PO Cabin (Male)(4) & Bath GrpB
3296 PO Cabin (Male)(4) & Bath GrpB
2846 CO Cabin & Bath
2828 Chain Locker Sump
2855 CO Storeroom
3098 Medical Storeroom
3089 Medical Consultation Room
3395 Sick Bay
3080 Linen Locker
3386 Ships Office
3341 Daily Provision Room
3368 SD Storeroom
3458 Specialist Cabin (Female)(6)
2963 Engineer Officer Cabin
3206 Officer Cabin (Female)(2) & Bath
3215 Officer Cabin (Female)(2) & Bath
3224 Officer Cabin (Female)(2) & Bath
3467 Specialist Cabin (Female)(6)
3233 Laundry (Officer & PO)
3476 Laundry (Specialist)
3350 Recreation Room
3548 Library
3575 XO Cabin & Bath

Appendix D: List of compartment drivers by hierarchy using only quality designs

From Figure 4.7: Ranking of drivers via hierarchy using only quality designs. Compartment categorization is highlighted.

3593 Main Machinery Rm. Diesel (1stPlatform)
3557 Trash Room
3602 Auxiliary Machinery Room (AMR)
3377 Sewage Treatment Machinery Room
2702 Aft Pump Room
3323 POL & Paint Locker (Storage)
3332 POL & Paint Locker (Service)
3611 Mechanical Workshop (General)
3053 Fwd Pump Room
2720 Air Conditioning Room
3584 Main Machinery Room Diesel (Hold)
2729 Anchoring & Mooring
2711 Air Conditioning Room
3485 Steering Gear Room
2837 Cleaning Gear Storeroom (Below Decks)
3494 Steering Gear Room
3062 Galley & Scullery
3359 Refrigerator Machinery Room
2747 Battery Locker and Charging
3242 PO & Specialist Dining Room
3251 PO & Specialist Dining Room
3260 PO & Specialist Dining Room
3620 PO & Specialist Dining Room
2738 Auxiliary Propulsion Room
2819 Chain Locker
2972 Enclosed RIB Stowage
3116 Mooring Area & Gear Storeroom (Aft)
2801 Bosun Storeroom (MainDeck)
2810 Bridge
2765 Boat Gear Locker
3107 Mooring Area & Gear Storeroom (Fwd)
3125 Mooring Area & Gear Storeroom (Aft)
3503 Electrical Switchboard Room
3017 Fan Room (Hull)
2783 Bosun Storeroom (Fwd Mooring)
3521 Electrical Switchboard Room
3071 General Stowage
3512 Electrical Switchboard Room
2774 Bosun Storeroom (Aft Mooring)
3008 Fan Room (Hull)
2927 Electrical Equipment Room
2999 Fan Room (Hull)
2945 Electrical Equipment Room
3566 Wardroom
3530 Electrical Switchboard Room
2792 Bosun Storeroom (MainDeck)
3044 Foul Weather Gear Locker
2954 Electrical Equipment Room
2864 Cool Cold Dry Provisions
2909 Electrical Equipment Room
2990 Fan Room (Hull)
3026 Fan Room (Deckhouse)
2918 Electrical Equipment Room
2882 Electrical Equipment Room
2891 Electrical Equipment Room
2900 Electrical Equipment Room
2828 Chain Locker Sump
2981 Fan Room (Hull)
2873 Electrical Equipment Room
3035 Fan Room (Deckhouse)
2936 Electrical Equipment Room
2756 BC Medical Facility
3134 Officer Cabin (Male)(2) & Bath GrpA
3143 Officer Cabin (Male)(2) & Bath GrpA
3152 Officer Cabin (Male)(2) & Bath GrpA
3161 Officer Cabin (Male)(2) & Bath GrpA
3170 Officer Cabin (Male)(2) & Bath GrpB
3179 Officer Cabin (Male)(2) & Bath GrpB
3188 Officer Cabin (Male)(2) & Bath GrpB
3197 Officer Cabin (Male)(2) & Bath GrpB
3431 Specialist Cabin (Male)(6) GrpB
3422 Specialist Cabin (Male)(6) GrpA
3413 Specialist Cabin (Male)(6) GrpA
3440 Specialist Cabin (Male)(6) GrpB

3449 Specialist Cabin (Male)(6) GrpB
3269 PO Cabin (Male)(4) & Bath GrpA
3278 PO Cabin (Male)(4) & Bath GrpA
3287 PO Cabin (Male)(4) & Bath GrpA
3404 Specialist Cabin (Male)(6) GrpA
3296 PO Cabin (Male)(4) & Bath GrpB
3305 PO Cabin (Male)(4) & Bath GrpB
3314 PO Cabin (Female)(4) & Bath
3539 Training Room
2855 CO Storeroom
3395 Sick Bay
2846 CO Cabin & Bath
3089 Medical Consultation Room
3098 Medical Storeroom
3341 Daily Provision Room
3386 Ships Office
3080 Linen Locker
3368 SD Storeroom
2963 Engineer Officer Cabin
3206 Officer Cabin (Female)(2) & Bath
3215 Officer Cabin (Female)(2) & Bath
3224 Officer Cabin (Female)(2) & Bath
3458 Specialist Cabin (Female)(6)
3467 Specialist Cabin (Female)(6)
3476 Laundry (Specialist)
3233 Laundry (Officer & PO)
3350 Recreation Room
3548 Library
3575 XO Cabin & Bath

Appendix E: List of compartment types by median r_1-rank for Combination F

From Figure 4.15: The range of r1-rankings for each space type in Combination F and the baseline hierarchy rank. Space types are sorted left-to-right by ascending median r1-rank.

Trash Room
Sewage Treatment Machinery Room
Aft Pump Room
Fwd Pump Room
Main Machinery Room Diesel (Hold)
POL & Paint Locker (Storage)
POL & Paint Locker (Service)
Mechanical Workshop (General)
Main Machinery Room Diesel (1stPlatform)
Galley & Scullery
Bridge
Air Conditioning Room
Cleaning Gear Storeroom (Below Decks)
Steering Gear Room
Anchoring & Mooring
Refrigerator Machinery Room
Enclosed RIB Stowage
PO & Specialist Dining Room
Bosun Storeroom (MainDeck)
Bosun Storeroom (Fwd Mooring)
Fan Room (Deckhouse)
Foul Weather Gear Locker
Mooring Area & Gear Storeroom (Aft)
Auxiliary Propulsion Room
Battery Locker and Charging
Auxiliary Machinery Room (AMR)
Fan Room (Hull)
Electrical Switchboard Room
Mooring Area & Gear Storeroom (Fwd)
Bosun Storeroom (Aft Mooring)
Electrical Equipment Room
Cool Cold Dry Provisions
General Stowage
BC Medical Facility
Chain Locker
Wardroom
CO Cabin & Bath
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpB
Specialist CaLLOCAabin (Male)(6) GrpB
Specialist Cabin (Male)(6) GrpA
Boat Gear Locker
Training Room
Medical Consultation Room
Sick Bay
Chain Locker Sump
Medical Storeroom
PO Cabin (Male)(4) & Bath GrpB
PO Cabin (Female)(4) & Bath
PO Cabin (Male)(4) & Bath GrpA
CO Storeroom
Daily Provision Room
SD Storeroom
Officer Cabin (Female)(2) & Bath
Ships Office
Engineer Officer Cabin
Linen Locker
Specialist Cabin (Female)(6)
Laundry (Specialist)
Laundry (Officer & PO)
Recreation Room
Library
XO Cabin & Bath

Appendix F: Direct seed compartment allocations

Refer to Figure 2.7 (page 28) for structural zone numberings.

From Figure 6.9: Sample allocation via direct seeding using 22 communities.

Zone 005
Fan Room (Hull)
Linen Locker
Electrical Switchboard Room

Zone 006
Electrical Equipment Room
POL & Paint Locker (Storage)
POL & Paint Locker (Service)

Zone 007
Anchoring & Mooring
Chain Locker
Chain Locker Sump

Zone 009
Auxiliary Propulsion Room
Electrical Equipment Room
Fan Room (Hull)

Zone 010
Electrical Equipment Room
Fan Room (Hull)
Fwd Pump Room

Zone 011
Bosun Storeroom (Fwd Mooring)
Electrical Equipment Room
Mooring Area & Gear Storeroom (Fwd)

Zone 013
Bosun Storeroom (MainDeck)
Electrical Switchboard Room
Auxiliary Machinery Room (AMR)

Zone 014
Specialist Cabin (Male)(6) GrpA
Specialist Cabin (Male)(6) GrpA
Specialist Cabin (Male)(6) GrpA

Zone 015
Cleaning Gear Storeroom (Below Decks)
Electrical Equipment Room
Fan Room (Hull)
Sewage Treatment Machinery Room
Trash Room

Zone 016
BC Medical Facility
Bridge
CO Cabin & Bath
CO Storeroom
Fan Room (Deckhouse)
Medical Consultation Room
Medical Storeroom
Sick Bay

Zone 017
Officer Cabin (Male)(2) & Bath GrpB
Officer Cabin (Male)(2) & Bath GrpB
Officer Cabin (Male)(2) & Bath GrpB
Officer Cabin (Male)(2) & Bath GrpB

Zone 019
Aft Pump Room
Main Machinery Room Diesel (Hold)
Main Machinery Room Diesel (1stPlatform)
Mechanical Workshop (General)

Zone 020
Battery Locker and Charging
Mooring Area & Gear Storeroom (Aft)
Refrigerator Machinery Room

Zone 021
Electrical Equipment Room
Foul Weather Gear Locker
Electrical Switchboard Room

Zone 022
Boat Gear Locker
Electrical Equipment Room
Enclosed RIB Stowage

Zone 023
Fan Room (Hull)
Fan Room (Deckhouse)
Electrical Switchboard Room

Zone 025
Air Conditioning Room
Bosun Storeroom (MainDeck)
Electrical Equipment Room
Steering Gear Room

Zone 026
Electrical Equipment Room
General Stowage
SD Storeroom

Zone 027
Cool Cold Dry Provisions
Galley & Scullery
Laundry (Officer & PO)
PO & Specialist Dining Room
PO & Specialist Dining Room
PO & Specialist Dining Room
PO Cabin (Male)(4) & Bath GrpA
PO Cabin (Male)(4) & Bath GrpA
PO Cabin (Male)(4) & Bath GrpA
Daily Provision Room
Recreation Room
Ships Office
Specialist Cabin (Male)(6) GrpB
Specialist Cabin (Male)(6) GrpB
Specialist Cabin (Male)(6) GrpB
Specialist Cabin (Female)(6)
Specialist Cabin (Female)(6)
Laundry (Specialist)
Training Room
Library
PO & Specialist Dining Room

Zone 028
Engineer Officer Cabin
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Female)(2) & Bath
Officer Cabin (Female)(2) & Bath
Officer Cabin (Female)(2) & Bath
PO Cabin (Female)(4) & Bath
Wardroom
XO Cabin & Bath

Zone 030
Air Conditioning Room
Electrical Equipment Room
Steering Gear Room

Zone 031
Bosun Storeroom (Aft Mooring)
Mooring Area & Gear Storeroom (Aft)
PO Cabin (Male)(4) & Bath GrpB
PO Cabin (Male)(4) & Bath GrpB

From Figure 6.10: Sample allocation via direct seeding using 19 communities.

Zone_Deck_005
Bosun Storeroom (MainDeck)
Electrical Equipment Room
Electrical Switchboard Room

Zone_Deck_006
Electrical Equipment Room
POL & Paint Locker (Storage)
POL & Paint Locker (Service)

Zone_Deck_007
Air Conditioning Room
Anchoring & Mooring
Chain Locker
Chain Locker Sump
Fan Room (Hull)

Zone_Deck_009
Auxiliary Propulsion Room
Electrical Equipment Room
Electrical Switchboard Room

Zone_Deck_010
Battery Locker and Charging
Bosun Storeroom (MainDeck)
Fan Room (Hull)

Zone_Deck_011
Bosun Storeroom (Fwd Mooring)
Mooring Area & Gear Storeroom (Fwd)
Sewage Treatment Machinery Room
Trash Room

Zone_Deck_013
Air Conditioning Room
Fwd Pump Room
Electrical Switchboard Room

Zone_Deck_014
Unfilled

Zone_Deck_015
Cool Cold Dry Provisions
Galley & Scullery
General Stowage
Linen Locker
Laundry (Officer & PO)
PO & Specialist Dining Room
PO & Specialist Dining Room
PO & Specialist Dining Room
PO Cabin (Male)(4) & Bath GrpA
PO Cabin (Male)(4) & Bath GrpA
PO Cabin (Male)(4) & Bath GrpA
Daily Provision Room
Recreation Room
SD Storeroom
Ships Office
Specialist Cabin (Male)(6) GrpB
Specialist Cabin (Male)(6) GrpB
Specialist Cabin (Male)(6) GrpB
Specialist Cabin (Female)(6)
Specialist Cabin (Female)(6)
Laundry (Specialist)
Training Room
Library
Auxiliary Machinery Room (AMR)
PO & Specialist Dining Room

Zone_Deck_016
BC Medical Facility
Electrical Equipment Room
Medical Consultation Room
Medical Storeroom
Sick Bay

Zone_Deck_017
Bridge
CO Cabin & Bath
CO Storeroom
Fan Room (Hull)

Zone_Deck_019
Aft Pump Room
Electrical Equipment Room
Main Machinery Room Diesel (Hold)
Main Machinery Room Diesel (1stPlatform)
Mechanical Workshop (General)

Zone_Deck_020
Unfilled

Zone_Deck_021
Cleaning Gear Storeroom (Below Decks)
Electrical Equipment Room
Fan Room (Hull)
Steering Gear Room

Zone_Deck_022
Boat Gear Locker
Enclosed RIB Stowage
Foul Weather Gear Locker

Zone_Deck_023
Electrical Equipment Room
Fan Room (Deckhouse)
Officer Cabin (Male)(2) & Bath GrpB
Officer Cabin (Male)(2) & Bath GrpB
Officer Cabin (Male)(2) & Bath GrpB
Officer Cabin (Male)(2) & Bath GrpB
PO Cabin (Male)(4) & Bath GrpB
PO Cabin (Male)(4) & Bath GrpB

Zone_Deck_025
Unfilled

Zone_Deck_026
Electrical Equipment Room
Specialist Cabin (Male)(6) GrpA
Specialist Cabin (Male)(6) GrpA
Specialist Cabin (Male)(6) GrpA

Zone_Deck_027
Electrical Equipment Room
Fan Room (Deckhouse)
Electrical Switchboard Room

Zone_Deck_028
Engineer Officer Cabin
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Male)(2) & Bath GrpA
Officer Cabin (Female)(2) & Bath
Officer Cabin (Female)(2) & Bath
Officer Cabin (Female)(2) & Bath
PO Cabin (Female)(4) & Bath
Wardroom
XO Cabin & Bath

Zone_Deck_030
Fan Room (Hull)
Refrigerator Machinery Room
Steering Gear Room

Zone_Deck_031
Bosun Storeroom (Aft Mooring)
Electrical Equipment Room
Mooring Area & Gear Storeroom (Aft)
Mooring Area & Gear Storeroom (Aft)

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