Design for Modularity: Volume 1: Optimisation of Ship Design and Operation for Life Cycle

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Chapter 10
Design for Modularity

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Abstract

Design for modularity refers to decisions taken at the design stage of the ship lifecycle, addressing how we can decompose and encapsulate ship system elements in order to both improve design and manufacturing process efficiency and ship operational performance. At the design stage, modularity can concurrently support both standardization and diversification using a product platform strategy and lay the foundation for a configuration-based design process. Modularity is relevant in the production phase in supply chain design, modular production, early outfitting and outsourcing. In the operation phase, modularity implies flexibility, providing opportunities for adapting the vessel's to changing markets, technologies, regulations and customer needs.

Keywords: Modular Design, Modular Adaptable Ships, Configuration-Based Design

Abbreviations:
MID: Modularity in Design
MIP: Modularity in Production
MIU: Modularity in Use
MAS: Modular Adaptable Ship

10.1 INTRODUCTION TO DESIGN FOR MODULARITY

By "design for modularity" we refer to explicit actions towards sub-dividing the ship into well-defined parts and components that can later be recombined according to given rules and procedures. There might be various motivations for modularity that are relevant for different phases of the ship life cycle. For example, in the ship design and acquisition phase, modularity may support an efficient ship configuration process towards specific customer needs based on a ship product platform. In the ship production phase, a modularization strategy can support distributed production with turn-key suppliers, enabling a high degree of pre-outfitting. In the operation phase, modularity supports flexibility towards missions, markets, and technical and regulatory changes.

This chapter will provide an overview of the many aspects related to ship design for modularity. First, the concept of modularity is more precisely defined, and placed in a wider context by relating it to adjacent topics such as product platforms, product architectures and configuration-based design. This is followed by a review of design for modularity for each of the three main phases of the ship lifecycle – modularity in the design phase aimed at providing a ship design and configuration platform, followed by modularity in production, and finally on modularity in operation for providing flexibility and handling uncertainty. For each of these, the benefits and challenges are discussed, models and methods are reviewed, and industrial applications are presented.

10.2 DEFINING AND DELIMITING MODULARITY

From a systems perspective, modularity is basically a strategic approach to handle complexity, whether this complexity is structural, behavioral, contextual, perceptual or temporal (Gaspar, Rhodes et al. 2012). This is achieved by dividing a system into manageable, self-contained parts. Modularity as a concept is used in widely different fields such as biology, computer science, languages, mathematics and engineering. Even though there are significant variations in the way modularity is both understood and implemented between these different fields, there are some basic characteristics that can be summarized as follows:

1. The division of a larger system into smaller parts or components
2. The principle of (relative) self-sufficiency of the individual parts
3. The recombination of the parts into multiple end products, according to a set of "rules" given by an overall systems architecture

These aspects are also captured in (Schilling 2000), where modularity is defined as "*A general systems concept: it is a continuum describing the degree to which a system's components can be separated and recombined*".

Intrinsically, modularization involves both *decomposition* and *encapsulation*. Decomposition typically follow hierarchical structures of the system, for instance functional breakdown structures or assembly/part structures, denoted by (Simon 1962) as a primary strategy for architecting complex systems. Encapsulation involves an effort to hide the complexity of each part behind well-defined interfaces, thus controlling complex interactions. This relates to the axiomatic design theory (Suh 1990), where the *independence axiom* states the preference of one-to-one mappings between functional requirements and design parameters.

The definition of modularity implies that simply splitting up a product for later assembly is not necessarily termed a modular approach, such as for instance in section and block oriented ship production strategies. There needs to be a certain level of flexibility in the way that the parts are recombined, such as for the Sigma Modular Ships or the Littoral Combat Ship. This will be discussed in more detail later, related to modular production strategies.

However, this is quite a wide range of definitions for the term "modular", and in several sources it is also used for all types of assembly and packaging of systems and elements. In an early reference on this topic from 1974, the following definition is used (Jolliff 1974):

"*Pre-Packaging a collection of equipment (systems or components) for the purpose of their assembly and check-out prior to delivery to the ship for installation and for ease of installation and removal of the package (module)*"

This definition also captures the division of the ship into blocks, sections and modules as part of the ship production process. Here, the purpose is not "mass customization", but rather a "divide-and-conquer" strategy for a division into chunks that are fit for the production facilities (weight and size of crane, docks, halls, ports, production equipment, etc.) and the production process (planning units, parallel production, procurement units, material management, etc).

10.2.1 A Modular or an Integral Product Architecture?

The product architecture defines "the scheme by which the functions of a product are allocated to physical components" (Ulrich and Tung 1991). Thus, the product architecture describes the structure of a system, in defining the main function and entities of the system and how these are related to each other.

The basic choice of product architecture needs to be determined at the outset of the design process. In a simplistic world, we have to choose between an *integral* or a *modular* architecture.

This can be illustrated using a very simple example. Consider two basic functions for a seaborne transport vessel:

F1: Provide cargo support
F2: Provide thrust through water

In a traditional design, these two functions are, at a high level, allocated to a single ship "chunk", as illustrated in Figure 10.1. To the extent that this overall chunk can be separated into a hull module and a machinery & propulsion module, the interaction between these modules are complex and not well defined. For instance, an increase in speed would typically require a larger and heavier propulsion system that in the next step would require an increase in hull displacement. Thus, these two modules have a high degree of dependency, which is a typical characteristic for *integral architectures*. From an axiomatic design perspective (Suh 1990), we have a coupled design, that is not in adherence to the *independence axiom* requiring a (close to) one-to-one mapping between a function and the corresponding form element.

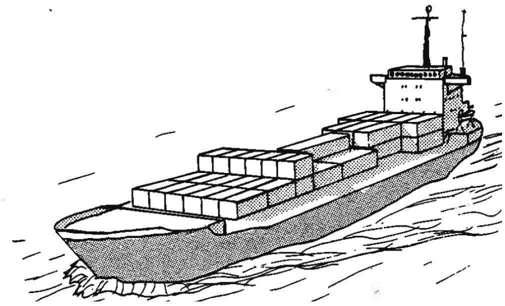

Figure 10.1: A traditional monohull ship is an example of an integral architecture, (Erichsen 1989)

In general, *integral architectures* are characterized by the following properties (Ulrich 2008):

- Product functions are implemented using more than one chunk or module

- A single chunk or module implements many product functions
- There is a high degree of (complex) interaction between the product modules

The opposite of an integral architecture is a *modular architecture*. Here, the different functions of the product are, to the extent possible, allocated to separate product modules, and the interaction between these modules is small or non-existent.

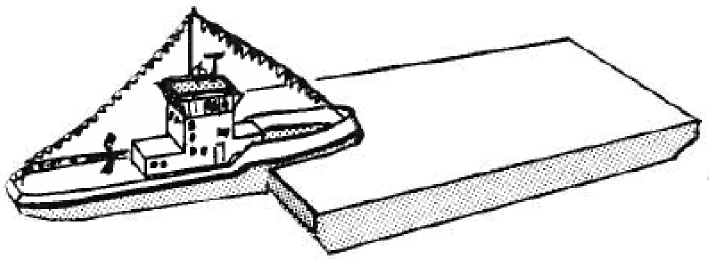

Figure 10.2 Assigning the cargo support and thrust provision function to separate modules provide a more modular architecture, (Erichsen 1989)

For the seaborne transport example, a more modular architecture could be achieved by separating the system into a cargo unit, such as a barge, and a propulsion unit, such as a tug (Fig. 10.2). In this case, an increase in speed would only require a change in the "tug module", and not *per se* influence the "barge module". (However, this functional independence does not hold the opposite way).

From a business perspective, modularity has many benefits, primarily related to cost savings, in all phases of the ship life cycle, as will be exemplified later in this chapter. However, full modularity is not always possible to achieve from a technical perspective, typically due to weight and size constraints (Hölttä-Otto and de Weck 2007).

10.2.2 Related Concepts

Modularization is closely related to several other systems concepts and technologies that have received considerable attention lately. Modules provide the basic elements in a product platform. They also provide the building blocks in a configuration-based design strategy, in which customized products can be derived by scaling and combining standardized modules towards specific end-user needs, i.e. "mass customization". The relations between these concepts are illustrated in Figure 10.3.

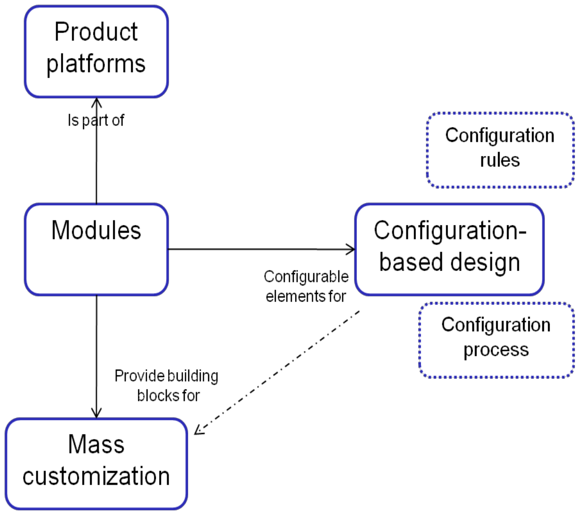

Figure 10.3 Core concepts related to modularity and their interrelations, (Erikstad 2009)

10.2.3 Modularity Types

It is common to distinguish different types of modularity based on how the modules are interconnected, as well as how they are attached to a common platform. In (Salvador, Forza et al. 2002) four main types are identified, as illustrated in Figure 10.4.

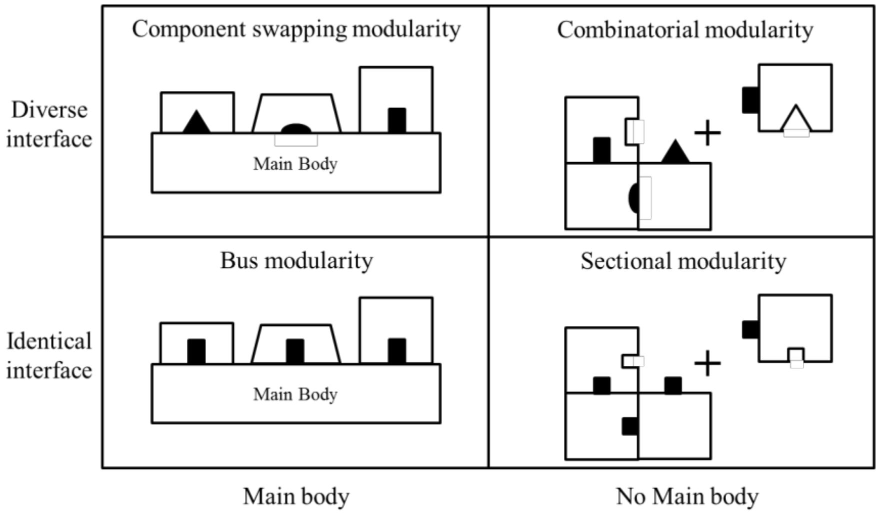

Figure 10.4 Different types of modularity (Salvador, Forza et al. 2002)

In *component swapping modularity*, which is a sub-type of slot modularity (Ulrich 2008), the interfaces are specific to the module type. An example can be seen in Figure 10.5 showing a US Navy concept that allows for different configuration and rapid refit, but with a predefined location for each equipment type where the appropriate interface slot is available. A variant of this is the combinatorial modularity, also with a diverse set of interfaces, but without a main body.

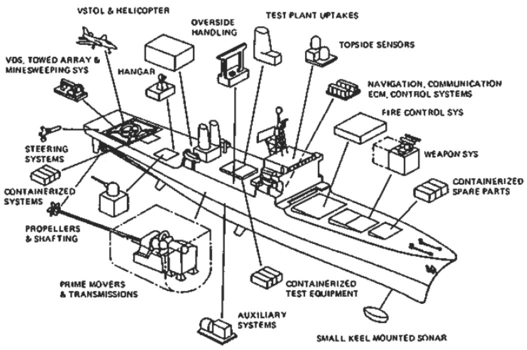

Figure 10.5 Component swapping modularity in US Navy TES concept (Jolliff 1974)

In *bus modularity* the interface is standardized across several module types. This type of modularity is required when different selections and combinations of (equipment) modules are used to customize the product towards different purposes. One example is the US Navy Littoral Combat Ship, see Figure 10.6, where containerized mission modules can be replaced in operation.

Figure 10.6 The Littoral Combat Ship is an example of bus modularity, where different mission modules, packaged as containers, can be plugged into a standard interface to provide a wide array of different mission capabilities, (AOC 2018)

In *sectional modularity* there is no “platform” module in which the other modules attach. Rather, all modules have one or a few common interfaces, which typically allow a larger variety in the physical layout of the product. On a ship, piping and HVAC systems typically exhibit sectional modularity. We have also seen this on a ship level, for instance with the SIGMA modular ship, where standardized hull sections are arranged according to specific needs and mission requirements.

Figure 10.7 Ship piping system, illustrating sectional modularity, (Erikstad 2009)

10.3 MODULARITY IN THE DESIGN PHASE

In the design phase, modularity is important for:

- Enabling both standardization and diversification/customization using a product platform strategy
- A more efficient design process through a configuration-based design process
- Supporting innovation by exploring the design space through modular re-combinations

In general, modularity in design enables ship designers to reuse earlier designs and makes structural complexity manageable with simplified representation due to the hidden interactions within modules. This simplification is necessary for holistic approaches to ship design because ship designers have to deal with a large number of subsystems and the conflicting requirements of multiple stakeholders (Papanikolaou 2010).

10.3.1 Supporting a Product Platform Strategy

During recent years many industries have moved from designing individual, "one-of-a-kind" products towards developing *product platforms*. A "product platform" can be defined as "*a structured, coherent collection of resources, including systems and template hierarchies, textual components, variants, rules and interface definitions, from which a range of customized product definitions can be derived*" .

There are numerous cases from diverse industries on how this technology has improved the product development process (Simpson 2003). For instance, Volkswagen has applied platform technology across their Audi, Volkswagen, Seat and Skoda brands. Black & Decker has developed a common platform with extensive component reuse both across different brands and across different product types. Product platforms have contributed to reduced cost, shorter development cycles and the ability to maintain a broad product range while standardizing and reducing the number of different components and configuration elements (Wuuren and Halman 2001). The impact of product platform technologies has been more limited within the maritime industries, and in particular on a vessel level as a consequence of the high degree of customization, not only on the vessel configuration, but also on the make of core systems components. Thus, platform technologies have had a higher degree of adaptation among ship equipment suppliers.

One of the forerunners in Norway in this technology area was Ulstein Design. They developed a product platform for offshore supply and service vessels, see Figure 10.8, and used this platform to configure individual vessels based on customer requirements. Their vision has been that the design reflected in the very early specification phase shall be as consistent as possible with the downstream detail engineering, and in the end production, with as little (re)work as possible.

Figure 10.8 Selected products in the Ulstein Design portfolio (Source: Ulstein Design)

Modularization is related to product platforms in terms of being the building blocks from which the product platform is built. By adding, removing, replacing or scaling modules, the product platform can be targeted towards specific markets or customer requirements. Core research challenges include efficient strategies and methods for determining the sub-division into modules and the number of variants of each, the recombination of these modules into product families of products, and how these are leveraged to target specific market segments and niches. The primary tradeoff in the platform design process is between commonality and distinctiveness (Simpson 2003), or between cost-cutting and increasing market shares (Ericsson and Erixon 1999).

10.3.2 Design Process Efficiency by Configuration-based Design Based on Modularity

An important driver for modularity in the design phase is to reduce the lead time and resource expenditure in responding to tender invitations. Today, even for routine designs, it is quite common that this process starts from a previous tender, possibly for another customer with slightly different requirements. This is then "cleaned" for project specific content, and the particular requirements for the current customer are incorporated. Typically, the tender documents need to be checked with the different disciplines, such as structures, machinery and electrical. Obviously, both quality and response time are under pressure.

With a modular design platform with a well-structured configuration system on top, this process may be considerably improved both in terms of efficiency, quality, and reduced risk, as well as indirectly through increasing the likelihood of winning the contract. For a ship design office, this is important for improved productivity, as illustrated in Figure 10.9.

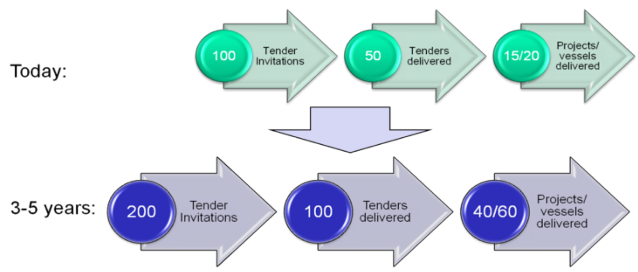

Figure 10.9 A modular design platform may improve the efficiency and quality of tender project development, and possibly leading to both increased handling capacity and higher hit rate, (Erikstad 2009)

Generally, a design configuration system, can be defined as: "A (software) system that enables a structured definition of a valid design solution from a given set of customer requirements, by applying pre-defined rules and templates to select, scale and synthesize a collection of modules" (Brathaug, Holan et al. 2008). This decouples the design work into two distinct stages, a platform development stage in which the modules are developed and integrated into a product platform, and a "configure-to-order" stage in which individual tenders and designs are customized towards the individual needs of each customer. This is illustrated in Figure 10.10.

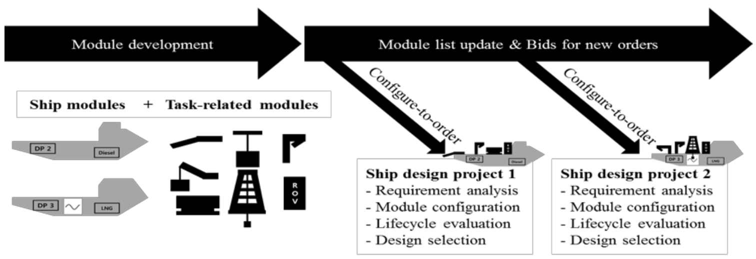

Figure 10.10 Dividing the design process into a platform development stage and a "configure-to-order" stage (Choi, Erikstad et al. 2018)

Configuration may be described as a particular class of routine design, in which the major design elements – modules – are known, and that these can be combined into a solution that meets the customer requirements without involving the development of new solution elements. Configuration is in many aspects the opposite of the more common "copy-and-edit" approach taken in projects with short lead times and only a limited set of changes from existing projects.

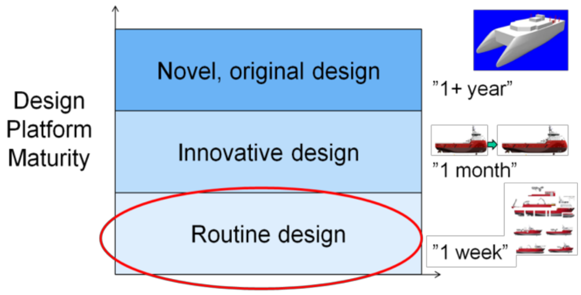

Figure 10.11 Configuration of a module-based platform as a specific class of short lead time, routine design process

The adaptation of configuration-based design in ship design has been relatively limited in segments other than low-complexity, standardized vessels. This is likely because of the complexity related to highly customized requirements and the extensive inter-relationships between different systems. Further, non-technical factors may be important, such as the shipbuilding culture for "customized prototypes", and less tradition for standardized platforms. This leads to a focus on the individual projects rather than process improvements. Compared to many other industries facing a similar complexity level (say, automotive and aviation), the typical length of a series in particularly European shipbuilding is short. This implies fewer projects to share the costs of developing a configurable product platform.

A product configuration system will comprise three main elements:

1. A collection of configuration entities. This mainly consists of a collection of modules, combined with parameter sets both on a vessel and on a module level. The parameters will further be divided into those representing customer and functional requirements, and those representing a description of the design solution. The secondary representation contains a 3D model, a textual specification and performance documentation, all which can be derived from the primary representation.
2. A configuration process representation. It is preferable to base the process implementation on a workflow management system. This enables a "plug-

in” type of external application integration, as well as a declarative, configurable process logic definition.

3. A configuration knowledge representation that captures the rules and constraints required for defining legal, meaningful product variants from the module platform.

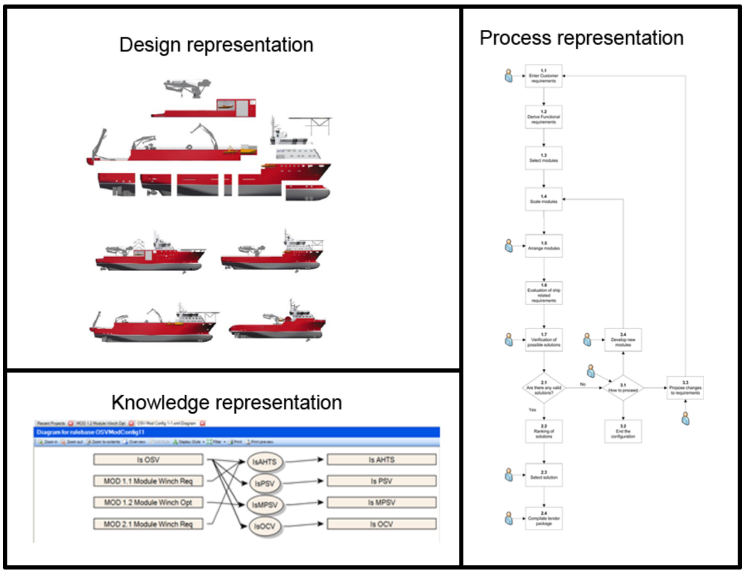

Figure 10.12 The three main elements of a product configuration system (Brathaug, Holan et al. 2008)

10.3.3Modularity Supporting Design Exploration and Innovation

Like Lego bricks, modules can be used to explore the design space and create innovative design solutions by rearranging modules into different spatial configurations. Some examples of this is system-based design ((Erikstad and Levander 2012), building-block design (Andrews 2003) and the packing approach (Oers 2011). In particular, this is applicable to what has been termed “configuration-driven ships, that is, ships were the “performance of the vessel is driven by the arrangement of spaces” (Droste, Kana et al. 2018) connections between modules – configuration-driven ships – driven by the layout/arrangement of the vessel.

In system-based design (SBD) the modules are derived from the functional breakdown of the vessel. For most of the functions, one or a set of corresponding modules may be defined. Each module is scaled according to the area and space requirements derived from existing vessel general arrangements as part of the SBD model. The sized modules can then be arranged either freely, or by using templates defining the topology of the modular arrangement. The template states where a module should be positioned, while the breadth and height are automatically scaled based on the main characteristics of the vessel. Then the length is scaled to satisfy the volume demand. As an example, the winch module be placed in front of the deck module and made as wide and high as possible within the constraints and then scaled by length.

Modules combined with templates will support a quick and partly automated sketching of the design solution, (Vestbøstad 2011). The key point here is the decoupling between the modules selection/scaling, and the arrangement synthesis., thus reducing the needs for the "balancing out" process captured in the design spiral model.

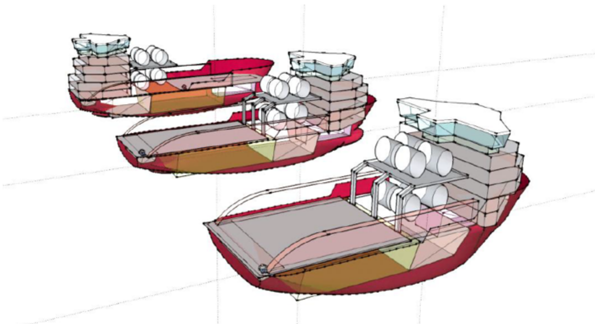

Figure 10.13 3D models showing alternative vessel configurations based on different templates, all using the same set of modules derived from functional area and volume requirements (Vestbøstad 2011)

This is similar to the "building block approach", see Figure 10.14, advocated by Andrews points to the importance of establishing a module-based platform that can be configurated in different ways to support the exploration of alternative solutions, as well as providing a basis for understanding and communication with key stakeholders the impact of the initial requirements (Andrews 2011).

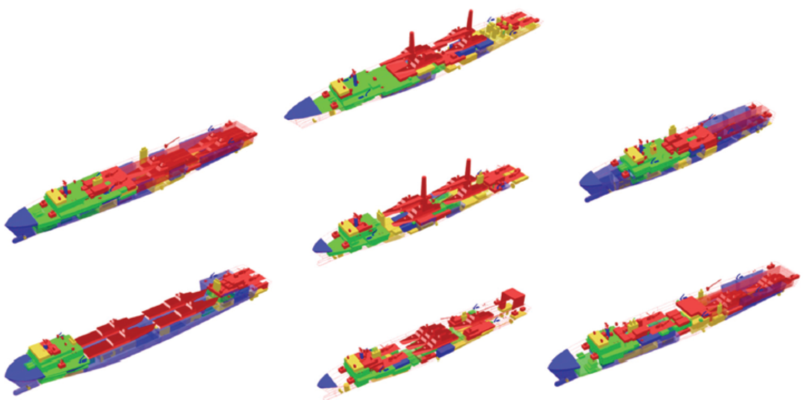

Figure 10.14 Configuration of a vessel from building blocks from a library, for rapid evaluation and requirements elucidation in early design stages (Andrews 2011)

The same underlying principles are further developed towards arrangement optimization by (Oers, Stapersma et al. 2007) and optimization (Daniels and Parsons 2007). Here, a set of modules to be contained in the ship is defined, and an optimization routine finds the solutions that best balance a set of criteria, see Figure 10.15. This requires the definition of a set of distinct modules, and their corresponding interfaces both with the ship platform and towards other modules.

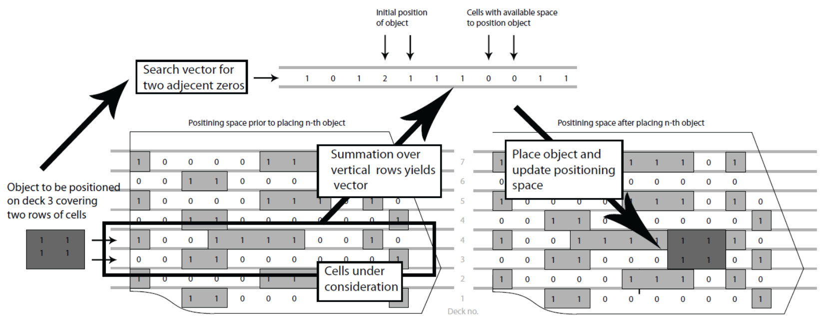

Figure 10.15 Module-based approach used in the arrangement optimization in the early design of a warship, in (Oers, Stapersma et al. 2007)

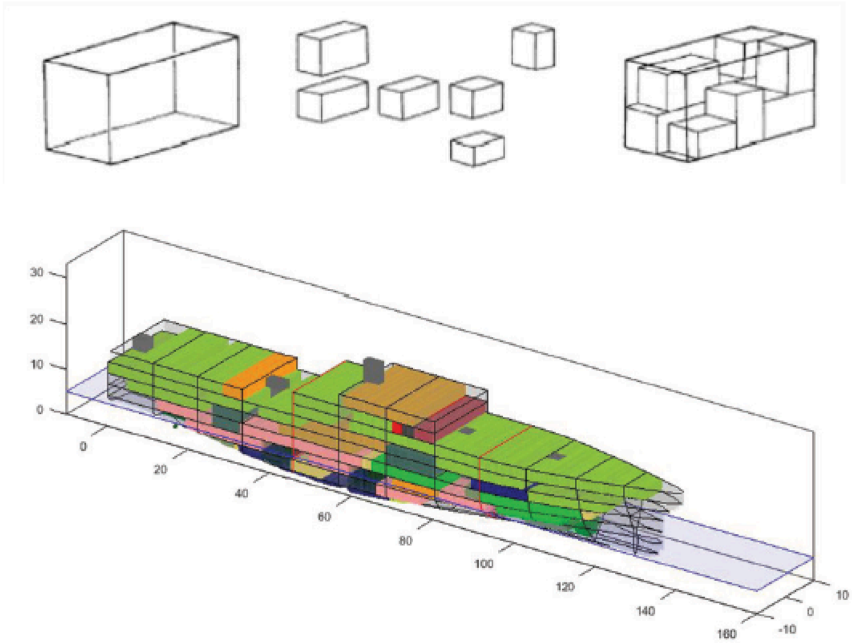

Figure 10.16 Arrangement-driven design based on a modular architecture, (Droste, Kana et al. 2018)

The examples above were based on deriving the modules from the functions. Alternatively, the modules can be derived directly from the block structure of the vessel. One example is the Sigma class corvette that is designed and built by Damen Schelde Naval Shipbuilding. “Sigma” is an abbreviation for “Ship Integrated Geometrical Modularity Approach”. In this design, the hull segments are modularized, and can be assembled in different numbers and sequences, thus using a sectional modular approach. Off-the-shelves equipment is used to the extent possible. The modular approach allows the client to configure a vessel out of these standard blocks, and different versions with 12, 13 and 14 sections have been sold to three different navies. This is an example of sectional modularity. The advantage is a relative simple configuration pattern, but at the expense of flexibility in terms of function-space allocation.

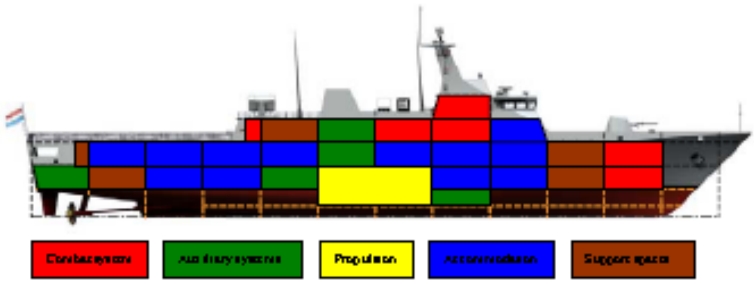

Figure 10.17 The SIGMA modular naval vessel from Damen Schelde (https://www.damen.com)

10.3.4 Modularity in Ship Design - Summarized

Modularity is an important driver also at the design stage of ship´s lifecycle. Modules encapsulate complexity, thus enabling both more efficient processes, as in product platforms and configuration-based design, as well as enabling a wider search for new and innovative solutions throughout the design space.

10.4 MODULARIZATION IN SHIP PRODUCTION

In the production phase, modularity is important for

- Supply chain design and production outsourcing
- Modular production and early outfitting
- Procurement packaging

In the ship production phase, a modular approach offers a number of opportunities for improvements. First, it is an enabling technology for more flexible, and increasingly, global production chains. A clear modular structure, with well-defined interfaces between the modular “chunks”, opens up for the outsourcing of a larger share of the total production. Alternatively, by enabling the reuse of standardized components across multiple design variants, it may provide a basis for a higher degree of automated production of longer component series. This may result in an insourcing of production, enabled by automated production that possibly is competitive in high-cost countries like Norway.

10.4.1 Effects on the Ship Production Value Chain

A core question is to what extent there is a connection between the shipyard's modularization strategy and the supply chain structure. And given that this connection exists, which one is the "cause" and which one is the "effect"? Historically, the connection between modularization and outsourcing has been weak. The former has been approached as a design and manufacturing principle in engineering communities, while outsourcing has been discussed within the realms of economics, management and strategy (Fixson, Ro et al. 2005).

The product's architecture is a key determinant for the opportunities for manufacturers outside the company boundaries to produce individual components to be part of the final product. A classic example referred to in many papers is the modular structure introduced with IBM's 360 system. This opened up for individual manufacturers to provide components to this platform, eventually driving prices down and making components such as hard drives and memory chips commodities.

The impact that modularization has on the production value chain may also lead to changed power balances between the different actors in the value chain. One example is the shift in control over the specification. In a more "traditional" process the shipyard to some extent play the role of a sub-contractor designing and developing a solution constrained by the requirements in the outline specification. With a modular, product platform-based design, this is shifted towards a situation where the owner is, at least in principle, selecting from a set of possible designs derived from a platform. Thus, the yard has to some extent regained the control of the specification.

10.4.2 Early Outfitting

Thus, the definition of a product architecture based on a functional model of the product is an important first step in a modularization strategy. There has been some work related to this in Norway some ten years ago, related to the MARINTEK lead project "Procurement in the Sales Phase". In this project, several diagrams were developed for the main systems of the vessel. One example of this can be seen in Figure 10.18.

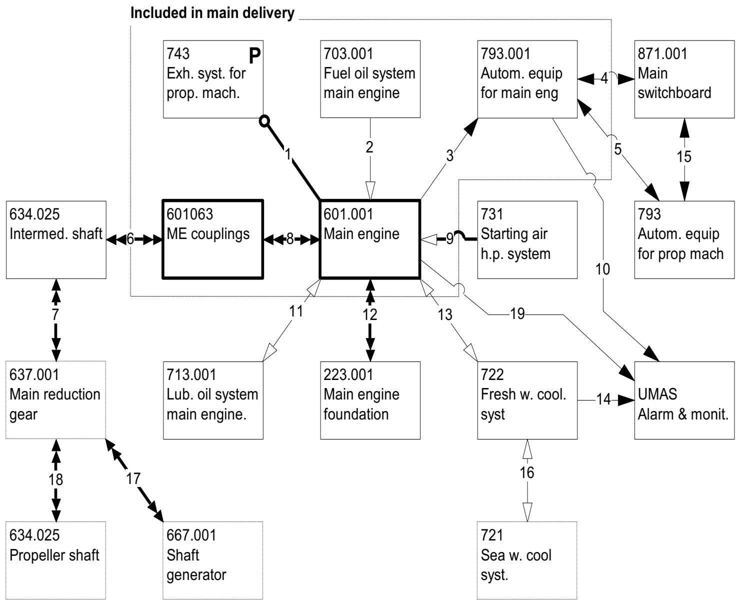

Figure 10.18 System diagram for the main propulsion system (Marintek 1998)

Though these systems diagrams were primarily developed to serve as a basis for the specification of procurement packages, they may be used as the architectural backbone for defining modular product platforms for ships. This process would involve the grouping of a set of functional entities as a modular “chunk”, and the definition of the interface towards other modules based on the various relations between functional units depicted as different types of arrows in the diagram.

The overall aim was to develop a rational methodology supporting the procurement process in shipyards. This was a collaboration project between Ulstein Yard and MARINTEK. A core topic was the procurement of project critical equipment, where a coherent framework for performance-based specifications was developed.

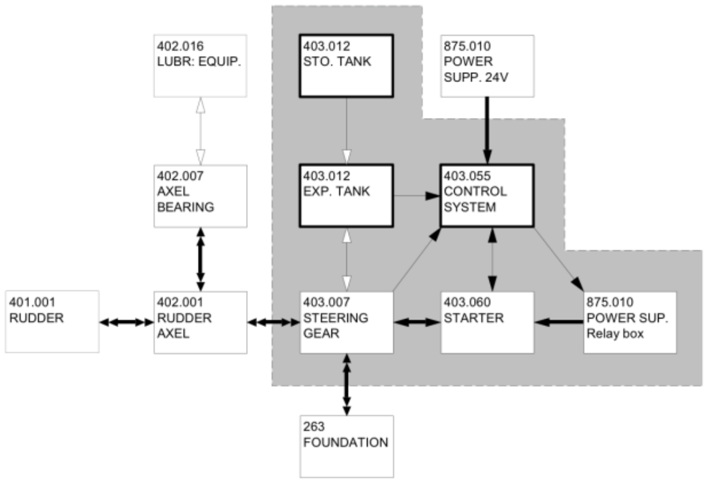

Figure 10.19 Identifying procurement modules by functional grouping

These specifications were based on a functional modeling of core ship systems. These are used as a backbone for the procurement plan, and for identifying the scope, content and interfaces of the individual specification packages. Thus, this project may provide valuable input to the process of defining the required modular architecture to serve a global sourcing strategy.

In the maritime industries, the product platform concept has been employed first and foremost with equipment manufactures. One example is Wärtsilä which has developed sales configuration principles and software. Their vision was that a significant part of the engineering and production planning, as well as price quotes, should be a direct result of the enactment of different configuration rules (Sortland 2001).

Another example from the maritime industry is Rolls-Royce Deck Machinery. They have performed extensive work in using modularization and product platform principles. This has caused a complete redesign of some product lines, significantly reducing the number of configuration elements. This is illustrated in Figure 10.20. The result is both in a significant increase in the range of possible product configurations offered to customers, a substantial shortening of development time for new products and both reduced costs and throughput time in the sales projects (Andreassen 2005).

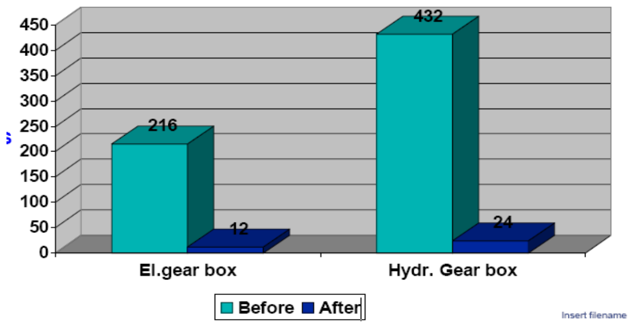

Figure 10.20 The number of configuration elements before and after PDM project at Rolls-Royce Deck Machinery (Andreassen 2005)

Figure 10.21 Modularity has also played a significant role in cruise ship cabin manufacturing. Traditionally, cabins were outfitted as an integral part of the ship building project (Jogeva 2014)

10.5 MODULARITY IN OPERATION

The incentives for modularization from an operational point-of-view may be:

- Later modifications, for instance because of new regulations, technical development, or changed operating profile/mission
- Easy component/system replacement because of failures or breakdown
- A maintenance policy based on component/module rotation and "offline"/"off-site" maintenance. This module rotation maintenance can be found in the aviation industry
- A "service-oriented" operating regime involving remote monitoring and operation, typically by the system supplier

10.5.1 Modularity for Flexibility in Operation

In the operations phase, modularity is a central strategy for offering ships with operational flexibility that can adapt to changes in the vessel´s operating environment, whether this is related to regulations, technology, missions, markets, fuel, etc., see Figure 10.22 . A key research area is the use of real options in design, that is, decisions related to investments in future operational flexibility already at the newbuilding stage. Examples of such investments ranges from providing sufficient structural and powering support for upgrading cranes, to investing in hybrid powering systems and additional power reserves beyond what is required for the vessel's first contract.

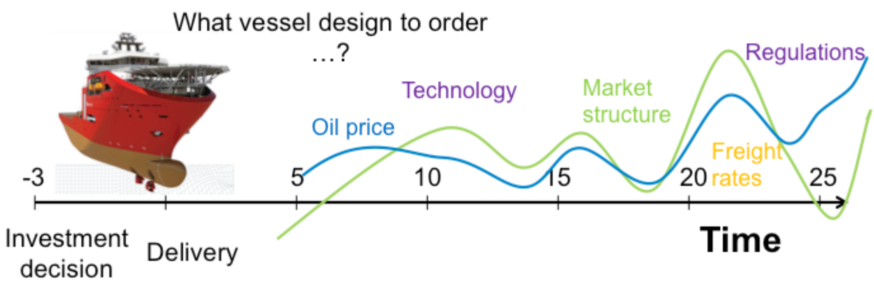

Figure 10.22 Modularity is an enabler for providing flexibility to handle future uncertainty, (Erikstad and Rehn 2015)

Modularity plays a key role in this. The profitability of exercising flexibility in operation will be dependent on both the time it takes, and the cost incurred. A proper modular architecture will generally provide a more competitive cost-benefit ratio for exercising options than an integral architecture with the same functionality.

Time aspects are also of importance, which leads to the choice between *versatility vs. retrofittability* (Rehn 2018). A given set of lifecycle capabilities of the vessel can either be made possible by a multi-functional vessel capable of handling all required missions, or by a modular design for which the mission capabilities are retrofitted in operation when the need arises. Both the cost profile (CAPEX, OPEX) and the *agility,* i.e. the time delay to enter new missions, will be significantly different for these two alternatives. There is no obvious best strategy – for different market conditions and different sets of mission requirements we have seen both solutions being preferable in retrospect. Generally, strong markets tend to favour versatile vessels, while weak markets and a high degree of uncertainty tend to favour retrofittability.

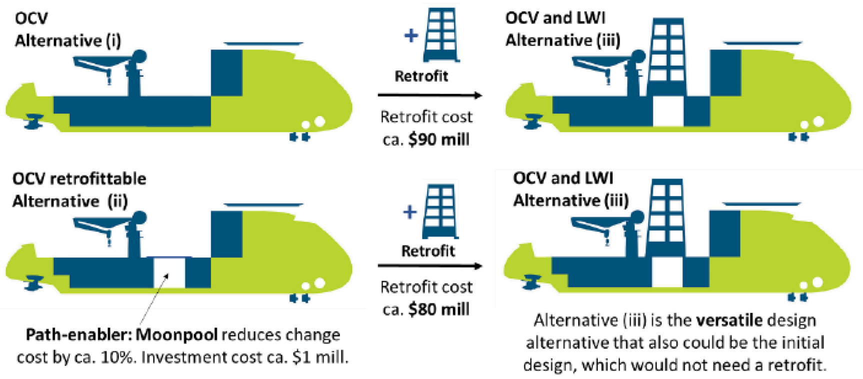

Figure 10.23 Preparing for module installations will influence the total retrofit cost for an OCV (Rehn and Erikstad 2018)

Also for naval vessels the importance of flexibility in the operational phase has been addressed. In recent years there has been a considerable focus on what is termed "Modular Adaptable Ships" (MAS), in particular within the US Navy (Doerry 2016). Naval vessels have to meet an extensive range of missions to cover all national security requirements. They typically have high procurement cost, combined with long development and production cycles. Thus, most naval programmes experience significant changes in mission requirements as well as technology development, with a corresponding high impact on both the total cost and mission capability. The Littoral Combat Ship (LCS) is perhaps the archetypical example of the use of modules for providing multi-mission flexibility in operation. The goal with the LCS program in the US Navy was to develop a near-shore combat ship that could be developed at a low cost, and with a flexibility that made it possible to rapidly shift from one type of warfare to another. It consists of a base module – sea frame – that is the warship platform. In addition, a range of different modules may be plugged in, providing capabilities such as Anti-surface warfare, Mine Counter Measures, Anti-Submarine Warfare, Intelligence, Surveillance and Reconnaissance, Special Operation Forces support and Logistic support. These mission modules integrate to the extent possible, into the sea frame's command and control architecture.

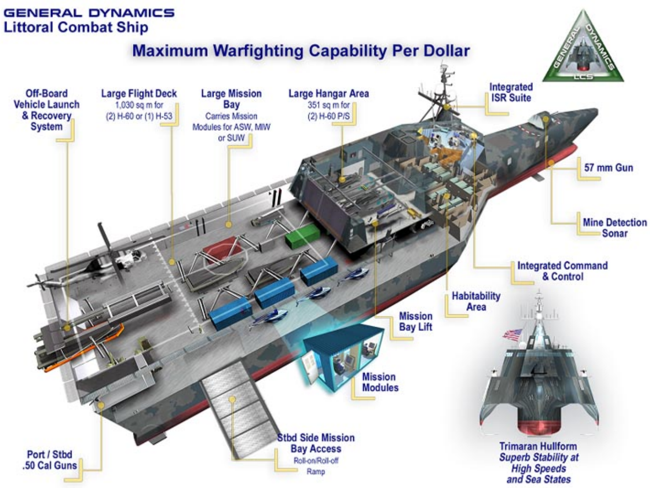

Figure 10.24 The Littoral Combat Ship providing operational flexibility through replaceable mission modules in a bus modular architecture (Doerry 2016)

10.5.2 Modularity for Easy Retrofit and Modernization

In the US Navy, the combination of modularity and flexibility is considered as one of the primary strategies for reducing the time and cost of modernizing in-service vessels and adapt to uncertain future operating scenarios (Schank, Savitz et al. 2016). The MAS initiative has many aspects, including very specific recommendations for ways to reduce mid-life modernization costs. This includes:

- Improve access to modernized equipment, such as designing for easy access to any major equipment that has a reasonable expectation of being replaced during the vessel´s lifecycle. This must be balanced towards survivability
- Minimize the number of foundations changed during a modernization, which implies designing new equipment towards the existing foundation standards. From a modular perspective, this relates to interface management
- Minimize the amount of new cable and fiber during a modernization, by power margins, extra electrical capacity and new equipment designed for utilizing existing infrastructure

- Increase power, cooling, and data exchange. This pertains in particular to bus type modular systems, where new systems with same interfaces may be re-installed, but with higher requirements in term of power
- Increased pre-installation testing, improved planning, and coordination alternative.

10.5.3 Design Methods for Modular Adaptation in Operation

Having discussed the benefits and challenges of providing operational flexibility by modularity, the next question becomes how design stage decisions for developing the associated operational platform can be supported. In (Choi, Erikstad et al. 2018) an optimization model for a modular adaptable ship (MAS) platform is presented. The model selects modules to be associated with slots of the vessel platform in a set of likely operating scenarios during the ship lifecycle, with the overall goal of minimizing the deviation between the desired capabilities derived from the associated missions, and the achieved capabilities of the vessel operating platform.

Figure 10.25 illustrates the relationship between ship modules, slots, and task related modules using a class diagram described by the unified modeling language (UML).

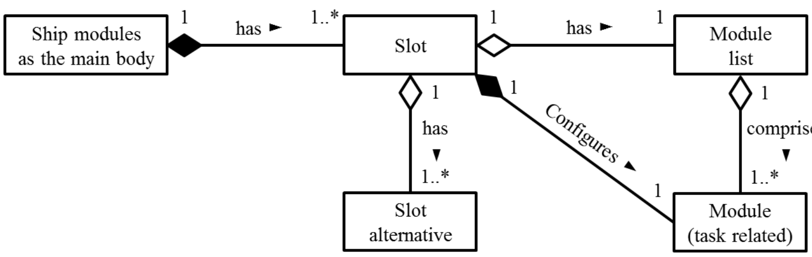

Figure 10.25 Description of ship modules, slots, and task-related modules using a class diagram in the unified modeling language (Choi, Erikstad et al. 2018)

In the corresponding optimization, these entities are captured in a goal programming model (Equations 10.1 to 10.10). The objective function (10.1) minimizes the normalized, weighted deviations from desired capabilities. The actual mission capability is a function of vessel platform variables ($\boldsymbol{x}$), slot variables ($\boldsymbol{y}$) and module variables ($\boldsymbol{z}$), and is compared with the desired capabilities B_{np} in (10.2). (10.3) to (10.9) are feasibility constraints capturing slot assignment rules, vessel technical and economic performance (stability, life cycle cost, …) and allowable module combinations. (10.10) to (10.12) are model variable bounds. The details of the model can be found in (Choi, Erikstad et al. 2018).

$$\text{Min} \quad \sum_n \sum_p \frac{W_{np}^-}{R_p} \cdot d_{np}^- + \sum_n \sum_p \frac{W_{np}^+}{R_p} \cdot d_{np}^+ \tag{10.1}$$

$$f_{np}^U(\mathbf{x}, \mathbf{y}, \mathbf{z}) + d_{np}^- - d_{np}^+ = b_{np} \qquad n \in N, p \in P \tag{10.2}$$

$$d_{np}^-, d_{np}^+ \geq 0 \qquad n \in N, p \in P \tag{10.3}$$

$$y_{sa} \cdot z_{nsm} \leq H_{sam} \qquad n \in N, s \in S, m \in M_s, a \in A_s \tag{10.4}$$

$$(1 - F_{sa}) \cdot y_{sa} \cdot z_{n_1sm} = (1 - F_{sa}) \cdot y_{sa} \cdot z_{n_2sm} \qquad n_1, n_2 \in N, s \in S, m \in M_s, a \in A_s \tag{10.5}$$

$$\sum_{a \in A_s} y_{sa} = 1 \qquad s \in S \tag{10.6}$$

$$\sum_{m \in M_s} z_{nsm} = 1 \qquad n \in N, s \in S \tag{10.7}$$

$$g_{nj}(\mathbf{x}, \mathbf{y}, \mathbf{z}) = 0 \qquad n \in N, j \in \{1, \ldots, N^{EC}\} \tag{10.8}$$

$$k_{nk}(\mathbf{x}, \mathbf{y}, \mathbf{z}) \leq 0 \qquad n \in N, k \in \{1, \ldots, N^{IC}\} \tag{10.9}$$

$$\begin{array}{ll} x_i \in \{0, 1\} & \text{if } x_i \text{ is a binary variable,} \\ L_i^X \leq x_i \leq U_i^X & \text{otherwise,} \end{array} \qquad i \in \{1, \ldots, |\mathbf{x}|\} \tag{10.10}$$

$$y_{sa} \in \{0, 1\}. \qquad s \in S, a \in A_s \tag{10.11}$$

$$z_{nsm} \in \{0, 1\}. \qquad n \in N, s \in S, m \in M_s \tag{10.12}$$

The model has been applied for designing a standard operation platform for a modular adaptable offshore support vessel (OSV), and comparing this with a multipurpose vessel having the same capabilities across missions. As we can see in Figure 10.26, the mission capabilities are basically the same, though the flexible platform has the ability to downscale non-required capabilities in the platform supply operations. In a lifecycle cost perspective, as seen in Table 10.1, we see that modular adaptation can reduce the CAPEX by requiring a smaller vessel platform, that in this case is partly offset by reconfiguration cost. Thus, it is not possible to draw a general conclusion on the preferences between modular or not – it will depend on both the uncertainty and variability of the vessel's operating context, as well as the cost structure associated with a modular platform.

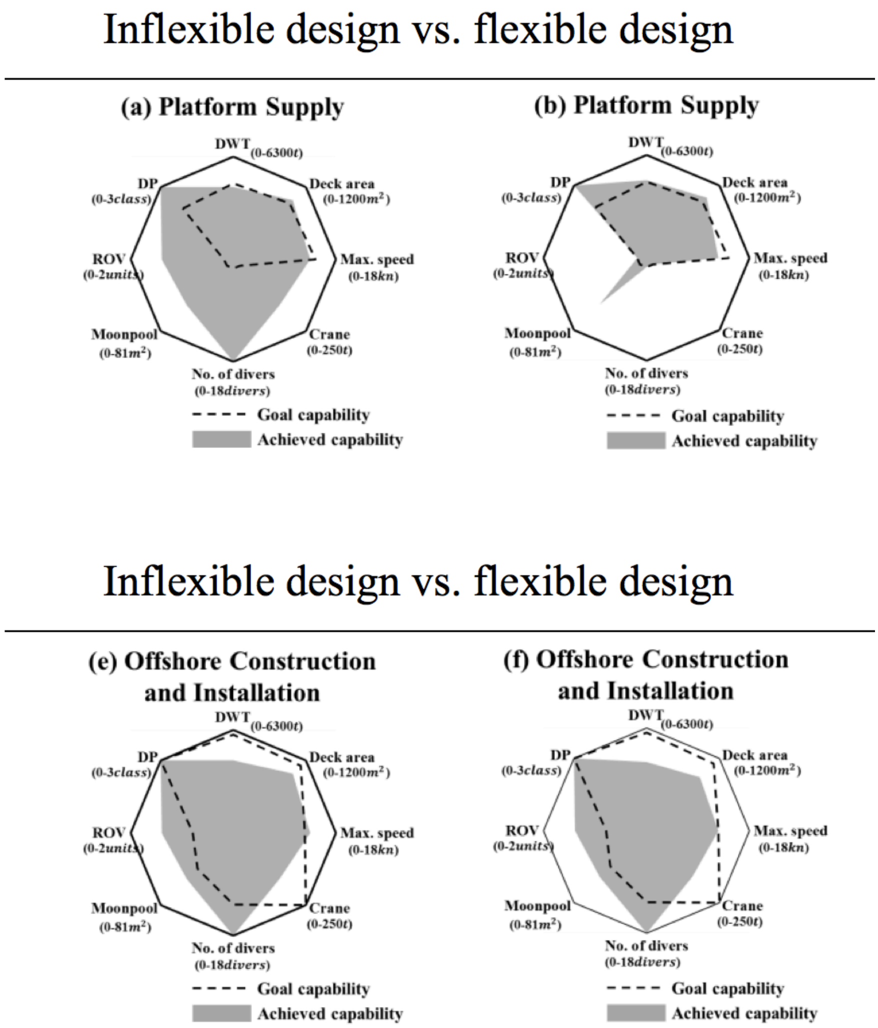

Figure 10.26 Capability diagrams for both flexible and inflexible designs for two mission types, (Choi, 2018)

Table 10.1 Cost comparison of flexible (modular) and inflexible platforms

Lifecycle cost of optimal platforms				
Design	**Expected lifecycle cost**	**Platform acquisition cost**	**Expected module acquisition cost**	**Expected ship reconfiguration cost**
Inflexible design	$61.31 M	$32.31 M	$29 M	$0
Flexible design	$58.91 M	$28.24 M	$29 M	$1.68 M

10.6 CONCLUSIONS

In this chapter we have seen that different stakeholders have different motivation for modularization. Key drivers and motivating factors are a higher product variety and customization using product platforms, improved production efficiency through standardization on parts, reduced lead time both by isolating functional enhancements as well as supporting parallel development and production, reduced risk, and cost and efficiency improvements through outsourcing and globalization of supply chains.

Modular concepts aimed at providing operational flexibility, such as the Littoral Combat Ship, may contribute to a cost-efficient modernization of obsolete equipment, upgrades, and adaptation to changed external conditions (new markets, trades, regulatory regimes, etc). This may both contribute to increasing the operational efficiency of the vessel, as well as extending the vessel's operational life.

Modularity may contribute to a more efficient recycling of the vessel along the interfaces defined by the modular architecture, and possibly also to the reuse of those components for which the economic life time is longer than for the ship itself.

We have also seen that modularity in most cases comes at a cost. These include less optimized physical architecture, and correspondingly increased weight and size. An integral architecture with the same technical performance will typically be more energy efficient. Also, again compared to an integral architecture, modular solutions can experience less optimized performance.

References of Chapter 10

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