Capability-Based System-of-Systems Approach in Support of Complex Naval Ship Design:

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Abstract. Naval ship design can be understood to be a networked System-of-Systems (SoS) multidisciplinary process whereby a decision on one aspect of the design may have simultaneous, multiple order effects on other aspects of the design. Modern naval ship design should therefore consider the systems of interest as components subsumed by a holistic environment encompassing assets and capabilities inorganic to a naval platform. This position paper propose a starting point approach intended to provide a more defined means of establishing and improving the ship design process as part of a multi-layered maritime domain warfare enterprise. Fundamental is the tenet that capability levels transcend several hierarchical echelons and exist across many functional domains. The proposed methodology provides a structured and cohesive approach for identifying and assessing ship capability portfolio with traceable and better known impacts on mission effectiveness, affordability and risk, in the early stages of ship design within the scope of a naval system-of-systems.

1 Introduction

The ship design of major surface combatants capable of effectively responding to all possible missions within the spectrum of modern conflicts and military operations other than war is increasingly difficult due to the complex nature of the rapidly evolving and unpredictable global threat environment. Traditional naval ship design methodologies have evolved from the sequential nature of the design spiral to more advanced computational methods enabling the simultaneous manipulation of several degrees of freedom to better understand the interdependencies between factors such as cost fluctuations, design parameters, technology selections and mission success [1].

The issue persists nevertheless that although we may have a multidisciplinary team applying domain knowledge and experience onto systems engineering analysis, the optimization of the design process may remain restrained by designing ships within intrinsic ship capabilities as opposed to designing ships subsumed by a holistic environment encompassing assets and capabilities inorganic to a naval platform.

2 Motivation

The proposed method is intended to provide a more defined means of establishing and improving the ship design process as part of a multi-layered maritime domain warfare enterprise. To achieve this, the design approach is dependent upon high levels of confidence in the fidelity of the analyses, and is based on shared understanding and a common language.

Alike best practice in portfolio, programme and project management [2], using such an approach should deliver a range of benefits which will be revisited throughout the paper, these include:

- Identifying capability strengths and interests to be maintained, developed and exploited.
- Identifying capability deficiencies (shortcomings or surpluses) to be remedied or accepted.
- Providing a more structured and cohesive approach to identifying and assessing ship capability portfolio.
- Creating a common language and conceptual framework for the way to manage and improve capability-based planning within a ship design process.
- Educating stakeholders on the fundamental elements of capability-based ship design and how they relate to their roles and responsibilities.
- Involving more relevant stakeholders at all levels in the capability-based ship design process.
- Ranking ship variants based on operational effectiveness, capability and affordability trade-offs across a spectrum of missions' priorities.

- Facilitating comparisons, identifying and allowing the sharing of best practice across major ship acquisition projects within an organisation or a community of practice.
- Assessing and presenting the findings from a variety of reviews in a format that is easy to understand.

The aspiration is to show how these benefits can be realised through a combination of techniques including the adroit use of model-based systems engineering (MBSE): the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [3].

Recognizing that MBSE has as its foundation the use of models, the approach is limited to construct an abstraction of selected aspects of the behaviour, operation, or other characteristics of a real-world SoS [4]. The purpose therefore is not to eliminate all uncertainties and cover all options related to ship conceptual design but to circumscribe them so to distil a deeper appreciation of the critical factors.

3 Naval Surface Combatants as System-of-Systems

3.1 SoS in Defence

Applications of systems engineering (SE) and SoS principles abound in Defence. Indeed, a growing proportion of the acquisition, sustainment, and management of materiel and non-materiel of military capabilities is sought through a SoS approach [5]. Moreover, the adoption of enterprise architectural framework in Defence by several nations is a definite step towards providing a more rigorous approach to life-cycle management including governance, design, building, analysing, and change management [6]. For instance, the UK Ministry of Defence Architecture Framework (MODAF) offers the following benefits within the acquisition processes [7]:

- Improved clarity on the context within which a new capability will operate.
- Clearer and more comprehensive requirements documents.
- Improved ability to resolve interoperability issues between systems.
- Better understanding of the mapping of system functions to operational needs and hence the ability to conduct improved trade-offs.

The proposed approach aims to utilize an architectural framework similar to MODAF to embody the SoS elements, unify their capabilities at the appropriate hierarchical levels, and define their interdependencies to provide a common picture of the SoS measure of effectiveness (MoE).

3.2 SoS in the Navy

Basic sets of architecting principles were proposed by Maier as discriminating factors to assist in the design of SoS [8], which later generated five characteristics that define SoS more appropriately [9]. This useful taxonomy may be used to draw the

SoS boundaries for a naval platform, namely: operational independence of the individual systems, managerial independence of the systems, geographic distribution, emergent behaviour and evolutionary development.

Recognizing that a single platform is a contributing element of a naval SoS, it follows that we should attempt to define the measures of effectiveness (MoE) of that SoS. In naval terms, models of hierarchical complexity could be translated into naval ranks and typology such as those described in Fig. 1 [10]. The legend could be used to characterise the MoE of a naval SoS hierarchically from a naval force capable of independently carrying out all the military roles on a global scale to that which has minimal ships' capabilities and is intended to only perform the most limited of constabulary functions. Mapping against the typology levels could facilitate the ranking of ship variants based on potential operational effectiveness and capabilities trade-offs across a spectrum of missions' priorities.

Rank	Typology	Naval SoS Description
1	**Complete Major Global Force Projection**	Capable of carrying out all the military roles of naval forces on a global scale. It possesses the full range of carrier and amphibious capabilities, sea control forces, and nuclear attack and ballistic missile submarines, and all in sufficient numbers to undertake major operations independently.
2	**Partial Global Force Projection**	Possesses most if not all of the force projection capabilities of a "complete" global navy, but only in sufficient numbers to undertake one major "out of area" operation.
3	**Medium Global Force Projection**	May not possess the full range of capabilities, but have a credible capacity in certain of them and consistently demonstrate a determination to exercise them at some distance from home waters, in cooperation with other Force Projection Navies.
4	**Medium Regional Force Projection**	Possesses the ability to project force into the adjoining ocean basin. While may have the capacity to exercise these further afield, for whatever reason, do not do so on a regular basis.
5	**Adjacent Force Projection**	Possesses some ability to project force well offshore, but not capable of carrying out high-level naval operations over oceanic distances.
6	**Offshore Territorial Defence**	Possesses relatively high levels of capability in defensive (and constabulary) operations up to about 200 miles from shores, having the sustainability offered by frigate or large corvette vessels and (or) a capable submarine force.
7	**Inshore Territorial Defence**	Primarily inshore territorial defence capabilities, capable of coastal combat rather than constabulary duties alone. This implies a force comprising missile-armed fast-attack craft, short-range aviation and a limited submarine force.
8	**Constabulary Defence**	Not intended to fight, but to act purely in a constabulary role.

Fig. 1. Naval System-of-Systems Levels.

4 Capability-Based Framework

4.1 Capability Definitions

Military concepts generally use a lexicon of frequently interchangeable terms with sometimes only subtle differences in meaning and often dependent entirely upon context. For instance, words such as mission, role, function, task, activity, and capability may have both a descriptive sense ("what") and a process sense ("how"). The descriptive sense defines the purpose or basic functions of an organisation and identifies the precise nature of an operation to be conducted in pursuit of an assigned mission or objective. The operational sense denotes the precise activities to be undertaken or achieved which in combination contribute to mission success [10].

It is recognized nevertheless that there are those essential capabilities which are common to any naval force at any time, as required to exercise any of the missions, roles, functions or tasks that might be assigned to it. The degree to which these core competencies are required and met is predicated upon the needs of the local and temporal situation. Ergo, they will be considered as capability priorities summarised by the basic naval concepts of float, move and fight for the purpose of this study.

Of note, the United States Department of Defense (US DoD) defines a capability as the ability to achieve a desired effect under specified standards and conditions through combinations of "ways" and "means" to perform a set of tasks [11]. This definition joins the previous definitions in that the "ways" are the strategic and operational methods describing "how" to conduct military operations to accomplish the specific military objectives, the "ends", while the "means" describe "what" resources are adequate to achieve these objectives within an acceptable level of risk.

Lastly, the level of operational capability and the potential response time constitute the basis for the concept of readiness which is a measure of the ability to undertake an approved task, at a given time. Four readiness levels are considered in this study [5]:

- Extended Readiness (ER): Not operational.
- Restricted Readiness (RR): Transitioning between readiness levels or subject to deficiencies in personnel, materiel and training severely limiting employment.
- Standard Readiness (SR): Capable of conducting core naval continental and expeditionary missions that do not entail the possibility of high intensity, full spectrum combat.
- High Readiness (HR): Capable of conducting the full-spectrum of combat operations.

As will be seen in the next section, these definitions may be used to create a common language and conceptual framework that may facilitate identifying capability strengths and interests to be maintained, developed and exploited; but also identifying capability deficiencies (shortcomings or surpluses) to be remedied or accepted.

4.2 Cross-Functional Capability Framework

This position paper espouses the tenet that capability levels transcend several hierarchical echelons and exist across many functional domains. For instance, from a marine platform systems viewpoint, a hierarchy of equipment-based capabilities prescribe the minimum materiel standard necessary to support the intent of materiel safety [12]. That baseline level identifies the equipment that must be available for ships to proceed and remain at sea, i.e., float and move capabilities in higher than restricted readiness. Other equipment may now be selected to enhance the platform systems capability levels or elevate the combat systems capabilities enabling fighting at the standard or high readiness levels.

Fig. 2 and Fig. 3 illustrate examples of capability-based frameworks showing how materiel availability at the equipment level could be mapped to operational effectiveness using the definitions offered for temporal capability priorities, platform and combat systems capabilities, and operational capability readiness levels.

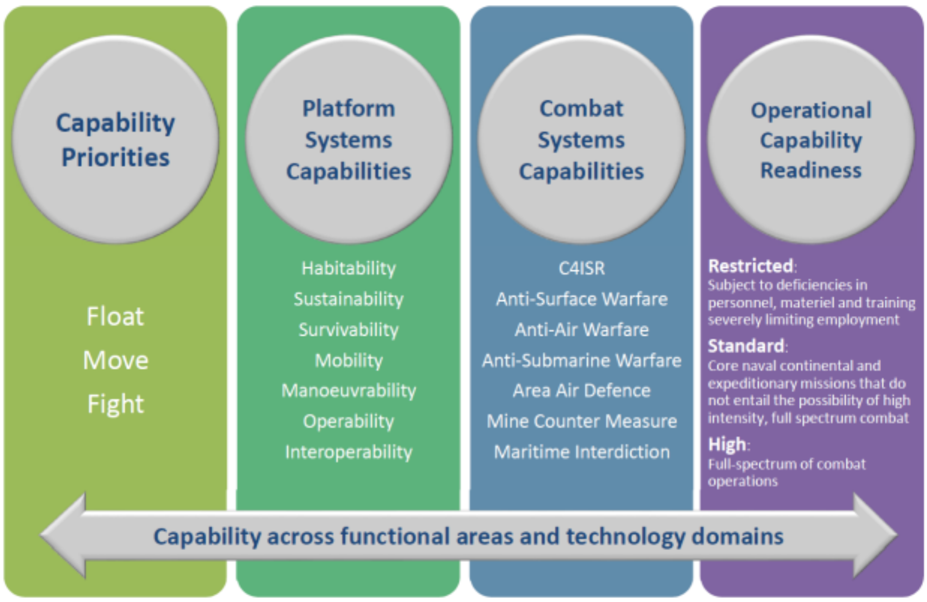

Fig. 2. Cross-Functional Capability Framework – Example 1.

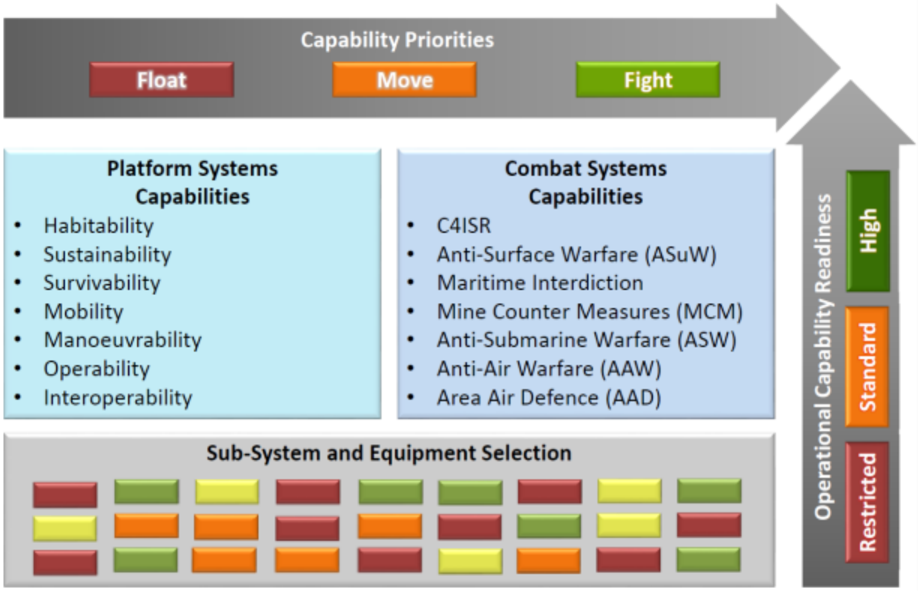

Fig. 3. Cross-Functional Capability Framework – Example 2.

4.3 Capability-Based Planning

Concepts of capability-based planning (CBP) in enterprise architecture can be invoked to explain that capabilities can be horizontal, going against the grain of business processes (platform and combat capabilities), or be vertical, being handled in the context of the business organizational structure (task group, flotilla or squadron) [13]. Applied to the military context, CBP evolved from threat-based planning, and is envisaged as the framework that will permit the military forces to optimize their capacity to respond to the range of plausible missions in which they may be called upon to serve.

CBP is a systematic approach for identifying the levels of capabilities needed to meet government priorities. Using scenarios, CBP explicitly connects capability goals to strategic requirement to develop force options more responsive to uncertainties, economic constraints and risk [14]. CBP is thus not estranged to the Defence realm and its principles were used as a pillar to the proposed ship design methodology.

5 Methodology

5.1 Hierarchical Capability Decomposition

Inspired from hierarchical functional decomposition (HFD) principles, the proposed approach suggests to decompose, prioritize and recompose capability requirements through the strategic, operational, tactical and technical levels of abstractions enabling both the descending “top-down” approach from political aspirations and the ascending “bottom-up” approach from equipment-level capabilities. The hierarchy can span any set of functional levels, but it should always include as its lowest level a tangible set of requirements that can be mapped to physical systems and performance constraints. The process generates upward, lateral and downward connections to produce a collectively created and shared picture of the SoS being designed.

These ship-level platform and combat systems capabilities, which correlate to system-level key users requirements, could be mapped to tactical-level capabilities usually pertaining to effectively conduct a combination of naval functions under prescribed conditions, with other SoS elements. The overall achievement of naval functions would subsequently propagate up the hierarchy to analyze the effect that a given set of ship systems capabilities have on higher level operational and strategic capabilities.

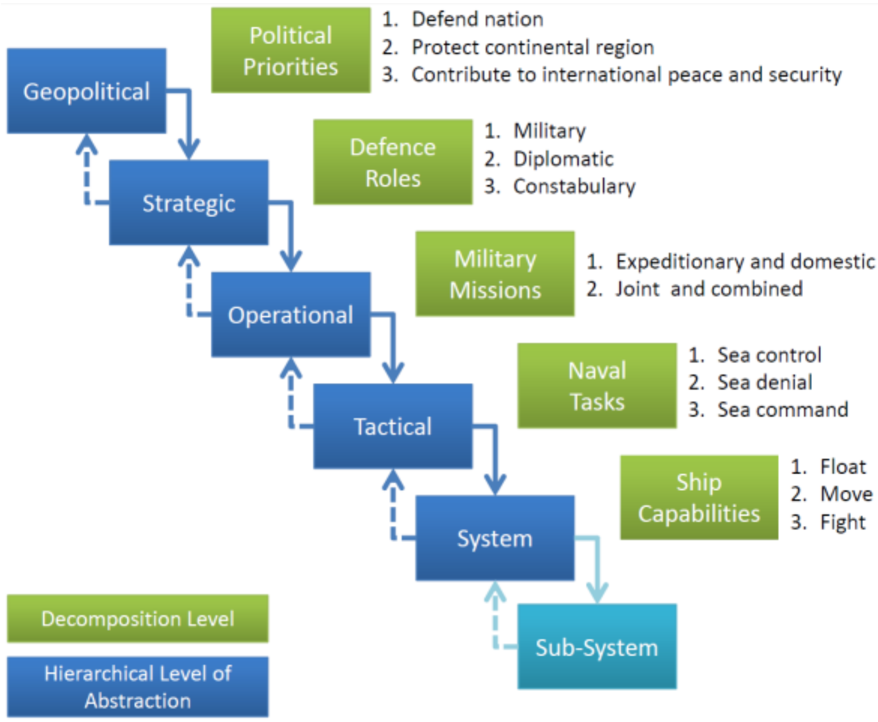

Fig. 4. Approach to Hierarchical Capability Decomposition.

As shown in Fig. 4, the process involves eliciting capabilities by mapping and prioritizing strategic-level defence roles with operational-level domestic and expeditionary missions which are in turn linked to tactical-level naval functions. These naval functions are the bridge to ship-level capabilities where the SoS is decomposed into its elements by systems, sub-systems and equipment.

5.2 Interactive and Dynamic Capability-Based Trade Studies

This approach creates a dynamic SoS architecture decomposing and linking high-level organizational goals to key performance parameters. By integrating all design analyses, including cost models, into a single environment, probabilistic methods and surrogate models can be used to facilitate parametric trade studies and capture the propagated uncertainties impacts.

As summarized in Fig. 5, the interactive and dynamic trade-off studies will results in design variants at the ship-level capabilities which better define the performance of the ship independently of mission scenarios, or as an element of a SoS, in the early stages of ship design. It follows then that when taken as an element of a SoS, much consideration is applied to create a solution with a higher MoE. The equipment and systems-level study will generate better key user requirements selected on merit because they are critical to the achievement of operational needs and the appeasement of political pressures.

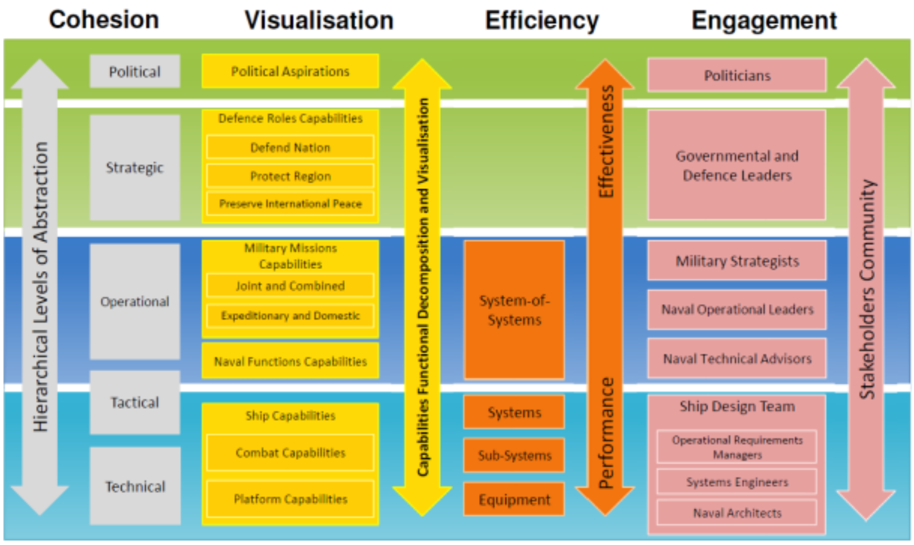

Fig. 5. Capability-Based SoS Approach for Ship Design.

The intent of the capability analysis is to capture the knowledge and experience of the subject matter experts (SMEs), so as to allow a decision maker to assess a large number of potential ship capability combinations without the need to query the SMEs each time.

One of the objectives is to unify the stakeholders' community such that a naval architect can readily understand the impact of a design configuration or equipment selection on the effectiveness to achieve a specific mission at the SoS level. Conversely, a strategist may better understand the technological implications of privileging a given political defence priority. By involving more relevant stakeholders at all levels, greater awareness and education may be reached on the fundamental elements of capability-based ship design and how these canons relate to the stakeholders' roles and responsibilities.

5.3 Visualization

Communicating the potentially complex fused common operating picture encompassing the interdependencies between domains and disciplines to the stakeholder community is essential to sharing a collective understanding of the issues. The use of dashboards is an obvious first choice as they are visual displays that can often communicate with greater efficiency (can be more intuitive) and have richer meaning than text alone. Moreover, as exhibited in Fig. 6, a well-designed and customized dashboard would summarize the information most needed to achieve specific objectives in a single screen using clear and concise displays mechanisms that are easy to comprehend [15].

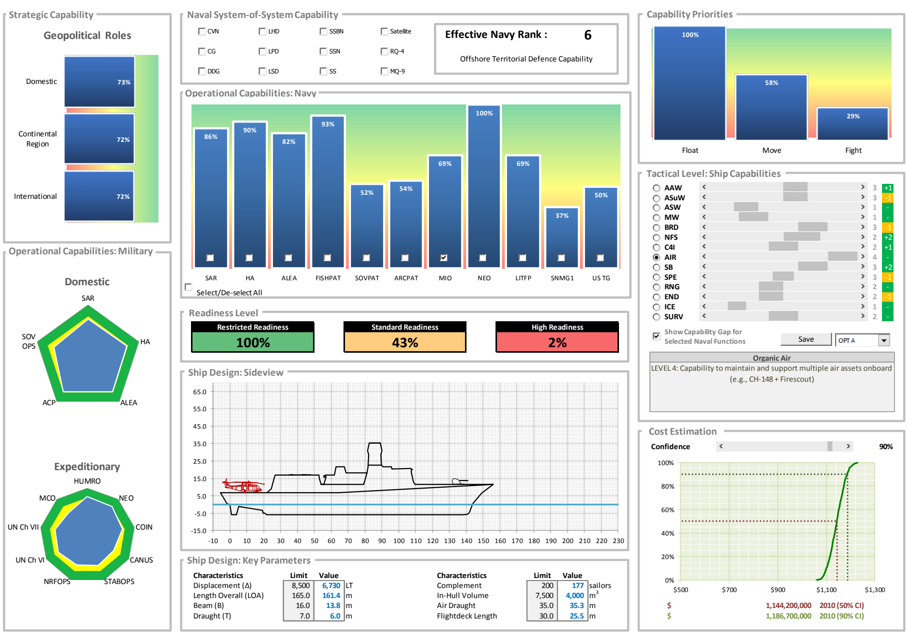

Fig. 6. Ship Design Synthesis Dashboard

These visualization methods may assist assessing and presenting the findings from a variety of reviews in a format that is easy to understand. Ultimately, the visualization of these outcomes provides the catalyst for decision-makers to more confidently consider options they would otherwise ignore and move forward based on well-founded assumptions.

It is acknowledged that verification and validation of the characteristics and behaviours of the SoS comply with the design intent is usually performed while the systems are being integrated and upon completion of sea trials and ship acceptance. But as earlier stated, correctly applying MBSE methods within an architectural framework may improve the ability to resolve interoperability issues between systems, and improve clarity on the context within which capabilities will operate.

6 Conclusion

This position paper proposed an initial approach intended to provide a more defined means of establishing and improving the ship design process as part of a multi-layered maritime domain warfare enterprise. The proposed methodology provides a structured and cohesive initial way forward for identifying and assessing ship capability portfolio with traceable and better known impacts on mission effectiveness, affordability and risk, in the early stages of ship design. The epistemic nature of the proposed process allows the collective generation and evaluation of scenarios which challenges prevailing mind-sets and presumed correlations between uncertainties, while reducing subjective interpretations. Again, the purpose is not to eliminate all uncertainties and cover all options related to ship conceptual design but to circumscribe them so as to instil a deeper appreciation of the critical factors.

7 Disclaimer

This paper is an unclassified position paper containing public domain facts and opinions, which the authors alone considered appropriate and correct for the subject. It does not necessarily reflect the policy or the opinion of any agency, including the Government of Canada, the Canadian Department of National Defence, or the Georgia Institute of Technology.

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