Design for Adaptation - Ships and the Systems of the Future

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Synopsis

Tomorrow's warships must break free from the handcuffs of yesterday's technology. In a world where the lifecycles of combat and mission systems are dramatically shorter than those of the ships that deploy them, a fundamental design challenge exists for ship designers. That is, to design a ship that can adapt and evolve alongside whatever the next generations of emergent technology might throw at it. When one fails to comprehend or address this challenge from the outset of design, they resign themselves to a static capability that will be rapidly surpassed and render its crew ill-equipped for the fight of the future. What may once have been a prized asset at delivery quickly becomes a costly liability for inefficient upgrade or disposal taking considerable sunken costs with it to the grave.

So how can the design of a warship mitigate the risks of future technology integration and increase the likelihood of successful capability upgrades throughout its life? This paper explores the effectiveness of conventional methods such as growth margins, modular systems and controlled sub-system interfaces in the context of past programs and experiences. Issues of spatial allocation and the trade-offs associated with compartment and deck arrangements for a generic next-generation surface combatant from a previous paper by the authors is summarised. Its second-order impacts and inter-dependencies with several design features including topside design, survivability, and ship performance are expanded upon. Lastly, a set of guiding principles are offered as an aid for requirements development in the early stages of naval ship acquisition programs in order to ensure a sensible balance of adaptability is specified and achieved.

Keywords: Ship design; Adaptability; Upgrade; Obsolescence

1 Introduction

The rate of advancement of combat system technologies is rapid and at odds with the longevity of our warships. In order to remain relevant in its operational context, it is important that warships maintain technological advantage or at least equivalency with adversaries. Therefore, over the span of a warships life it is not a matter of 'if' but 'when' combat system elements need upgrading. The questions of 'which elements?', 'where located?' and 'how often?' produce greater consternation and demand deliberate trade-offs.

Representing major capital investments at a national level, the number of warship platforms that can be afforded and supported is limited and faces constant public scrutiny. This is particularly true for middle-power navies including Australia. As a result, enabling longevity of warships is core concern of decision-makers seeking to maximise their 'return on investment'. However, long-lived warships are expected to see greater technological changes, and with them increasing pressures for combat system upgrades. While being upgraded, warships are effectively idle and offer no return on investment. For smaller fleets, the absence of individual warships may even jeopardise national security assumptions. Therefore, the level of efficiency achieved in upgrades is critical both in calculating the total cost of ownership as well as managing operational availability.

One major driver of inefficiency in warship upgrades is the rework of platform systems needed to support new combat system elements. Through a deliberate and disciplined approach to early-stage design of future warships,

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Authors' Biographies

Joseph Cole is the Director of Naval Ship Concept Design within the Royal Australian Navy's Engineering Branch. Joe is responsible for leading the rebuild of the Navy Engineering capability for early-stage design and trade studies in support of capability development. He has extensive experience of the RAN surface combatant program, having handed over the accountable role in Navy Engineering in late 2022. Joe has experience delivering studies and concepts associated with future surface combatants, patrol vessels and landing craft. Joe completed his Bachelor of Engineering (Naval Architecture) degree at the Australian Maritime College in 2002, graduating with Honours.

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Gethin Barden holds the position of Mechanical Engineer in the Naval Ship Concept Design team. Gethin is responsible for supporting the RAN and other ADF maritime stakeholders in early-stage concept, requirements, and project support. Gethin's previous experience includes test and activation systems engineering on Hobart Class destroyers, systems engineering during early-stage acquisition phases for frigates and Army watercraft programs, ship construction assurance of Arafura Class vessels and analysis of reference ship designs to support project sponsors. Gethin has completed additional studies, achieving a Graduate Diploma in Naval Engineering.

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the authors of this paper believe that warship platforms can be better configured to tolerate combat system upgrades, thereby increasing operational availability and cost effectiveness over their service lives.

This paper summarises the traditional approaches for managing the warship upgrade ‘problem’ and explores practical options that improve the chances of compatibility with future combat system needs. It also considers how the physical arrangement of combat system elements affects warship performance and survivability. Finally, it seeks to offer practical guidance for sponsors and designers when developing future warships.

2 Traditional Approaches

Traditional approaches for managing combat system upgradability and the interface with platform systems include the use of margins, modularity, standardisation, and wholesale redesign (including batch building). Previous discussion and findings by the authors [Cole, Smith & Barden, 2024] are summarised in this section.

2.1 Margins

Margins are the most common way that ships are designed and built to endure future change. Margins are the difference between the ship’s status in a certain characteristic and a limiting value of that characteristic. Typically, margins for space, weight, stability, power and cooling are allocated for one or more phases of the capability lifecycle (i.e. design, build, in-service). These margins attempt to identify and control sources of growth and enable trade-off decisions. However, margins alone are insufficient to guarantee compatibility with desired changes. Once built, a warship’s ability to tolerate combat system upgrade is affected by many additional factors including routing of cabling and piping, capacity and quality of power, interactions of electromagnetic interferences and security considerations both physical and cyber. Although there are several technical and programmatic benefits of applying margin management, it is important to recognise their limitations particularly in the context of major upgrades.

2.2 Modularity and Standardisation

Modularity has been adopted by many vessels for various purposes, often by design customisation or operational flexibility. The Blohm & Voss MEKO 200 family of frigates is an example of the former, featuring modular design features which have enabled rapid tailoring of a core design to the unique needs of eight independent navies over almost 40 years. The US Navy Littoral Combat Ship (LCS) and the Danish STANFLEX system are examples of modularity which were intended to allow ships to be rapidly reconfigured for different missions.

Modularity relies on standardised unitisation. In the context of upgrade, this can be advantageous when units with the same external interfaces allow replacement with upgraded functions or performance levels. Once interfaces are defined, modularity allows for much of the design, build, outfitting and testing to be carried out independently from the ship itself. As a result, cost savings and improved operational availability can be generated because of the shortened time that the warship is idle during upgrade. However, the penalty of modularity is that the defined interfaces are also hard constraints which force sub-optimal design compromises. Examples of these unintended modularity consequences include inefficient use of weight and space for structural ‘packaging’, use of additional connectors and adaptors that are otherwise avoidable, and unnecessary duplication of common elements when scaled for overall capacity using multiple modules. Since it is difficult to anticipate the correct interfaces of unknown future technologies, over-reliance on modularity can constitute a liability for future upgrades.

2.3 Wholesale Redesign

Where the level of change required for an upgrade is beyond the available margins and/or interfaces of an existing platform system, then additional redesign may present as the only option. An example is the anti-ship missile defence focussed upgrade of the Australian ANZAC Class frigates. In order to increase buoyancy and stability needed for mast and radar upgrades, the aft quarterdeck was enclosed and ballast was added. Another speculative example is the US Navy Arleigh Burke Flight IIA DDG MOD 2.0 upgrades, where increased cooling capacity associated with combat system upgrades may force a change to primary machinery arrangements. The refit period for this upgrade is predicted to take between 12 and 26 months [Hutchinson, 2023]. Although achievable, extensive design change is expensive and jeopardises operational capability until completed.

The level of platform design change required to support some upgrades may be beyond the limits of existing warships and a new build may be the only feasible alternative. Although generally more expensive, this approach has the benefit of avoiding impacts to extant fleet operations. Batch building is prevalent in many countries,

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reflecting an explicit intent to address technology development directly through build rather than upgrade, while retaining the many commercial and operational benefits of commonality and continuity. The Arleigh Burke program has demonstrated the ability to incorporate an improved helicopter capability in the Flight IIA by lengthening the hull through the batch building process. Such a change would not have been viable through an upgrade of earlier existing hulls. However, the downsides of a batch-building approach include higher costs associated with a larger fleet sizes, overheads of managing multiple configuration baselines of sub-classes, and omission to address degraded capabilities of earlier builds.

3 Concept for Enabling Combat System Upgrade

The authors previously outlined a novel approach to warship design that anticipates and accommodates significant change within the combat system [Cole, Smith & Barden, 2024]. The concept was underpinned by a spatial arrangement with two large combat system equipment ‘enclaves’ connected by dedicated ‘galleries’ for associated cabling and services. These spaces formed a key physical interface between combat and platform systems at the highest possible level. The concept is illustrated in Figure 1 and 2, where red zones denote the two combat system enclaves. Constraints associated with lower-level standardisation and modularity were deliberately avoided and the installation designer was instead empowered to optimise within the physical boundaries of the enclaves for a particular installation configuration. This was intended to mitigate the integration risks of future upgrades by reducing the impact of change rather than constraining it. This section expands on some of the features that were explored as part of the concept's development.

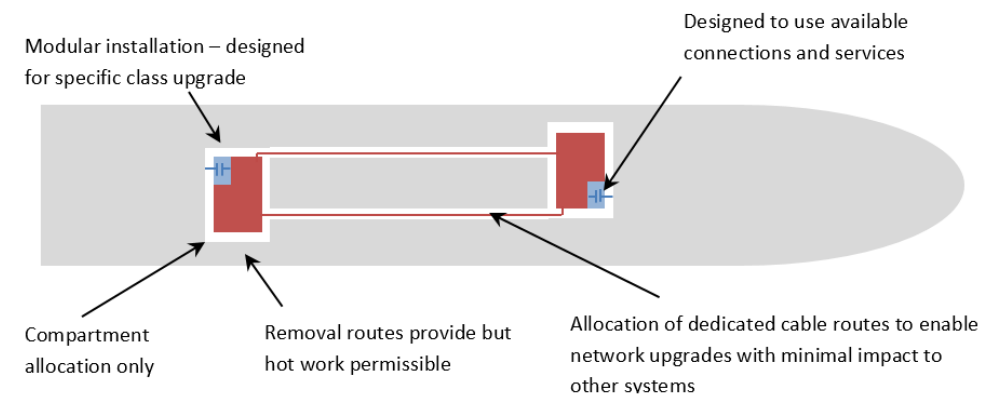

Figure 1: Concept illustration.

Figure 2: Indicative implementation of combat system enclaves (red) linked by galleries (pink).

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3.1 Modularity for Upgrade

The approach presented previously and expanded in this paper is primarily focused on simplifying the interface between combat and platform systems to the level of the compartment boundary. The decision to include modularity within these spaces at a container or rack level or totally reconfigure compartments are deferred to the installation designer. This treatment of modularity, standardisation and flexibility may provide an advantage for upgrades. Examples of modular installations include the DDG 1000 Electronic Modular Enclosures and the CVN Flexible Infrastructure program [Doerry, 2012]. Taking inspiration from installations like the Astute Class Command Deck Module, large modules could potentially be developed based on entire compartment footprints. Although this would come with some penalties in module structure weight and the requirement for large removal routes, it allows significant groups of equipment to be pre-integrated, tested and installed as a unit.

Returning to the authors' concept arrangement shown in Figure 3, several considerations are required when arranging a 'standard interface' modular system such as one based on an ISO container footprint. As the aim for the modular system is not mission flexibility but upgradability, the ability to swap modules in and out in a timeframe of hours is not necessary. As such, hard patches requiring hot work were judged to be acceptable, and removable soft patches were not deemed necessary. The other major consideration of the example arrangement is that installation paths for some modules are blocked by other modules which are closer to the patch. In the example installation arrangement, only three of the seven modules can be removed without removing others. Verification that any equipment temporarily removed for access was replaced and retested may add schedule and cost to an upgrade. As discussed previously, modular installations present opportunities to test equipment independent of the ship. As such, the net impact to schedule of removing, replacing and retesting obstructing modules may still be neutral or positive.

Figure 3: Combat system equipment room modular installation example.

In this concept, modularity remains deliberately at the discretion of the designer. Seeking to keep the future upgrade designer in mind, the initial designer may implement forms of modularity that support anticipated levels of upgrade. A continually evolving enterprise combat system provides additional opportunities to manage the long term aims across different generations of installation designs. The illustrated 'ISO container' arrangement is only one example of a modular solution, and alternatives might include modularity among electronics racks, compartments and/or entire enclaves. In this context, standardisation is not the objective, but larger formats simply provide a common foundation to enable pre-integration, test and installation to reduce upgrade times. These could be unique to each compartment installation design.

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3.2 Topside Design and Mast Arrangements

In addition to the internal spaces, the upper deck arrangement or ‘topside’ design also represents a key area where balance between the platform and combat systems is needed. Considerations include combat system equipment positioning, cabling and electromagnetic interaction, alongside other arrangement drivers such as the bridge visibility, machinery exhausts routing and flight deck placement.

For the survivability of mission critical equipment, separation and redundancy of key sensor capabilities such as air search radars is advantageous. This can be achieved by separating the installations of equipment between fore and aft superstructures or masts. There are several examples of this kind of separation in warship programs. The US Navy Ticonderoga Class distributes the faces of the SPY1 array over opposite corners of the forward and aft superstructures. The German F125 separates the faces of its phased array radar over different forward and aft masts. The US Navy San Antonio Class LPD has integrated composite masts, which support a number of sensors and emitters including radars. The Thales I-Mast fitted to Royal Netherlands Navy warships constitutes an integrated mast solution. Each of these different configurations has different implications for balancing whole of ship design and represents an early-stage decision in the design process for each class which would be difficult to alter later in an upgrade context. Figure 4 illustrates how the internal arrangement concept discussed previously might be combined with different examples of mast configurations, each with unique performance, survivability and integration implications.

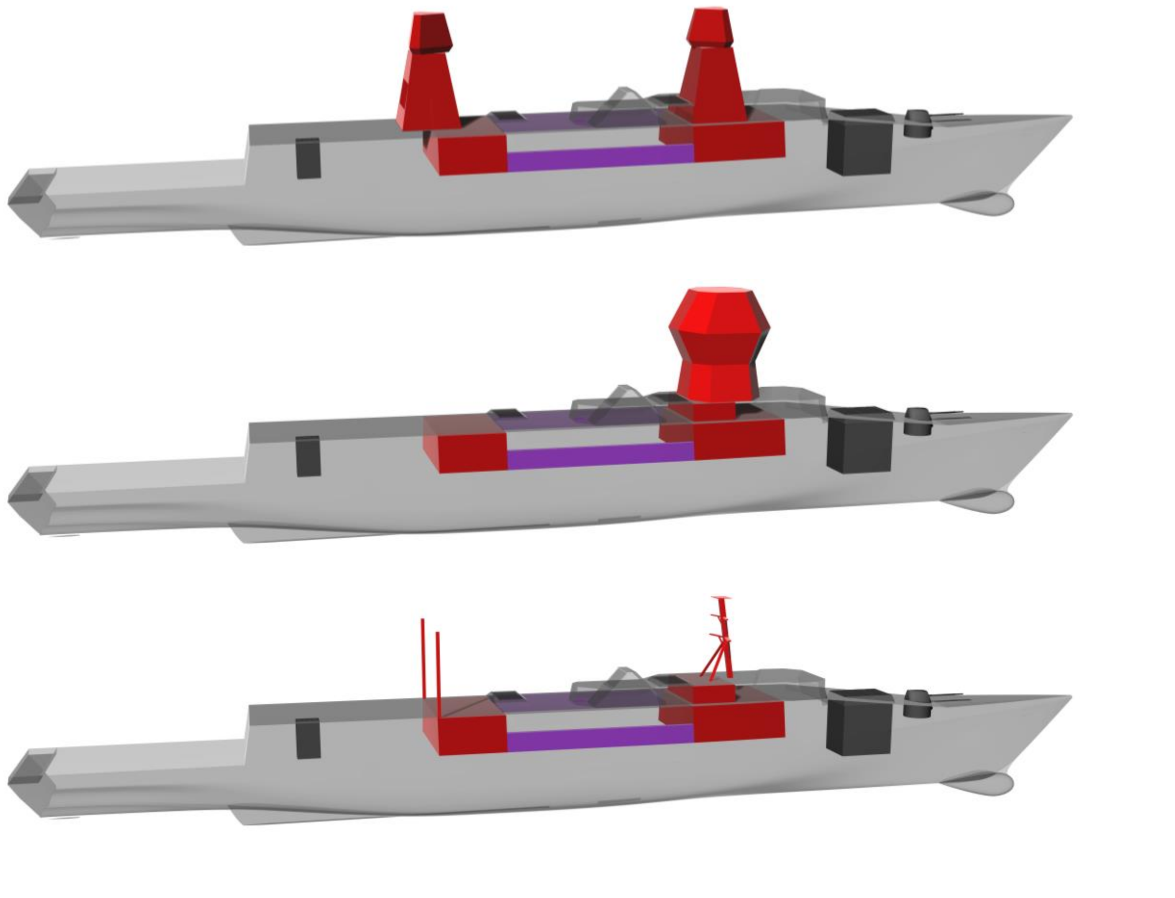

Figure 4: Examples of different mast configurations.

Once a warship has been designed to support a particular mast and topside arrangement it is difficult to make substantial changes to it without compromising the platform design. The extent of topside redesign undertaken by both the ANZAC and Hunter Class programs demonstrates the complexity of this activity and the associated compromises that become necessary in other aspects of the capability.

Platform and combat system objectives can be in considerable tension when it comes to mast arrangements, necessitating trade-offs to balance the design. Beyond the allocation of equipment weights and centres of gravity, the above-water lateral area silhouette is another crucial factor in the determination of vessel stability. As wind heeling criteria often produce limiting cases for warship stability compliance, operability can be quickly eroded by growth in combat system elements, particularly when mounted high on masts.

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Upper deck arrangements are also sensitive to separation distances to prevent electromagnetic interference between equipment and sensors as well as clear arcs for transmitting or receiving communications, deploying weapon systems, or operating aircraft. To enable future upgrades of equipment located on the topsides, it may also be of benefit to include explicit provisions for spatial margins for these areas. Such margins could be represented explicitly in 3D models to inform arrangements and linked to design calculations for windage and electromagnetic interaction.

In the case of complex upgrades, changes to the mast and topside design should be treated holistically. Parametric constraints such as weight, centre of gravity, spatial allocation and wind profile would allow flexibility for the upgrade installation designer, analogous to the recommendations for treatment of internal combat system enclaves. For example, an installation designer may choose to mount sensors or equipment internally within oversized mast structures, or leverage opportunities for bolted rather than welded structural connections for mast foundations. However, caution should be exercised against arbitrarily standardising interfaces which may increase initial complexity and cost, while also constraining the options available to future upgrade installation designers.

3.3 Survivability

The distribution of key sensors and effectors across two separate masts provides potential survivability advantages. In the event that one mast experiences damage or failure, the remaining mast remains capable of providing some level of coverage. For example, if a phased array radar with six faces were distributed between two masts so that the three faces on each mast achieved a near 360-degree coverage, then a high level of survivability is achieved. Coupled with separate and redundant internal combat system enclaves and protected cable routing within dedicated galleries, the concept has potential to achieve a very high level of combat system survivability that would be consistent with other key systems such as propulsion. The ability to achieve separation maximises the benefits available from existing levels of equipment redundancy, meaning that significant survivability improvements may be achievable with limited additional equipment.

4 Guidance on Adaptability Requirements

4.1 Guidance for Capability Sponsors

A capability sponsor (or ‘end-user' representative) must weigh several competing factors when determining the ‘what’ and ‘how’ to manage their project or program outcomes. For warship acquisition in an Australian context, the ‘how’ is increasingly pressured by the time to deliver initial capability. This approach has been reaffirmed by the recent 2024 National Defence Strategy which has shifted focus toward ‘minimum viable capability’ and ‘places greater emphasis on speed to acquisition’ [Australian Government, 2024]. It is important that decision-makers are aware of the opportunities and limitations that warship adaptability (or lack thereof) will have upon the enduring capability relevance over a platform’s typical 20-30 year service life. For warship programs, the following upgrade considerations should be assessed:

1. Are there known system upgrades that will be incorporated during the ship’s service life? Early identification of foreseen upgrades allows designers to enable successful integration, by incorporating necessary aspects with minimum impact to other design elements. Where specific details of future upgrades are known, they can be captured and communicated via “Fitted For But Not With” contract provisions.
2. How mature and resilient are the operating and support concepts against disruption by emerging technologies? Where foundational concepts are susceptible to significant change over the ship’s service life, then design adaptability may be necessary to retain capability relevance. Furthermore, high-level identification and communication of candidate systems that are most likely to be affected may warrant prioritised design arrangements which simplify their mid-life replacement.
3. How consistent is the upgrade philosophy with the relative costs of the platform and combat systems? If a platform system is significantly cheaper than its combat system, then batch-building new platforms for future combat systems may offer a more cost-effective approach than upgrading mid-life. However, as platform system costs are rarely trivial, the barrier to early replacement of warship platforms remains high. In practice warships operate for 30 years or more and capability gaps manifest when existing warships exhaust their ability to upgrade their combat systems.

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4. How tightly constrained is the broader requirement set? Given that warships are a compromise of myriad trade-offs, design feasibility must be ensured. If the possible solutions are already heavily constrained (e.g. physical dimensions, performance, cost) then provisions for future adaptability may force unacceptable compromise in the initial capability.
5. Does the design and build strategy support decoupled development of platform and combat systems? A longer platform build timeline may mean that combat system elements are rendered obsolete before or soon after delivery. There may be opportunities to commence construction on the platform system ahead of the combat system, opting to integrate the newest possible combat system elements into the build. This approach carries technical and commercial risk, but has potential to achieve a better capability outcome.
6. Does the concept proposed in this paper suit the operational context and end-user needs? If the upgradeability and/or survivability benefits of decoupled platform and combat system design are desirable features, then the initial capability needs and requirements that inform the acquisition strategy should reflect these principles. Consideration should also be given to how the proposed approach supports a continuously evolving enterprise combat system.

4.2 Guidance for Design Authorities

Once a decision is made to incorporate adaptability as a central tenant of a program, the responsibility for achieving effective adaptability is transferred to the design authority. Specific considerations for platform system as well as combat system installation design to maximise the likelihood of withstanding future upgrades include:

1. Adaptable platform design is predicated on having sufficient growth margins for support services such as electrical power and cooling system supply. To minimise platform system disruption during upgrade, these support services need to provide margins at the combat system interface. Margins should also be considered for cabling and piping as well as penetrations between combat system elements and supporting platform machinery spaces.
2. Whole of ship performance margins such as speed and range should be considered, especially where degradation below a certain threshold may compromise the operational needs. Traditional stability margins relating to displacement and vertical centre of gravity remain important, but additional novel metrics such as above-water area margins which capture wind heeling impacts of topside arrangement changes may be of benefit.
3. Combat system arrangement designers should be cognisant of elements which are expected to undergo early upgrades or are subject to high technology refresh rates. These elements should be arranged in positions that allow for replacement via dedicated routes and have provisions for flexibility in mounting and connectivity.
4. Where combat system equipment removal routes are established, these should be clearly identified and captured in configuration documentation and protected from unintended obstruction by other design changes.
5. Dedicated cabling and piping routes for combat systems, such as via combat system technical galleries, should be considered for the benefit they provide in controlling the scope of systems impacted by upgrade work. The inclusion of technical galleries may also reduce the number of bulkhead penetrations and increase the physical security of sensitive cabling.
6. Where combat system spaces can be co-located to form ‘combat system enclaves’, this would reduce the complexity of interfaces and minimise constraints to upgrade. Such an approach affords maximum flexibility to upgrade installation designers, while avoiding extensive rework of platform systems.
7. The initial spatial allocation of topside arrangements and any combat system enclaves should be based on conservative assessments of current and anticipated combat system elements, and include margins for design, build and upgrade.
8. Once adopted, the allocations for topside arrangements and any combat system enclaves (including their interfaces and margins), should be considered as constraints for the installation design of future combat system upgrades.
9. Where improved warship survivability is desired, the designer might consider the distribution of equipment across topside arrangements and enclaves to maximise separation and redundancy .

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5 Conclusions

Warships are significant national investments that must remain relevant amidst constantly evolving technologies and changing threat environments over decades of service. As the refresh rates of platform and combat system elements are not aligned, upgrades are unavoidable and provisions are needed within warship designs that enable upgrade while mitigating the total cost of ownership and minimising distribution to operational availability. While traditional approaches such as margins, modularity and spatial arrangements all affect upgradeability, there are some unique and novel opportunities for the consideration of capability sponsors and designers if a disciplined approach is adopted from the earliest stages of design. The concepts discussed in this paper also identify synergetic opportunities to improve the survivability of warships alongside improved upgradeability. While it is recognised that some future technologies will drive changes beyond the abilities of even the most adaptable warships, it is possible that the approaches outlined in this paper may provide an occasional and valuable exception to this rule.

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