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From One-Off Projects to Modular Product Family Ecosystems for Adaptive, Digitally-Enabled Naval Acquisitions

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Abstract

Criticism of large-scale defence acquisitions has grown over the years as projects have become increasingly complex, lengthy, and costly. This has led to high-profile programs being scaled back or abandoned—such as the Zumwalt destroyer and Littoral Combat Ship in the United States, and the Hunter Class Frigate program in Australia. These examples highlight a fundamental issue: traditional acquisition approaches, which have remained largely unchanged for decades, are struggling to keep pace with accelerating technological change and a volatile geopolitical environment. This paper proposes an alternative acquisition paradigm that reconceptualizes naval procurement from a programmatic, one-off project mentality to an ongoing organizational perspective. Central to this approach is the adoption of Modular Product Families (MPF), a concept proven in the automotive sector to balance efficiency, reuse, and adaptability. Applying MPF to naval acquisition would allow vessels to be developed as members of an evolving modular family, reducing costs, shortening lead times, and supporting continuous upgrades in response to emerging threats and technologies. To situate MPF within acquisition practice, we introduce a novel typology that links system complexity and rate-of-change to appropriate acquisition strategies, ranging from predictive to agile to hybrid. We further argue that successful implementation requires digital enablers—Model-Based Systems Engineering, ontologies, and semantic data integration—to create the digital threads necessary for collaboration, interoperability, and adaptability across acquisition ecosystems. By advancing this modular, digitally enabled framework, the paper seeks to break the boundaries of entrenched defence acquisition practices and provide a pathway toward more resilient, adaptive, and value-driven procurement strategies.

Keywords

Modular Product Families, Naval Engineering, Defence, Acquisition, Adaptive response, Innovation Ecosystems.

Introduction

Acquiring large-scale, complex systems has long been a central domain of systems engineering. However, the accelerating pace of technological change and environmental uncertainty increasingly expose limitations in traditional acquisition approaches. In sectors such as defence, programs take decades, consuming significant resources, yet often deliver platforms that are outdated upon arrival. Research on megaprojects highlights the 'iron law' of overruns in cost, time, and relevance. As the volatility of the acquisition environment grows, new approaches must be considered to ensure enduring stakeholder value. The U.S. Navy, GAO, and Congress have raised concerns about the escalating costs and long timelines of naval acquisitions (Bounds, 2019; Page, 2022), compounded by fears that the U.S. is losing its innovation edge to China and Russia (Weisgerber, 2014). The current state of naval acquisition planning in the US navy is as follows: the United Sates Navy (USN), will outline their resource allocation decisions in a Program Objectives Memorandum (POM) in accordance with the Guidance for Development of the Force (GDF) and Defense Planning Guidance (DPG) for the next 5 years as part of the Planning, Programming, Budgeting and Execution (PPBE) process (Letts et al., 2024). Current planning through the PPBE process is criticized for being constrained by cognitive biases such as loss aversion (Lemaster, 2023) and sunk-cost fallacies, limiting flexibility (Gunter, 2023). As technology and geopolitics evolve rapidly, existing acquisition methods risk producing obsolete assets. This paper argues that naval acquisition must be fundamentally revised, drawing lessons from industries like automotive that employ Modular Product Families (MPF) to balance adaptability, efficiency, and scale. The strategies adopted by automotive sectors (Hind et al., 2022; Pandremenos et al., 2009) have made a shift to Modular Product Families (MPF) (Bonvoisin et al., 2016; Gauss et al., 2021) to remain competitive in a market, demanding mass customization whilst still retaining the cost benefits derived from economies of scale.

This paper argues that the current U.S. Navy (USN) acquisition approach must be fundamentally revised to remain effective. With accelerating technological, sociotechnical, and geopolitical change, existing methods are too slow and risk delivering obsolete assets (Page, 2022). de Haan et al. (2025) developed a generic flow diagram for applying Modular Product Families (MPF) to large-scale acquisitions. While not a “one size fits all” solution, the process provides design guidance to align acquisitions with organizational objectives, introduce modularity considerations early, and highlight when MPF is most suitable. Building on Gauss et al. (2021) and Bonvoisin et al. (2016) the framework was adapted for large-scale environments and tailored herein for naval acquisition. Using open-source USN data, the paper explores how naval procurement—currently conducted as unique, one-off projects—could shift toward a modular, continuous acquisition model. Inspired by automotive practices, this approach would better accommodate recurring technology insertion, fleet renewal, and mission capability needs. While governments seek to reduce naval shipbuilding costs, increase flexibility, and expand fleet size, these goals are not yet reflected in the USN force structure.

Background

The persistent issues surrounding naval acquisition programs in the United States and Australia over the past two decades have illustrated the inadequacies of traditional procurement models. Major projects like the Zumwalt-class destroyer and the Littoral Combat Ship (LCS) underscore the systemic failures that have led to significant cost overruns and delays. The Zumwalt-class destroyer, initially envisioned as a fleet of 32 vessels, was reduced to only three due to escalating costs—each vessel nearing $4.3 billion, which is comparable to some aircraft carriers' costs. This situation not only triggered a Nunn-McCurdy breach but also illustrates the challenges of modifying outdated acquisition practices (Ritschel, 2012). The Government Accountability Office (GAO) has described these procurement difficulties as emblematic of deeper issues within the Department of Defence (DoD) weapons systems acquisitions. The LCS program has been particularly criticized for its performance issues and costly modifications, mirroring patterns observed in large-scale infrastructure projects, where cost overruns often occur due to inadequate planning and risk management (Smirnoff & Hicks, 2008). Notably, historical data indicate that cost growth in DoD programs can exceed original budgets by significant margins, with some estimates suggesting average cost growth reaching upwards of 40% (Smirnoff & Hicks, 2008). This exposes taxpayers to considerable fiscal burdens without corresponding enhancements in military capability or readiness. Australia's naval acquisition saga parallels that of the United States, particularly in the case of the Hunter-class frigate program, initially budgeted at approximately AU$45 billion but now estimated to rise to over AU$65 billion. The Australian National Audit Office (ANAO) has critiqued this initiative as "chronically over-budget" and significantly delayed, reflecting issues akin to those in U.S. naval procurement. The accumulation of delays in Australia's top 21 defence projects has been reported as totaling around 36.8 years, with cost overruns estimated between AU$18 billion and AU$41 billion (ANAO, 2024). Such delays in weapon system delivery amid rapidly evolving geopolitical environments, especially considering the Russia-China alignment, pose strategic risks of deploying outdated defence platforms as adversaries advance their technologically. Flyvbjerg (2021) work asserts large infrastructure projects often exceed initial time and cost forecasts. The challenges within both U.S. and Australian naval projects can be interpreted similarly. Flyvbjerg noted that a significant number of large-scale projects, including those in the defence sector, typically fail to manage costs and timelines effectively, resulting in undesirable outcomes. The ramifications of these procurement failures are multifaceted, extending beyond financial challenges to encompass reduced military readiness and heightened strategic vulnerabilities. As both nations confront these issues, clearly sporadic reforms to procurement models have not sufficiently addressed the fundamental inefficiencies inherent in large-scale military acquisitions (Bounds, 2019; Ritschel, 2012). The procurement challenges faced by naval programs in the U.S. and Australia not only exemplify high-profile cost overruns but also reflect a broader trend of strategic misalignment and risk in defence spending.

Addressing these challenges necessitates a re-evaluation of acquisition paradigms to improve efficiency and effectiveness in a rapidly changing global defence landscape. Several approaches have been proposed to address the ongoing challenges in naval acquisition, yet each exhibits significant limitations when applied to complex, high-stakes platforms. These approaches are as follows:

1. Traditional Acquisition (Forecasting & Planning): The conventional model relies heavily on long-term forecasting and detailed upfront planning, predicated on the assumption that early requirements remain stable across lengthy development cycles. While effective in stable environments, this model fails when subjected to high uncertainty and rapid technological or geopolitical shifts. No recent citations needed here, as this is a foundational theory.
2. Agile Methods: Agile principles, originating in software development, have been introduced to defence acquisition to promote iterative delivery, stakeholder engagement, and responsiveness. The DoD's Agile adoption aims to deliver functional software within a year, in contrast to the decades-long timelines of traditional “waterfall” methods (GAO, 2023; Modigliani & Chang, 2014). However, program-wide adherence remains inconsistent; the Government Accountability Office (GAO) found that many weapon system programs still do not comply with Agile guidelines, limiting the method’s transformative potential (Hill, 2023). Defence organisations often contend that “failing fast” is untenable when individual platforms cost billions and involve thousands of suppliers—a risk of overshadowing Agile’s theoretical benefits.
3. Mission Engineering: Recognized by the DoD as an approach to better align acquisition with operational goals, Mission Engineering reframes the "mission," rather than discrete platforms, as the system of interest. It integrates emerging capabilities and operational needs into a cohesive mission framework, enabling improved investment decisions (DoD, 2023). Nonetheless, while Mission Engineering enriches decision-making and scenario analysis, it operates within the constraints of existing acquisition structures and does not upend the industrial or organizational norms of shipbuilding.
4. Modular Open Systems Architecture (MOSA): MOSA promotes the design of systems with modular, loosely coupled components and open standards that enable parallel development and vendor competition (Shah, 2021). Legislative mandates now require its adoption "to the maximum extent practicable" in major defence acquisition programs (Williams, 2021). Despite this, practical implementation remains slow (GAO, 2025). This review highlight planning gaps, industry resistance, coordination issues, and added integration burdens.

These approaches, while promising incremental value, fall short of delivering the transformational adaptability and responsiveness required. They either work within rigid acquisition paradigms, fail to scale to naval platform complexity, or stall during implementation. This recognition underscores the need for a holistic reconceptualization: one that treats defence procurement as an ongoing, modular ecosystem operating with agility, architectural coherence, and digital integration. This motivation leads naturally to the exploration of Modular Product Families (MPF) as a more systemic, scalable alternative, which is the goal of this paper. IN the next section and its 6 subsections, we present our model of responsive acquisition.

Responsive Naval Acquisition Approach

Naval acquisition has long recognized the benefits of modularity, yet the adoption of Modular Open Systems Architectures (MOSA) has been slow due to institutional resistance and integration challenges (Davendralingam et al., 2019; Shah, 2021). Modular Product Families (MPF) build on MOSA by extending modularity beyond individual systems to encompass entire families of platforms. Central to MPF is the development of stable, reusable platform architectures that can support multiple product variants through standardized interfaces (Pandremenos et al., 2009). This approach, widely applied in the automotive sector, allows manufacturers to rationalize platforms across different brands while tailoring modules and features to diverse customer needs (Ben Mahmoud-Jouini & Lenfle, 2010).

In naval shipbuilding, modularity has been considered at different levels—from mission modules to broader platform-level concepts (Chaves et al., 2015; Davendralingam et al., 2019; Doerry & Koenig, 2017). However, practice remains dominated by treating each vessel as a bespoke acquisition, requiring extensive resources, prolonged approval processes, and lengthy development cycles (Letts et al., 2024; Page, 2022). In essence,

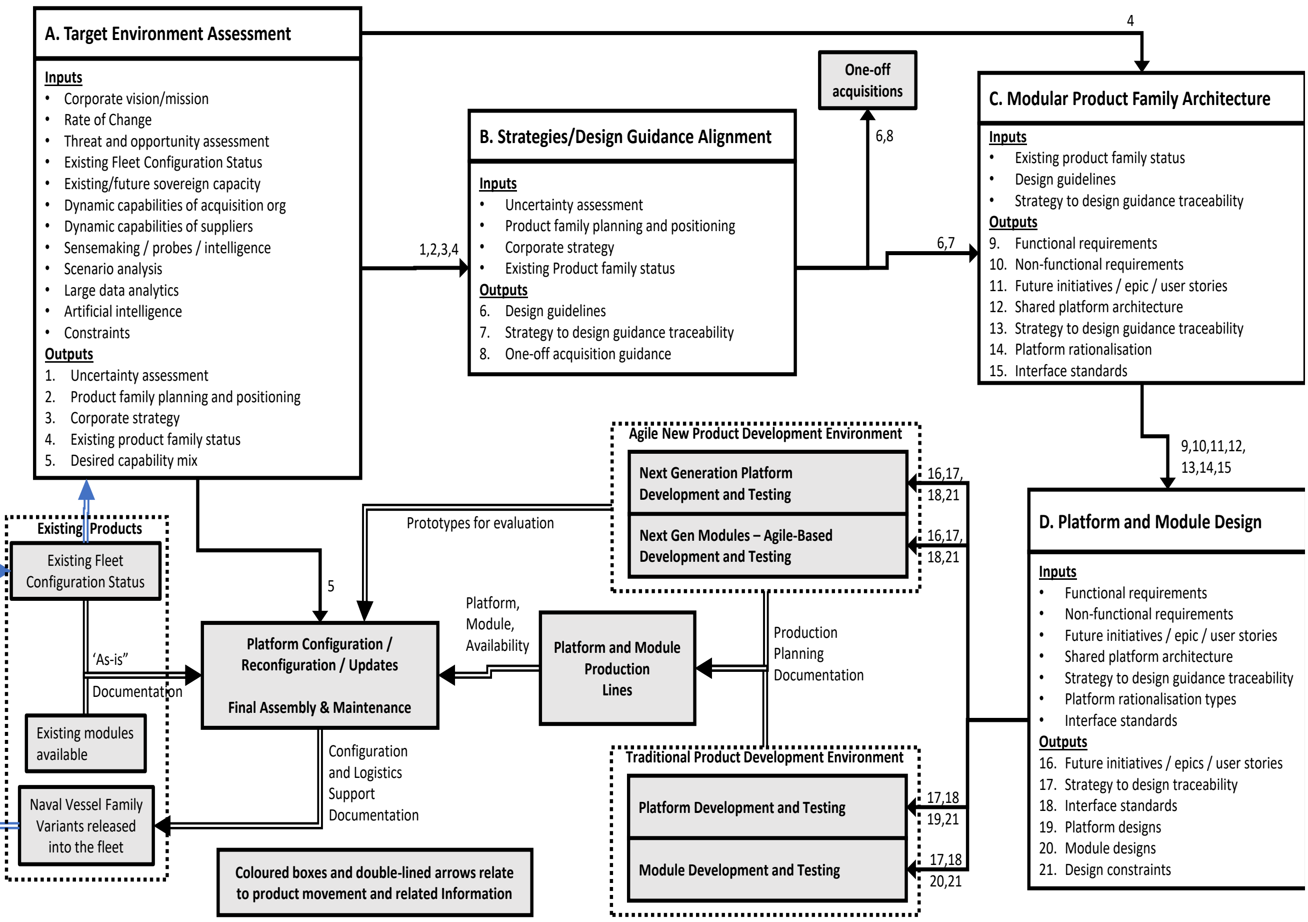

Figure 1: Tailored Modular Product Family (MPF) acquisition process for naval platforms, illustrating the continuous flow of information across strategic foresight, design alignment, modular development, and lifecycle adaptation. The model highlights key feedback loops, modular integration points, and opportunities for flexibility in response to changing operational and technological conditions.

MPF offers a pathway to break this pattern by enabling continuous innovation: new modules can be integrated into existing platforms while future generations of platforms and interfaces are developed in parallel. Such an approach would allow navies like the USN to reduce lead times, accommodate emerging technologies more effectively, and maintain fleet relevance in rapidly changing geopolitical and technological environments.

Figure 1 illustrates the continuous shipbuilding cycle proposed in this paper; it is designed to improve responsiveness to a dynamic operating environment. These activities are now discussed along with their implications and constraints.

The framework in *Figure 1* should never be interpreted as a rigid, sequential process, but as a continuous adaptive flow of information. Activities occur concurrently and are driven primarily by changes detected in the operational environment. This creates an ecosystem in which information is constantly shared and decisions are continuously updated. A useful analogy is the global automotive sector, where distributed suppliers, manufacturing, assembly, and post-production support function in parallel rather than in strict sequence. Similarly, platform and module production is conducted at scale, not on a vessel-by-vessel basis.

A. Target Environment Assessment

Target environment assessment refers to the systematic evaluation of the external conditions—geopolitical, technological, economic, and operational—that shape the effectiveness and relevance of naval acquisitions. Its purpose is to ensure that acquisition strategies remain aligned with a rapidly evolving context, where assumptions made at project initiation can quickly become invalid. In stable or predictable environments, it may be possible to forecast capability needs across 10–20 years. However, in today's climate of accelerating technological innovation, intensifying geopolitical competition, and greater global interconnectivity, such long-range predictions carry high risk. Platforms conceived under traditional acquisition models often take decades to deliver, by which time the environment has shifted, leaving navies with assets that are costly yet partially obsolete. A dynamic environment, characterized by frequent perturbations and uncertainty, requires continuous monitoring rather than periodic reviews. The frequency of assessments should correspond to the rate-of-change in key dimensions of interest—such as adversary force development, emerging technologies (e.g., AI, hypersonics, uncrewed systems), industrial capacity, and strategic alliances. Effective surveillance of this environment requires pooling of insights across multiple stakeholders, including defence organisations, industry, academia, and allied partners. Such collaboration not only broadens perspective but can reduce the cost and duplication of intelligence gathering. Various analytical techniques could be applied—such as horizon scanning (Stevens et al., 2021), scenario planning (Fitzsimmons, 2018), wargaming (Davis & Bracken, 2025), trend analysis (DTIC, 2015), and sensemaking (Kurtz & Snowden, 2003). A detailed discussion of these methods lies outside the scope of this paper; nevertheless, what is important is that the target environment assessment provides the input conditions against which the ongoing acquisition process is tested and adapted. For naval acquisition, three illustrative objectives highlight the importance of this activity:

1. Reducing unit costs of vessels by ensuring procurement strategies exploit economies of scale and modularity rather than bespoke builds.
2. Enhancing fleet flexibility and agility by aligning acquisition to modular designs that can evolve alongside changing threats and technologies.
3. Maintaining technological superiority by continuously integrating innovations, ensuring that delivered platforms remain operationally relevant.

By systematically assessing the target environment, acquisition decisions can shift from being static, one-off commitments to becoming adaptive, ongoing processes that anticipate and respond to change.

B. Strategic/Design Guidance Alignment

In this part of the acquisition approach, experts assess different design approaches to address the changing needs of the target operating environment based on the needs of decision makers. They should also seek to continually improve the performance of the acquisition system. Importantly, this group will decide how various goals can best be achieved. There is an assumption in this example that MPF approach would be the optimal way for the USN to achieve its core objectives based on the logic used to assess the core business objectives outlined in this section. But there may be instances where the experts will recommend that the objectives can best be met by a separate project outside of the MPF mainstream approach. They may recommend MOSA still be applied to the project, or due to special circumstances, they may advise that the specified products should be optimised for performance.

In this instance the rationale for recommending an MPF approach to address the core naval business objectives has been summarised with the following breakdown.

1. Reduce the unit costs of vessels

Reducing the unit costs of naval vessels is a central objective of acquisition reform, and modular product family approaches offer multiple pathways—spanning production, integration, sustainment, and reconfiguration—to deliver significant savings while enhancing fleet flexibility.

Production: Significant cost efficiencies in naval production can be achieved through the rationalization of hull types and the adoption of modular design principles. Standardizing hulls promotes repetition, shortens build times, and enables production line optimization, delivering economies of scale. A parallel can be drawn to the automotive sector, where Volkswagen's MQB platform underpins dozens of different vehicle models, reducing costs by sharing components across product lines. Similarly, modularity in naval shipbuilding allows systems to be decoupled through standardized interfaces, enabling modules to be integrated during or after hull construction and reused fleet-wide. As module manufacturers benefit from scale economies, overall unit costs decline.

Decoupling vessel and module production timelines also minimizes bottlenecks, giving shipbuilders greater flexibility and resilience against delays.

Systems Integration: Once initial hull and module combinations are validated, subsequent efforts can focus less on full-system integration and more on quality assurance and unit-level testing. Standardized interfaces allow early proof-of-concept testing and simplify verification, so new modules require only unit-level validation before deployment. This reduces integration costs across the fleet. A structured acquisition pipeline further enhances interoperability, ensuring that tested configurations can be reused, sustainment simplified, and operational requirements more readily aligned. For example, the U.S. Navy's Littoral Combat Ship (LCS) mission module concept attempted such modular integration, but uneven implementation and integration challenges highlight the need for rigorous standardization and early validation (DoD, 2022).

Warehousing and Maintenance: Common modules and components across the fleet streamline sustainment logistics, lowering operational costs. Standardization reduces the variety of parts in inventory, easing warehousing and supply chain management. Modularity also enables a "remove and replace" maintenance model: faulty systems can be swapped rapidly and serviced offline, improving vessel availability. Interchangeable modules across multiple platforms mitigate the risk of supply shortages and further consolidate production lines, enhancing readiness and resilience.

Upgrades and Disposal: Standardized interfaces make it possible to modernize vessels through targeted module replacement rather than costly platform-wide overhauls. This modular upgrade approach reduces lifecycle expenditure and ensures technological currency across the fleet. Modules can also be reused or redistributed as platforms are retired, maximizing asset value and reducing obsolescence. At end-of-life, modularity simplifies disassembly, demilitarization, and recycling. Designing platforms and modules with disposability and reconfiguration in mind ensures adaptability and supports principles of circular logistics throughout the fleet's lifespan.

Reconfiguration and Repurposing: Finally, modular naval architectures enable vessels to be reconfigured or repurposed for new missions without major reconstruction. Emerging technologies or operational capabilities can be rapidly integrated as new modules, allowing the fleet to adapt without waiting for lengthy acquisition cycles. This flexibility extends platform lifespans, improves responsiveness to evolving threats, and enhances strategic agility while containing costs.

2. Make the Navy agile and responsive to a changing environment.

Agility in naval acquisition must extend beyond manufacturing efficiency to the operational flexibility of the fleet. A modular architecture enables platforms to be rapidly reconfigured to meet diverse mission requirements without requiring entirely new ship classes. For example, the Danish StanFlex system demonstrates how standardized module slots can allow a single hull type to switch roles—from mine countermeasures to surface warfare—within days. Such an approach reduces dependence on purpose-specific vessels and allows navies to adapt more quickly to evolving threats or mission profiles. The same principle can be applied at scale for the U.S. Navy. By standardizing hulls and modular interfaces, configuration decisions can be deferred until late in the build process, or even after commissioning. This flexibility means ships can be tailored to emerging missions—such as uncrewed operations, electronic warfare, or directed energy weapons—without waiting for the next acquisition cycle. Containerized or plug-and-play mission modules, already tested in NATO contexts, further enhance this adaptability by enabling capability swaps at sea or during port calls. Agility also extends to fleet management and deployment. A modular force structure enables the Navy to rebalance capabilities quickly, shifting module inventories across the fleet in response to changing geopolitical circumstances. This reduces lead times for force projection, avoids tying capability to a limited number of specialized platforms, and allows the Navy to maintain a more versatile and resilient posture. Taken together, these practices ensure that naval acquisition is not only faster and more efficient but also strategically responsive to the uncertainties of modern conflict.

3. Most technologically advanced navy

A modular approach to naval capability development allows platforms and modules to evolve independently, creating a more adaptable and future-ready force structure. By decoupling platform development from module integration, naval architects can introduce new hull designs or platform variants without immediately reconfiguring production facilities, provided new designs align with existing infrastructure. This supports incremental upgrades to production lines, maintaining continuity and minimizing disruption. In parallel, modules are developed under standardized interface protocols and design constraints, ensuring compatibility across multiple platform generations. This standardization enables emerging technologies to be trialed in real-world conditions by substituting modules with minimal integration effort. As a result, technology development can proceed using agile methods—iterative design, early validation, and rapid prototyping—before stable configurations are moved into formal production. This dual-track model balances innovation with efficiency and strategic coherence. Although rationalizing hull types may be controversial, it can deliver substantial savings in both time and cost compared to bespoke designs. Enforcing standardized interfaces ensures interoperability and maximizes flexibility: any module meeting defined interface and constraint requirements can be fitted into any designated slot across the fleet.

C. Modular Product Family Architecture

The central challenge of a Modular Product Family (MPF) approach is designing a naval architecture that spans multiple core platforms while remaining adaptable to technological and operational change. Even building one class of ship is complex; extending common architectures across an entire fleet is daunting. The task, therefore, is to determine which functions should reside within the base platform and which should be modularized. At its simplest, a naval vessel consists of a platform (hull, propulsion, and infrastructure) fitted with systems, payloads, and accommodation spaces (de Haan et al., 2024). This ontology provides a common language for multidisciplinary design. As more detail is added, the ontology can evolve into models supporting acquisition and fleet planning. Using publicly available U.S. Navy fleet data, a rationalization exercise suggests four platform categories (excluding carriers and submarines as special cases):

- **40,000 tons:** Amphibious assault ships, drone carriers, oilers, and replenishment ships
- **25,000 tons:** Amphibious transport docks, expeditionary sea bases, supply ships
- **15,000 tons:** Cruisers, destroyers, ASW/ASuW vessels, minehunters
- **3,500 tons:** Frigates, littoral ships, coastal defence, mine countermeasures

This rationalization minimizes unique hull types, enabling cost savings and production efficiency. Platform design discussions must also consider stealth shaping, material choices, hull forms, and—critically—how modules can be easily accessed, exchanged, and upgraded. A key principle is assigning functions with the highest exposure to change into modules, thereby reducing platform obsolescence risk. Requirements for maintainability and reconfigurability also guide the platform–module boundary. While some systems remain platform-integrated, modularization ensures adaptability and lifecycle efficiency. Automation and autonomy are expected to reduce crew sizes in future fleets, and some vessels may even operate uncrewed. This makes accommodation, galleys, sanitation, potable water, and sewage systems prime candidates for modularization, fitted only when required. Such flexibility aligns with emerging concepts of optionally crewed ships and avoids unnecessary investment in onboard services. Similar thinking applies to power and propulsion, as power-hungry systems such as lasers, railguns, directed-energy weapons, and drone deployment facilities demand adaptable energy architectures. Options like gas turbines, diesel engines, modular nuclear reactors, and advanced batteries must be designed for interchangeability, while a shift to electric drive could eliminate traditional shafts, freeing hull space and enabling more flexible layouts. Ensuring propulsion and energy systems remain upgradeable is critical to accommodate emerging technologies and evolving mission needs. The superstructure also plays a pivotal role in modular design. Its configuration strongly influences available layouts and making it upgradeable or relocatable could improve long-term flexibility. Core functions often located in the superstructure—bridge, communications, and radar—are especially vulnerable to rapid

technological change and should be modularized. Scalable radar suites and modular

Table 1: Suggested allocation of Functions to Platform vs. Modules in a Modular Product Family (MPF) Architecture

Category	Platform (Core, Stable)	Modules (Variable, Upgradable)
Hull & Structure	Hull form, displacement, structural integrity, survivability	Hull appendages (mission bays, modular stern/flight decks, ballast)
Propulsion & Power	Propeller shafts, electric drive baseline, structural mounts	Gas turbines, diesel gensets, modular reactors, energy storage (batteries, fuel cells)
Accommodation	Core habitability interfaces (HVAC, water/power distribution)	Galley, sanitation, potable water, sewage, berthing spaces (scalable to crew size / autonomy)
Superstructure	Core structural framework	Bridge layouts, radar arrays, comms suites, sensor masts (scalable/replaceable with new tech)
Mission Payloads	Launch/recovery infrastructure (e.g., hangars, stern ramps)	Weapons systems, missile modules, drones, ASW/ASuW suites, medical bays, cargo, humanitarian aid
Lifecycle Elements	Base service-life design.	Upgrade kits, recycling/disposal modules, reusable components across fleet

communications, for example, would enable fleet-wide standardization while preserving technological relevance. Beyond this, payloads and mission modules are the key drivers of operational versatility. Weapons, helicopter bays, drone launch systems, medical facilities, and cargo holds should all be modular, scalable, and swappable across hull classes. This approach allows a single platform to support diverse missions, from strike operations to humanitarian relief. The Danish StanFlex system demonstrates this principle in practice, where modules can be exchanged within days to re-role a vessel.

Modularization further supports cost efficiency across the lifecycle. Rationalized hull families and reusable modules simplify sustainment, enable targeted upgrades, and extend platform lifespans. Retired vessels can release reusable modules, preserving capability and reducing obsolescence, while modular disassembly facilitates recycling and aligns with circular logistics principles. Managing this complexity requires robust data and ontology support. The vast technical information generated by modular fleet design is best captured in semantic ontologies connected to visual models (Hagedorn et al., 2020). These representations improve interdisciplinary communication, ensure consistency, and integrate with Model-Based Systems Engineering (MBSE) to support digital threads. Rationalizing hull types and systematically modularizing accommodation, power, superstructures, and payloads (see suggestions in *Table 1*) enables transition to a fleet organized around a Modular Product Family architecture. This would reduce acquisition and sustainment costs, enable faster adaptation to technological and geopolitical change, and create a more resilient and responsive naval ecosystem.

D. Platform and Module Design

One of the most important advantages of the Modular Product Family (MPF) approach is the decoupling of platform architecture from mission and system payloads, enabling concurrent development of ship layouts and modular systems. This separation increases design flexibility and facilitates the integration of advanced digital tools and methods. For example, le Poole et al. (2023); le Poole et al. (2022) utilized a "black box" approach to naval layout design where functional spaces are abstracted and optimized around mission needs and evolving system configurations. Their "on-the-fly" design rationale method supports real-time collaboration—both co-located and distributed—allowing dynamic early-stage design iterations in highly complex naval environments. Mallam (2016) adds a complementary perspective, emphasizing spatial and cognitive optimization in ship layouts and highlighting the importance of toolchains that integrate human factors with system-level reasoning. Other studies, such as (Gualeni et al., 2021; Jung et al., 2018; Jung & Simpson, 2017; Ljulj & Slapničar, 2020) advocate holistic design practices that link form, function, and adaptability. These approaches align closely with the triple-V model proposed by de Haan et al. (2025) in which verification, validation, and viability are considered simultaneously throughout the lifecycle. To remain responsive to evolving requirements, these design models must be supported by ontologies that provide traceability across the design ecosystem (Hagedorn et al., 2020; Madni, 2022; Papaioannou et al., 2021; Patel et al., 2023). Preliminary platform definitions and module interfaces should be semantically linked to requirements, design rules, and architectural constraints, enabling AI-assisted verification, validation, and reuse. This ensures that mission-defined modules can be upgraded or replaced incrementally without requiring a full platform redesign. Ontologies could feasibly provide a bridge between system models and enterprise-level systems such as Product Lifecycle Management (PLM), Manufacturing Resource Planning (MRP), and Enterprise Resource Planning (ERP), although this integration remains an emerging area of research. Digital engineering tools and AI could further enhance MPF design. Natural Language Processing (NLP) can extract requirements and capture design rationale from historical documents, while generative design and rule-based configurators could automate layout optimization. Simulation-based testing and modular libraries can add a feedback-rich environment that supports rapid decision-making, human–machine collaboration, and improve design traceability. Together, these capabilities transform platform and module development from a sequential, stove-piped process into a dynamic, collaborative, and future-ready ecosystem. A key challenge remains the integration of systems engineering and naval engineering practices. Researchers continue to explore ways to link CAD and PLM environments with Systems Engineering and Model-Based Systems Engineering (MBSE) (Bottero, 2025). Advances in semantic ontologies, such as the Web Ontology Language (OWL) (Lu et al., 2021; Zhang et al., 2023), if combined with methods like Multidisciplinary Design Analysis and Optimization (MDAO) (Xu et al., 2025) and Knowledge-Based Engineering (KBE) (Sanya & and Shehab, 2014), provide opportunities to unify these domains. Progress in applying MBSE to MPF design (Hanna et al., 2023) will further strengthen this integration. Ultimately, the goal is to ensure that clearly defined requirements are allocated to platforms and modules within preliminary designs, which are then subjected to analysis, verification, and simulation. Requirements that are uncertain or highly dynamic should be assigned to modules wherever possible and developed iteratively using agile methods. This balance allows stability preservation in core platforms while enabling continuous adaptation at the modular level.

Product Development and Production Considerations

For projects based on a stable baseline—with well-defined requirements, documented interface standards, and preliminary designs—development and testing can follow a more traditional systems engineering approach. In these cases, modules and platforms evolve within clear constraints, reducing risk and uncertainty. Conversely, modules that face higher levels of uncertainty, rapid technological change, or poorly defined requirements should be developed using an agile approach, allowing them to adapt iteratively to emerging needs and new technologies. Standardized interfaces ensure that once a prototype module has completed preliminary testing and proven compatibility with other existing "in-operation" modules, it can be fast-tracked to a proof-of-capability trial on board an available vessel. This accelerates the adoption of innovative technologies and capabilities. However, this does not negate the need for comprehensive testing of all module combinations to detect negative emergent properties. Equally important is the requirement to capture and integrate all test results into semantically connected digital threads, ensuring traceability and reuse across the design ecosystem. A critical step in development and testing is confirming that platforms and modules are production-ready, with complete supporting documentation provided to the manufacturing line. Decision-makers then have two options during platform construction: fitting available modules at the time of production, or deferring configuration to the post-production stage. This flexibility reduces bottlenecks and allows vessel configurations to be changed at any point in the acquisition cycle. In practice, existing modules can be installed on newly built platforms to bring them into service quickly, while innovative new modules are still in development. Once a vessel is commissioned, the configuration status of the fleet is updated within the digital architecture. This enables decision-makers to monitor how different configurations influence fleet behaviors in the target operating environment and to use these insights to inform future acquisition and capability decisions.

Conclusion

The Modular Product Family (MPF) approach represents a major shift in how naval capabilities are designed and sustained. It separates platform engineering from module development, creating two complementary streams that deliver both stability and adaptability. Platforms such as hulls and propulsion continue to follow traditional systems engineering, while mission modules—like weapons, sensors, and payloads—are developed using agile methods. This reduces time-to-field by enabling concurrent progress and rapid integration of new technologies. A key enabler is the creation of modular libraries—digital repositories of pre-validated modules, interface standards, and performance data. These libraries accelerate design cycles, reduce engineering overhead, and support scalable development across teams. Standardized interfaces further simplify integration: once compatibility is proven, modules can be validated with streamlined unit testing. Digital twins and virtualized testbeds reduce risk by validating performance before physical prototypes are built. Operationally, modularity improves fleet readiness and lifecycle efficiency. Modules can be swapped or serviced offline without removing platforms from service, reducing downtime and extending vessel lifespans. Reusable and upgradeable modules also promote circularity, lowering costs and environmental impact. Success, however, depends on a strong digital and semantic backbone. Ontologies must underpin acquisition by linking requirements, design rules, and constraints, ensuring traceability and reuse. Integration with enterprise systems such as PLM, ERP, and MRP creates a unified data environment, while AI, NLP, and blockchain offer tools for faster analysis, knowledge capture, and secure traceability. Equally important is organizational reform. Current acquisition practices are platform-centric and risk-averse, which can stifle innovation. Governance frameworks must evolve to support agile, distributed decision-making, aided by AI-assisted policy enforcement and automation. Without these institutional changes, modularity risks being constrained by legacy processes. Ultimately, MPF is not just about efficiency but about maintaining technological and operational dominance. Rationalizing hull types, modularizing critical systems, and embedding digital infrastructures will help achieve the Navy's three core goals: reduced unit costs, greater agility, and sustained technological superiority. Although implementation requires significant upfront investment, the long-term benefits are compelling—a more resilient, upgradeable, and strategically agile force. Business-as-usual approaches may appear safer in the short-term but will leave the U.S. Navy disadvantaged against faster-moving competitors. Embracing modularity, digitalization, and organizational agility is essential to ensure future fleets remain cost-effective, flexible, and dominant in an increasingly volatile environment.

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