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AUTHORS
Peter de Haan, Mahmoud Efatmaneshnik, and Ady James

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Towards an Ontology-Driven Adaptive Acquisition System

Peter de Haan
University of South Australia
Mawson Lakes, SA, Australia
peter.dehaan@unisa.edu.au

Mahmoud Efatmaneshnik
University of South Australia
Mawson Lakes, SA, Australia
mahmoud.efatmaneshnik@unisa.edu.au

Ady James
University of South Australia
Mawson Lakes, SA, Australia
ady.james@unisa.edu.au

Abstract

Systems engineering has historically provided an effective framework for managing large-scale acquisitions. Yet, as systems grow in size, complexity, and timeframe, traditional approaches are becoming less effective. Accelerating rates of change and high levels of uncertainty reduce the long-term value of acquired systems, while the scale of modern programs increases costs, coordination demands, and timelines—heightening the risk of obsolescence before delivery. These pressures raise fundamental questions about the continued viability of conventional acquisition practices. In response, tools such as Model-Based Systems Engineering (MBSE), Agile Systems Engineering (AgileSE), and digital engineering have been introduced. While these provide incremental performance gains, they do not resolve the core challenge: how to manage acquisition in environments where predictability and uncertainty coexist? Doing the same things faster is not enough; a shift in mindset and method is required. This paper proposes that an ontology-driven approach could provide the foundation for that shift. Ontologies—machine-readable representations of concepts, relationships, and constraints—create a semantic backbone to integrates models, data, and stakeholder perspectives. Based on recent research, by embedding ontologies into acquisition systems organisations could simultaneously bridge predictive and adaptive paradigms, enhance traceability and interoperability across technical, financial, and operational domains, and enable automated reasoning to expose dependencies, conflicts, and opportunities. The result is an acquisition ecosystem that is not only more coherent and collaborative but also adaptive to the dynamic conditions of the 21st century. Many of the elements needed for this transformation already exist; the critical step forward is adopting ontologies as the integrative layer that unites them.

Keywords

Ontology-Driven Acquisition, Systems Engineering, MBSE, Digital Engineering.

1. Introduction

There is broad agreement that defence acquisition requires fundamental change: it is slow, cumbersome, costly, and too often fails to deliver on expectations. Analyses such as Gunter (2023) study of behavioral decision biases in the Navy's POM (Program Objective Memorandum) process. These findings are supported by Lemaster (2023) application of behavioral economics to the Planning, Programming, Budgeting, and Execution (PPBE) process and underscores that many acquisition challenges are not purely technical but systemic and cognitive. Decision-making structures remain shaped by entrenched behaviors, risk-averse cultures, and outdated mental models, all of which perpetuate inefficiencies and misaligned outcomes.

While engineering practice is evolving—through digital engineering, MBSE, and increasing use of data-driven methods, the acquisition process has changed little. The greatest barriers to adapting new approaches are not technical but ideological and epistemic. Even when compelling theoretical and empirical evidence exists, management often defaults to planning, forecasting, and control-oriented structures (Snowden, 2011). These preferences are reinforced by deeply embedded structural, cultural, and institutional factors: legacy organizational designs, managerial identity tied to control, risk aversion, and performance systems that reward predictability over adaptability (Giangreco, 2000; Stacey, 2007). As a result, emerging approaches that emphasize flexibility and responsiveness encounter resistance from entrenched practices. In *Figure 1* van Eijnatten (2004) captures this tension as a clash between old thinking and doing and new thinking and doing. In acquisition, this clash is manifested in a reluctance to embrace adaptive methods that acknowledge uncertainty and complexity. Put differently, acquisition cannot be fixed by simply bolting new tools (AgileSE, MBSE, digital engineering) onto old paradigms. Both a new mindset, one which accepts uncertainty, complexity, and adaptation, and new practices are required. It is argued herein that semantic ontologies (Gutierrez et al., 2004) can be a critical enabler of this dual shift. As semantic frameworks can facilitate shared understanding by providing the scaffolding for new knowledge, multi-ontologies can bridge the divides by retaining necessary governance structures whilst enabling adaptive, cross-disciplinary collaboration.

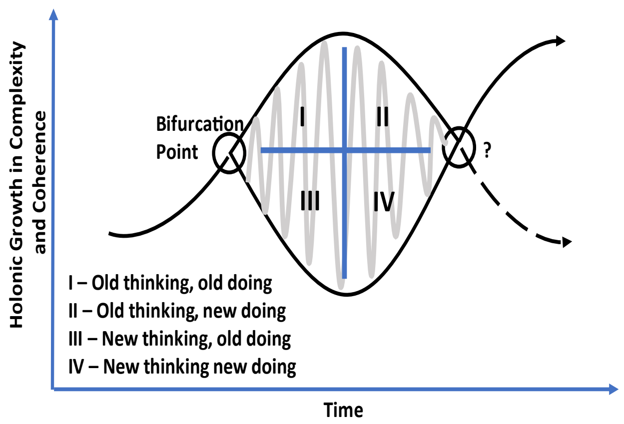

Figure 1: Non-linear development (van Eijnatten, 2004)

The central premise of this paper is that unless ingrained systemic and behavioral issues are addressed, acquisition reform will remain superficial. The transition required is not just technical but epistemic. It required new perspectives associated with thinking and behaving that align and respond to the complexity and uncertainty of 21st-century acquisition environments.

Traditional approaches to large-scale acquisition are increasingly unable to keep pace with a rapidly changing world, across sectors in general (Flyvbjerg, 2021) and defence in particular (Bounds, 2019). The persistence of old thinking and doing has slowed the adoption of more adaptive practices, even as evidence mounts that responsiveness is essential. These clashes highlight the need for a pluralistic perspective, one that accommodates both stability and adaptation depending on context. This paper examines several of these tensions and proposes that semantic ontologies, in conjunction with epistemic fluency could provide a unifying framework for reconciliation. Multi-ontologies can enable shared understanding, semantic traceability, and integration across disciplines, and lay the foundation for more agile, adaptive, and context-sensitive acquisition approaches leveraging modular constructs. This paper explores how an ontology-driven approaches could transform defence acquisition from a rigid, forecast-based process into an adaptive, knowledge-driven ecosystem. Specifically, it examines how ontologies can provide the semantic framework for integrating predictive and adaptive strategies. By bridging technical and organizational silos, this can enable more agile and resilient acquisition outcomes. By utilizing ontologies to underpin a modular acquisition processes, we argue that it is possible to reconcile traditional control-oriented paradigms with the demands of dynamic, uncertain environments.

The use of ontologies in systems engineering and digital acquisition has been steadily gaining traction, with recent research highlighting the potential to address the limitations of traditional and model-based approaches. Ontologies offer a structured, machine-readable means of representing knowledge – capturing concepts, relationships, and constraints – (as can be seen in *Figure 2)* that can enhance interoperability, traceability,

```
@prefix : <http://example.org/naval-surface-modular#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix sh: <http://www.w3.org/ns/shacl#> .

########################################################################
# Ontology header
########################################################################

<http://example.org/naval-surface-modular> a owl:Ontology ;
  rdfs:label "Modular Surface Naval Vessel Ontology (Archetypes + Upperworks
  rdfs:comment "Adds mast/bridge/upperworks as modules, with deck footpri
3.5k/15k/25k/40k archetypes. Supports crewed and uncrewed designs." .

########################################################################
# Minimal core needed here (abridged from unified build)
########################################################################

:Platform a owl:Class .
:Module a owl:Class .
:Hull a owl:Class .

:Interface a owl:Class .
:MechanicalInterface a owl:Class ; rdfs:subClassOf :Interface .
:ElectricalInterface a owl:Class ; rdfs:subClassOf :Interface .
:DataInterface a owl:Class ; rdfs:subClassOf :Interface .
```

Figure 2: Example of Semantic Ontology using RDF formatting

and automated reasoning across disciplines (Yang et al., 2019). Several studies have demonstrated the value of ontologies in complex engineering contexts. Arista et al. (2024) applied an ontology-based methodology to reconfigurable manufacturing systems for aerospace, showing how semantic representations could support modularity and adaptability in production environments. Similarly, Sanya and Shehab (2014) developed an ontology framework for aerospace knowledge-based engineering systems, emphasizing platform independence and reuse. Feng (2008) demonstrated the potential of multi-agent and ontology approaches for collaborative ship design, illustrating early recognition of their role for naval contexts. Within systems engineering practice, the integration of ontologies with MBSE has been a major focus. Ashari et al. (2021) proposed rules for transforming SysML requirement diagrams into OWL ontologies, directly addressing the challenge of connecting requirements with machine-readable semantics. Wu and Levinson (2021); Wu et al. (2024) extended this by designing an ontology for cognitive threads that support traceability management in MBSE, highlighting the importance of semantic structures in maintaining coherence across system lifecycle phases. Shani et al. (2016) further emphasized the use of ontologies to break down tool silos in MBSE, enabling semantic mediation between heterogeneous tools and models.

The role of ontologies in digital engineering and interoperability has been particularly prominent in recent work. Dunbar et al. (2023) described how semantic integration of models with ontologies can drive interoperability across digital threads, while Hagedorn et al. (2020) argue how ontologies enable the knowledge representation required to integrate augmented and artificial intelligence into systems engineering processes. Building upon this, Madni (2022) introduced the concept of a “minimum viable model” to demonstrate how ontologies can create immediate value propositions for MBSE, underscoring their practical importance in early adoption. Qasim et al. (2023) contributed a system reconfiguration ontology linking design to operations, showing how semantic structures can ensure continuity between acquisition, deployment, and sustainment phases. Recent work has also emphasized the challenges of overlap and integration between conceptual models. Djurica et al. (2024) explored methods for presenting ontological overlaps effectively, addressing a key barrier to adoption in multi-stakeholder environments. This aligns with efforts such as those of Yang et al. (2019) argue that the primary contribution of ontologies in systems engineering lies in enabling interoperability and communication across diverse disciplines and stakeholder groups. They also highlighted how the current body of research and literature demonstrates that ontologies are emerging as a critical enabler of next-generation systems engineering. Not only by extending MBSE by embedding semantic traceability and interoperability, but also providing the foundation for adaptive, ecosystem-based approaches to acquisition. By linking requirements, design, operations, and stakeholder perspectives through machine-readable knowledge, ontology-driven approaches have the potential to transform acquisition systems into dynamic, responsive ecosystems capable of evolving with environmental change and complexity.

This paper will now explore the different barrier to change mentioned earlier. Section 2 explores the contrast between forecasting and adapting paradigms and how ontologies can bridge them. Section 3 examines traditional, agile, and mission-engineering approaches, showing how ontologies enable integration; and section 4 compares modularity and optimization, demonstrating the role of ontologies in managing trade-offs. Section 5 addresses requirements engineering, contrasting traditional and agile methods with ontology-driven approaches. Dynamic capabilities and the role of ontologies in enabling acquisition ecosystems are discussed in Section 6. Finally, Section 7 will conclude with implications for defence acquisition reform and recommendations for future research.

2. Forecasting vs Adapting

Forecasting and adapting represent two contrasting paradigms for managing uncertainty in acquisition. Forecasting relies on identifying patterns in historical data and extrapolating them to project future outcomes Makridakis and Bakas (2016). *Table 1* is adapted from (Makridakis & Bakas, 2016) which has been framed using Rumsfeld (2011) terminology. This illustrates how the accuracy of predictions varies for different levels of uncertainty. The table underscores a central challenge for acquisition: forecasts can only be trusted when the operating environment remains stable, making it essential to understand the broader context in which strategies are developed. As Zellner et al. (2021) highlights, quantitative forecasting methods are increasingly sophisticated and can be highly effective under conditions of known or knowable uncertainty. Adapting, by contrast, assumes that conditions may change in ways that cannot be reliably predicted. Scholars such as Stacey (2015); Stacey (2007); Teece et al. (2016) emphasize organizational agility as the dynamic redeployment of capabilities in response to shifting circumstances, as central to resilience. In acquisition, adaptive approaches manifest through iterative development, scenario planning, and agile decision-making processes. These enable organizations to respond when forecasts fail, ensuring relevance even in volatile or ambiguous contexts.

Both forecasting and adapting, support acquisition, but in different ways. Forecasting enables efficiency and long-term planning when change is slow or incremental, while adapting provides resilience and responsiveness when change is rapid or disruptive. The challenge is that acquisition programs often span years or even decades, during which both stable and unstable conditions may arise. Treating forecasting and adaptive approaches as mutually exclusive is, therefore, limiting. The common thread across both perspectives is that, both the rate of change and the overall complexity of the environment must guide how

Table 1: Forecasting Accuracy, Uncertainty and Risk

	Known	***Unknown***
Known	**Known/Knowns** (majority of real-life situations under normal/usual conditions) **Inaccuracy:** Reasonable accurate (depending on specific factors) **Uncertainty (thin tailed):** Measurable **Risk:** Can Be Estimated (assuming normality of errors and consistency in the prevailing, normal conditions)	**Unknown/Knowns** (knowing but not wanting to believe and act) **Inaccuracy:** Can Be Large (influenced by judgmental biases and irrationality) **Uncertainty:** Large, immeasurable and usually under-estimated significantly **Risk:** Underestimated (due to judgmental biases, and irrationality and hope)
Unknown	**Known/Unknowns** (most real-life situations under unusual/special situations) **Inaccuracy:** Large to Great **Uncertainty (fat tailed):** Large to Great **Risk:** Hard to Estimate (usually underestimated)	**Unknown/Unknowns** (Black Swans: Unexpected events with severe consequences). **Inaccuracy:** Impossible to foresee **Uncertainty (Entirely Unpredictable):** Infinite **Risk:** Inconceivable (adoption of antifragile strategies)

organisations apply their acquisition strategies. When the future acquisition timeframe is judged to be predictable, forecasting methods offer value; but when it is uncertain, then adaptive approaches become essential. These distinctions are summarized in *Table 2*, which contrasts predictive and adaptive paradigms. Yet the table also highlights a critical gap: acquisition programs rarely operate in purely predictable or purely uncertain contexts. Most often, they must navigate both aspects simultaneously.

An ontology-driven approach provides the bridge. Ontologies create machine-readable, semantically structured representations of acquisition knowledge—covering concepts, relationships, constraints, and assumptions. By embedding this semantic layer into acquisition processes, ontologies make it possible to:

- Integrate Forecasting and Adapting by capturing the assumptions that underpin forecasts while structuring the dependencies and scenarios needed for adaptive strategies.
- Enable Traceability and Interoperability across technical, financial, and operational domains, ensuring that when conditions change, impacts are visible system wide.
- Support Automated Reasoning to check constraints, identify conflicts, and propose alternative courses of action, thereby complementing both predictive analysis and adaptive planning.

In practice, ontologies do not replace forecasting or adapting but provide a unifying framework that allows acquisition organisations to exploit the strengths of both. Forecasting can still guide long-term plans, while adaptive mechanisms ensure responsiveness when reality diverges from projections. Ontology-driven approaches bridge these paradigms by embedding shared, semantic knowledge into the acquisition system—making it more coherent, integrated, and capable of evolving alongside its environment.

Here, we consider a naval acquisition program for a new class of surface combatants. Forecasting methods might predict the ship's operational requirements, fuel consumption, and lifecycle costs based on historical fleet data and stable mission assumptions. This enables long-term budgeting, industrial planning, and workforce allocation. Adaptive methods, by contrast, are needed when

Table 2: Management Approach - Predictive vs Adaptive vs Ontology Driven

Aspect	Forecasting (Predictive)	Adapting (Responsive)	Ontology-Driven (Integrative)
View of the Future - Predictability	Assumes stability; probabilities can be quantified	Assumes volatility; probabilities cannot be quantified	Explicitly captures assumptions and dependencies; supports both stable forecasts and adaptive shifts
Primary Methods	Quantitative analysis, risk modelling, insurance, hedging	Scenario planning, iterative cycles, agile strategies	Semantic models, digital threads, automated reasoning linking forecasts with adaptive scenarios
Decision Strategy	Structured, plan-based	Iterative, exploratory, flexible	Hybrid: supports long-term planning while enabling rapid adjustment when conditions change
Core Orientation	Control, mitigation	Resilience, responsiveness	Integration, interoperability, and coherence across domains
Knowledge Handling	Data stored in discipline silos	Knowledge shared through feedback loops	Ontologies unify knowledge across technical, financial, and operational domains
Risk Management	Planned mitigations based on stable assumptions	Continuous reassessment of risks	Automated reasoning highlights conflicts, cascading impacts, and alternative courses of action

the security environment shifts—such as the sudden rise of unmanned threats, cyber warfare requirements, or the need for new missile defence capabilities. Here, iterative development and rapid integration of emerging technologies can ensure the platform remains relevant. An ontology-driven approach bridges these paradigms. By embedding naval domain knowledge (e.g., ship subsystems, capability requirements, regulatory standards, cost models, and operational scenarios) into a semantic ontology, decision-makers can trace how a new threat or regulatory change cascades across design, sustainment, and operations. For example, the ontology could reveal that adding a directed-energy weapons not only impacts power and cooling subsystems but also alters training requirements, logistics chains, and budget allocations. Instead of starting from scratch, stakeholders can query the ontology to identify feasible integration pathways, assess trade-offs, and maintain coherence across the acquisition ecosystem. In this way, ontologies enable the Navy to exploit the efficiency of forecasting where conditions are stable, while simultaneously supporting adaptive responses when disruptive changes occur.

3. Traditional vs Agile vs Mission-Engineering for Project Integration

Another contest of ideas shaping acquisition arises from the growing influence of Agile methods. Originally developed to manage the demands of software development, Agile practices have since spread widely into business and organizational management (Aghina et al., 2018). They are often contrasted with more traditional approaches, which emphasized planning, control, and linear execution. By comparison, Mission Engineering (DoD, 2023) represents a defence-oriented approach that seeks to align acquisitions with the overarching purpose of fulfilling mission objectives. At their core, all three approaches rely on decomposition, breaking large visions into smaller, actionable components. The difference lies in when and how that decomposition is refined. Traditional approaches resolve detail early, locking in requirements and plans; Agile defers detail until execution, allowing teams to engage stakeholders continuously and adjust to ambiguity; Mission Engineering emphasizes

Table 3: Traditional, Agile, Mission Engineering, and Ontology-Driven Integration

Aspect	Traditional Approach	Agile Approach	Mission Engineering	Ontology-Driven Integration
Vision / Purpose	Strategic plans, long-term programs	Initiatives, evolving goals	Mission need statements and operational intent	Semantic links across mission needs, strategies, and evolving user requirements
Decomposition	Early, detailed breakdown of strategies and tasks	Iterative refinement into epics, features, user stories	Mission threads and capability sets structured around operational goals	Ontology ties decompositions across approaches, ensuring traceability and coherence
Requirements Handling	Front-loaded, fixed	Incremental, adaptive	Capabilities and functional requirements tied to mission outcomes	Semantic models capture both stable and evolving requirements, enabling hybrid handling
Stakeholder Engagement	Primarily at start and end	Continuous, embedded feedback	Structured around mission stakeholders and warfighting communities	Shared ontology ensures perspectives are represented, accessible, and interoperable
Alignment	Efficiency, compliance, cost control	Responsiveness, innovation	Mission fulfillment and operational effectiveness	Ontology integrates technical, operational, and mission models, ensuring system-wide coherence
Best Fit Context	Stable, predictable environments	Volatile, uncertain environments	Mission-oriented acquisitions with clear operational drivers	Mixed environments where stability, uncertainty, and mission priorities coexist

decomposition that traces directly to mission need statements and operational concepts. These perspectives are not inherently opposed but highlight different strengths. Traditional methods suit predictable environments where requirements are stable; Agile thrives in uncertain conditions by anticipating change; and Mission Engineering ensures alignment between technical work and mission outcomes. Yet in practice, acquisition organisations must often navigate across all three contexts at once.

Here, an ontology-driven approach offers a way to integrate the paradigms. By capturing mission needs, system requirements, operational concepts, and stakeholder perspectives in a shared semantic framework, ontologies allow:

- Traditional decomposition to retain traceability to higher-level objectives;
- Agile flexibility to be contextualized within mission goals; and
- Mission Engineering artifacts to remain interoperable with technical and organizational models.

This integration is illustrated in *Table 3*, which compares the three paradigms and shows how ontologies bridge them. In naval ship acquisition, a traditional approach might fix design requirements for a destroyer early in the program, ensuring predictability in schedule and cost but risking obsolescence. An Agile approach could allow iterative development of subsystems such as combat management software, enabling rapid integration of new capabilities. Mission Engineering ensures that both approaches remain aligned to overarching mission needs, such as fleet air defense or anti-submarine warfare. An ontology-driven acquisition framework links these together: requirements for propulsion (stable), combat systems (evolving), and mission objectives (strategic) are semantically connected, ensuring that changes in one area are immediately visible across the program.

4. Modularisation vs Optimisation

The summary of optimization vs. modularization and ontology driven integration is illustrated in *Table 4*.

Modularity has long been recognized as a powerful response to dynamic complexity (Baldwin & Clark, 2000). As Ulrich (1995) noted in the context of product architecture, modularity allows systems to be broken into interchangeable components, a principle that extends from software engineering to manufacturing and organizational design. Its effectiveness, however, depends heavily on trade-offs made early in the design phase and on contextual constraints (Hölttä et al., 2005).

Empirical studies have shown that modularity correlates strongly with performance (Jacobs et al., 2007), particularly when performance is defined in terms of non-functional attributes such as upgradeability, maintainability, and lifecycle flexibility.

Table 4: Modularity, Optimization, and Ontology-Driven Integration

Aspect	Optimization Approach	Modularity Approach	Ontology-Driven Integration
Design Focus	Performance maximization under fixed constraints	Flexibility, re-use, adaptability	Captures constraints and interfaces, enabling both performance optimization and modular adaptability
Strengths	Efficiency, control, predictability	Upgradeability, innovation cycles, resilience	Semantic traceability across modular and optimized elements; supports hybrid strategies
Limitations	Rigid in dynamic environments; poor adaptability	May sacrifice peak performance for flexibility	Automated reasoning balances trade-offs and highlights cascading impacts across domains
Best Fit Context	Stable, predictable operating environments	Volatile, uncertain, innovation-driven environments	Mixed environments where stability (e.g., propulsion) and volatility (e.g., weapons systems) coexist

In contrast, optimization seeks to maximize performance or efficiency by refining systems against fixed parameters and constraints. Optimization is powerful in stable contexts where system requirements and operating conditions can be reliably predicted, but it can also lead to rigid designs that struggle to accommodate unexpected change. Both paradigms—modularity and optimization—offer value in acquisition, but they also represent contrasting philosophies. Modularity emphasizes flexibility, reuse, and adaptability, while optimization emphasizes efficiency, performance, and control. The challenge for acquisition programs is that both needs often coexist; propulsion systems may demand optimization for efficiency and safety, while combat systems may require modularity to enable rapid technology insertion. Here, an ontology-driven approach provides a means of integration. Ontologies capture the relationships, constraints, and trade-offs inherent in modular and optimized components, making it possible to reason across both paradigms. They allow acquisition organisations to:

- Represent modular structures semantically, ensuring that interfaces, dependencies, and upgrade pathways are explicit and traceable;
- Represent optimization goals and constraints alongside modular design choices, supporting trade-off analysis; and
- Enable automated reasoning across modular and optimized subsystems, identifying conflicts, synergies, and impacts across the system.

In a naval acquisition, propulsion systems are typically optimized for efficiency, safety, and endurance, with relatively stable requirements over decades. Combat systems, however, benefit from modularity, allowing rapid insertion of new sensors, weapons, or electronic warfare capabilities as threats evolve. An ontology-driven framework supports both simultaneously by acting as the semantic layer that makes trade-offs explicit. For modular systems, ontologies define standard interfaces, module dependencies, and upgrade pathways in machine-readable form. This ensures that when a new radar or missile is introduced, its compatibility with existing platforms, logistics systems, and training requirements can be automatically assessed. For optimized systems, ontologies capture detailed performance constraints—such as power budgets, thermal tolerances, and endurance profiles—so that changes introduced by modular upgrades can be traced to their impact on optimized subsystems. For example, adding a directed-energy weapon through a modular interface may appear straightforward, but an ontology-driven analysis can reveal cascading implications: increased power draw affecting propulsion efficiency, cooling requirements influencing internal layouts, and impacts on crew training, maintenance, and supply chains. By making these interdependencies explicit, ontologies enable acquisition teams to balance the benefits of modularity with the demands of optimization—ensuring coherence across the entire ship design and lifecycle.

5. Traditional vs Agile Requirements Handling

All practitioners agree that high-quality products must address the needs of stakeholders and end-users. The debate lies in how best to achieve this. Traditional requirements engineering (RE) approaches are often static and linear, which creates challenges when managing complex or evolving needs (Xu et al., 2024). Agile RE emerged in software engineering to address these limitations, emphasizing iteration, flexibility, and continuous engagement with stakeholders (Hoy & Xu, 2023). Each method offers strengths and weaknesses but treating them as mutually exclusive limits their utility in acquisition contexts where both certainty and uncertainty are present.

High-quality acquisition outcomes depend on effectively capturing and managing requirements. Yet approaches to requirements engineering (RE) diverge in important ways (*Table 5*):

- Traditional requirements engineering emphasizes comprehensive, front-loaded requirement gathering, detailed documentation, and formal change management. This approach works well when requirements are stable and predictable but often struggles in dynamic environments.

Table 5: Traditional, Agile and Ontology-Driven Requirements Engineering

Aspect	Traditional RE	Agile RE	Ontology-Driven RE
Planning & Timing	Front-loaded; extensive early requirement gathering	Incremental; continuous refinement over iterations	Captures both upfront requirements and evolving needs in structured, reusable form
Flexibility & Change	Resistant; formal change control processes	Embraces change; frequent reprioritization and adaptation	Semantic mappings preserve consistency while allowing change across both paradigms
Stakeholder Engagement	Limited to early and late project phases	Continuous; embedded feedback loops	Ontology ensures all stakeholder perspectives are represented and accessible
Documentation	Comprehensive, detailed, often static	Lightweight (user stories, acceptance criteria)	Machine-readable semantics combine detail with automation and interoperability
Requirements Detail	Exhaustive upfront specification	"Just enough" detail for each iteration	Supports hybrid levels of detail with semantic traceability between coarse and fine-grain requirements
Risk Handling	Planned mitigations based on early analysis	Risks managed iteratively through feedback cycles	Ontology reasoning highlights conflicts, dependencies, and cascading risks dynamically
Validation	Final validation at project completion	Continuous validation through iterative demos	Ontology enables automated consistency checks, alignment across domains, and ongoing validation

- Agile requirements engineering evolved in software contexts to address rapidly changing user needs. It focuses on incremental refinement, user stories, and continuous stakeholder engagement, enabling flexibility but sometimes at the cost of coherence across large, complex systems.
- Ontology-driven requirements engineering provides a unifying layer between these paradigms. Ontologies represent requirements, relationships, and constraints in a machine-readable semantic framework, enabling consistency, traceability, and reasoning across both traditional and agile practices.

For example, consider a destroyer acquisition program, where traditional RE may comprehensively specify propulsion and survivability requirements upfront, ensuring compliance with safety standards. Agile RE may be applied to evolving subsystems like combat management software, enabling rapid updates in response to emerging threats. An ontology-driven RE framework can connect these perspectives: propulsion requirements, mission objectives, and evolving user stories are captured in a shared semantic model. When new missile defence capabilities are introduced, the ontology can automatically highlight implications for power systems, crew training, logistics, and regulatory compliance. This ensures coherence across traditional and agile requirements while preserving adaptability to future change.

6. Ontologies and Dynamic Capabilities

A common theme across the different perspectives considered – forecasting versus adapting, traditional versus agile, modularity versus optimization, and requirements handling – is that acquisition strategies have historically been grounded in control and decomposition. Traditional methods decompose problems to refine detail, fix requirements, and assign responsibility. Alternative approaches use decomposition to isolate ambiguity, modularize complexity, and facilitate adaptation under uncertainty. Research by McKinsey & Company (Aghina et al., 2018) shows that organisations are increasingly shifting toward agility to cope with volatility, a shift now impacting both government and private sectors. Acquisition must

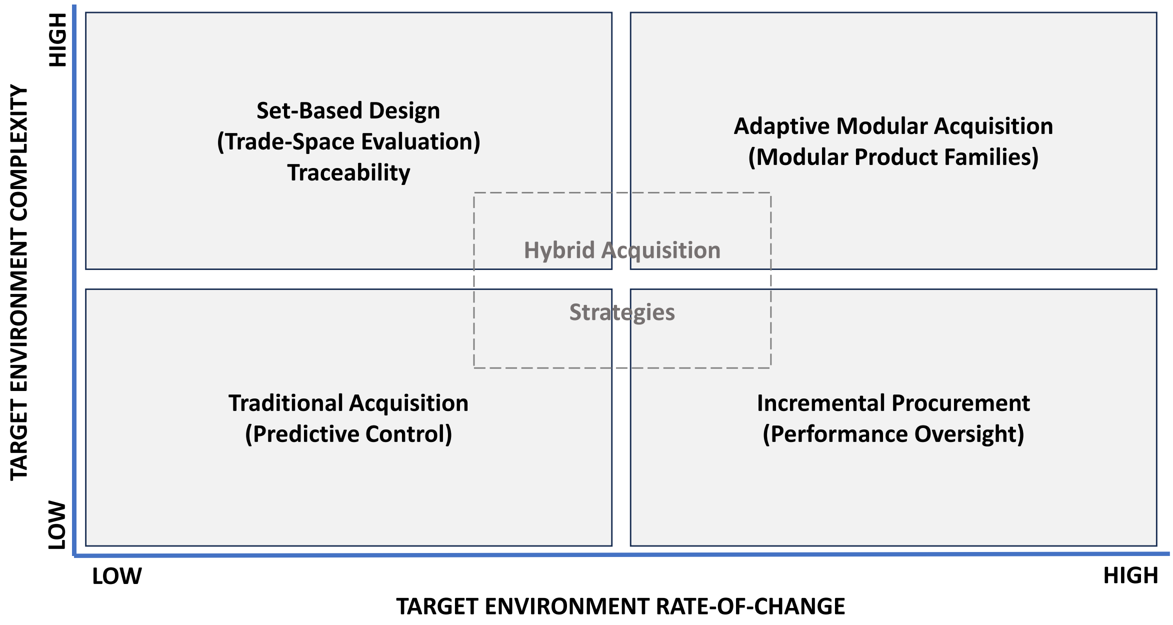

Figure 3: Acquisition Strategy Typology by Complexity and Rate-of-Change

also adapt to a changing reality. This implies that acquisition strategies should be sensitive to both the rate-of-change and the complexity of the environment. *Figure 3* illustrates this as an acquisition strategy typology: when change is slow, traditional approaches suffice; when change is rapid, adaptation is essential. Hybrid strategies are often required where stability and volatility coexist. However, simply alternating between traditional, agile, or modular strategies is insufficient. What is needed is a semantic layer that unifies these paradigms and enables organisations to shift seamlessly between them. Ontologies provide that layer.

Ontologies represent knowledge in machine-readable form by capturing concepts, relationships, constraints, and assumptions within a given domain (Jepsen, 2009). Unlike traditional models that exist in isolation, ontologies can integrate models, datasets, and stakeholder perspectives into a single interoperable framework. This allows:

1. Traceability across approaches: ensuring that traditional requirements, agile user stories, and mission engineering artifacts all align with strategic intent.

2. Interoperability: connecting MBSE models, logistics data, and financial systems without duplication of information.

3. Automated reasoning: enabling systems to check constraints, identify conflicts, and propose adaptive options.

As systems engineering transitions toward model-based practices, the role of ontologies is expanding. Researchers Dunbar et al. (2023); Maleki et al. (2025) and Yang et al. (2019) have demonstrated how combining MBSE with ontology based languages such as OWL can create digital threads via semantically interconnected repositories that support interdisciplinary communication and external tool integration. This evolution promises acquisition systems that are not only technically rigorous but also contextually adaptive. For example, in naval acquisition, propulsion systems optimized for endurance and safety (stable requirements) can be captured traditionally, while evolving combat system requirements (subject to rapid technological change) can be modelled through agile practices. An ontology-driven framework ensures that both are semantically interconnected whenever necessary, so the cascading impacts of change – on power budgets, training, logistics, and costs – are visible across the entire ecosystem.

The organizational dimension is equally critical. Without changes in governance and structure, digital and semantic architectures will be constrained by hierarchical mindsets. Ontologies can enable ecosystem-based acquisition, where multiple stakeholders—government, prime contractors, SMEs, and academic partners—collaborate through a shared digital platform. This requires trust, transparency, and traceability, which can be provided by technologies such as blockchain, AI-enabled analysis, and ontology-based digital architectures (Surucu-Balci et al., 2024). As Jacobides et al. (2024) and Foss et al. (2023) propose that ecosystems thrive when leadership develops the dynamic capability to orchestrate diverse actors without centralized control. Ontology-driven acquisition ecosystems embody this principle: they provide the shared semantic foundation that allows different organisations, tools, and processes to interoperate, adapt, and evolve. In doing so, they will transform acquisition from a rigid, project-by-project endeavor into an adaptive, knowledge-driven system capable of meeting the demands of the 21st century.

7. Conclusion

The work underpinning this paper has focused on finding a path forward to facilitate large-scale naval acquisition that is adaptive and sustainable. The central goals remain clear: shorten lead times, reduce lifecycle costs, improve maintainability, and lower future upgrade expenses. These aims mirror lessons learned in other industries, such as automotive, where flexibility, responsiveness, and cost efficiency are delivered through integrated production ecosystems. In defence acquisition, however, the challenge lies not only in modularizing platforms or optimizing production lines, but

in providing a unifying framework that enables coherence across diverse and evolving requirements. Here, an ontology-driven approach provides the critical connective tissue. Ontologies allow acquisition systems to capture design constraints, subsystem dependencies, and operational requirements in both human-readable and machine-readable form. This semantic backbone enables:

- Traceability across system elements (from propulsion to combat systems), ensuring changes in one domain cascade transparently across others.
- Balance between stability and agility, supporting traditional approaches where requirements are predictable (e.g., propulsion systems) while enabling iterative adaptation where change is rapid (e.g., weapons and sensor systems).
- Digital integration via semantic data and MBSE, making models interoperable and simulations repeatable across multiple disciplines in real time.

The implication is that an adaptive acquisition systems cannot rely solely on modular architectures or optimization strategies. It requires a digital, ontology-enabled knowledge structures that integrates technical, organizational, and operational perspectives. For naval acquisition, this means treating the enterprise itself – government, industry, and partners – as a system-of-systems. Interfaces between actors, mechanisms for knowledge sharing, and protections for intellectual property must all be semantically defined to enable traceability through semantic linked digital threads. Only then can collaboration become seamless across different stakeholders, large and small.

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Biography

Peter de Haan

Peter is an PhD candidate at the University of South Australia where he is conducting research into the effects of uncertainty on large scale acquisitions. He has B.App.Sc in Computer Science (1994), Master of Project Management (2005), Master of Innovation and Entrepreneurship (2002) and a MBA (2015). Peter has considerable experience on defence projects in areas such as software/systems engineering, project management and overseeing the development environments for large projects.

Dr Mahmoud Efatmaneshnik

Mahmoud is program director for Master of Systems Engineering program at the University of South Australia. He has a PhD in Complexity Management of Design Process (2009), and a ME in Manufacturing Engineering (2005) both from UNSW. He has a BE in Aerospace (1999) from Tehran Polytechnic University. He is a member of INCOSE and IEEE. He is the editor in chief of Australian Journal of Multidisciplinary Engineering.

Associate Professor Ady James

Ady is an Associate Professor at the University of South Australia where he teaches Systems Engineering, Space Studies and Space Science. He is Co-Director for the Southern Hemisphere Space Studies Program and the Director of Education & Training with the SmartSat CRC.

He obtained a Ph.D. in Space Science at University College London's Department of Space and Climate Physics in 1997, where he developed a fast ion spectrometer for the Russian Mars 96 spacecraft. After completing his PhD he worked on various space programs including Mars 96, Cluster II, XMM Newton, MOSES and, most recently, Solar-B (Hinode) launched in 2006. He then spent 4 years as project manager for the Basic Technology Smart X-ray Optics program up until October 2010 and then as Systems Engineer for the VIS instrument on the ESA Euclid Space project until early 2012. In early 2012 Dr James moved to Australia to establish a local node of the Mullard Space Science Laboratory (MSSL), From 2013 until it's closure in 2017 Dr James was the Academic Director for the UCL Australia campus. Dr James has been involved in the Southern Hemisphere Space Studies Program since 2012 and was co-Director for the 2018, 2019 and 2020 programs.