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Everything, everywhere, all at once: undersea surveillance coverage in the Indo-Pacific

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Abstract – Undersea surveillance is a vital yet challenging undertaking for protecting the security and economy of maritime nations like Australia. It looks beyond the surface to provide maritime domain awareness of critical undersea infrastructure and sea lines of communication. For the island nation of Australia, the vast expanse of its maritime jurisdiction and the broader Indo-Pacific is disproportionate to the crewed naval assets it can bring to bear. How can the Royal Australian Navy possibly monitor everything, everywhere, all at once? Fortunately, the proliferation of uncrewed systems promises increased surveillance capacity at a fraction of the cost. The spectrum of modern uncrewed systems offers a range of benefits, but also an expanding trade space and complexity for the force design of naval fleet architectures. What is the optimal fleet mix of crewed and uncrewed systems for the Navy? Which classes of uncrewed systems should be adopted, and where do they provide the greatest utility for undersea surveillance? Which systems offer the greatest 'bang for buck'? This paper summarises techno-economic modelling that yields answers to these open problems. The techno-economic model integrates technical performance measures with cost modelling to assess the technical feasibility and economic viability of candidate fleet architectures. It empowers force designers and capability managers to make value-for-money decisions, whilst seeing both the forest (the fleet) and the trees (the surveillance assets). Ongoing research in this field is the first of its kind to apply a techno-economic approach to assessing fleet architectures for undersea surveillance. Using public domain data and surveillance scenarios, the modelling found solutions that more than doubled surveillance coverage whilst maintaining current budget and crewing profiles. This paper demonstrates a strong case for applying techno-economic modelling to naval fleet architectures for undersea surveillance. By guiding the adoption of maritime uncrewed systems, it can aid the Navy in progressing towards achieving maritime domain awareness of everything, everywhere, all at once.

1 Introduction

The importance of maritime domain awareness (MDA) to Australia's security and economy is well established. As an island nation, Australia is dependent on sea lines of communication for 99% of its trade [1] and undersea cables for approximately 97% of its digital connectivity to the world [2]. Undersea surveillance is a challenging contribution to MDA, looking beyond the ocean's surface to monitor critical undersea infrastructure and threats that may not be detectable by above-water sensors.

Despite the Government's acknowledgement of the criticality of persistent undersea situational awareness [3], the Royal Australian Navy (RAN)'s lean force structure is disproportionate to the vast maritime environment surrounding Australia in the Indo-Pacific. Australia has one of the largest Exclusive Economic Zones (EEZs) [4], a Search and Rescue Region covering one-tenth of the Earth's surface [5], and reliance on maritime-based infrastructure that extends beyond these regions to other continents [6]. Yet the RAN's fleet of crewed platforms lacks the capacity to match the surveillance demands of this maritime environment. Figure 1 highlights Australia's disproportionate surveillance resources for its EEZ area in comparison with other nations.

With the proliferation of uncrewed vehicles and sensors over the past decade, a broad spectrum of uncrewed systems is now available to support undersea surveillance. Uncrewed systems have been proven, through numerous studies, trials, and adoption, to offer surveillance capacity at a fraction of the fiscal cost and personnel requirements of crewed naval platforms [7]. In response to these technological opportunities, the RAN has begun investing in the development and acquisition of uncrewed systems, including the Ocius Bluebottle USV, C2 Robotics LUUV, and Anduril GhostShark XLAUV [8, 9]. Furthermore, the Australian Department of Defence has committed A$5.2-$7.2 billion of investment over 10 years towards subsea warfare capabilities and new autonomous and uncrewed maritime vehicles, including through AUKUS Pillar II [10].

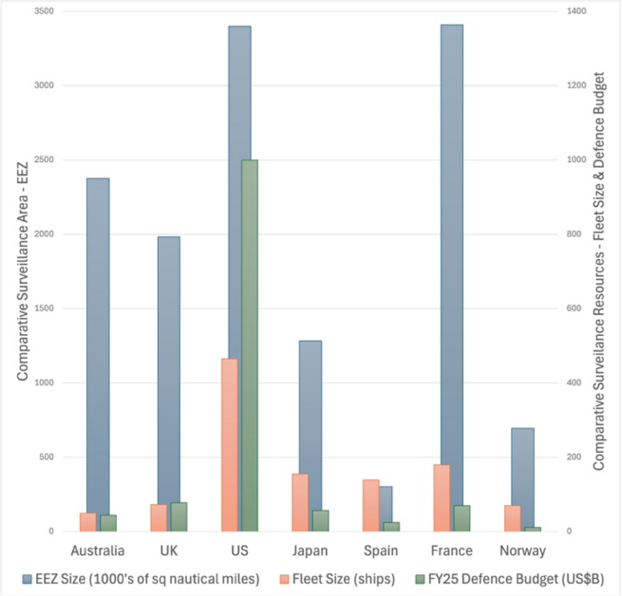


Fig. 1. Comparison of Surveillance Areas and Resources.

However, with limited budgets, a complex and expanding trade space, and rapidly increasing geostrategic imperatives driving demand for surveillance capacity, how will the Navy's capability managers and force designers decide what to invest in? Naval fleet architectures are complex systems of systems. To modernise the RAN fleet with uncrewed systems requires techniques that can manage this complexity and inform timely, value-for-money investment decisions. This will set the RAN on a path towards maritime domain awareness of everything, everywhere, all at once.

This paper outlines ongoing PhD research undertaken by the author. It presents a case for techno-economic modelling of naval fleet architectures to assess the value for money of uncrewed systems.

2 Research Questions

The key research questions from the author's PhD research that are examined by this paper are:

RQ1: How much undersea surveillance coverage can be achieved by fleet architectures incorporating crewed and uncrewed systems?

RQ2: Which classes of uncrewed systems can provide the most significant improvement to undersea surveillance for the RAN?

RQ3: Which candidate fleet architecture offers the greatest value for money to the RAN for undersea surveillance in the Indo-Pacific?

3 The Novel Approach

Techno-economic modelling is a novel methodology that assesses the technical feasibility and economic viability of alternative fleet architectures. This integrated methodology focuses assessment on value for money, yielding actionable insights for Defence decision-makers. Alternate approaches in the literature handle technical assessment and financial modelling separately, thereby providing only part of the answer.

Details of the techno-economic modelling methods for this research have been previously published by the author [11]. A summary of the techno-economic framework for this research is reproduced in Figure 2.

This methodology handles the structural complexity of naval fleet composition and the dynamic complexity of changing surveillance demands through a systems-of-systems approach that incorporates numerous system analysis techniques. These include systems engineering, system architecture, system dynamics, modelling & simulation, operations research, and design for six sigma. Through techno-economic modelling, decision-makers can clearly see both the forest (the fleet) and the trees (surveillance assets), as it models the impact of individual platforms and the characteristics of the fleet as a whole. For this reason, techno-economic approaches have gained prominence in other domains for cost-benefit analysis of complex infrastructure, such as the rollout of 5G/6G infrastructure and LEO satellite constellations [12, 13].

Furthermore, techno-economic assessment drives 'speed to clarity' for decision-makers. The modelling is centred around Measures of Effectiveness (MoEs) that are identified as key levers in the trade space and expressed in measures that are interpretable by decision-makers.

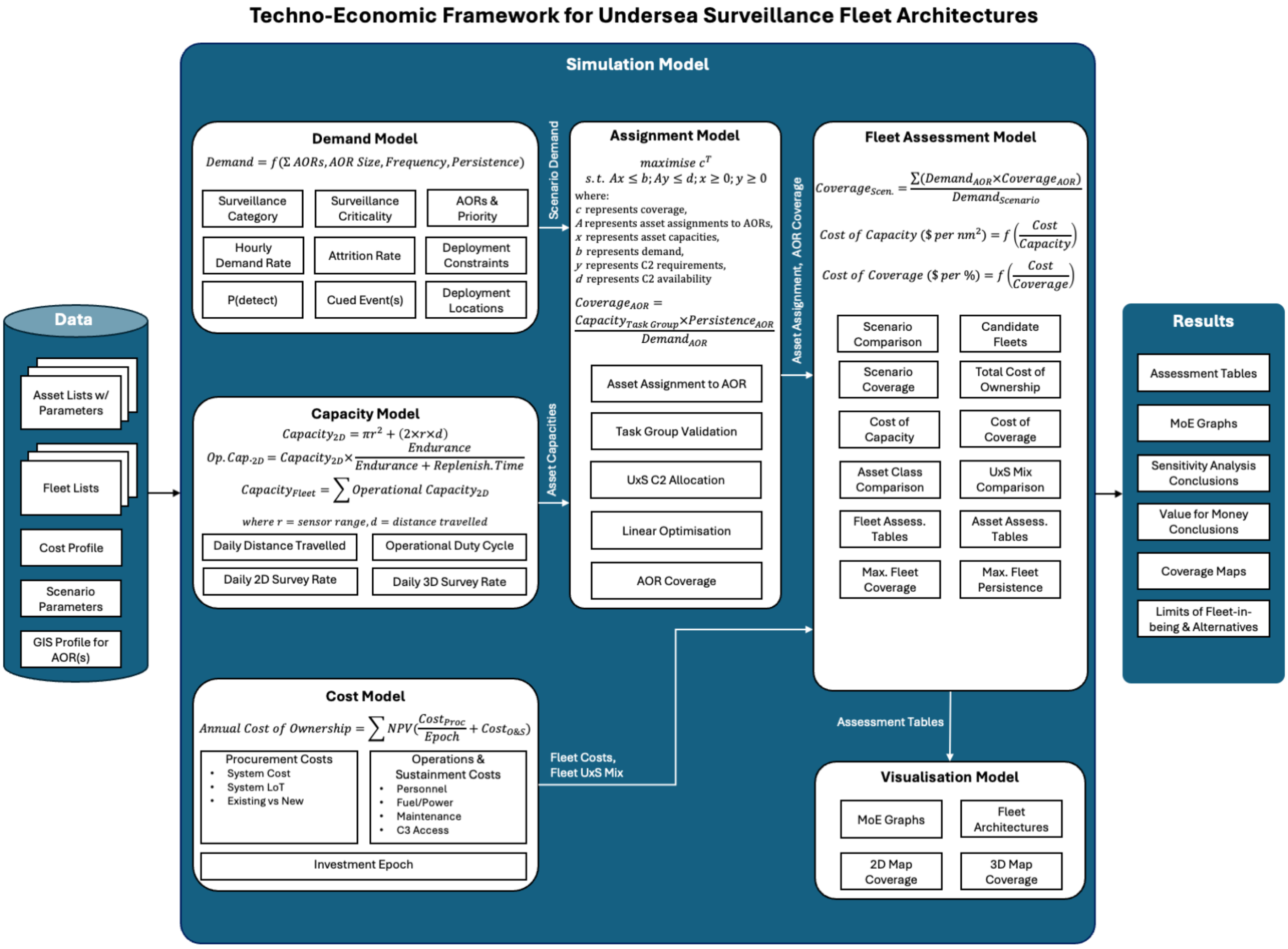


Fig. 2. Techno-Economic Framework adapted from [11].

Figure 2 identifies MoEs in the framework:

- Surveillance demand is measured in square nautical miles (nm^2) of ocean to be surveyed, for defined durations, under defined surveillance conditions.
- Asset surveillance capacity is measured in nm^2 per day, subject to operational limitations.
- Fleet surveillance coverage is measured as the percentage of the scenario's demands that the fleet's capacity can meet.
- Fleet cost is measured as the total cost of ownership (TCO) of the constituent systems. This incorporates procurement costs (CapEx) over a defined investment epoch as well as operations & sustainment costs (OpEx) over the life of type.
- Value for money is measured as the fleet's surveillance coverage (%) per dollar spent.

The surveillance coverage of alternate fleet architectures can be compared for a fixed budget profile based on value for money. Value for money is a core procurement principle for the Australian Department of Defence [14]. Techno-economic modelling of candidate fleet architectures lends itself to the Australian integrated capability assessment and integrated force design processes, complementing the traditional approaches of wargaming, mission engineering, and operations analysis.

The research's techno-economic framework is modular, as shown in Figure 2. This ensures the modelling implementation is flexible and extensible for new features to be added. The modularity of the framework decouples the scenario data and platform performance data from the software performing the simulation and modelling. As such, the modelling can be easily re-run for new scenarios, fleet compositions, or surveillance assets, without modifying the simulation and modelling software application.

The application is computationally lightweight due to its focus on MoE-based stochastic modelling, rather than physics-based modelling. The Simulation Model shown in Figure 2 has been developed as a Python application, which can assess over 100 candidate fleets against a dozen surveillance scenarios in under 10 seconds when running on a commercial laptop. In contrast, physics-based models and traditional operations analysis may take many hours to run on high-performance computing.

For these reasons, the techno-economic modelling developed by this research can empower the RAN's capability managers and force designers with timely insights for modernising the fleet with uncrewed systems. Decision-makers can see both the whole 'forest' and the details of the 'trees', with attributes expressed in measures they are familiar with. They can re-run the assessment in real-time to explore 'what if' scenarios and to understand the sensitivity analysis of different datasets. This approach uniquely allows decision-makers to uncover 80% solutions (or greater) in 20% of the time (or less). It is achieved by focusing on the key levers for decision-makers and by integrating technical and economic assessments to propose holistic force design recommendations.

4 Insightful Results

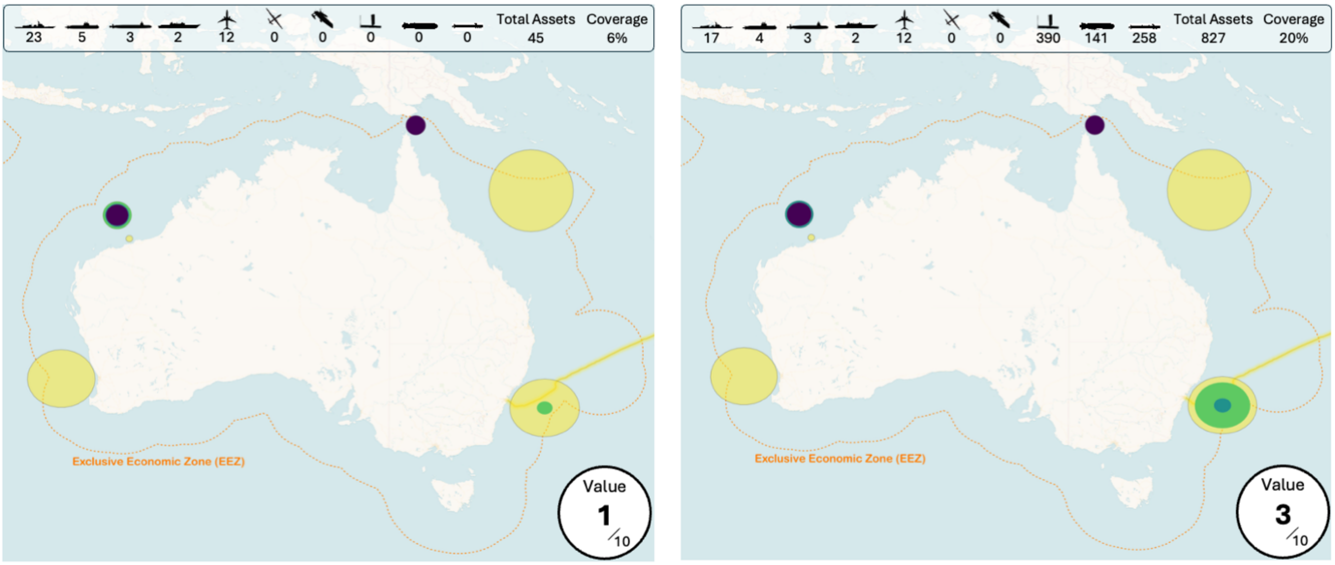
Whilst detailed results, analysis, and discussion of the techno-economic modelling have been published [11], this section summarises more recent results from the ongoing research and discusses the latest insights pertinent to the three research questions in Section 2.

Using public domain data and open access publications, several surveillance scenarios were developed using Australian and broader Indo-Pacific geospatial information. The scenarios had varying parameters to assess candidate fleets in different situations, such as conflict level (peacetime vs wartime), location/size and prioritisation of surveillance areas of responsibility (AORs), types of surveillance missions (ISR, ASW, search & rescue, monitoring of infrastructure, oceanography, etc.), and duration and persistence of surveillance.

Similarly, candidate fleet architectures were developed using public domain RAN fleet information, Australian Government announcements on future naval investments, and industry databases of maritime systems. All candidate fleet architectures were constrained to existing budget forecasts from 2025 to 2040, ensuring that all fleets were based on consistent, fixed budgets and personnel forecasts. The scenarios and candidate fleet architectures were loaded into the techno-economic model, producing the sample of results described in this section. A broader set of results is included in the published research paper [11].

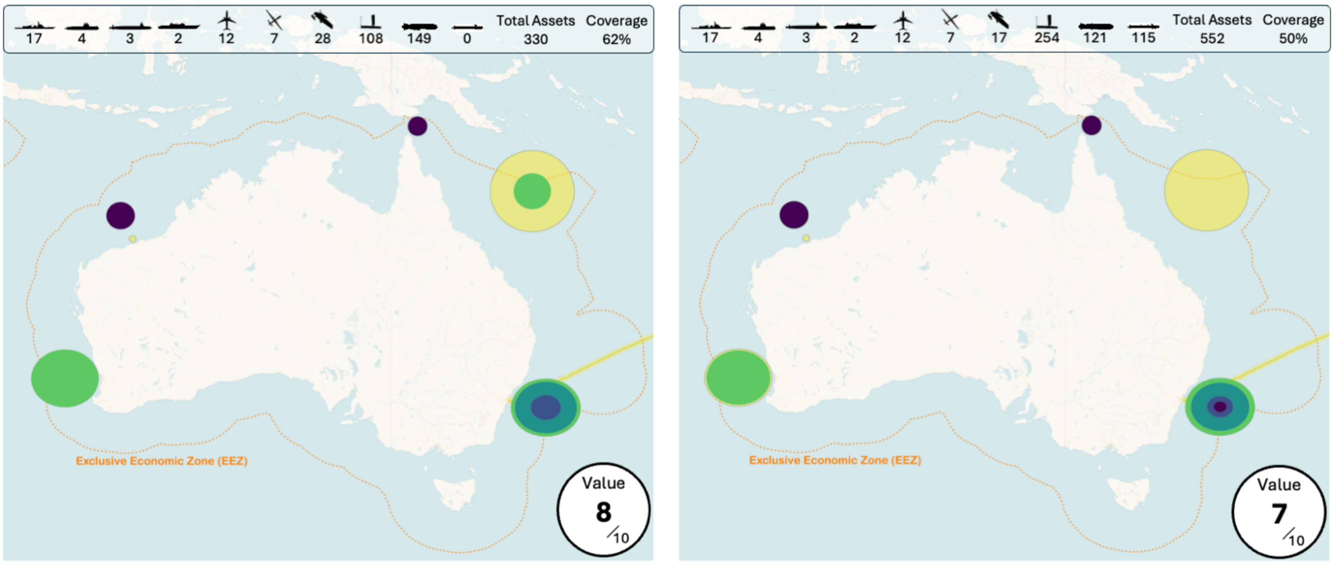
Figure 3 illustrates the surveillance coverage of candidate fleet architectures for a high-demand, peacetime surveillance scenario. This scenario required 106,520,229 nm^2 of surveillance over 90 days. All maps depict the scenario's surveillance demand across seven yellow AORs. Each map shows a sample fleet's coverage of these AORs, with colours indicating the fleet's expanding coverage across investment periods from 2025 to 2040. Map a. is for a fully crewed fleet, with 0% of the budget assigned to uncrewed systems. Maps b. to d. are for fleets where 10% of the budget is invested in different mixes of uncrewed systems. None of the candidate fleets achieved complete coverage of all the AORs in this scenario, indicated by the remaining yellow areas. The bar above each map summarises the fleet composition and surveillance coverage in 2040. In each simulation, the candidate fleet's surveillance assets were optimally assigned to AORs to maximise coverage, subject to operational availability, command & control (C2) structures, and asset range/endurance. The value for money score in the bottom-right corner of each map is a normalised, comparative score out of 10, based on the results in Figure 4.

In response to RQ1, based on the scenario and candidate fleets highlighted in Figure 3, surveillance coverage for the crewed fleet ranged from 2.8% to 5.6% over time. Year on year, fleets with 10% uncrewed systems increased their surveillance coverage compared to the crewed fleet. Notably, the fleets that invested in strategic uncrewed systems, or a hybrid mix of strategic and tactical uncrewed systems, achieved significantly higher coverage than investment in tactical uncrewed systems. For the scenario used in these sample results, maintaining the crewed fleet achieved 5.6% coverage by 2040. By comparison, the fleet that invested 10% of its budget in strategic uncrewed systems achieved 61.6% coverage by 2040. This is an order of magnitude increase in surveillance coverage for the same budget allocated over the years from 2025 to 2040.



a. Crewed Fleet Surveillance Coverage

b. 10% Tactical Uncrewed Fleet Surveillance Coverage



c. 10% Strategic Uncrewed Fleet Surveillance Coverage

d. 10% Hybrid Uncrewed Fleet Surveillance Coverage

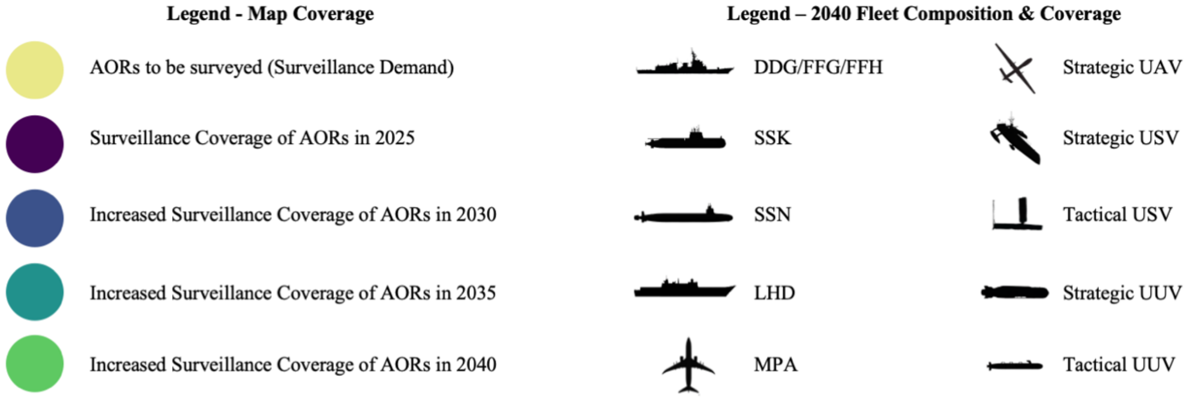


Fig. 3. Candidate Fleets Surveillance Coverage Comparison.

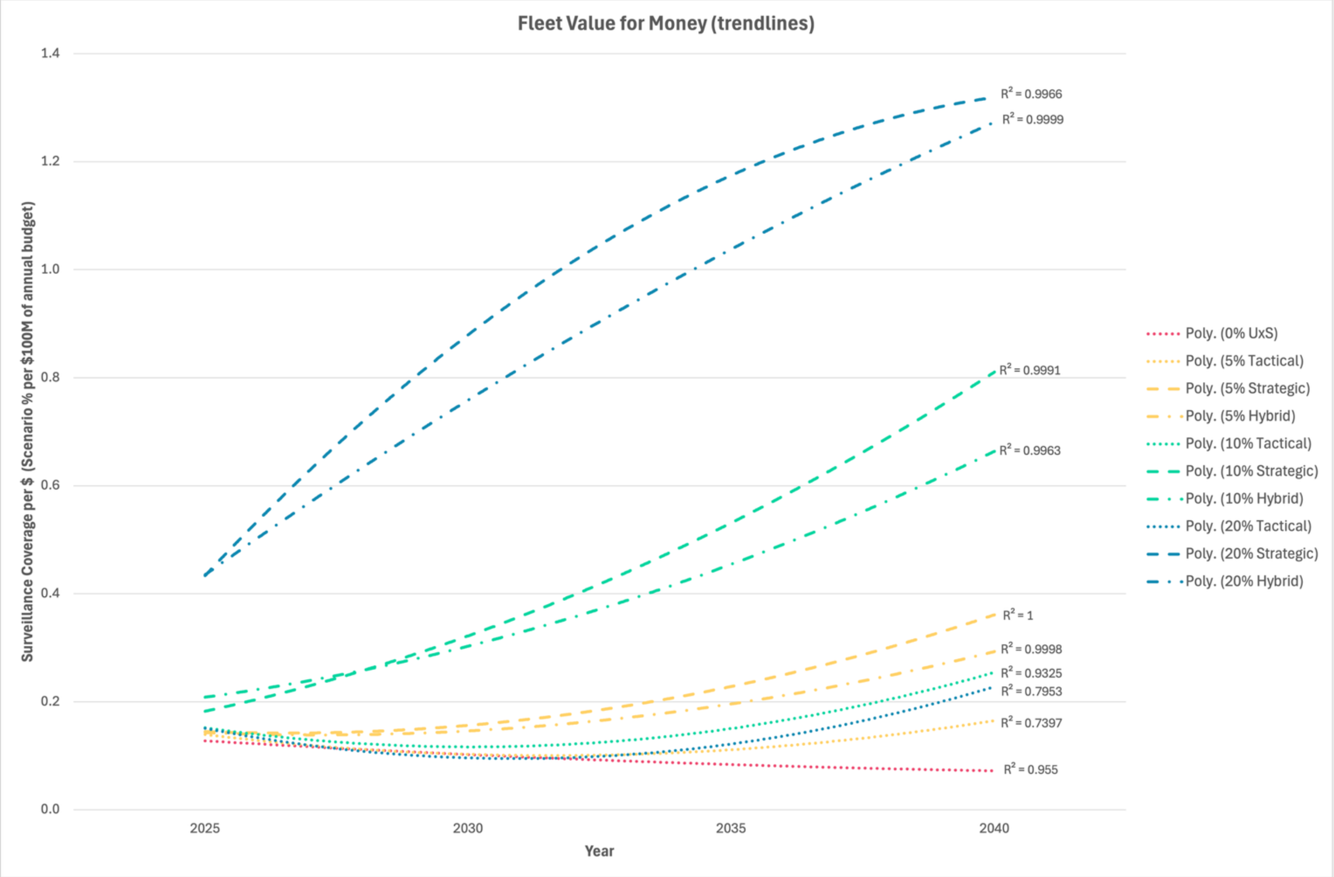


Fig. 4. Candidate Fleets Value for Money Comparison.

In response to RQ2, a detailed analysis of the research results has characterised the contribution of individual asset classes (strategic USV, tactical UUV, DDG, FFG, MPA, SSN, etc.) to each fleet's overall surveillance coverage. For the scenarios and candidate fleets modelled, the following trends were identified:

i. Smaller, tactical uncrewed systems, such as small USVs and UUVs, extended the surveillance coverage of crewed (host) assets in their assigned area of operation. However, their limited endurance/range and reliance on host assets resulted in only a minor contribution to complex surveillance scenarios.

ii. Persistent uncrewed systems, such as seabed arrays and sail USVs, improved enduring maritime domain awareness in known areas of interest. For stationary infrastructure locations or choke points known well in advance, these assets offered the greatest coverage for the longest time on station.

iii. Strategic uncrewed systems, equipped with long-range sensors and higher transit speeds, such as the medium USV with a towed array sonar, had the largest impact on the fleet's surveillance coverage. These cheaper assets matched the detection ranges and surveillance capacity of their crewed counterparts, whilst increasing time on station. Their self-deployment and higher transit speeds provided them with the flexibility to move within (and sometimes between) AORs for a timely response to dynamic or emergent surveillance needs.

iv. The medium USV with a towed array sonar was identified as a significant contributor to surveillance coverage, but is highlighted as a gap in the current RAN investment plans.

Figure 4 shows the value for money delivered by different candidate fleets for the same high-demand, peacetime surveillance scenario. Value for money is represented by the % scenario coverage achieved per $100M of budget. The candidate fleets included the crewed fleet (red series), a 5% investment in uncrewed systems (yellow series), a 10% investment in uncrewed systems, and a 20% investment in uncrewed systems. The different dashed line formats indicate whether the candidate fleet focused on tactical uncrewed systems, strategic uncrewed systems, or a hybrid mix of both tactical and strategic. Each series is graphed as a polynomial trendline, where an R^2 value close to 1 indicates a good fit to the raw results.

In response to RQ3, it is clear from the graph that the fleets with increased adoption of uncrewed systems delivered greater value for money, particularly when investing in strategic uncrewed systems. Figure 4 also illustrates that investment in uncrewed systems increases the value for money over time. Conversely, the value for money of the crewed fleet decreases over the years to 2040. Although its surveillance coverage marginally increases, the cost per annum also increases, resulting in a net decrease in value for money. For this surveillance scenario, the candidate fleet with 20% allocation of strategic uncrewed systems offers the greatest value for money for undersea surveillance in the Indo-Pacific. However, given the fleet's responsibilities beyond undersea surveillance, a 20% allocation to uncrewed systems may be infeasible. As such, the candidate fleet with 10% allocation to strategic uncrewed systems still offers significant value for money. The composition of all the candidate fleets is detailed in the research paper [11].

5 Further Research

Ongoing PhD research on this topic will continue to develop and refine the techno-economic framework and modelling. Further simulation runs will be conducted on additional surveillance scenarios to draw comprehensive conclusions on the utility of alternative fleet architectures under varying surveillance conditions.

The techno-economic framework and modelling can be provided to the Australian Department of Defence to run with their ‘real’ data and yield actionable insights for their force design. This is possible due to the framework’s decoupling of the simulation modelling from the data.

Finally, the research’s impact could be expanded by exploring other applications of the techno-economic framework. Although this conference paper highlights an acute need for techno-economic modelling by the RAN in the Indo-Pacific, it is equally applicable in a European context and for other navies. It could also be applied to other instances of the generalised fleet mix optimisation problem, such as commercial airlines or shipping.

6 Conclusion

This paper outlined the significant benefits of techno-economic modelling of fleet architectures for informing the RAN’s adoption of uncrewed systems. It demonstrates the improvements of uncrewed systems in undersea surveillance and empowers decision-makers to understand where there is value for money. This research is a stepping stone toward seeing everything, everywhere, all at once.

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