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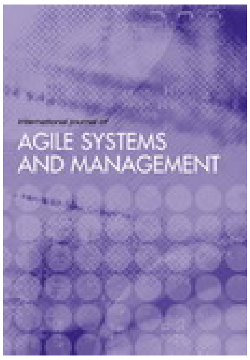

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Agile framework for minimum viable capabilities in traditionally linear engineering acquisition cultures

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Abstract: Capability acquisitions based on agile methodologies are becoming attractive due to the inherent benefits of the agile philosophies to handle complicated and complex developmental cycles when there are high and growing proportions of software functionality involved. However, in major platform capabilities, there remains significant cultural and procedural attachment to the classic waterfall approach with limited iteration and early experimentation for risk discovery and reward. An acquisition framework was conceptually developed to mature technological solutions from a model to a platform-level capability based on the concepts of minimum viable product. Using workshops with acquisition experts, the framework was improved, refining definitions of key concepts, using digital engineering to structure developmental modelling and simulation, and providing appropriate governance throughout the framework process. A retrospective acquisition is used to illustrate and verify the framework and to encourage acquisition agencies to trial it. Further research is needed to validate the framework across a portfolio of representative acquisitions.

Keywords: agile techniques; capabilities; minimum viable product; MVP; minimum viable capability; acquisition; digital engineering; governance; modelling and simulation; M&S.

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Biographical notes: Boris Kazakevich is a Systems Engineer with over 25 years of industry experience in designing and developing motion control systems for industrial and defence applications. In his previous roles, he led multidiscipline engineering teams and managed the delivery of complex turnkey projects for universities and research centres in the area of materials and product testing. He has a Bachelor's degree (Honours) in Mechanical Engineering and is currently studying a Master of Systems Engineering at ADFA, UNSW, Canberra. As part of the study, he is conducting a research project on the application of agile methodologies in complex multidisciplinary developmental projects.

Keith F. Joiner was an Air Force Aeronautical Engineer, Project Manager and Teacher for 30 years before joining UNSW to teach and research test and evaluation. As the Director-General of Test and Evaluation he was awarded a Conspicuous Service Cross and for drawdown plans in Iraq a US Meritorious

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1 Background and introduction

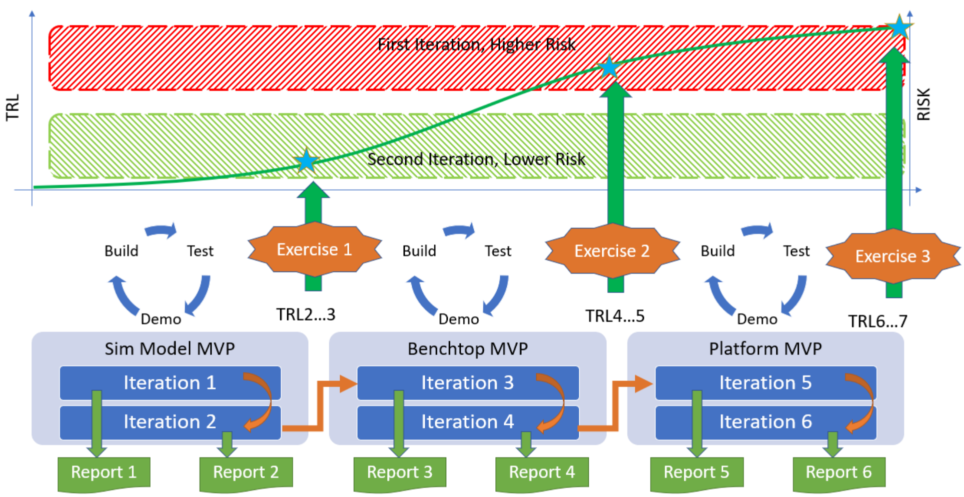
The concept of minimum viable product (MVP) is one of the foundation principles of a proposed acquisition management framework recently developed by Kazakevich and Joiner (2023). The authors define MVP and propose the benefits as follows:

> "The concept of minimum viable product (MVP) (Ries, 2009) has been a popular tool for soliciting user feedback to validate a value proposition the products bring to market. The author defines an MVP as: "That version of a new product which allows a team to collect the maximum amount of validated learning about customers with the least effort." The concept was initially developed with a startup business focus; however, it has since been adopted as a valuable tool for product development in software and other activities. The following five key benefits may be realised when applying the concept in the context of new product development (Curtis, 2020):
>
> - focus on the core issue needed to be solved for the customer
> - rapid and ongoing testing within a set budget
> - market validation in real-time with real users
> - shorter development time
> - reduced cost because of shorter development time and focused effort."

Acquisition management centred on MVP is an elegant but stubbornly elusive process of iterative development beginning with an initial value proposition followed by a cycle of build, measure, and learn, consistent with human factors engineering (Lee et al., 2017). In the framework proposed by Kazakevich and Joiner (2023), the product is built on defined and prioritised features and created first as a simulated model that allows representative users to interface with the simulated model in structured test and evaluation. The build-measure-learn cycles repeat with increasingly real systems as the technological readiness level (TRL) (Sauser, 2024) matures through benchtop (i.e., some hardware-in-the-loop) and finally on platform testing. Such seamless maturation requires a mature digital engineering (DE) capability (Madni et al., 2023), or what the military earlier defined as live, virtual and constructive (LVC) simulation (Joiner and Tutty, 2018).

The proposed MVP acquisition framework is illustrated in Figure 1. The three product development phases, *simulation and modelling*, *benchtop* and *platform* MVP, are mapped to the graphic at the top of the diagram. The horizontal axis is the timeline of the development. The left-hand vertical axis represents measures of the maturation and is depicted by the curved growth line. The two rectangles on the graph map the risks associated with each phase of the development. The top rectangle is the higher-risk activity that occurs in the first iteration. It is aimed at addressing unknowns and new technologies. The follow-up, or subsequent iterations, build on the results of the first iteration and are intended to implement the solutions found in the first iteration. It is envisaged that the risk is significantly reduced during each of the subsequent iterations.

Figure 1 Originally proposed MVP-based acquisition framework reproduced with permission from Kazakevich and Joiner (2023) (see online version for colours)



Since its proposal, the subject framework has been workshopped with acquisition experts in industry forums, where three areas were identified as key to its acceptance and thus future trial use.

First, the MVP concept, originally conceived as a marketing tool, has established itself as a viable strategy to develop a solution for complex problems at an accelerated pace, offering desired flexibility within a given budget. The success of the development is dependent on the practitioner's ability to define an MVP as a deliverable for the activity. A well-defined MVP leads to achieving desired outcomes and sets the foundation for the success of the next iteration in the spiral development. Conversely, a poorly defined MVP is likely to increase the efforts and extend the development cycle with little return. This research article takes a closer look at available definitions and interpretations of the MVP term to create more clarity and guidance for project management organisations to apply the proposed framework.

Second, DE is transforming traditional systems engineering, which is based on well-documented processes, methods, and extensive paper-based reports, to digital models representing cross-functional multidomain relationships and mission-focused solutions. Digital models and associated data are becoming the single source of truth that supports development from the systems engineering point of view across the capability lifecycle (PSM, 2022b). The proposed MVP framework now identifies the importance of the digital model and model simulation to generate digital artefacts. The initial phase of the framework, called ‘modelling and simulation (M&S)’, aims to deliver the MVP in the form of a digital model with associated simulation as a demonstration of the capabilities. Exploring elements of DE and incorporating them in the framework supports accelerated development, while simultaneously maintaining and refining systems and functional requirements.

Third, the MVP framework is strongly aligned with the agile philosophy and its principles. This alignment includes self–managed team arrangements, minimum requirements on documentation, lack of traditional project management performance measures, and so on. Taken out of context, these features more often raise concerns that Agile projects lack the governance and oversight necessary for developing mission-critical solutions. Hence, this research also investigates an appropriate governance model and its inclusion into the proposed MVP framework. By managing risk and technical debt, such a governance approach should better assure practitioners to apply the methodology to mission-critical and safety-critical system acquisitions.

Following an outline of our methodology, this article examines applicable research literature concerning the three areas identified with acquisition experts. The proposed framework is then reexamined from its first outline in these three critical areas for acceptance and use. We then present a retrospective case study to illustrate the likely benefits and issues of the framework based upon the authors’ prior experiences.

2 Methodology

Following the conception of the proposed MVP-based acquisition framework in 2023 (Kazakevich and Joiner, 2023) the framework was presented and workshopped at two major industry forums in 2024. The first workshop was an annual engineering symposium for a major defence-oriented firm consulting to the UK and Australia, with all its Australian-based project management and engineers participating online, around 80 staff. The second symposium was an industry forum known as ‘ProjectCHAT’, which was held in Adelaide in early 2024 and involved over 200 attendees from all sectors doing project management in Australia. Feedback from the question-and-answer sessions was grouped into the aforementioned three themes, where acquisition experts wanted greater clarity. These sessions also revealed some cultural division around the right approach to modern project complexity, where some acquisition staff were attracted to the elegance of the MVP-based approach and others were sceptical that a more complicated process would be needed to meet growing complexity. Hence, in addition to exploring the literature in the three areas identified, literature supporting complex systems governance was reviewed and overviewed to better explain the framework’s elegant approach.

Following the literature review in these areas, the MVP-based acquisition framework is revised with the additions and checked for completeness using a retrospective case study based on the author’s experiences. Presenting the literature, additions, and our retrospective reflection are important steps to encouraging others to trial the revised framework.

3 Results

3.1 Complexity theoretical support

Acquisition development in mission-critical applications is often referred to as complex, certainly being the preeminent reason given for acquisition difficulties (Gupta et al., 2019). The complexity is usually associated with a fast pace of change, interdependence through increasing connectivity, and behavioural emergence coming from the open systems and self-organisation, often introducing unpredictability and disillusionment (Hodge et al., 2019; Keating and Katina, 2019). Complexity is usually signified by connectivity across multi-proprietary, multi-generational, and multi-security systems of systems (Dahmann and DeLaurenits, 2023). Traditional project management has been challenged for many decades and requires changes to remain effective and relevant (Jaafari, 2003). Keating and Polinpapilinho (Gorod et al., 2019) provide practical advice and definitions in applying a complex system governance (CSG) methodology to incrementally improve acquisition governance.

The Cynefin framework, introduced by Snowden and Boone (2007), considers complexity in the context of five domains, offering methods of how to identify situations and make sense of individual behaviours. Constraints are either non-existent or enabling in the *chaotic* and *complex* domain environments, signifying novel or exaptive systems. The best governance behaviours suggested by this framework are to probe or act first and respond based on the sensed feedback. The *complicated* and *clear* domains are proposed to be governed with fixed constraints. Suggested governance behaviours include understanding and sensing the environment and responding or acting based on the analysis or categorisation of the sensed data. The fifth domain is called *confusion,* where the situation is unclear and can't be attributed to any of the other four domains. Clearly defining *complex* helps to recognise it in an appropriate context and develop efficient ways of dealing with the complexity, rather than using traditional solutions to deal with it (The Cynefin Company, 2024). In summary, complex systems research has shown that elegant adaptive responses are better than accretional growth in complicated acquisition processes (Keating and Katina, 2019; Keating et al., 2018; Weiss and Patt, 2022).

3.2 First workshop-identified area – MVP definitions and interpretations

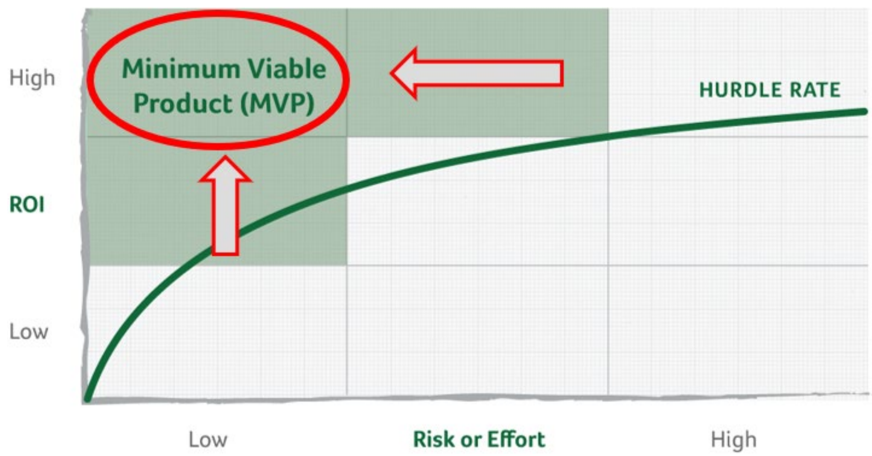
MVP definition has evolved since it was introduced as a "product with maximum (return on investment) ROI divided by risk" (Robinson, 2001).

MVP is positioned in Figure 2 as a product that delivers the highest return on the minimum amount of effort. As conceived, MVP underpins the iterative development of the solution, as quoted by Robinson:

> "It says, think big for the long-term but small for the short-term. Think big enough that the first product is a sound launching pad for it and its next generation and the roadmap that follows, but not so small that you leave room for a competitor to get the jump on you."

The application of MVP in acquisition serves many purposes. Commercial product and marketing managers often see MVP as the most convenient vehicle to deliver the product to the market at an accelerated pace with minimum effort. The most successful applications of the MVP concept, particularly in software development, incorporate it into the product roadmap to be part of the end-to-end developmental process. An example of an early MVP-based approach (Cooper and Vlaskovits, 2010) uses a framework consisting of several steps to create so-called final MVP and intermediate instances. The intermediate MVPs are created to treat the risks identified in the product development cycle. The framework is built on the notion of the value path. The path takes the product through several iterations, starting with initial assumptions based on the user's needs and finishing with a marketable product as shown in Figure 3.

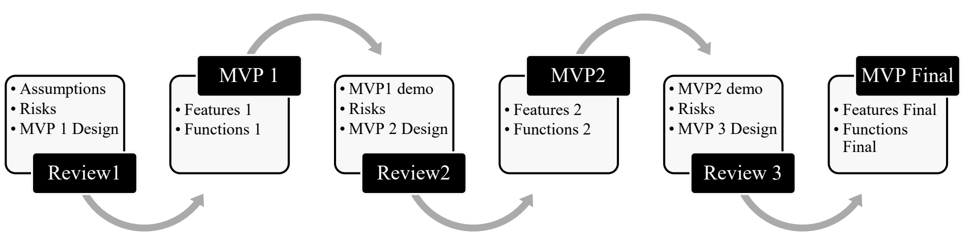
Figure 2 Return-on-risk analysis (see online version for colours)



Notes: ROI is return on investment.

Source: Adapted from Productboard (2024)

Figure 3 MVP value path example from



Source: Cooper and Vlaskovits (2010)

The example is based on a three-iteration process. The number of iterations depends on the ability to understand and control the risks, whereby it is recommended to increase the number of iterative steps for more innovative and risk-prone solutions. It is assumed but not shown on Figure 3, that each iteration review contributes not only to the future MVP definition but also feeds updates into the requirements engineering process. Updating requirements should converge and compromise as they better reflect the user needs, as those users are better informed by product instantiations.

The objective of the MVP, particularly in the initial stages of development, is to be able to determine the feasibility of a solution based on user feedback. The strategy proposed by Alberto Savoia called 'pretotyping' (Savoia, 2019) simply defines an MVP as ‘the right it’ using the motto of “make sure that you are building ‘the right it’ before you build it right”. According to the author, the strategy supports defining a successful MVP using a set of techniques, including testability, often exemplified by the motto, “fail fast, fail cheap”.

MVP-based acquisition strategy needs some differentiation between early-phase developments and deliverable operational products or solutions. Binder (2018a) finds the originally defined MVP limited to a niche area of *early-stage development*. The author argues that complex systems with unpredictable behaviour must address the technical risks and release planning for enduring programs. Binder offers the term ‘minimum viable capability’ to address shortcomings of MVP for complex systems. The fundamental differences in MVC compared to MVP, according to the author, are:

- capability, being an aspect of the product, allows for adjusting the focus to a specific area rather than the whole product
- linking capability to a measure of effectiveness builds the case for early and rigorous validation
- ability to address multi-domain and more complex architectures than the ones present in software products, for example, software as a service (Kabbedijk et al., 2015).

The frequency of release is another point of differentiation between MVP and MVC (Binder, 2018b). According to the author, the system architecture dictates the release schedule for MVC, and the schedule requires more attention in several areas, such as the necessary support structures that may not be part of the capability but are required to achieve it. He surmises that the use of an MVP conceptual approach alone is best limited to pure software development with an assumed fixed architecture and reliance on user feedback as the validation methodology.

3.3 Second workshop-identified area – M&S with DE

Complexity and the need for accelerated delivery of the capabilities in defence and other mission-critical solutions are behind the evolution of DE. It serves the purpose of managing the end-to-end processes through the capability lifecycle (Shepard and Scherb, 2020). The US DoD defines DE as (Office of the Deputy Assistant Secretary of Defense Systems Engineering, 2017):

> “An integrated digital approach that uses authoritative sources of systems’ data and models as a continuum across disciplines to support lifecycle activities from concept through disposal. A DE ecosystem is an interconnected infrastructure, environment, and methodology that enables the exchange of digital artifacts from an authoritative source of truth.”

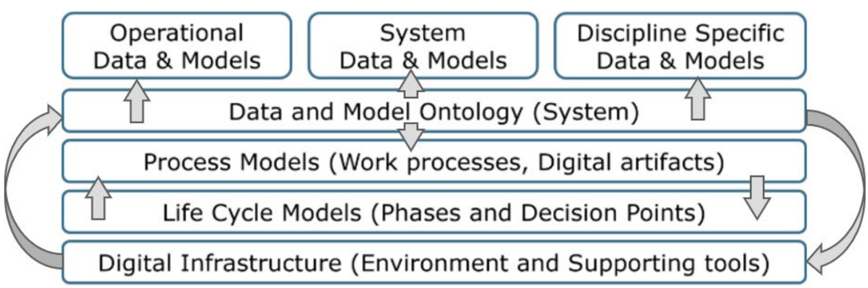
Model-based systems engineering (MBSE) is considered a necessary element to coordinate DE and has attracted increased interest in the systems engineering community. There has been limited practical application (McDermott, 2020), except in some niche areas like submarine support (Rogers and Mitchell, 2021) and space systems. MBSE is originally defined by (Systems Engineering Vision 2025 Project Team of INCOSE, 2014) as:

> "The formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."

Simulated models generate necessary artifacts, enabling the concept of a single source of truth, also known as an authoritative source of truth (AST). This approach establishes better collaboration between stakeholders and increases data consistency and accessibility. It leads to increased efficiency in running engineering processes with accelerated design iterations (Kruse and Blackburn, 2019).

MBSE usually starts with basic relational modelling that is formally 'acausal', whereby it can assist managers to ask, 'are our requirements right?' as much as 'what does a solution look like?', and to look for sensitivities in between (Schweiger et al., 2020). Figure 4 illustrates the activities associated with the DE and MBSE approach, and their interactions. Digital Infrastructure includes the necessary processes and tools to support engineering activities at the lowest level. DE spans across the capability life cycle and supports established phases and milestones associated with project or program requirements (*Systems Engineering for the Digital Age: Practitioner Perspectives*, 2024). DE needs to be governed by appropriate work processes that produce necessary artifacts stored and shared between established stakeholders. The artifacts are maintained in a digital repository so that all parties involved in the project execution work from the same models and dataset, defined by the domain ontologies to facilitating better data management and sharing (Mukhopadhyay et al., 2023; Shepard and Scherb, 2020). A set of models defines the system and operational use, together with domain-specific models and datasets produced by simulations (PSM, 2022a).

Figure 4 Work breakdown view of DE space (see online version for colours)



Source: Adapted from PSM (2022a)

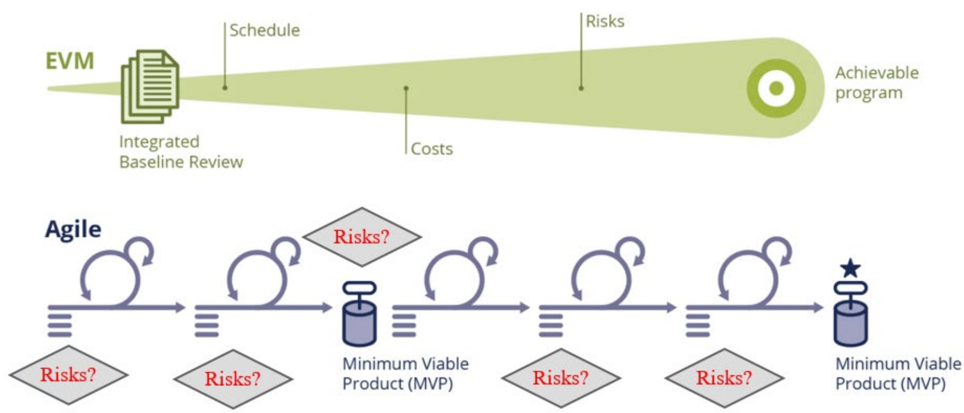
3.4 *Third workshop-identified area – governance and oversight in the agile environment*

Luna et al. (2014) refer to governance as the mechanisms and responsibilities to exercise authority, enabling decision-making concerning strategies developed by organisations or enterprises. The authors are extending the governance in the context of agile to six so-called meta-principles (Luna et al., 2023):

1. good enough governance, adapting the level of governance to the organisational context[1]
2. business-driven decision-making to facilitate greater flexibility and faster response time
3. human-focused, fostering creativity and the value of individual contributions
4. based on quick wins, small success accelerates progress
5. systematic and adaptive approach, specifically an ability to handle a change by being adaptable
6. simple design and continuous refinement, optimising the desired outcome with available resources.

These principles align well with research by Yesudas et al. (2020) into easing project management tensions and by Copeland et al. (2015) and Kramer et al. (2015) on the benefits of prototyping. Risk management is one of the important pillars of governance and oversight in project execution. Complex programs utilising earned value management (EVM) require conducting an integrated baseline review (IBR) that examines risk together with cost, schedule, and performance to assess feasibility based on the developed plans. Wilson et al. (2023) argue that EVM and agile MVP are compatible, stating that MVP demonstration can be considered as part of the IBR. The authors provide a comparative view between the two approaches as illustrated in Figure 5.

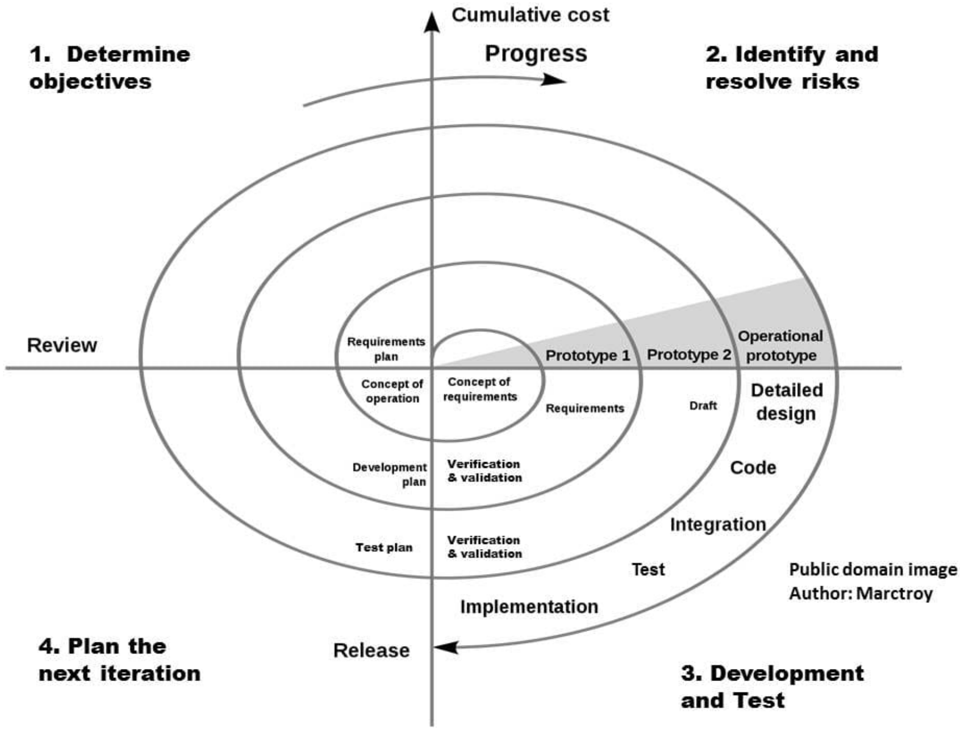
Figure 5 EVM plan vs. agile MVP (see online version for colours)



Source: Adapted from Wilson et al. (2023)

For decades, it has been recognised that a successful project needs both agility and discipline (Boehm and Turner, 2004), yet domains like defence are still trying to find a balance (Weiss and Patt, 2022). Agile and so-called 'plan-driven methods' could be combined or hybridised successfully to suit specific needs. The authors suggest that balancing both methods involves careful consideration of technology, management, and people. The solution to balance agility and plan-driven discipline must come from using risk analysis and carefully tracking risk mitigation measures with adjustments to the plan as required. The incremental commitment spiral model (ICSM) is an evolution of the original work by Boehm (1988), introducing a risk-based process that is combined with iterative solution development. The spiral model proposed by Boehm is pictured in Figure 6.

Figure 6 The spiral model

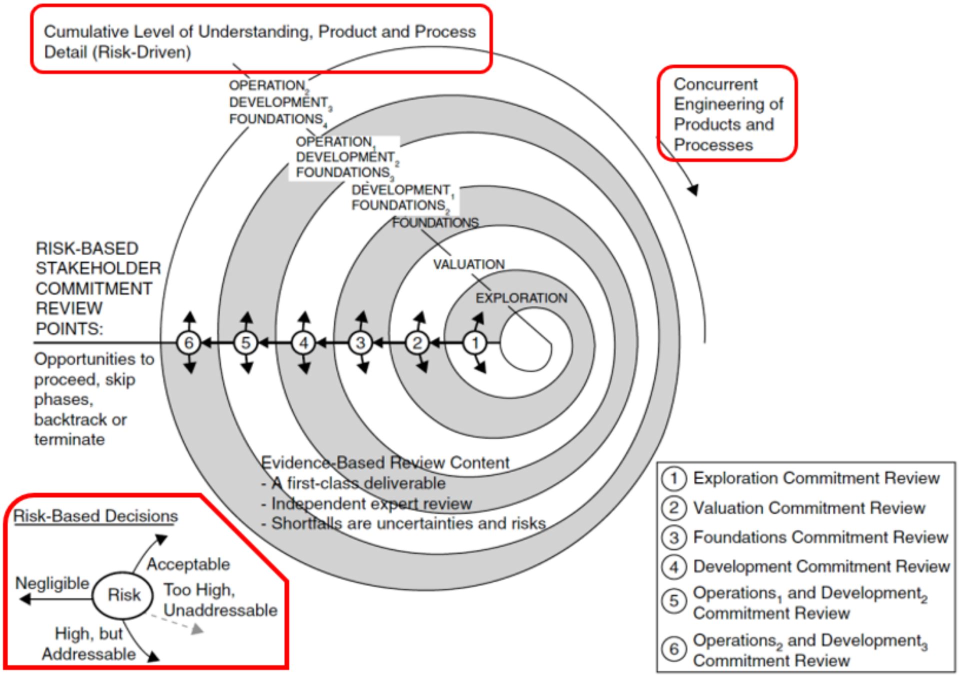


Source: Adapted from Font (2023)

The prime purpose of the spiral model is to assist software developers in dealing with larger, complex projects lasting between six months and two years. The model guides developers through system requirements definition, including evidence-based data on system functionality, interfaces, and performance. The risks are carefully evaluated with consideration of alternative solutions, re-use of existing technologies, build-versus-buy analysis, and core-development versus subcontracting. The risks must be resolved to an acceptable level before starting the activities. Upfront considerations are given to the evaluation of the solutions and the testing needs. Planning of the next iteration is based on the previous activities with updated requirements and associated emergent risks, if any.

The evolved model, ICSM, maintains focus on addressing the need for a more flexible and responsive system engineering (Boehm and Turner, 2015). The spiral view of the model, shown in Figure 7, includes an explicit definition of risk-based decisions together with a mandatory series of reviews to support spiral commitments.

Figure 7 The ICSM (see online version for colours)

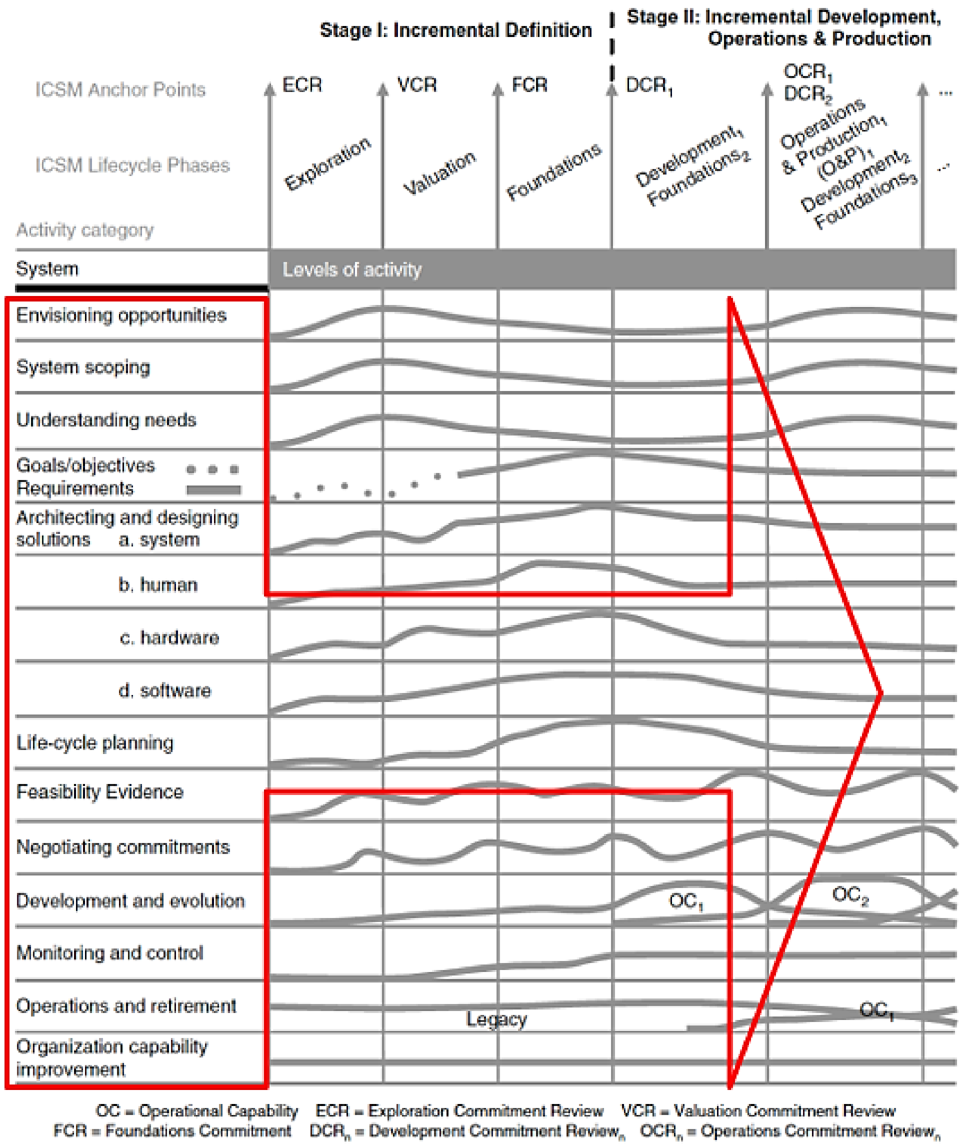


Source: Adapted from Boehm and Turner (2015)

The four principles are essential in applying the ICSM model: stakeholder value-based system evolution, incremental commitment and accountability, concurrent multi-discipline engineering, and evidence and risk-based decisions (Boehm et al., 2014). The authors point out that ICSM is "not a single one-size-fits-all process model, but a process generation model, in which a project's particular risk patterns and process drivers steer it toward achieving success concerning its particular objectives, constraints, and priorities". The ICSM calls for a concurrent process of addressing product development activities supported by management and engineering artifacts, together with evidence of their combined feasibility (Boehm and Turner, 2015). Each spiral of the process model addresses requirements, alternative solutions, products, and associated processes, hardware and software, human factors, etc. (Boehm, 2013). Concurrent exploration of needs and opportunities together with concurrent engineering of hardware, software, and human factor aspects is underpinned by so-called 'anchor point milestones' such as commitment reviews, as shown in Figure 8, and called respectively exploration, valuation, and foundation commitment reviews.

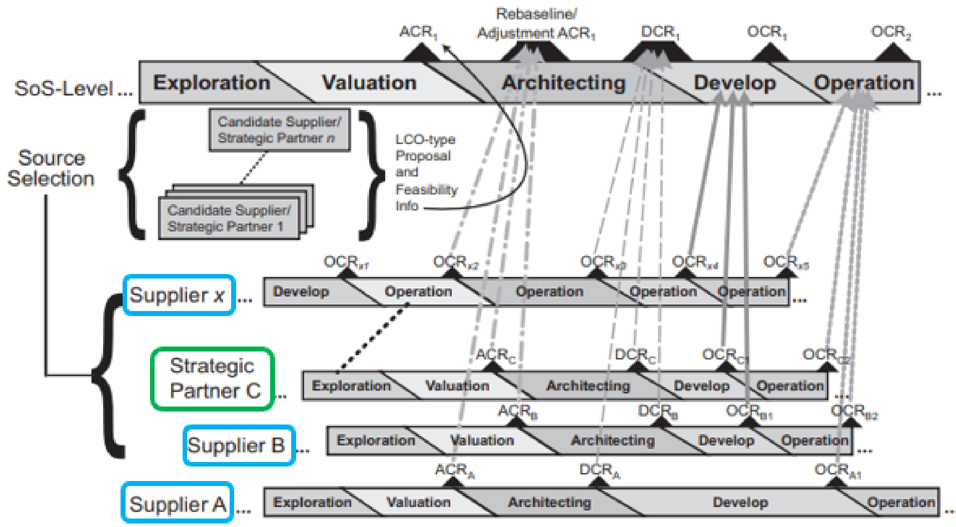
The ICSM framework can be scaled to govern the acquisition of complicated and complex systems (Adams and Keating, 2011). The model expands early phases called *exploration and valuation* to cover supply chain activities, selection of the sources, etc. Figure 9 shows the interdependencies and management of risks associated with vendor selections and supplier management. Boehm et al. point out that SoS needs to address systems and components that vary in technology maturity and are likely to be delivered on different schedules. We refer to these factors as multi-proprietary and multi-generational, and note they can be at a foundational software level from the work by Ferreira et al. (2021). The critical point is that the interdependencies and supplier evolutions could be anticipated better and incorporated into the initial planning as there will be times when the project will face complex problems. Such emergence will challenge the design team, and needs to be adjusted to deliver an interim but operational solution until the complexity is resolved.

Figure 8 Concurrency view of ICSM (see online version for colours)



Source: Adapted from Boehm and Turner (2015)

Figure 9 Supplier selection and management using ICSM (see online version for colours)



Source: Adapted from Boehm and Lane (2007))

The concept of ICSM has been successfully used in several Defence acquisition programs (Tuffley, 2024). Tuffley goes as far as proposing ICSM as a methodology to answer the challenges posed in the recent Australian Defence Strategic Review (DSR). Her proposal would deliver platforms in service when they achieve MVC of 80–85% and iteratively approach 100%, reflecting the modern technology cycle at an accelerated pace, whilst embracing the risks. Further, she argues the possibility of achieving the 80% threshold by completing Phase 2 of the ICSM Stage II part of the process (Figure 8). Critical factors to attain this high goal, according to Tuffley, are observing commitment review milestones, phase or spiral reflections focused on requirements, solutions, hardware and software, products and processes, human factors, and ‘alternatives’ reviews.

3.5 *Summary of identified changes*

The review has identified that our MVP-based acquisition framework can better define the overall MVP for the activity and align it with phased MVPs to help deliver a better solution faster. The MVC term could play a role in iteratively managing requirements by aligning MVC with goals and objectives using measures of effectiveness (MOE) and performance. This addition would also bring improved rigor in the validation and verification of an MVP, likely reducing the risks.

Elevating the significance of DE through M&S across all three phases of development, rather than simply focusing on it during the initial phase, would enhance the framework’s resilience to unavoidable changes during capability development and operational use. Integrating DE in the process would also reduce the documentation burden and strengthen requirements management by using models and associated artifacts as authoritative sources of truth.

Governance and oversight add necessary rigor to the developmental process especially when development is executed at speed and incorporates new technologies in the mission-critical solution. The inclusion of ICSM strategies in our MVP-based acquisition framework will add risk-based governance through commitment reviews and prevent undesired outcomes that would lead to increased technical debt and the cost burdens associated with redesign rework. Such reviews would also likely increase desired customer and user engagement in key decisions of the developmental process.

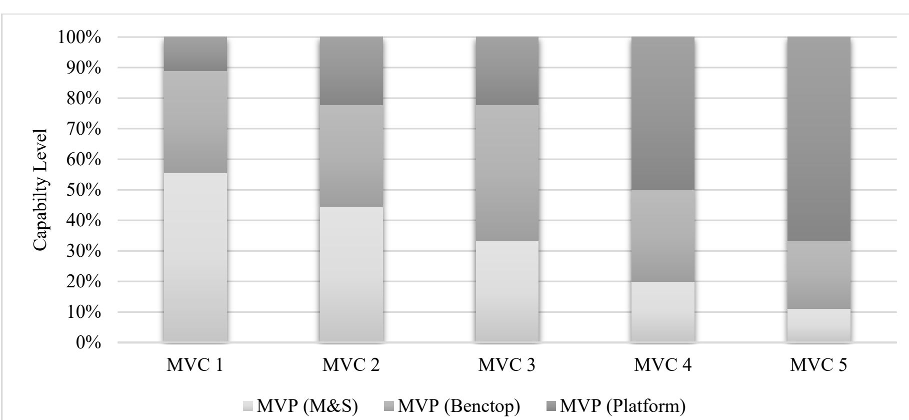
3.6 Revised MVP-based acquisition framework

This section consolidates and explains changes to the proposed MVP-based acquisition framework. A combined definition of MVP and MVC is considered an appropriate update based on the literature review findings. The key points for the definition updates are:

- an MVP is a set of MVCs that has been set to reflect the capability level
- MVCs are aligned with MOE for the capability (system or product) according to the capability mission
- final MVCs fulfil all MOE to complete the mission; intermediate MVCs, by extension, can be assigned for a specific capability level in agreed percentage terms
- MVP for the specific phase (M&S, benchtop, and platform) is defined as a capability that meets set levels of MVC for the specific point in the development cycle.

The revised MVP and MVC concept is illustrated in Figure 10. The hypothetical example shows five MVCs contributing to the development of the capability across the acquisition cycle, including M&S, benchtop, and final platform phases. Further, the example shows MVC1 and MVC2 prioritised in the early phases, with the rest of the capabilities realised in the later phases. The capability level for a given MVC is expressed in the percentage term. The assignment is a consensus-based decision between subject matter experts, systems engineers, and stakeholders (customers and end users). Interdependency between MVCs must be carefully considered together with the validation of the attainment at the demonstration levels. Other factors to consider should include organisation capabilities in terms of resources (skills and capacity), suppliers and partners' capabilities, facilities (operational and testing), and financial and contractual obligations.

Figure 10 Idealised example of capability growth using MVP and MVC definition (see online version for colours)



Similarly, each phase of the development should be planned by distributing MVCs across the required number of stages. The originally proposed framework recommended at least two iterations – first with a higher risk profile, followed by the consolidation and corrections iteration. The number of iterations for the specific phase shall be defined prior to phase commencement and depends on the combination of factors described earlier. The activities at the execution level can be conducted as a set of Agile sprints. The choice is largely dependent on the organisation's needs, its structure, and the nature of the activities.

It is envisaged that the delivery of the MVP is likely to be aligned with attaining initial operational capability (IOC). Extending the concept beyond IOC would lead to several additional cycles that lead towards achieving final operational capability (FOC). The iterative approach includes not only developing hardware but also other important elements, such as supportability (often termed fundamental inputs to capability in the Australian Defence).

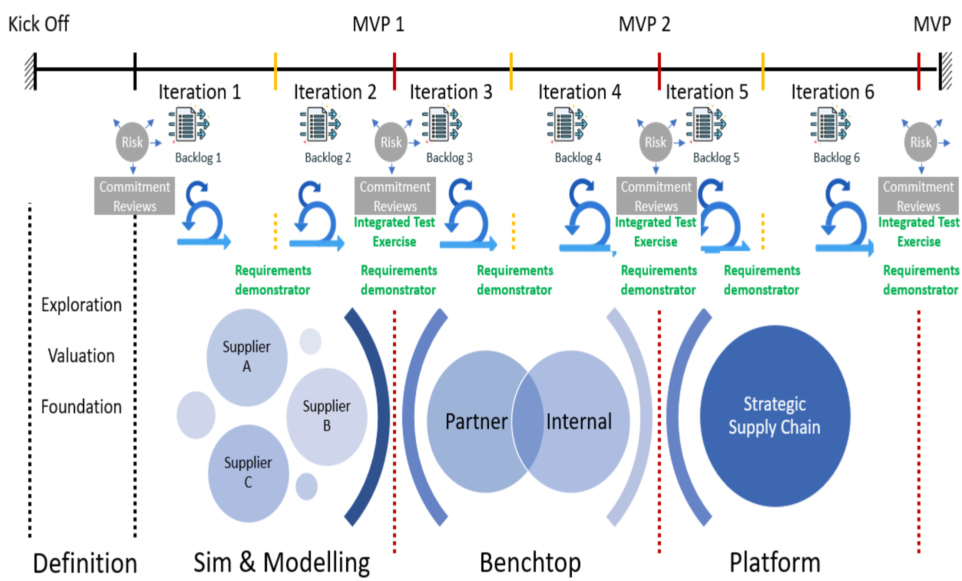
The definition phase at the beginning of each MVP full cycle enhances the framework from the planning and governance point of view. The definition concept comes from the ICSM model and could be scaled and adapted to suit specific development needs and the organisational structure. A risk evaluation method feeding into commitment reviews remains at the core of the definition phase, overlaying planning activities for the systems engineering work and supporting functions such as supply chain and operations. The concurrency principles of ICSM support mission-focused development and form the key strategy for the MVP framework. Injected changes reflecting user needs and future technological advances are considered and addressed during commitment reviews.

M&S is the first MVP-based activity in the proposed framework. The M&S phase is also a foundation for establishing the required set of models and datasets to form the repository for the collection of knowledge, artefacts, and other data in support of future system and functional requirements, product specifications, and test and evaluation plans. In line with INCOSE guidelines and principles, appropriate measures need to be established to support and enforce the AST model that is accessible to developers in a controlled manner to avoid duplication and maintain an enduring and accurate data repository. Once the foundational work is completed during the M&S stage, the models and artifacts must continue to evolve to remain relevant and accurate concurrently with the hardware and software developments. These models ought to be multi-fidelity throughout life, as explained by Seif et al. (2024).

The version control and necessary level of digital documentation must be sufficient not only to be able to roll back the development in case of the emergence of a better alternative solution, but also to support solution modularity. The solution modularity in this context means the ability to create variants of the systems to meet a mission's needs without the need for a complete redesign (Efatmaneshnik and Ryan, 2016). Such partitioning of requirements works well for the development cycles with many iteration steps, making the engineering solution more modular and robust, given that each iteration should incorporate a required degree of testing (Wickert, 2019). This approach works if the digital documentation does not become a burden and thus obscures the real value of the process. The guidance provided in (McDermott, 2020) together with carefully chosen metrics to monitor DE value-add, will help the successful implementation of DE in our MVP-based acquisition framework.

The concept of a digital twin, considered as a by-product of DE, is defined by the Defence Acquisition University (Office of the Deputy Assistant Secretary of Defense Systems Engineering, 2017) as “an integrated multiphysics, multiscale, probabilistic simulation of an as-built system, enabled by digital thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin”. The inclusion of probabilistic simulation in the definition is useful for the context of complex development to assist in predicting system performance in terms of uncertainties and variation in products and subsystems. A more recent, thorough academic review and definition is by VanDerHorn and Mahadevan (2021); however, this definition loses the probabilistic simulation term, which we prefer. The digital twin models can include artificial intelligence (AI)-based algorithms so that the physical models benefit from the inclusion of reinforcement learning models coupled with sensor fusion and data processing (David et al., 2021). Such AI learning can be accomplished using simulated data and test results, supporting the principle of using own data (Savoia, 2019).

Figure 11 Updated MVP framework (see online version for colours)



Our proposed framework, incorporating the MVP definition together with governing principles of ICSM and the incorporation of DE, is illustrated in Figure 11. Inclusion of the *definition phase*, as discussed earlier, sets the tone for the governance and oversight of the development needed for the acquisition. There is no universal solution when it comes to complex and mission-critical acquisition; therefore, the foundation phase likely helps establish the necessary balance between agility and control to conduct the activity. The balance is set and owned by the stakeholders, including the customer and end user. The commitment reviews, annotated with a risk circle in the diagram, allow stakeholders to manage this balance depending on the test evidence or artifacts and subject matter expert advice. There is an opportunity to either accelerate the pace of development when the risk is minimal or to increase the rigor and conduct additional activities to resolve uncertainties identified as unacceptable high risk. The requirements are updated and managed through the same evidence-based approach. It means that the system is being developed under requirements that should be more relevant, correct, and verifiable, following the foundation principles of systems engineering.

Concurrent development ensures the engineered solution matures together with supporting structures. An important element of the acquisition is the development of the network of suppliers forming the strategic supply chain. Early phases of development may use different suppliers than the operational phases. Ideally, the majority of organisations have well-defined core activities that are conducted in-house, and the activities that are outsourced in the supply chain are of lower risk. The supplier development engineers ideally need access to a DE repository to work with the existing suppliers and to onboard new ones concurrently with other developmental activities. The management and resilience of the supply chain is ideally modelled in MBSE, as globalised supply chains and multi-generational system reuse are in constant flux, and thus complex in their own right (Carnovale and Yeniyurt, 2021; Sabahi and Parast, 2020). The facilities necessary for the system development, production, and testing must be concurrently stood up and managed within appropriate iterations and phases.

4 Discussion

4.1 Retrospective case study illustration

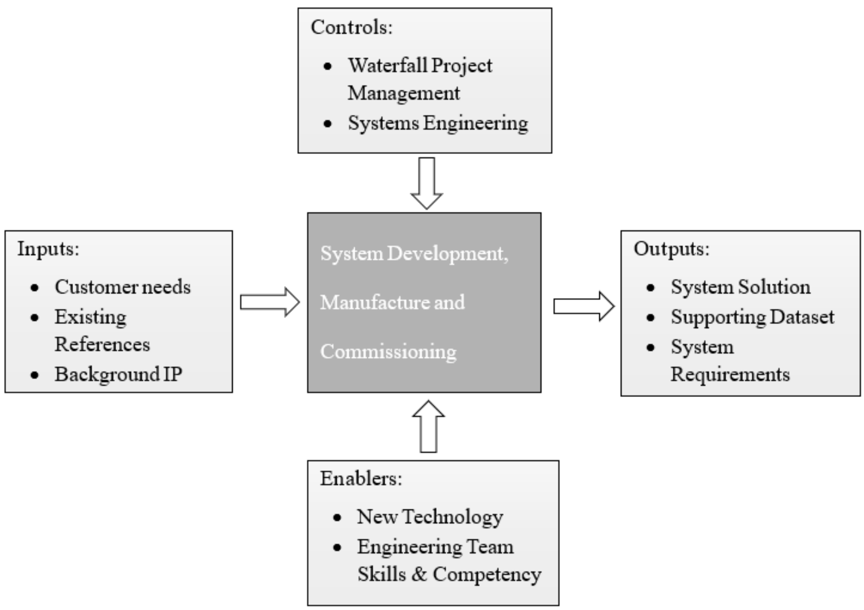
To facilitate discussion, this retrospective case study examines one of the systems developed and delivered recently using a traditional systems engineering approach and waterfall project management. The study looks at a hypothetical scenario of applying the proposed MVP-based acquisition framework for the original system's acquisition process to highlight potential benefits and improvements if the proposed framework were used. The developed system controls the actuation mechanisms for maritime and naval platforms.

4.1.1 Background

The original system was developed to replace an existing solution used by the customer in many similar applications. The customer was looking for a more energy-efficient solution, reductions in size, weight, and power (SWaP) by transforming the centralised power source to a distributed one. Other benefits sought were reduced environmental impact and a significantly simplified maintenance program. While there was no expectation of performance improvement compared to the original solution, the customer perceived a benefit in moving away from a traditional solution to a hybrid system by reducing the time-in-site installation and commissioning. The customer required the activity to be developed using a systems engineering process, with expectations that systems requirements developed under the project would help create a modular solution that can be applied with minimum non-recurring engineering effort across similar applications with several platforms. The customer assumed that it would not require a significant effort to engineer system requirements, given that the supplier delivered many components for the same application in the past. The supplier's business development staff agreed with this assessment.

The input-process-output (IPO) diagram in Figure 12 provides an overview of the case study system development using a template proposed by INCOSE (Walden et al., 2015). The system has been developed, manufactured, and delivered in service based on the needs articulated by the customer, supplemented with the provision of existing references containing data on similar systems and background IP held by the supplier. The activities were governed by the traditional waterfall project management process, applying systems engineering principles that were new to the customer. The new technology readiness level, using a defence technology readiness definition (Australian Research Council, 2023) was approaching Level 7, but with no known systems fielded in similar applications. The project engineering team's skills enabled the supplier to navigate to the solution that proved successful in the field.

Figure 12 Case study IPO diagram



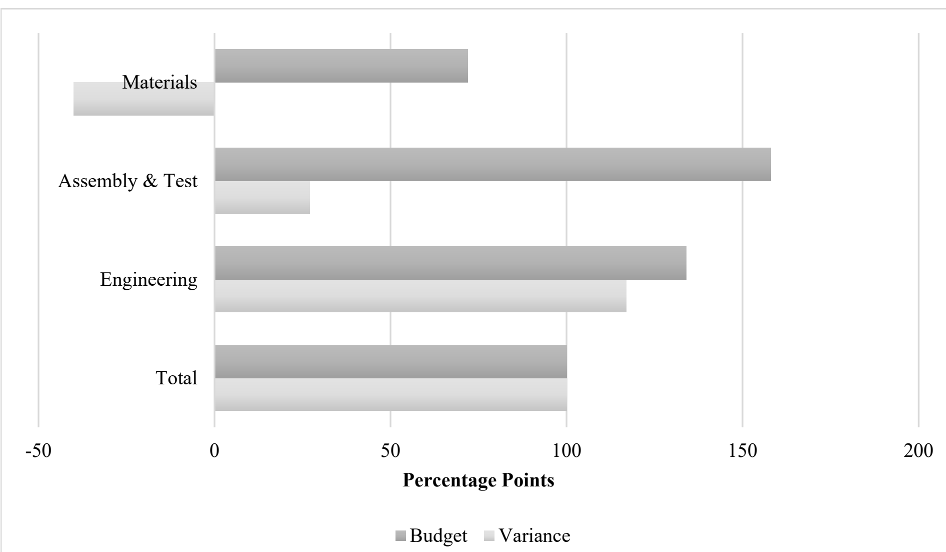
The customer requested the system's requirements as deliverables to fulfil the need for a scalable and modular solution so that future systems can be quickly produced without significant engineering effort and at a faster rate than the case study project.

Contractual obligations of the customer to the end user in terms of cost and schedule put significant limitations on the system development. An aggressive timeline for the development and hardware delivery conflicted with the systems engineering process, causing significant friction between supplier engineers and the customer during the requirements engineering phase. System and functional requirements, as the first deliverable for the project, were rushed through, suffering in quality with many untested assumptions. As a result, the documents lacked the level of detail expected by the customer and did not cover the full breadth of the applications. A compressed timeline drove significant resource demand in the requirements engineering phase, consuming all the budget allocated for the requirements delivery, such that no update was conducted on the requirements after the initial release.

The initial plan included a prototype development for the requirements verification and validation purposes. The plan was revised to a production system development, skipping the prototype phase. This revision led to making significantly more conservative engineering decisions in the sizing and capacity of the components that formed the solution. There was no room for taking some risks and no tolerance for failure during acceptance testing and evaluation. Limited developmental testing occurred during the system acquisition; however, some verification testing was conducted as risk mitigation measures. The verification testing was aligned with a conservative design and could not contribute to knowledge growth beyond already known performance points.

Despite significant effort in requirements engineering at the beginning of the system development, several interface mismatch issues had to be resolved during detailed design, manufacture, and even acceptance test stages. These difficulties were predominantly with limitations in interface control documentation, a common problem when prototype integration is skipped, and they typically drive significant cost and schedule overruns (Australian Senate, 2012). These difficulties were mainly related to digital interfaces, governed by the software, such as serial bus protocol incompatibilities, and insufficient resolution of the interfacing hardware devices. These integration issues caused additional engineering efforts from both the customer and supplier. Introduction of unplanned hardware packages led to cost overruns and delivery delays.

Figure 13 Retrospective case study project performance



The system was delivered three months behind the original schedule, impacting operational test (validation) activities, and requiring remote engineering support to resolve some operational issues. The project summary is illustrated in Figure 13. The activities have been broken down into three categories: *materials* [raw and purchased commercial off-the-shelf (COTS)], *assembly* and *test efforts* (technicians), and *engineering effort* (combined systems and design engineering activities). The two metrics chosen for the diagram are *Budget* and *Variance,* presented in percentage points. Total budget and variance are assigned 100 points. Individual values are the percentages of actual versus budget. Similarly, the total variance is 100 points; the individual values represent variance contribution for the specific effort. A negative variance signifies underspend, and a positive variance indicates overspend.

Using the above definitions, the key takeaways from the project performance were:

- the project was significantly over budget except for the material spend
- materials were overestimated due to a conservative solution approach in the face of applying new technology
- engineering effort was the main contributor to the variance – it was understood that significant engineering effort would be required to adopt the new technology for the solution, but it went well beyond the estimated effort
- the assembly and test portion of the project was not well understood and underestimated significantly – while it was not noticeable in variance terms, it contributed to project overrun.

The explanations provided through the lessons learned at the project's closed-out review pointed out that:

- Project was delivered on the revised timeline on time and passed all acceptance testing (verification) criteria.
- Inability to accurately estimate materials costs at the start of the project was attributed to incomplete systems engineering activities using significant management reserves.
- Assembly and testing effort could not be estimated accurately for the same reasons as mentioned earlier. In addition, the large amount of rework contributed to the overrun in the assembly process.
- New suppliers had to be quickly onboarded to provide machined parts to meet the tight schedule and new needs. The products had been delivered with some quality issues that required rework.
- Engineering effort associated with requirements engineering and subsequent systems engineering activities, including supporting documentation, was not properly understood, hence was significantly underestimated.
- Requirements solicitation and elaboration did not go to plan, despite the efforts to provide introductory training to customer stakeholders, resulting in multiple assumptions and rework.
- The customer did not anticipate the amount of data and internal effort required when the supplier becomes a system integrator rather than just a component supplier.

4.1.2 Retrospective approach

The proposed MVP-based acquisition framework, when applied retrospectively to this project, could hypothetically improve the outcomes in several areas. First, instead of beginning with requirements engineering with a customer that had no experience in this domain, the proposed framework would create a model and conduct some useful simulations for usability evaluation to better understand what the new technology is all about – its benefits, limitations and challenges that are associated with it (Joiner et al., 2018; Wickens et al., 2014). While some M&S was conducted by the supplier, it was primarily focused on the internal development needs and was not shared with the customer in a useful manner. The new approach would likely have improved engagement from customer stakeholders from both engineering and operational/business functions (Yesudas et al., 2020). Creation of a digital thread and incorporating a MBSE approach would improve the outcome from the modularity perspective and strengthen the case for broader application of the technology. An iterative design approach through all the phases would likely have improved the efficiency of the engineering effort, leading to a potential reduction in the engineering effort. Concurrent development of the hardware and software could have eliminated rework associated with incompatibility of the interfaces, or at least identified the problem at the early design stages, leading to potential savings. Ongoing test or validation activities of the proposed framework would likely have led to higher energy savings and reduced the amount of technical risk, whilst providing the necessary objective evidence for the stakeholders' decision-making.

Transitioning the model into a meaningful hardware prototype in the benchtop phase would have helped the project in multiple aspects. For example, this iteration would likely better tease out the requirements and their validation methods and give an earlier assessment of the performance and interfaces, together with the customer feedback. These benefits should collectively help reduce cost and delivery slippage. The intent within the MVP framework to understand the supply chain needs concurrently with solution development, would likely have enabled the supplier development engineer to stand up suppliers better suited for outsourced products and servicing without as much of the costly rework and delays.

4.2 Reflections overall

The potential advantages of the proposed MVP-based acquisition framework, when reflected by the authors through a retrospective case study, cannot simply be translated into any capability development project. The effort in supporting DE, modelling, and simulation, together with verification and validation (test and evaluation) activities, has to be commensurate with the unique risks identified in all areas of system development and project execution. The more innovative the solution is, and the more complicated the system is, the better the framework likely fits the activities. The proposed framework seeks to solve even complex problems through an iterative multi-phase approach, gradually resolving the complexity to an acceptable solution with a through-life ongoing development process commensurate to assure that complexity. Conversely, if the development needs are clearly understood and risks are insignificant, the traditional methods of project management and systems engineering would likely suffice. The phase zero, or planning phase, plays a big role in this analysis and formulates the future path of the development for any project, in particular, what credible activities inform any integration risk.

Connecting minimum viable capabilities to systems engineering terminology, such as MOE, provides a better degree of clarity and reassurance that the framework is built on rigorous foundations. Hierarchical structures of mission, goals, and objectives can now be traced to MVC and enable better system validation. Further, such an MVP-based framework aims to engender a requirement engineering process that occurs concurrently with the system development, delivering objective evidence throughout the process, rather than just at the end of the activity.

The incorporation of the ICSM into the proposed MVP-based framework provides a way to introduce appropriate governance and oversight with a risk-managed approach and evidence-based decision-making process appropriate to mission-critical and complex systems. The inclusion of ICSM does not overly constrain the agile nature of the proposed framework, but effectively apportions a level of governance that is agreed upon early between stakeholders from the supplier and the customer.

DE enhances the proposed MVP-based framework from both an efficiency and resilience standpoint. The concept of an authoritative single source of truth, together with a model-based approach, helps future-proof the MVP framework and make it an attractive tool for organisations that look for modularity of the system solution and the ability to reuse and adapt the system to fast-changing needs, such as the emergence of new technologies or threats. The combination of models developed in the acquisition cycle supports the user's needs in the operational cycle and beyond. Simulated models provide a foundation for training needs without significant additional effort. Digital twins support health usage monitoring systems (HUMS) or predictive maintenance desired in integrated logistics support (ILS), extending the life of the capability, and improving its availability and maintainability.

Future work will focus on the framework's scalability and addressing feedback provided by first adopters. Scalability in this context is the ability of the framework to meet the needs of internal research and development projects at the lower end of the scale and significant capability development for land, sea, or air platforms at the upper end of the spectrum. It is also assumed that the framework can be used for a mixed TRL system and maturing the capability to TRL 9 as an end goal (Sauser, 2024).

5 Conclusions

Early workshop exposure of an agile MVP-based acquisition framework found the proposed framework required clarifications around the right approach to govern complex systems, better definitions, alignment with DE, and refined governance measures. An extended literature review has improved the proposed framework in all these areas, and it has been illustrated with a retrospective reflection on a case by the authors. The revised MVP-based acquisition framework, Figure 11, supports complex system development through a phased iterative approach. Inclusion of incremental commitment spiral methods into the framework institutes the governance and resilience needed in developing complex and mission-critical systems. Implementing DE principles into the framework makes the development process more resilient, efficient, and supports solution modularity and scalability. The framework is intended to support accelerated capability development, managing fast-changing mission profiles and emergent needs of the end user. The framework usage is primarily focused on the capability development in the acquisition cycle for greenfield applications. The framework aims to support capability developments where the software-intensive applications are combined with the introduction of emergent technologies in hardware and artificial intelligence domains. The framework can also be scaled to cater to brownfield applications and upgrades. The phases need to be adjusted based on the evidence-based reviews of the existing capabilities and proceed in a similar iterative concept of delivering MVCs through the corresponding MVP. Future research is needed to validate the MVP-based acquisition framework across a portfolio of acquisition projects.

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Notes

1 Akin to the law of requisite variety (Ashby, 1956).