Selecting munition design features and operational concepts using a trade study supported by simulated operational scenarios

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Abstract. A development of an existing munition aimed at an entirely new target set was planned. A trade study was performed to identify the key design features and employment concepts that generate the optimum outcomes in a demanding operational scenario. The trade study was configured as a Multi-Attribute Tradespace Exploration (MATE) using a trade study matrix that considers the key design and operational variables to be investigated. The baseline munition concept was parameterised such that design changes are described by those key variables. For each set of tradespace variables the baseline munition design was optimised to maximise its operational range while complying with constraints and meeting the design requirements. The characteristics of each optimised munition was determined for input into a simulation model of an operational scenario modelling the operational environment and the threat systems to determine the best performing munition solution. This paper outlines the implementation of the MATE approach and the lessons learned that can be incorporated in the broader systems engineering discipline.

Introduction

The Council for Scientific and Industrial Research (CSIR) was approached to perform an operations research study on how the effectiveness of an upgrade to an existing air-launched munition design could be maximised in a suppression of enemy air defences (SEAD) scenario. The scope of the study included determining which combination of munition attributes, flight profiles and employment strategies were most effective in the operational scenario. This study was part of the concept definition phase for the development of the next addition to the client's munition family. The study used inputs from the system user as well as the Original Equipment Manufacturer (OEM) and provides inputs and recommendations to the OEM's munition concept definition phase. The study thus complemented and enriched the OEM's concept definition phase.

Performing such a study is not a simple undertaking. A munition has many design features like warhead, seeker, propulsion, guidance, airframe layout, etc. that combine to generate attributes like range, speed, manoeuvrability, signatures, etc. Also, there are many ways in which a given munition can be employed, encompassing choices like launch altitude and speed, cruise flight altitude, cruise speed, terminal flight profiles, direct or evasive flight paths, etc. Many constraints, whether regulatory, technological, political, or commercial, confine and direct the available design choices. Finally, the effectiveness of these design choices must be tested in a representative operational environment if the correct conclusions are to be made. At the same time the stakeholders have different concepts as to what factors are important and how all the different outcomes are weighed and combined to form a preferred solution.

A typical missile concept design framework is shown in Figure 1 (Fleeman, 2001). A notable difference between this workflow and the one required for the operational study is that while the mission is defined, the scenario is presented as a simulation model and the munition requirements and employment concepts are not defined: these definitions must be derived as part of the study, along with the synthesis of the munition concept design. This development in the munition concept design workflow is the rationale for this paper.

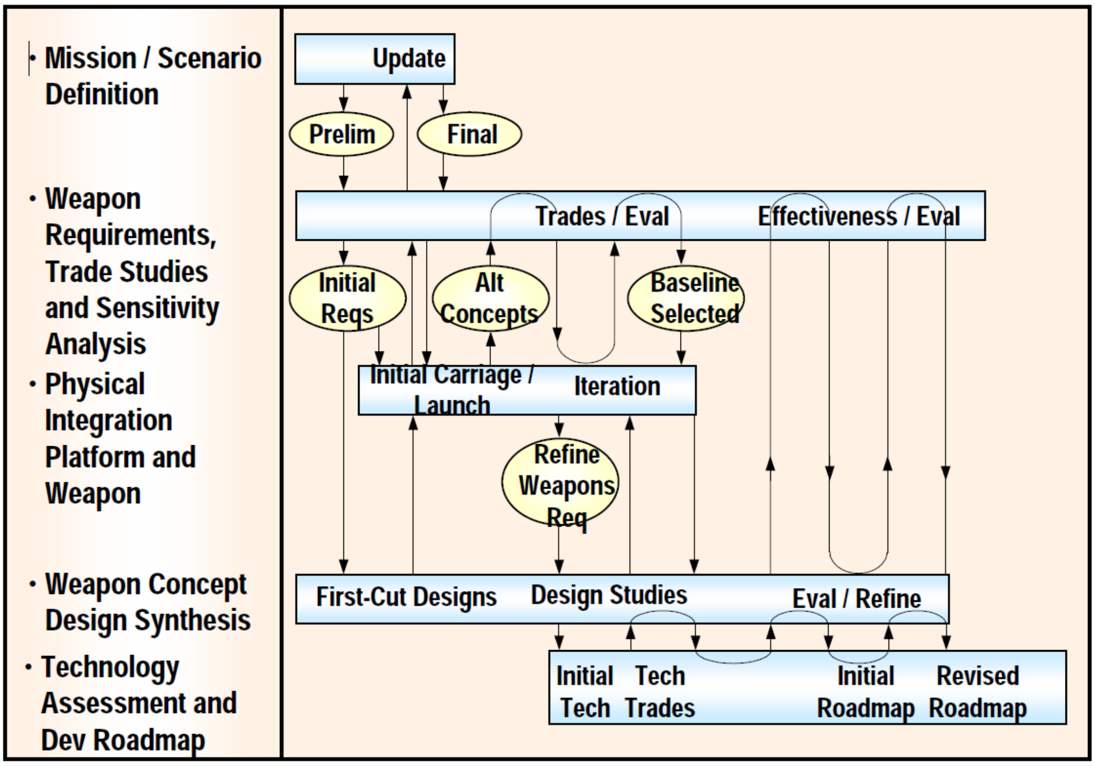

Figure 1. Typical missile concept design cycle (Fleeman, 2001).

A complex system will manifest unanticipated emergent system dynamics (Johnson, 2006). It is therefore important that the selected study approach takes an unbiased view on the potential outcomes and samples this design trade space as comprehensively as possible. Previously it was not technically possible to perform such an investigation of the trade space due to the difficulty and time required to perform the analyses and simulations. Also, the capability and fidelity of simulations of the operational environment were too limited to produce credible results. This scenario has now changed with the latest design and simulation tools such as the CSIR’s Mission Simulation Framework (MSF) becoming available to designers and it is now possible to make better-informed choices earlier in the system lifecycle. This concept is illustrated in Figure 2.

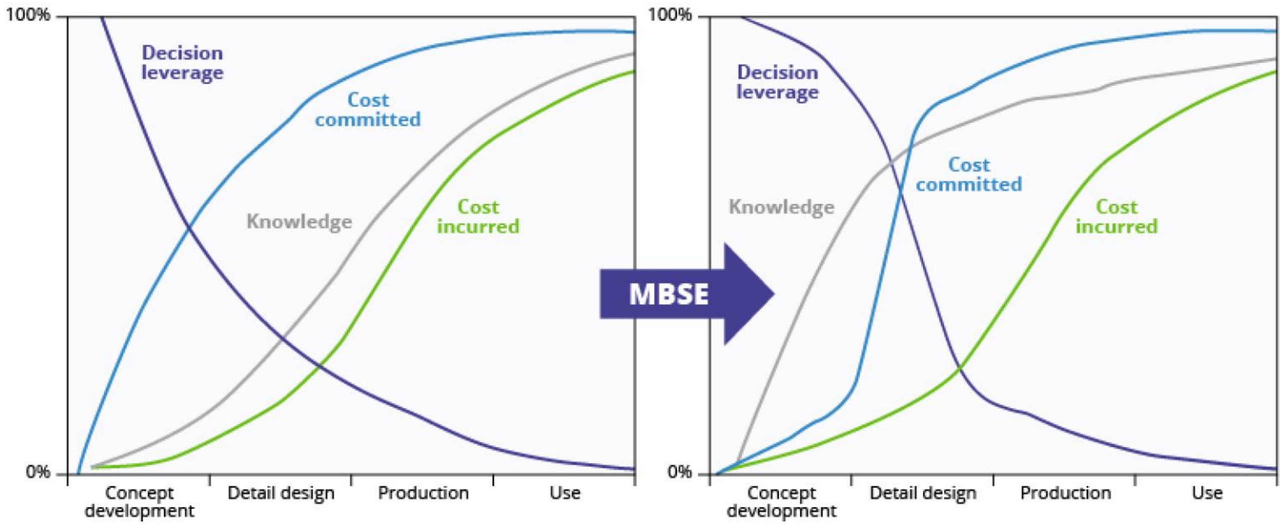

Figure 2. Impact of modelling on increased system knowledge early in system lifecycle (SEARI, 2008).

There are different ways the operational analysis could be structured (London, 2012). One approach is to formulate it as a decision matrix, a qualitative technique used to make design decisions by ranking possible design alternatives against a set of criteria options which are scored and summed to gain a total score which can then be ranked. It can be weighted or unweighted. A weighted decision matrix weights the criteria in order of importance. The resultant scores better reflect the importance to the decision maker of the criteria involved. Another approach is that of the trade study where system designs are evaluated by devising alternative means to meet functional requirements, evaluating these alternatives in terms of the measures of effectiveness and system cost, ranking the alternatives according to the appropriate selection criteria, and then dropping less important alternatives, and proceeding to the next level of resolution, if needed. A newer approach is trade space exploration where large numbers of design alternatives are simulated to give stakeholders an understanding of what is possible, feasible, doable, and achievable. It is a powerful way to explore the range of emergent properties that are possible from a system. Trade studies typically examine a relatively small number of alternatives while tradespace exploration aims to explore the entire design space.

The Multi-Attribute Tradespace Exploration (MATE) (Ross, 2003) approach using various CSIR modelling and simulation tools was selected for this study. The study approach will be explained in more detail and its application to the munition operations study will be described. The performance of the MATE study approach in this context will be evaluated and the lessons learned will be discussed.

The MATE approach to concept trade studies

Operations analysis and trade studies form part of the decision management process where the purpose is "…to provide a structured, analytical framework for objectively identifying, characterising and evaluating a set of alternatives for a decision at any point in the life cycle and select the most beneficial course of action." (ISO/IEC/IEEE, 2015). The SEBoK summarized the decision management process as a circular loop (Madachy, 2021) which illustrates the flow from framing the decision to be made, to developing objectives and measures, etc. that result in a recommendation for a decision. The decision-making process is iterative as the process uncovers information that could result in the decision parameters evolving.

The MATE approach maps well to the SEBoK decision management process, which is why it is an excellent framework for robust decision making. The MATE process in Figure 4 is colour-mapped to the Design-Value Loop as introduced by (Ross, 2015) in Figure 3, showing how the design and value models are connected to the process. The MATE process presented in Figure 4 (Ross, 2017) has been developed further from its original presentation (Ross, 2003) to incorporate sensitivity analyses on the results to assess the robustness of the best performing designs. The MATE methodology has been applied to munition trade studies previously (Derleth, 2003), following the (Fleeman, 2001) design framework shown in Figure 1.

The munition analysis process described in this paper extends the MATE process to incorporate scenario simulations in the tradespace exploration process. The application of MATE will be illustrated in this paper.

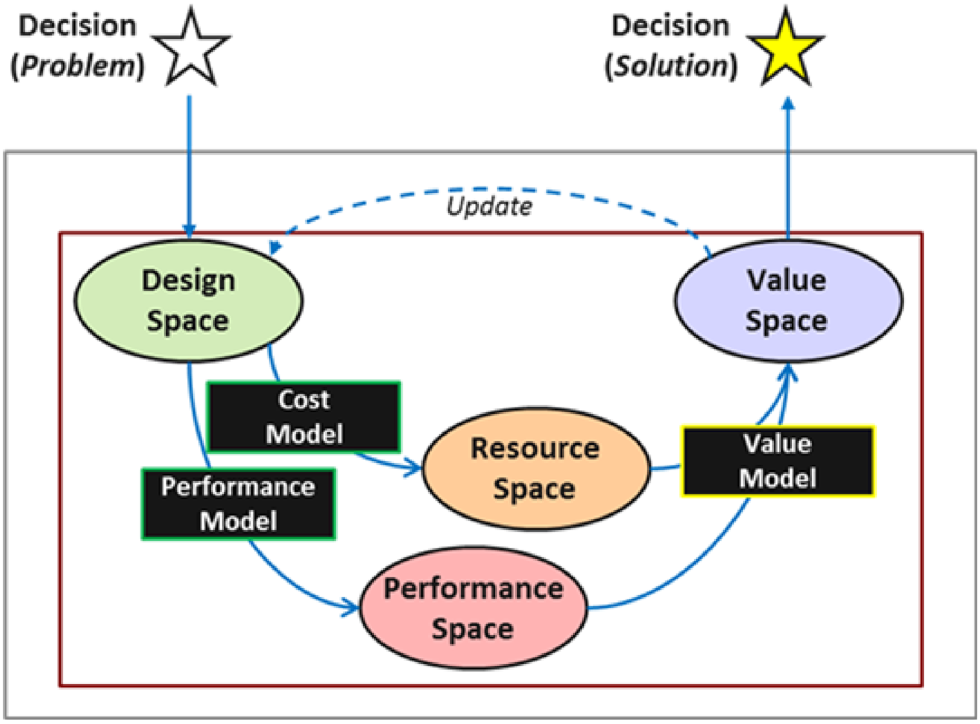

Figure 3. The Design-Value Loop (Ross, 2015).

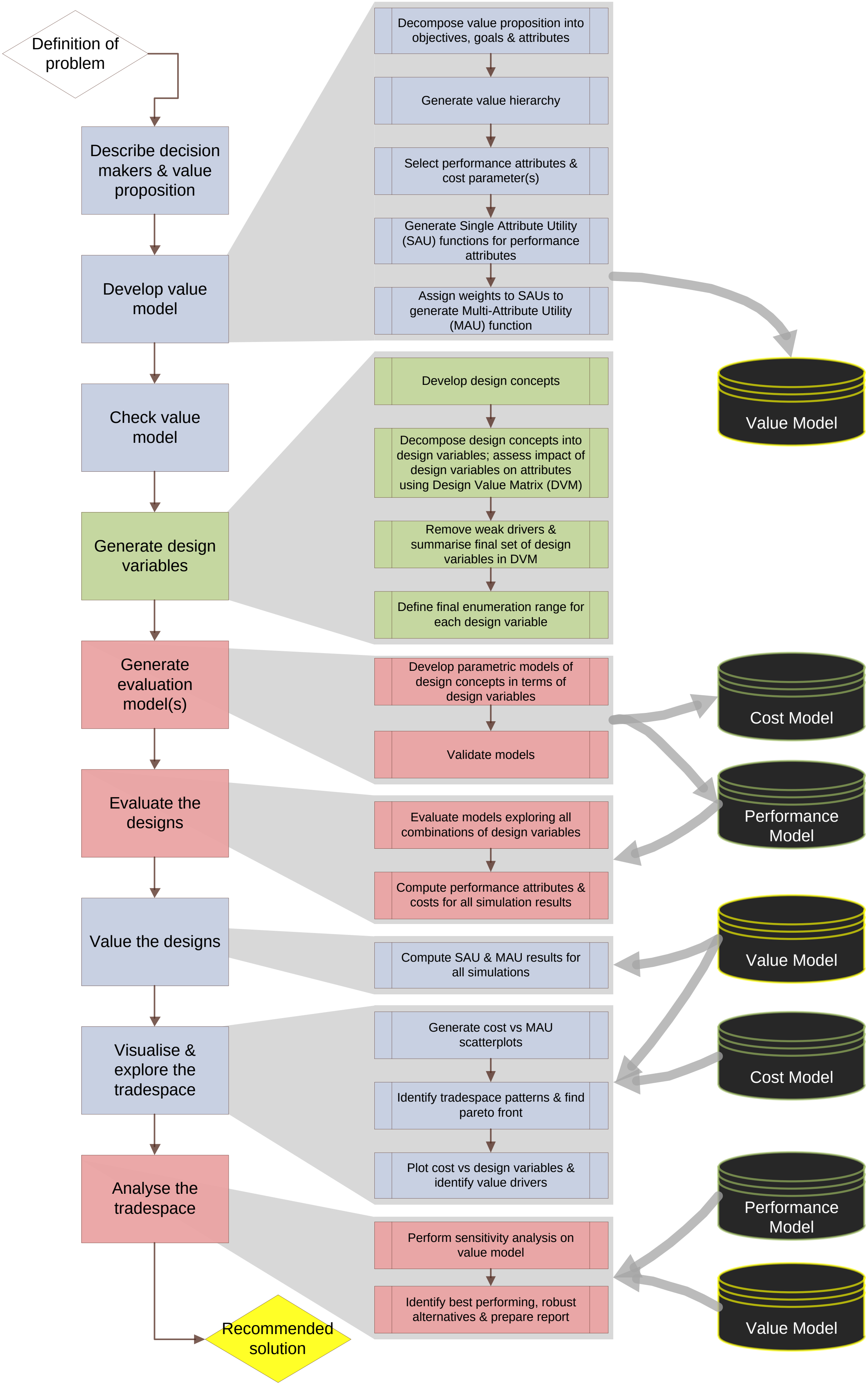

Figure 4. The MATE analysis process (derived from Ross, 2017) (the colours of the blocks map to the Design-Value Loop in Figure 3).

The munition trade study framework

The trade study analysis process adopted for the munition operational analysis is presented in Figure 5. The problem definition phase for the trade study commenced before the contract was placed on the CSIR and included several meetings with the munition OEM and their client to understand and define the problem space. There are therefore two distinct sets of decision makers in the project, the munition OEM, and their customer/system user. It was clear early on that while both parties were in broad agreement on the operational scenario required to test the munition design's performance, there was less agreement on the design objectives for the munition itself. The OEM was the primary decision maker and the only decision maker to remain involved after the project commenced. The inputs of the system user were documented and strongly influenced the design and the value criteria.

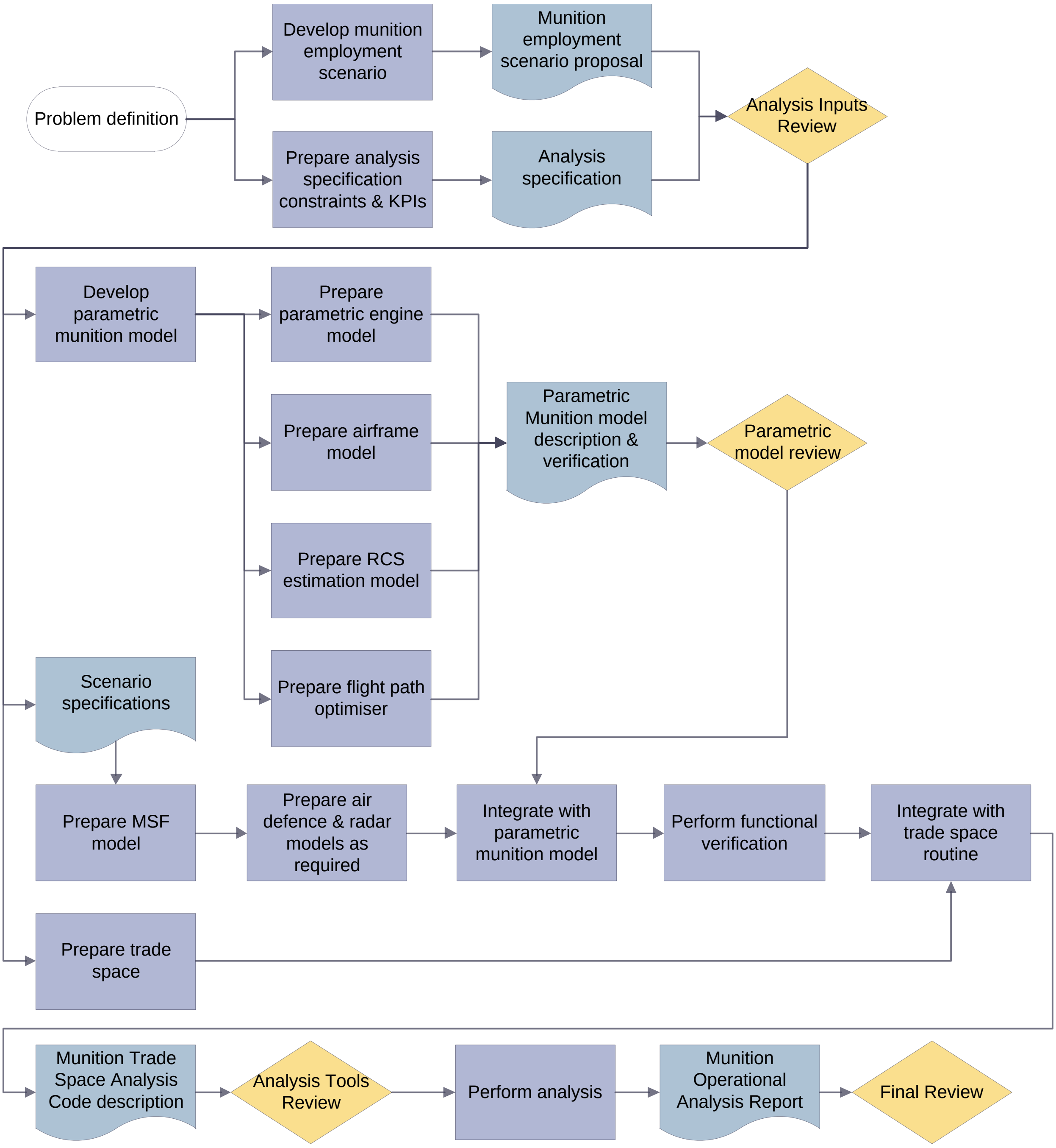

Figure 5. The overall munition tradespace analysis process.

The first phase of the munition analysis process involved unpacking the problem definition into two documents (i.e. Munition employment scenario proposal and the Analysis specification). The munition employment scenario proposal described the scenario in which the munition would be employed in detail. The Analysis specification specified the analysis, setting out the design criteria and constraints for the munition, the value model, performance criteria, design variables, etc. These documents were scrutinised by the OEM client at the Analysis Inputs review.

Acceptance of the analysis inputs by the client initiated the munition modelling phase. In this phase concept designs of the munition are developed that complied with the design requirements and constraints. These designs are then parameterised so they could be adjusted by the design variables such as the selected fuel capacity, design cruise speed, etc. To do this, airframe design and engine parameters of the baseline concept designs are modified. Tools were developed that analysed and characterised the performance characteristics of the modified designs. The three tools that were used were the airframe model that determined its aerodynamic and mass properties, the radar cross-section (RCS) tool that calculated the radar cross-section of the design and the engine model that generated a full performance map of the selected engine.

The outputs of the munition airframe models are integrated into a flight path optimisation tool that calculated the optimum flight path for the design given its specified flight profile and airframe qualities. All the models were validated against benchmark data and the report was reviewed with the OEM client.

In the meantime, the munition employment scenario had been developed into a full simulation software specification specifying each entity in the simulation in detail and its interfaces with the other players. The scenario was implemented in the CSIR’s Mission Simulation Framework (MSF) software and the new models specified and the integration with the parametric munition models were coded. A full software verification effort was done to ensure that all the specified capabilities were implemented and functional. The MSF model was integrated with the tradespace analysis framework such that the list of the different analysis scenarios and the associated munition designs could be imported, executed automatically and the outputs combined in an Excel spreadsheet for analysis.

The mission simulation model, the tradespace software and their integration and verification were documented and reviewed by the OEM client before the analysis phase commenced. The analyses followed by the sensitivity analysis were then performed and the final project report was issued with the recommendations for review.

Implementation of the trade study

Development of munition and scenario specifications

The munition problem statement, along with the inputs from the workshops with the decision makers were captured and expended into a full specification for the project in this phase.

The **analysis specification document** is used to specify the scope, purpose, objectives, approach, and constraints of the study to arrive at a recommended munition concept. The specification relates the selection and weighting of the attributes to the stakeholder’s requirements. The design variables are chosen based on an analysis of the impact that they have on the final design. The munition’s design alternatives, architecture, cost model, analysis process and the analysis criteria are specified in detail. The criteria for selecting promising designs and then testing their sensitivity are also prescribed.

The analysis specification document included the following major sections:

1. The study objectives. The outcome of the study provides the client with the following outputs and with appropriate justification evidence:
    a. Starting points for the munition architecture, configuration and layout that provides the best overall performance.
    b. Starting points for the munition's concept of operations, showing optimal ways to employ the munition for the given scenario and assumptions.
2. The purpose of the munition. In this case the munition's primary purpose is the suppression of enemy air defences (SEAD), with the attack of other high value targets within its capability being secondary missions.
3. The operational context (how it would be targeted, the type of targets, countermeasures, weather, collateral damage considerations, etc.)
4. The munition value propositions. The OEM and the system user's value propositions were captured.
5. Munition objectives. The value propositions were unpacked into a list of objectives.
6. Munition goals. The goals were derived from the munition objectives.
7. Munition value attributes. These are proposed based on the objectives and goals. The performance attributes are effectively the Key Performance Indicators (KPIs) for the munition. The attributes and their range are precisely defined. The cost attribute was defined as the average munition cost per target destroyed in the scenario.
8. Value attribute Single Attribute Utility (SAU) functions. Each performance attribute was converted into a SAU function with a value between 0 and 1. When the performance attribute value is out of range, the SAU result is n/a, and that munition concept is not considered further.
9. Multi-Attribute Utility (MAU) definition. The purpose of the trade study is to optimise the MAU based on these KPIs relative to the cost attribute. To determine the MAU, each KPI is converted into a SAU. The weightings applied to the SAU scores that are combined to generate the MAU score are defined.
10. Munition design criteria. Constraints used to govern the design of the munition are specified based on the inputs from the OEM and system user workshops. These included aircraft integration constraints, regulatory constraints like (MTCR, 2017) and other design constraints. A range of launch and cruise flight profiles combinations are specified. Several munition design alternatives are specified.
11. Component lists with estimated physical properties are specified to serve as the starting point for defining the concepts.
12. The cost model to be used to estimate the cost of the munition concepts is specified.
13. Trade study specification. This section specifies the trade study itself.
    a. Ten design variables were originally proposed which, had they all been accepted, would have resulted in a trade space of almost 35,000 combinations. A design-value mapping exercise (Ross, 2006) was performed against the value attributes where the impact of each variable was assessed subjectively using a 0-1-3-9 scale. Four variables were removed from the trade study, reducing the design space to 648 combinations. The removed variables all form part of layout design in response to the other design variables and can be automated within the design tools.
    b. The rest of this section addressed the processes to develop the design alternatives, characterize design alternative's performance, sample the design space, select the preferred solutions and to test the sensitivity of those solutions. These processes are described elsewhere in this paper.

The **operational scenario specification** researched the system user's threat air defence environment and based on the resulting material, presented, and specified a representative suppression/destruction of enemy air defences scenario to be used for the munition operational research study. The selected scenario was implemented in the CSIR’s Mission Simulation Framework (MSF) software as part of the study.

The scenario incorporated layered long-range, medium-range and short-range air defence systems in a high density, integrated together using datalinks in a centrally managed command and control system that automatically performs threat evaluation and weapons assignment (TEWA). The air defence system was laid out in a configuration and in terrain that is typical of that encountered by the system user. The scenario is used in the munition operational analysis to stress-test the system design attributes and reveal the design combinations that perform best in a very complex and difficult battlespace.

The operational scenario was expected to give representative results for a layered air defence system that is operated by trained and competent operators. It is naturally limited by its assumptions and sources of information. Beyond the researched specifications, the scenario incorporated the experience of several CSIR experts in military aeronautics, radar, optronics and command & control to ensure the behaviours were correct.

The specifications were reviewed together with the OEM client before the modelling work commenced. It was found that it takes time for the client to fully comprehend the approach and the direction that the study was taking, and both sets of specifications would be revised several times during the study.

A major lesson that was learned here is that it is advisable to budget more time and effort to communicate and clarify the substance of these specifications to the client. To this end, it is helpful to perform a simulated analysis using highly simplified “back of the envelope” designs and estimated simulation results to demonstrate to the client how the various attributes, variables and models play out and interact with each other. If this was done at the first review, a lot of rework could have been avoided.

Selection and development of modelling tools

To design and characterise the munition concepts within the tradespace study several modelling tools were used. As a significant number of munition concepts are to be examined while exploring the tradespace, the fidelity of the munition modelling must be traded against accuracy. While tools like computational fluid dynamics, for example can predict the aerodynamic characteristics of a body at a specific flight condition with great accuracy, the time to set up and execute each analysis is significant and these tools are not feasible for conceptual design studies. The emphasis here is to select and use tools that characterise the relevant parameters with adequate accuracy to make the correct configuration choices. Each tool was selected and validated using publicly published test cases.

The aerodynamic prediction tool selected for this project is Missile Datcom version 1997 (Blake, 1997), a widely used semi-empirical datasheet component build-up method for the preliminary design and analysis of missile aerodynamics and performance. Of all the semi-empirical tools evaluated, Missile Datcom was the most flexible in modelling typical missile geometries and robust in its predictions. For validation wind tunnel data for a slender wing/body and wing/body/tailfin combinations (Brooks, 1958) over the flight envelopes of interest was used. Additional aerodynamic corrections for the impact of jet flow on the base aerodynamics of the munition are implemented based on the empirical corrections published by the Engineering Sciences Data Unit (ESDU) (Garner, 2001).

The engines for the munition were analysed using the GasTurb 12 code to predict design point and off design point performance and to generate the engine performance maps used in the analyses. GasTurb 12 uses a complex algorithm to perform Brayton cycle analyses, which takes into consideration frictional losses, pressure losses, and temperature dependence of specific heats. Numerous validation cases have been published, see (Martinjako, 2014) for example. The GasTurb engine performance data was post-processed to generate the inputs required by the trade study analyses.

Determining the correct munition RCS profile to use in the scenario can have a significant impact on the mission outcomes. It is necessary to be able to predict and where possible reduce the munition's RCS. The CSIR's SigmaHat Radar Cross-Section and Electromagnetic Scattering Simulation software was used to analyse the munition's RCS. This is a computational electromagnetics (CEM) tool for the computation of the RCS and electromagnetic scattering of large objects such as aircraft, ships, etc. This tool implements two different asymptotic methods, the shooting-and-bouncing rays (SBR) and the SBR with incremental length diffraction coefficient (ILDC) methods.

Before using the tool, it was important to validate the results that it was producing for the munition. SigmaHat was validated by comparing the results produced for basic objects or features that would be present on the munition, to those produced by Altair FEKO, a CEM tool that uses exact methods within its solver. The results of this validation study confirmed that SigmaHat is sufficiently accurate for this application.

The process of computing the RCS involves firstly creating a three-dimensional model of the munition and then importing this model into SigmaHat wherein it is meshed and prepared for the analysis. The computation is carried out on a cluster of computers and is time consuming to characterise a range of aspect angles and radar frequencies. The long computation time limits the number of analyses that can feasibly be done in a trade study.

A tool was developed in Python to generate optimal flight paths for the munitions based on its structural, aerodynamic and propulsion attributes as characterised by the other codes. This tool generates a flight path for a specific munition given its launch altitude; cruise altitude and Mach number and selected terminal manoeuvres as inputs. These flight paths are imported into the MSF model.

Development of baseline munition designs

This step in the process develops practical munition architectures that can meet the requirements in the analysis specifications and provides a starting point for tradespace exploration using the selected design variables.

Both “small” and “large” design alternatives had been identified in the original analysis specification. The “small” munition designs had lightweight warheads that required a direct hit to destroy the target. This concept had the advantage of lower unit cost, higher aircraft loadouts (four could be carried on an aircraft pylon) and much lower collateral damage probability. The downside was that there would be little commonality with the client's existing munition family and the range of targets that could be destroyed was more limited. The “large” munition was more compact that the client's existing designs, increasing aircraft loadouts but retained significant component commonality.

The activities involved in this phase are presented in Figure 6. The starting point is the component properties presented in the analysis specification. A typical airframe design process is followed where the layout and mass properties are generated, aerodynamic design of the wings and control surfaces is done, and propulsion integration is performed. As soon as basic airframe aerodynamic properties, mission Mach numbers, altitude etc become available, engine cycle calculations can be performed for the various missions. followed by a performance assessment of the concept. This process repeated iteratively until a design is found that meets the constraints and performance objectives. An additional step in this design process is the use of radar experts in the design loop to advise on how the radar cross-section (RCS) of the concept design could be minimised. The concept design and analysis tools described in the previous section are utilised in this process.

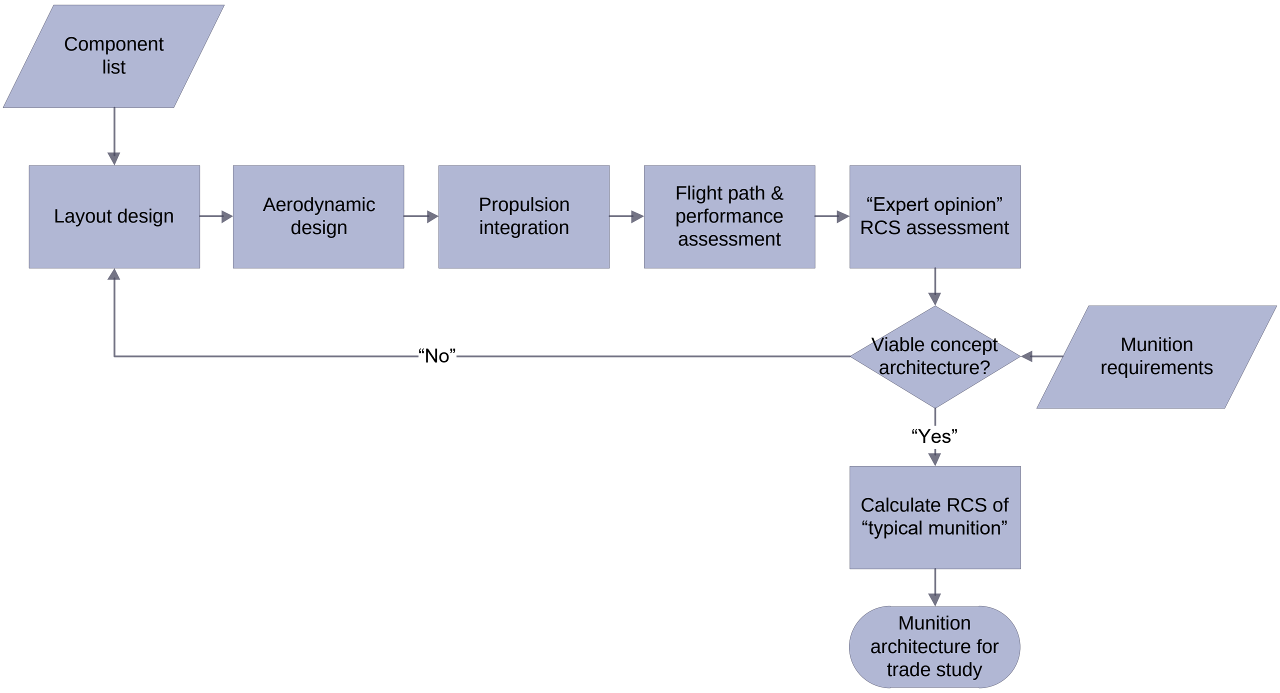

Figure 6: Baseline munition design process

Once viable baseline architectures were determined for the "small" and "large" munitions, their RCS was calculated using the CSIR's SigmaHat software. As the RCS at higher radar frequencies (X-band and higher which are typically used by tracking radars) are strongly influenced by small design details that are typically not defined in the concept design phase, the RCS at those frequencies were not calculated. The RCS calculations focused on quantifying the munition RCS at search radar bands used by the models implemented in the operational mission scenario. An example of this analysis is shown in Figure 7. The "hotspots" are easily apparent and can be mitigated in the next design iteration.

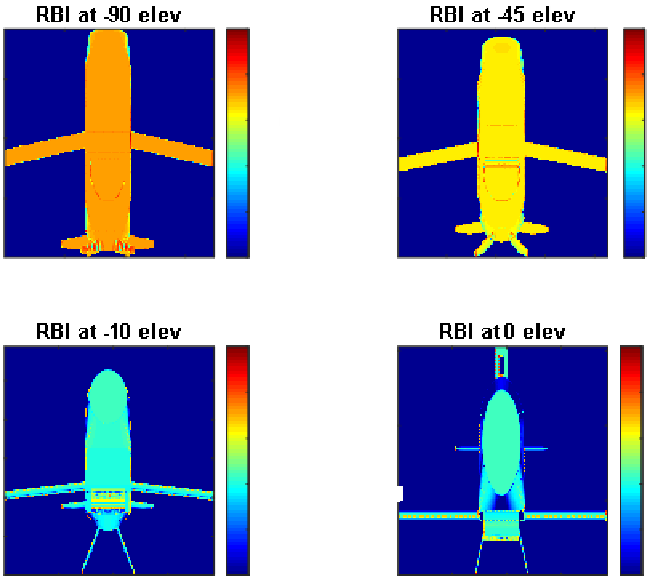

Figure 7 Real Beam Image (RBI) of an early iteration of the "small" munition concept at various elevation angles at 5 GHz

The "small" munition baseline shown in Figure 8 was developed first. When this concept was shared with the client, its lack of commonality with their existing munition family was immediately clear to their management and further work on this concept was stopped. The tradespace study was continued, focusing solely on the "large" munition concept. While the change in the study scope caused some delays, the remaining tradespace was smaller and more focused. The process of developing and presenting concepts in the trade study helped the client to develop a clearer vision of their requirements.

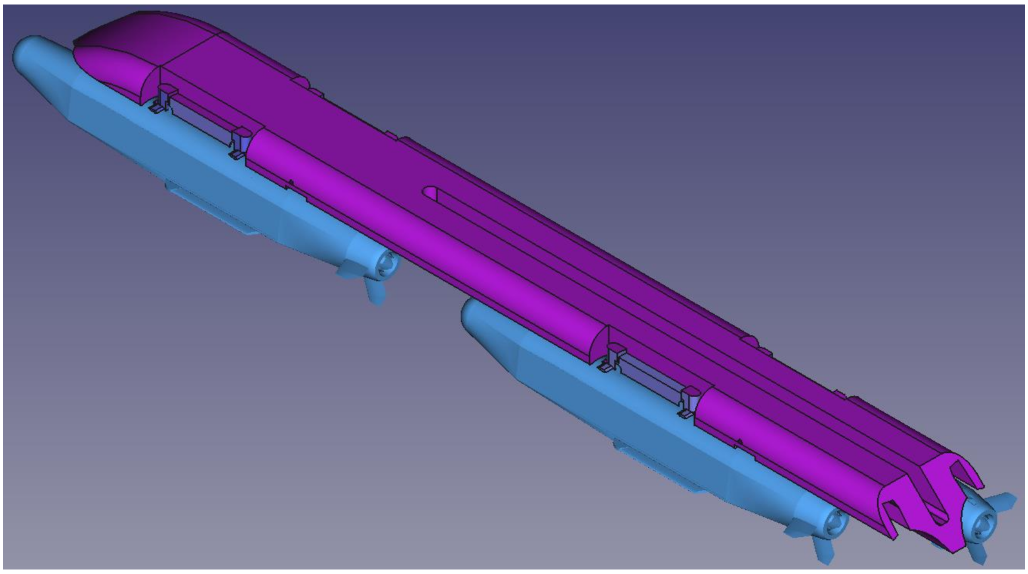

Figure 8: A "small" munition concept in carriage configuration on an aircraft quad-rack

Characterisation of munition designs

The process for characterising the munition designs is presented in Figure 9.

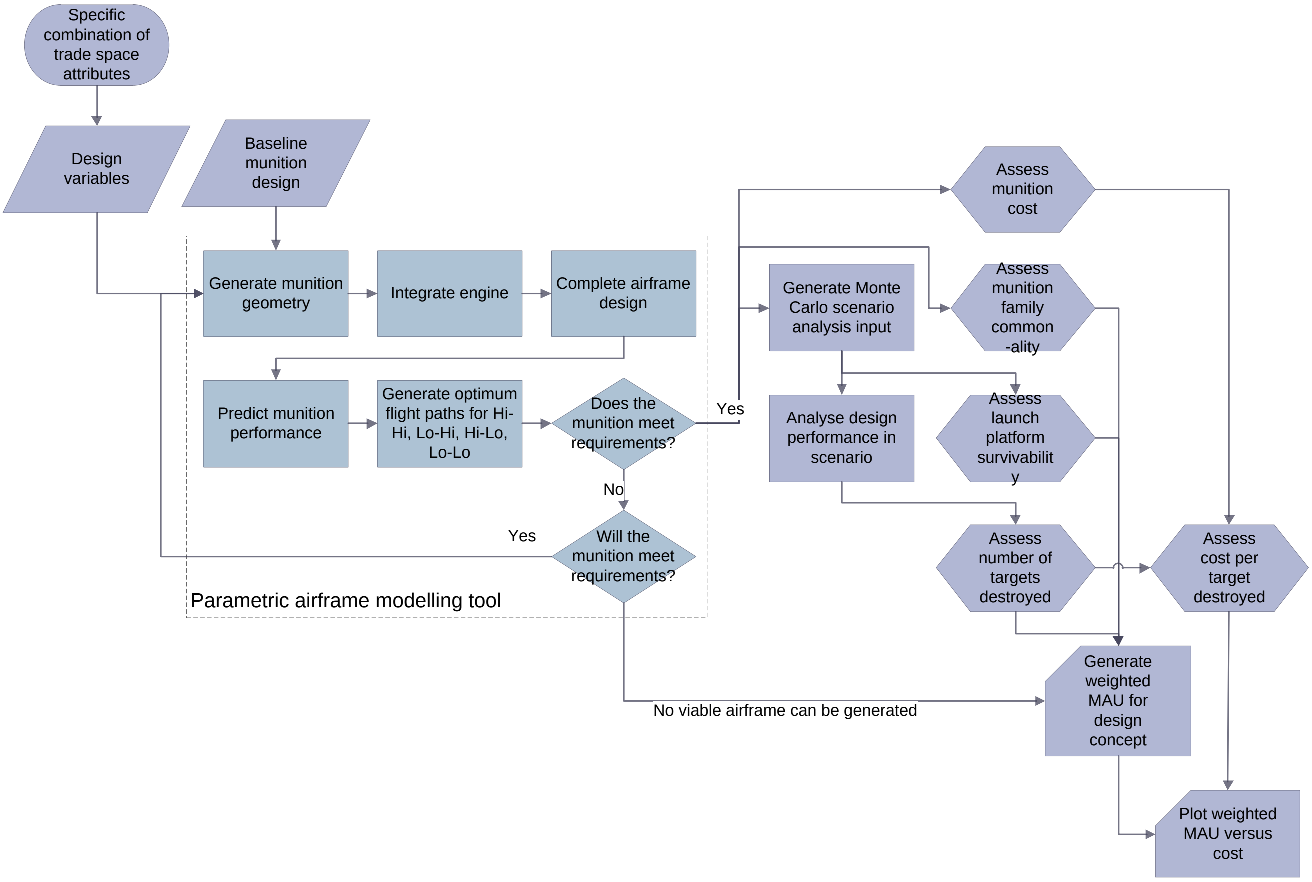

Figure 9: Analysis of a given munition design concept

The baseline large munition was used to generate numerous candidate designs. These candidate designs are derivatives of the baseline that have different design variables/points around which they were optimised, with the objective of improving the munition's effectiveness against an enemy air defence system. Each of the candidate munition designs begins as a set of 3 design variables — cruise Mach number, cruise altitude and manoeuvrability — which are input into the parametric model to generate an optimal munition design and a flight path for it. The three design variables combine into 12 distinct munition designs.

Once each munition was defined the inputs to the MAU could be generated. At this stage the cost of the munition and its commonality with the client's existing munition can be assessed. The characteristics of the candidate munition are determined and then imported into the Mission Simulation Framework (MSF) model where Monte- Carlo scenario simulation assesses the munition's effectiveness in the operational employment scenario. The main outputs of this analysis is the number of targets destroyed and the survivability of the launch platforms.

The analysis matrix to be analysed in Mission Simulation Framework (MSF) code has 6 variables including the 12 munition designs and a range of flight path and operational employment alternatives.

To optimise the number of analyses required in MSF, the analysis design software Design-Expert version 8.0.7.1 from Stat-Ease Inc. was used to generate the analysis matrix. Design-Expert is a very powerful tool for experimental design and analysis. To reduce the analysis matrix to manageable levels for initial investigations an optimised matrix was developed using Modern Design of Experiments (MDOE) techniques. With MDOE, all variables are changed simultaneously, resulting in significantly smaller matrices, although some (quantifiable) compromises must be made with the fidelity of the results. A IV-Optimal Response Surface MDOE technique reduces the initial analysis matrix to 87 scenarios. The point-exchange approach was used to generate the matrix and a quadratic model is fitted to the numeric variables. The model captured the main effects as well as the first-level interactions between the variables. This model facilitates an earlier understanding of which variables are significant.

Modelling the operational scenario

The CSIR has over many years developed a mission simulation capability to support the needs to the South African Air Force (SAAF). This capability is centred on the Mission Simulation Framework (MSF) code, a specialisation of the Live, Virtual and Constructive experimentation toolset (LVCx) that is utilised for mission planning (like at the 2010 Soccer World Cup), investigating requirements for new systems and to develop operational tactics and doctrines. This tool can model large scenarios with many players interacting with each other in both air-to-air and air-to-ground combat contexts.

The main characteristics of LVCx and therefore MSF are:

1. Scalability: it can run on a single node or distributed across several computers.
2. Faster than real-time operation, which can be synchronized with real-time if needed e.g. for live exercises.
3. Modularity: each specialisation of LVCx, such as MSF, is comprised of its own set of library models. Models and functionality can be loaded at runtime, meaning unused functionality does not weigh down on the execution speed. The same simulation back-end can be run with a visual front-end for planning and evaluation, or from the command line for efficient Monte-Carlo runs.

This drives the following model attributes:

1. Models are of a level of fidelity suitable for simulating the interaction between large numbers of systems, faster than real time.
2. The internal behaviour of a model is of lesser importance, and many subsystems are modelled as partial black boxes or look-up functions.
3. Variability in subsystem behaviour is captured in several statistical parameters, such that the average behaviour of the model across a large set of runs approximate the behaviour of the system that the model is based on.

For this trade study, a representative air defence system deployment model was developed. The system consisted of several different ground-based air defence units, such as target acquisition radars, missile launchers and anti-aircraft guns. Each unit consists of a combination of the following model types: platform, search radar, tracking radar, optical sensor, missile launcher with associated missiles, gun with associated shells, and an engagement controller. Each subsystem model, such as a target acquisition radar, was based on a generic model for which the available parameters were calculated such that the model behaviour represents a specific real-life air defence system. Examples of these parameters are timing and delays, fields of view and detection ranges.

Modern integrated air defence systems do not operate in isolation, therefore complex communication between the different units were modelled, along with a threat evaluation and weapons assignment (TEWA) algorithm. Threat evaluation consists of measuring the behaviour and characteristics of detected targets and assigning a threat value to each one based on specific rules. Some examples of these rules are that low-altitude targets have a higher threat value, and munitions are a greater threat than aircraft. These threats are then assigned to specific weapons systems according to the threat value as well as the effectiveness of that weapon against that threat. Figure 10 shows this multi-weapon multi-target engagement. Note that only two missile launchers were used in this initial launch, since they were calculated to be the most effective.

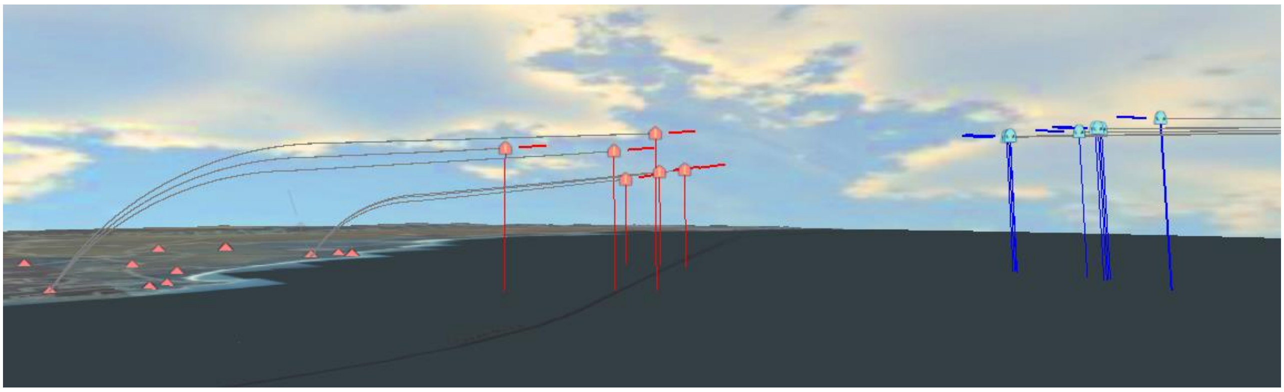

Figure 10: First set of missiles attempting to intercept incoming munitions, simulated in MSF

The weapons systems were placed into a simulated environment containing representative terrain features and atmospheric conditions. The air defence systems deployment layout was reviewed and approved by the customer. A sample defensive layout is shown in Figure 11. Acquisition radars are placed on the highest points in the terrain. Medium range systems such as missile launchers are spread out on other high terrain. Short range systems are placed along the route of most likely ingress, as well as to defend the high value acquisition radars.

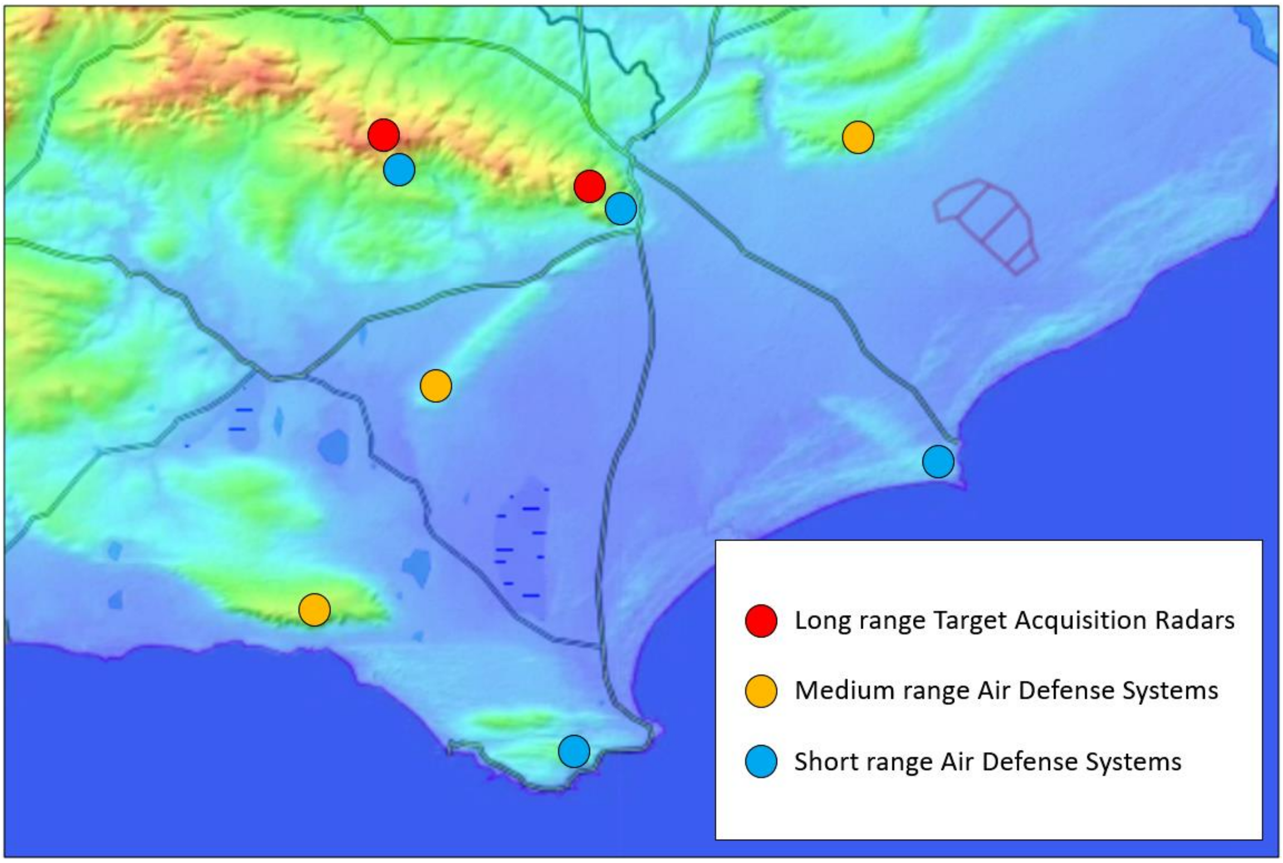

Figure 11: Sample Air Defence Systems layout

During the Monte Carlo simulation phase of the project, the different munition concepts along with their launching aircraft were simulated as attacking the air defence systems entities. Figure 10 shows a high-level attack, while Figure 12 shows the munitions approaching at low level, following the terrain. Each combination was simulated multiple times to determine the average performance while allowing variability in the performance of each individual air defence unit. All the parameters that feed into the Multi attribute value function were measured and aggregated across multiple simulation iterations.

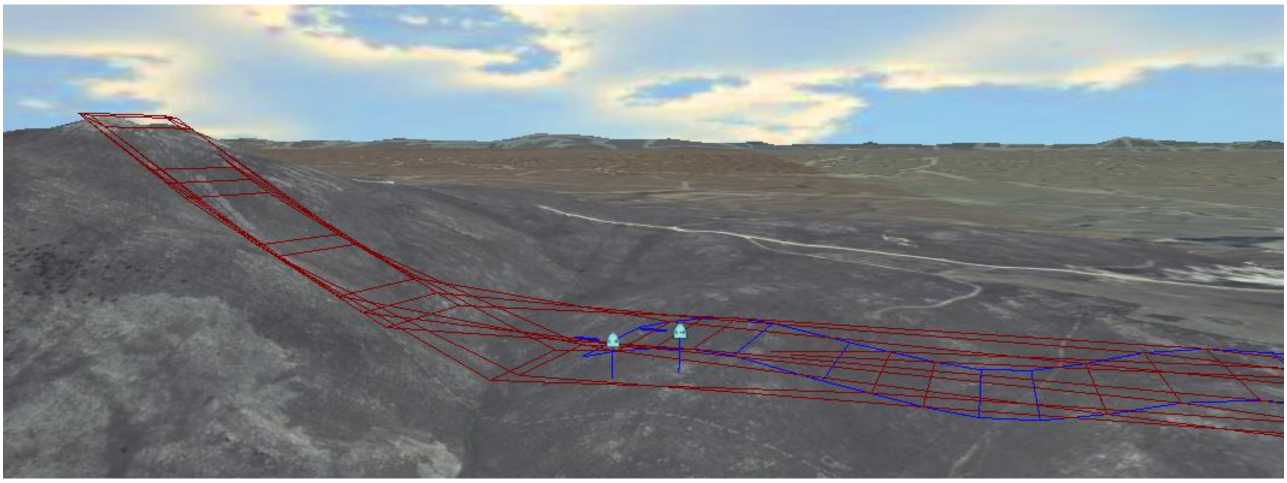

Figure 12: Terrain following munitions heading towards high value target

A lesson learned from the operational scenario modelling process in this study was that integrating the different air defence models together to create a multi-tier intetgrated air defence system (IADS) with a representative command and control system was more complex that expected and took longer than expected as well. Modelling complex systems correctly is challenging and allowances for the number of interfaces and complexity must be taken into account when planning the effort.

Analysing the results

Each scenario in the analysis matric was run at least 45 times in Monte-Carlo mode in MSF to quantify the probabilistic effects in the scenario. The number of Monte-Carlo runs required to obtain 95% confidence in the results are calculated for each scenario, based on the number of targets hit. This number varies significantly from scenario to scenario as some show high variability in the outcomes. The results from the original 87-scenario analysis matrix were plotted and the various parameters were explored in additional graphs. Evaluating the original 87 scenarios shows that the left region of the Pareto front consisted exclusively of scenarios that flew a specific flight profile. The other parameters were more ambiguous. The 87 scenarios were augmented with additional scenarios in the best-performing fight profile to further refine the results. This increased the matrix to 170 scenarios.

Examples of the results are shown in Figure 13 and Figure 14, a subset of the multitude of plots that are generated to explore the data. Note that while 170 scenarios were analysed, not all variable combinations were viable so fewer than 170 results are plotted. The pareto front is better defined and improved MAU/cost ratio points were found. The preferred designs are those that score best relative to the cost per target destroyed. The red line commences at the graph origin and the intersection with the left edge of the Pareto front theoretically identifies the best options. The three best performing munition designs and CONOPS are selected this way for further evaluation in the sensitivity analysis.

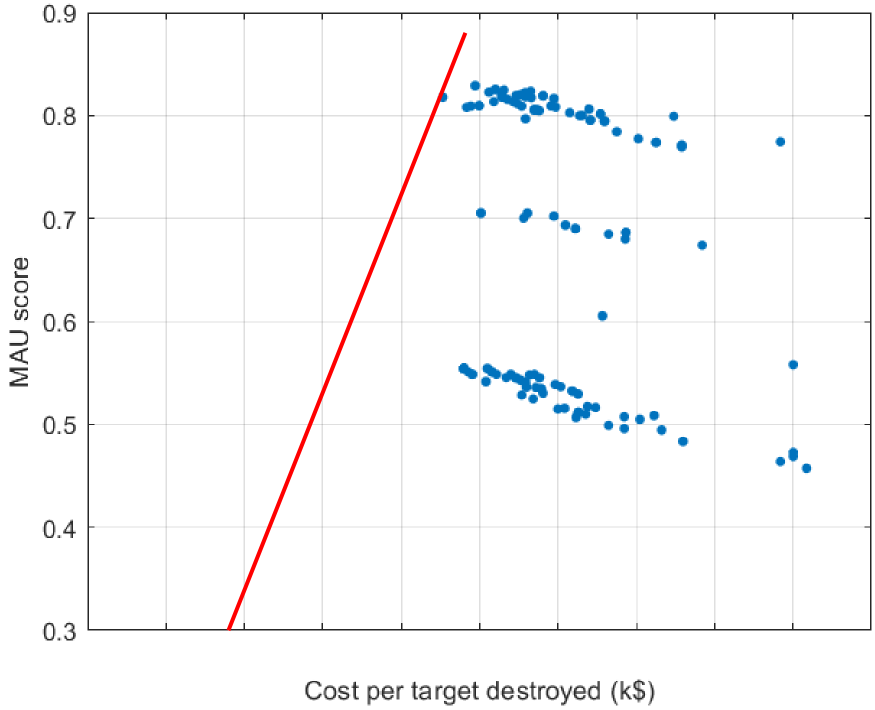

Figure 13: MAU vs Cost per target destroyed

Figure 14: Munition design influence vs Cost per target destroyed

Sensitivity analysis

It is important to assess the sensitivity of the study's outcomes to changes in key variables to understand the robustness of the results. Outcomes that change significantly due to small changes in the environment are undesirable as a starting point for a development program that takes years to produce a munition that must be capable and effective over many years in very different environments to the scenario evaluated here.

Examples of some of the sensitivity analyses are presented below.

1. Sensitivity to the weights in the MAU equation

   The SAU results are weighted to calculate the MAU result for each scenario. The question is whether the trade study results change materially when the weights of each different SAU value is adjusted 10% up or down. The change is proportionately spread across the rest of the MAU equation so all the weights add up to 1.0. The results showed that the MAU values and the scenario rankings did not change materially in response to 10% changes in the weights. The standard deviation of MAU value changes across all weight adjustments was in the order of 4%.

2. Sensitivity to the munition's radar cross-section

   The impact of the munition RCS on the preferred concepts was investigated by reducing the levels in the munition RCS table by 25% and repeating the simulations. Generally, the MAU score increased for most of the designs showing that even this limited reduction in RCS materially improves the performance of the munition.

   The best munition design and employment in the low RCS scenario is the same munition design as the best performing munition in the baseline analysis, but the optimum employment CONOPS changes.

3. Sensitivity to the aircraft launch speed

   The impact of the aircraft launch speed on the preferred concepts was investigated by increasing the aircraft speed during ingress, at munition release and during egress repeating the simulations. Generally, the MAU score increased slightly for most of the designs. There is however a noticeable decrease in the cost per target for some candidates. This is driven by an increase in the number of targets destroyed in the scenario for the best-performing candidates.

   To summarise, increasing the aircraft speed throughout the scenario improves the outcomes significantly without any change to the best munition concept. This outcome is partly due to the reduced time that the aircraft spends within the engagement zone of the air defence systems, improving the survivability portion of the score and partly due to the marginally reduced reaction time for the air defences that tipped the scale towards another target being destroyed. It is clearly beneficial to qualify the munition for release from the aircraft at the highest possible speeds.

Discussion

The design of any airframe is a highly complex problem with a multitude of conflicting constraints and performance criteria that must be traded off against each other during the concept design phase. The quality of the design decisions made during the concept phase have an enduring impact on the success of the system for the rest of its life cycle. It is therefore critically important to prove that the airframe design and employment concept is effective and optimally meets the stakeholder requirements. The CSIR was contracted to utilise its operational modelling tools to provide a simulated operational environment to evaluate the emergent impact of the design trade-offs for an air-launched munition in a highly complex scenario.

When considering the interactions between multiple complex systems, multiple unanticipated emergent properties may appear, and it is important to sample the full trade space covered by the system's variables. The MATE approach originally developed at MIT was selected as a vigorous trade space evaluation process that on one hand clearly links the analysis to the system's measures of performance and client preferences and secondly facilitates a rigorous exploration of the variables driving the airframe's design choices.

The study was carefully controlled by capturing the analysis requirements and the operational scenario in specification documents that were then reviewed with the client. The study process included multiple client reviews at appropriate points in the process which enabled the client to engage continuously with the study as it progressed. These reviews proved to be essential for keeping the study on track as not all requirements or constraints were captured in the original specification documents: key constraints only emerged later once the design alternatives being investigated were visually documented.

It was also found that simulating the study as an example before its implementation also facilitates client understanding and engagement with the proposed variables and analysis. If this step was done at the outset, the quality of the overall study could have been improved. It is recommended that this is done as part of the "Analysis Inputs Review" for all future MATE study projects.

Once the study specifications were accepted, a typical multi-disciplinary munition concept design process was followed to define "baseline" munition concepts that were then parameterised to be manipulated by the variables in the MATE framework. The relevant performance attributes of each munition concept were characterised using validated low-order tools for input into the operational scenario model. The use of baseline designs as the basis for each class of munition concepts ensured that the various munition design alternatives generated by the tools were realistic and credible. This process proved to be robust, but as expected there are many combinations of variables that produce physically unrealistic results that were automatically removed from the study. This does mean that out of the multitude of possible solutions defined by the analysis variables, the number of viable combinations that are submitted to the operational scenario is substantially reduced, making the analysis quite feasible in terms of effort.

The operational scenario that was simulated was very complex and it took a significant effort to implement and verify the specified air defence threat models and especially its integrated command and control system. The concern that the model is not representative as it cannot be validated against real systems is mitigated using an established air defence modelling framework and the use of experts to check the models.

A sensitivity analysis was done to test whether the preferred concepts are robust even when different weights and assumptions are used. The sensitivity analysis also provided significant insights into profitable avenues for improving the munition design in future design iterations.

A particular munition concept presented the best multi-attribute utility score and the performance of this concept proved to be robustly superior throughout the sensitivity study. It was noteworthy that the munition employment concept preferred by the analysis differed from what the analysts would have intuitively chosen and this proves the value of neutrally exploring the trade space. The discipline of rigorously implementing the entire MATE process increased the knowledge of the design concept and the factors that affect its operational performance significantly at a very early stage in the design process, supporting and verifying the argument presented in Figure 2.

Conclusions

A trade space exploration study has been described investigating the optimum design and employment configuration of a new development in an existing munition family to be optimised for SEAD. A set of munition requirements were developed based on extensive interactions with the client before and during the project. A viable baseline munition concept was developed that complied with the requirements. The study was structured as a Multi-Attribute Tradespace Exploration (MATE). A trade space matrix was developed considering the key design and operational variables that were to be investigated.

The MATE framework proved to be very effective for performing a complex concept design study like this. It facilitates a robust and unbiased exploration of the design space, testing the performance of the design alternatives in a simulated mission environment while ensuring that the impact of all the design constraints are accounted for. Involving the client step-by-step in the MATE process through regular reviews was very valuable and is vital for ensuring that the study meets the client's requirements.

The structured phases of specification development, trade study design, development of baseline designs, parameterisation, operational scenario development and then the analysis phases all worked together to develop significant insight into the trade-offs and operational interactions needed to make informed decisions about the system configuration during the concept design phase. Testing the design alternatives in the complex operational scenario modelled in the MSF software generated valuable insights that could not be obtained by other means in time to influence the design of the system concept.

It is recommended that trade space exploration studies supported by operational simulations should be used to support system concept definition studies broadly across the systems engineering discipline. Further case studies on MATE applications in other engineering fields will be useful to test this recommendation.

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Biography

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