A METHODOLOGY FOR THE MODULARIZATION OF OPERATIONAL SCENARIOS FOR MODELLING AND SIMULATION

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A METHODOLOGY FOR THE MODULARIZATION OF OPERATIONAL SCENARIOS FOR MODELLING AND SIMULATION

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LIST OF SYMBOLS AND ABBREVIATIONS

AA	Analysis of Approaches
AAF	Adaptive Acquisition Framework
AB	Agent-Based
ABS	Agent-Based Simulation
ACAT	Acquisition Category
AE	Analysis Environment
AFSIM	Advanced Framework for Simulation, Integration, and Modeling
AI	Artificial Intelligence
AoA	Assessment of Alternatives
AS	Approach Selection
BGA	Baseline and Gap Analysis
CBA	Capabilities Based Assessment
CDD	Capabilities Development Document
CFA	Combinatorial Feasibility of Approaches
CONOPS	Concept of Operations
DAP	Defense Acquisition Process
DAS	Defense Acquisition System
DCR	DOTmLPF-P Change Recommendation
DE	Discrete Event
DES	Discrete Event Simulation
DOTmLPF-P	Doctrine, Organization, Training, materiel, Leadership and Education, Personnel, Facilities, and Policy
DoD	Department of Defense

DoDAF	Department of Defense Architecture Framework
DoE	Design of Experiments
DPG	Defense Planning Guidance
DSE	Design Space Exploration
DSO	Design Space Optimization
EMD	Engineering & Manufacturing Development
EoA	Evaluation of Alternatives
FAA	Functional Area Analysis
FNA	Functional Needs Analysis
FSA	Functional Solutions Analysis
FY	Fiscal Year
GAO	Government Accountability Office
GR	Gap Reassessment
HADR	Humanitarian Aid and Disaster Relief
IA	Identification of Approaches
ICD	Initial Capabilities Document
IPPD	Integrated Product and Process Development
JCIDS	Joint Capabilities Integration and Development System
JCS	Joint Chiefs of Staff
MBSE	Model-Based Systems Engineering
MDD	Material Development Decision
MoE	Measure of Effectiveness
MoP	Measure of Performance
MSA	Materiel Solution Analysis
NATO	North Atlantic Treaty Organization

NDS	National Defense Strategy
NMS	National Military Strategy
NSS	National Security Strategy
O&S	Operations & Support
PD	Problem Definition
P&D	Production & Deployment
PDR	Preliminary Design Review
PPBE	Planning, Programming, Budget, and Execution Process
R&D	Research & Development
RFP	Request for Proposal
RFLP	Requirements, Function, Logic, Physical
SD	System Dynamics
SE	Systems Engineering
SF	Scenario Formalization
SME	Subject-Matter Expert
SoS	System-of-Systems
STORM	Synthetic Theater Operations Research Model
TMRR	Technology Maturation & Risk Reduction
UAS	Unmanned Aerial System
UJTL	Universal Joint Task List
USAF	United States Air Force
USN	United States Navy
VUCA	Volatility, Uncertainty, Complexity, Ambiguity

SUMMARY

As military operating environments and potential global threats rapidly evolve, military planning processes required to maintain international security and national defense increase in complexity and involve unavoidable uncertainties. The challenges in the field are diverse, including dealing with the reemergence of long-term, strategic competition over destabilizing effects of rogue regimes, and the asymmetric non-state actors' threats such as terrorism and international crime. The military forces are expected to handle increased multi-role, multi-mission demands because of the interconnected character of these threats.

The objective of this thesis is to discuss enhancing system-of-systems analysis capabilities by considering diverse operational requirements and operational ways in a parameterized fashion within the Capabilities Based Assessments process. These assessments require an open-ended exploratory approach of means and ways, situated in the early stages of the planning and acquisition process. Once the reflection of increased demands is introduced into the process, the integration of multi-scenario capabilities into a process with low-fidelity modeling and simulation is of particular interest. This allows the consideration of a high quantity of feasible alternatives in a timely manner, spanning across a diverse set of dimensions and parameters.

A methodology has been devised as an enhanced Capabilities Based Assessment approach to provide for a formalized process for the consideration and infusion of operational scenarios, and properly constrain the design space before the computational analysis. In this context, operational scenarios are a representative set of statements and

conditions that address a defined problem and include testable metrics to analyze performance and effectiveness. The scenario formalization uses an adjusted elementary definition approach to decompose, define, and recompose operational scenarios to create standardized architectures, allowing their rapid infusion into environments, and to enable the consideration of diverse operational requirements in a conjoint approach overall. Pursuant to this process, discrete event simulations as low-fidelity approach are employed to reflect the elementary structure of the scenarios. In addition, the exploration of the design and options space is formalized, including the collection of alternative approaches within different materiel and non-materiel dimensions and subsequent analysis of their relationship prior to the creation of combinatorial test cases.

In the progress of this thesis, the devised methodology as a whole and the two developed augmentations to the Capabilities Based Assessment are tested and validated in a series of experiments. As an overall case study, the decision-making process surrounding the deployment of vertical airlift assets of varying type and quantity for Humanitarian Aid and Disaster Relief operations is utilized. A demonstration experiment is provided exercising the entire methodology to test specifically for its suitability to handle a variety of different scenarios through process, as well as a comprehensive set of materiel and non-materiel parameters. Based on a mission statement and performance targets, the status quo could be evaluated and alternative options for the required performance improvements could be presented.

The methodology created in this thesis enables the Capabilities Based Assessment and general defense acquisition considerations to be initially approached in a more open and less constrained manner. This capability is provided through the use of low-fidelity modelling and simulation that enables the evaluation of a large amount of alternatives. In advances to the state of the art, the methodology presented removes subject-matter expert and operator driven constraints, allowing the discovery of solutions that would not be considered in a traditional process. It will support the work of not only defense acquisition analysts and decision-makers, but also provide benefits to policy planners through its ability to instantly revise and analyze cases in a rapid fashion.

CHAPTER 1. INTRODUCTION & MOTIVATION

This chapter provides insight into the prospective future operating environment and its highly dynamic and unpredictable nature, separating and assessing the various challenges that lie ahead. On a more abstract level, it discusses the general approach towards creating and maintaining a stable security environment and the inherent interdependencies when considering measures to change the means and ways of military operations. It concludes with a preliminary outline of the institutionalized process and the research objective of this study, filling a crucial gap in improving defense acquisitions moving forward.

1.1 Future Operating Environment

When assessing the global threat environment, one observes a rapidly evolving situation of increasing complexity, raising profoundly new challenges and the re-emergence of traditional strategic adversaries [1]. Non-state actors are evolving and obtaining increasingly sophisticated capabilities. Terrorist organizations are exploiting weaknesses in our technology-dependent societies, while defying military technological means in asymmetric confrontation. Rogue regimes, such as Iran and North Korea, continue to destabilize their regions. Revisionist, authoritarian powers, such as China and Russia, are raising the stakes in long-term, strategic power competition with the United States.

1.1.1 Potent Non-State Actors

Non-state actors play an increasing role both in security critical domains such as the cyberspace as well as in traditional categories of military confrontation. The development of the cyberspace poses an unknown threat, with its paramount role in every aspect of daily life, the ability of private actors to effect wide-ranging consequences with comparatively little resources and its relevance for the military and security critical infrastructure [2][3]. Within the air space as more traditional warfighting domain, states so far could rely on an almost exclusive air superiority, especially against non-state actors. However, since technologies such as unmanned aerial vehicles become more widely available and easier to build, that paradigm gets challenged [4]. While such action can be employed by criminal organizations or even rogue individuals by their own drive and for their own good, it can also be done on the behest of a state.

While criminal organizations harm society in a variety of ways, their existence and operations do not necessarily have security implications, although their conduct can qualify in that category. An example for security-critical non-state actors are drug trafficking organizations in Mexico, Central and South America who operate potent, heavily armed and large scale groups managing to defy border security for smuggling purposes, willing to engage in violence to achieve their goals and able to conduct business across the United States [5]. The fact that various drug cartels are able, through sophisticated networks and tactics, to deliver drugs from all across the continent over the border into every corner of the United States is relevant for national security as these established routes can in principle be used for any kind of goods or people including weapons and terrorists [6]. Another example for the threat potential of criminal activities are hackers gaining access to data from mobile providers. Data obtained and quickly analyzed by the New York Times Privacy Project enabled operators to deduce not only the locations of key politicians up to the President of the United States, but through long-term comparisons also the identification of operational patterns within organizations such as the Pentagon, Congress, and the White House [7].

Combating such non-state actors is no longer exclusively the task of law enforcement officials but becomes part of military operations due to their international operations and outlined criticality for national security. It includes deploying troops and assets to fight drug producers and smugglers or maintaining a unified combatant command to tackle a variety of cyber threats are already reality.

1.1.2 Terrorist Threat

Terrorist organizations, specific kind of non-state actors with blurring distinguishability from criminal organizations, continue to be a persistent threat with the ability to evolve and adapt to countermeasures [8]. Driven by ideologies and operating in unstable political and weak economic environments, their actions further destabilize critical regions across the globe causing a spiral effect. In our contemporary environment, they adapt and are utilizing technologies such as the internet and social media for their own purposes, while restraining technology use on other occasions to defy technology-dependent military approaches. The benefits of modern technologies such as easy access to information, interaction over distances, and easy outreach to a vast audience are also available and actively used by terrorist organizations for conducting harmful operations and for recruiting new members [9]. On the other hand, they actively show restraint in using technologies that could affect their detection or more general harm their operations [10].

Examples for the exploiting and evading tactics employed by terrorist organizations are numerous. Based on the spread of social media in general and the availability of internet across the Middle East and Africa, Al Qaeda run a digital magazine in English, which inspired the 2010 Boston Marathon bombers; the Taliban operated multiple Telegram channels in various languages, commanding multiple thousand followers, utilized for propaganda and demonstrating their ability to govern; AQAP in Yemen frequently tweets about community development, attempting to cater to international and national audiences to present themselves as viable government alternative [11]. Technology avoidance is exemplified by the operational scheme of Osama bin Laden uncovered after the raid in 2011. He frequently and extensively communicated via email, utilized couriers to send and receive the drafted messages at various unsuspicious places and was thereby able to continue to manage Al Qaeda while hiding, defying the technological superiority of his adversaries for an extended time [12].

Combating terrorist organizations remains an imminent necessity, and it is a major activity with regards to operational deployment abroad of the U.S. military. As indicated in Figure 1, based on data collected from government sources by the Smithsonian Magazine [13], the U.S. military is deployed in numerous countries, especially in the Middle East, South East Asia and Africa, to conduct counter-terrorism operations.

a

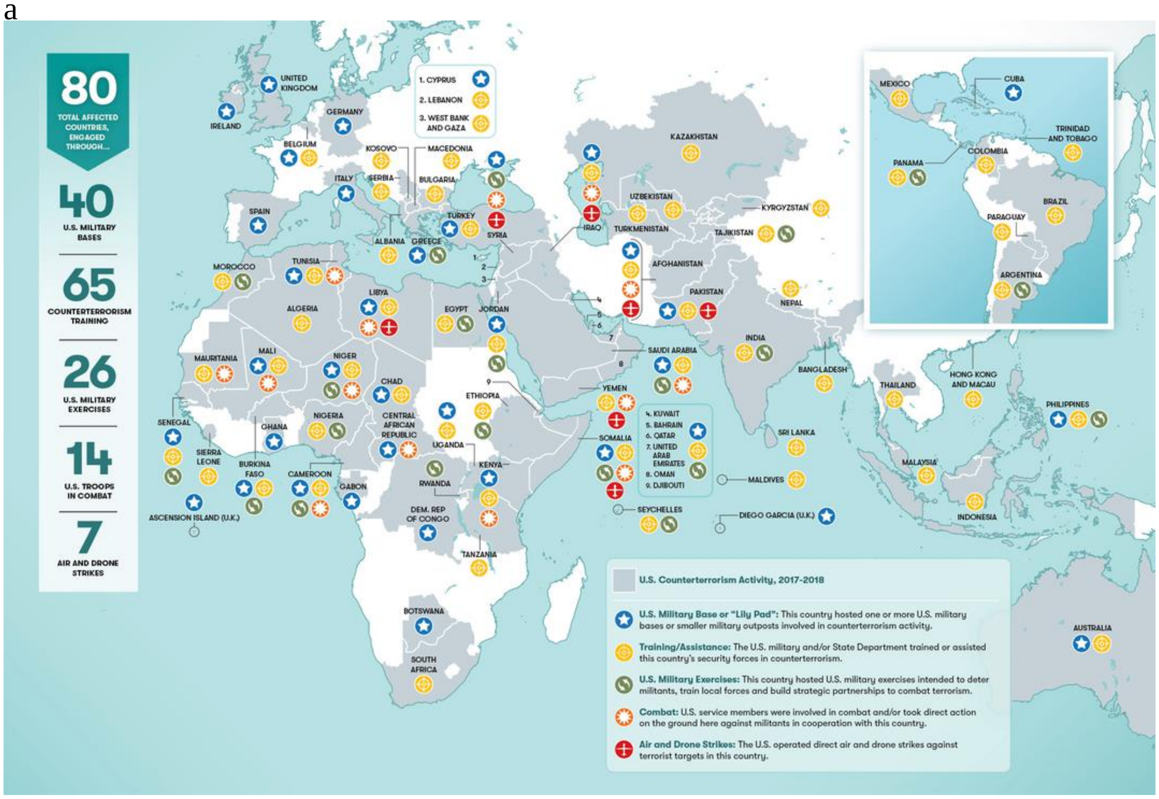


Figure 1: Map Showing U.S. Military Operations Combatting Terrorism (as of January 2019) [13]

1.1.3 Rogue States

The regimes in Iran and North Korea pursue nuclear armament in regions with critical non-nuclear allies and aim for regional influence and hegemony contrary to Western interests [14][15]. Iran in the Middle East is competing for regional dominance, fueled by the decades-old religious feud between the Shia and Sunni branches of Islam especially with the U.S. ally Saudi-Arabia [16]. Its actions occur in the form of proxy conflicts in regional theaters such as Syria and Yemen, state-sponsored terrorist activities, and the development of missile weapons systems to pose a credible and permanent threat to other regional powers. North Korea is struggling to satisfy the basic needs of its population in its isolated and secluded state, reliant on foreign aid to prevent a humanitarian catastrophe and internal breakdown [17]. Its regime is aiming first and foremost at surviving through military might by a mixture of conventional, unconventional and weapons of mass destruction, enabling coercive influence over key U.S. allies like Japan and South Korea and ultimately the United States itself. The nuclear armament aimed for by both regimes, currently in different stages of progress, can solidify the durability of the respective regime. The successful completion of their programs including long-range and intercontinental ballistic missile capabilities pose a threat to regional and global allies and could even enable an attack on the U.S. homeland.

1.1.4 Long-Term, Strategic Power Competition

The most relevant threat and prioritized challenge is the reemergence of long-term, strategic competition with revisionist powers such as China and Russia [1]. Both countries show more and more clearly the intention and subsequent action to revise and replace the current international order. Based on their respective domestic authoritarian model, they strive to gain significant influence up to vetoing authority on other countries diplomatic, military, and economic affairs.

1.1.4.1 China

China has seen a rise to the world's second-largest economy and number two in defense spending, bringing new dynamics into the global balance of power and inserting change into existing bilateral and multilateral arrangements [18]. The country is in a state where it can enter, or might have already entered, in an open rivalry with the United States by expanding its immediate sphere of influences at the cost of U.S. interests in the region and by working on deconstructing the elements of the international order contrary to its interests [19]. The reaction of the United States and subsequent interaction will drive the development of global affairs and define the future operating environment with regards to symmetric power competitions.

1.1.4.2 Russia

Russia, the successor of the Soviet Union as great power in the bipolar Cold War era, is actively working on regaining the status as equal amongst the global powers and a larger sphere of influences along its border [20]. Thereby, it faces the challenge of being "too nuclear and too big to fail, but also too big to secure" [21]. Its former status, as a significant military power, not only with respect to nuclear arms but also conventional capabilities, and the willingness of its leader to take significant and costly actions abroad set it on a trajectory for confrontation with other global powers [22]. Its security strategy of 'regional fracture', exploiting existing and creating new regional conflicts at its border to prevent consolidation of power and to enable the continuation of influence [21], creates breeding grounds for global security threats. Furthermore, its economic situation, the backbone necessary for every power to sustain long-term competition, significantly disfavors Russia compared to a variety of countries and especially China and the United States [23].

1.1.5 Consequences of the Prospective Environment

1.1.5.1 VUCA Environment

The changes in the operating environment describe a deterioration into the so called VUCA environment, characterized by volatility, uncertainty, complexity, and ambiguity

[24]. The origins of this term trace back to a coinage of the U.S. military after the Cold War to abstractly describe a new emerging type of warfare.

Volatility describes the effect of high interconnectivity of economic, social, and geopolitical factors that can yield rapid, strong, and unforeseeable changes to the status quo. In a strategic sense, one can surprisingly find itself both in advantageous and disadvantageous situation with regards to one's adversaries with new or diminished options to act and an unpredictable timing of further changes. In contrast to a stable world with limited number of relevant powers and containment of foreign and security affairs to state-to-state interaction, the progressing globalization yields an ever-fluid and hard-to-control security environment.

Uncertainty spreads due to the inability to use past or even present experience to develop sound future solutions. The more predictability getting removed from the planning process, the higher the number of possible paths of development. One can no longer rely on subject-matter experts and experience-based decisions, raising the need to develop a better sense of awareness of the general situation and to include the inherit uncertainty into the decision-making process to successfully cover multiple possible outcomes and paths.

Complexity derives from the aforementioned multitude of relevant forces and the connectedness that drive the development in the environment. Various non-traditional effects such as activities of non-state actors and the global mobility of people, knowledge and goods compete gain relevance and compete for attention with traditional challenges on different levels. Paired with uncertainty, the complex situation requires sophisticated solutions based on holistic views as opposed to specialized and compartmentalized approaches.

Ambiguity is a consequence of the three previous characteristics. Moving forward, even decisions with previously limited impact and scope can have far reaching consequences in other realms. Both the planning and execution process will become harder and more interconnected, requiring considerations and trade-offs that putting more strain on decision-making processes on every level.

1.1.5.2 Demands for Military Forces

While the future operating environment is evolving, the fundamental defense objectives of the United States remain the same: "defend the homeland, remain the preeminent military power in the world, ensure the balances of power remain [favorably], and advance an international order that is most conducive to [...] security and prosperity" [1]. However, accomplishing the objectives becomes harder and requires enhanced and improved efforts to be successful.

The different challenges of the operating environment need to be tackled by military forces. Interconnectivity of effects and threats demands quality forces that can cope with various situations. While specialization for sophisticated threats across the domains remains necessary, the ability to compartmentalize forces erodes when faced with multi-domain and interconnected challenges.

The most recent defense budget in FY21 provides the fundamental fiscal ability to satisfy these requirements, putting the U.S. military in a comfortable but not excessive spending position, yet failure can still occur if the necessary steps such as rescoped investments aren't taken [25]. However, traditional structures and thought processes might prevent the necessary changes [26]. Simply pushing for "more ships, more aircraft, and more troops" might be the path of least resistance between the different branches but does not address the inherent problems outlined so far.

In addition, the diverse requirements yielding from the changing security environment call into question the tendency of compartmentalization and specialization within the existing force and puts up demands for multi-mission and multi-role fitness as well as interoperability between different domains.

The inherent uncertainties call for robustness and resilience to not only meet foreseeable requirements, but also challenges that are only looming beyond the horizon. Based on the preliminary background information provided in this section it can be stated that**:**

Observation 1.1: The changing operating environment puts more diverse demands on existing and future assets.

1.2 Environment, Ends, Means, and Ways

To develop sustainable and effective security strategies, a balance between key variables must be achieved: ends, ways, means, and the security environment [26]. This balance is sensible to changes in any dimension and, presuming the inability to reverse an imposed alteration, demands the ability to adjust the remaining dimensions to accommodate. The evolution of the future operating environment and its degradation into a VUCA environment possess a significant change to the security environment and qualifies for the near and mid-term future as irreversible.

Historically, explained by international relations theory and the Long Cycle Theory by George Modelski [27], a deteriorating environment that includes the rise of new power approaching a dominant power ultimately has led to large-scale war. While the historic precedent of the United Kingdom challenged by both France and Germany in the 18th and 19th century, respectively, shows that the commencement of a new cycle does not necessarily mean a new dominant power [28], an ultimate confrontation with a challenger appears to be necessary either way. In our contemporary environment, since World War II and especially after the end of the Cold War, the United States are the only dominant power and they are faced with a multitude of challenges, ranging from the classical confrontation with challenger states such as China, to non-traditional spectrum threats like terrorism. This situation itself is already unprecedented, but if that was not enough, historical cases also do not account for the progressing globalization, nor they provide for considerations on nuclear weapons in the context of a potential global war.

Nonetheless, the geopolitical situation means there is a need for reaction by the dominant power, the United States. Adjustments with regards to ends, means, and ways need to be considered to provide either countermeasures to rebalance and extend the cycle, or to achieve decisive advantages to defy challenges and ultimately enter a second dominant power cycle.

1.2.1 Ends

Ends are the ultimate objectives and goals sought after [29] and are designated to be achieved by high-level strategic documents such as (in the United States) the National Security Strategy (NSS)[30], National Military Strategy (NMS)[31], National Defense Strategy (NDS)[1], or the Defense Planning Guidance (DPG). These objectives are usually strictly prioritized in a sense that higher priority items are either prerequisite for lower priority items, or simply of exceedingly higher relevance.

As already mentioned previously, the fundamental highest-priority objectives such as ‘protecting the homeland’ do not change as they are vital to the state and are often not bound to great power status but inherent to all states. When analysing strategic documents and their evolution, it becomes clear that while changes in the environment are identified the focus of new directives remains with upholding existing goals as opposed to adjusting them [1], even if such goals inevitably will violate the security interests of other countries including rising powers. This is in line with the assessment for the United States as contemporary dominant power that “[does] not readily lower their ambitions, even if doing so sometimes makes sense” [26].

1.2.2 Means

Means are the resources available to pursue the ends [29]. This includes both human and physical resources, personnel employed, and equipment used. It is a broad term, but ultimately all means can be traced back to a function they fulfil relating to the overarching objectives.

Changing the means is possible, and frequently practiced, in a variety of ways: with respect to quantity (more assets) or with respect to quality (better assets); the latter can be further subdivided into acquiring new assets or improving existing ones to satisfy the requirement. Talking about human resources, the available levers seem to be comparatively easy to comprehend: Increasing the number of military personnel, enhancing their education, and increase the different sorts of training to improve the force overall. With respect to equipment, existing assets can be upgraded by adding new technologies or replacing elements with improved versions; new assets can be procured phasing out older models, combining the functions of various predecessors into one, or fulfilling completely new roles contributing to the same goal in a different way. Both kinds of resources are interconnected as personnel is required to operate the equipment, thus the introduction of different assets requires adjustments on the personnel side as well such as different training and certification and more or less personnel per asset to operate.

An example for changes of means, the introduction of a new asset, is the tilt rotor aircraft V-22 Osprey into the U.S. Armed Forces [32]. It was introduced as replacement for medium lift helicopters in the Marine Corps but is equipped with a tiltrotor and can thus operate as a helicopter and fixed wing aircraft. It covers a capability gap discovered in the Iran Hostage Crisis in 1980 when existing vertical airlift assets were unable to operate with a sufficient range and speed. While requiring higher investments and thus raising affordability constraints for similar quantities, the type of asset enhanced operational capabilities. The improvement was sufficient for the general concept to be pursued for further developments such as the V-280, tackling flaws in the original design while maintaining the principal abilities.

Simply adjusting the means represents a traditional approach to military evolution. Building on system-immanent features within the military such as valuing experience in the understanding and decision-making process regarding assets and a generally cautious habit towards change. New means, compared to the other dimensions, can be extensively tested under closely-approximated operational conditions.

1.2.3 Ways

Ways are the methods to organize and apply the resources [29]. They are represented in multiple layers on the strategic, operational, and tactical level. The concept of ways is closely related to doctrine, which NATO defines as "fundamental principles by which the military forces guide their actions in support of objectives" [33]. While the guidance itself "is authoritative, [it] requires judgement in application" [33]; the latter provides the bridge to means and ends in the shape of implementation by personnel with regards to their aims.

The most common perception of ways occurs in the form of standardized rules, procedures and protocol that is employed by operators by order or in response to predefined events. This can include for example which public threat posture is taken towards an enemy, what size of overall force (units) shall be deployed to counter an enemy for a certain presumed strength, under which circumstances weapons can be used by personnel for defensive purposes without prior orders or specific authorization, or what patrol patterns are to be followed when conducting a search mission. In principle, the specified ways should yield from in-depth analysis and decision-making with respect to certain circumstances, presumably establishing 'the best practice' and subsequently provide a coherent framework to achieve uniform behaviour across the spectrum. By their nature, ways are more abstract than the clear performance characteristics of physical assets or the physical and cognitive abilities of personnel. Their successful definition and distribution require time and effort and will still show a certain variability due to the implementation by different people.

Changing ways, subsequently, is harder to achieve than changes in means, but it is nonetheless done on different scales on a frequent basis [34]. Such changes are considered and employed when changes in means are unattainable due to budgetary constraints, are implemented but turn out to be insufficient to address the problem or are general not suitable to tackle the changing environment. When confronted with such problems, militaries tend to start adapting their ways and probe new methods of fighting. However, analysing the prospects of new ways is significantly more complex compared to testing the performance of new means. While the latter can be done in closely-approximated situations, the efficiency of new ways ultimately needs to prove itself in combat with its comprehensive dynamics and retains considerable uncertainty when employed up to that point.

An example for a significant change of ways is the reorganization of units into Brigade Combat Teams within the current transformation process of the U.S. Army [35]. Prior to the process, the focus of unit orientation was lying on divisions and yielded from the Cold War posture of deploying to the theatre, presumable in Europe, and fighting in a symmetric conflict against an organized and structured adversary for a limited non-permanent period of time. The full range of different operations could thus only be conducted at this unit level. With post-2001 enduring deployments to Afghanistan and Iraq and the shifted environment for operations, amongst other things, changes to the force structure became necessary. The reorganization shifted the focus towards modularized brigades able to operate by themselves and being able to participate in a rotation scheme in and out of the theatre enabling overall quasi-permanent operations with different units. While this effort was floated within the U.S. Army already around 1999, it formally began in 2006 and up to this day it is still ongoing.

1.2.4 Interdependence of Ends, Means, and Ways

While the consideration of ends, means, and ways is paramount for any security strategy, the elements cannot be treated as completely separate and complementary to each other. Ends might provide the guidance what one might want to achieve, but the necessary devotion of means and the acceptance of required ways ultimately needs to be justified and deemed 'worth it' - most prominently, fiscal constraints might demand giving up certain lower priority objectives.

With ends being locked in, focussing on means and ways, we can observe various interdependencies: Some means can only affect significant improvements if they are operated in a certain way that might be consistent with current approaches, but doesn't necessarily have to be. While new assets can yield similar or slightly improved performance, they might fall short of their expected contributions due to hindering operational paradigms. Adhering to the status quo of 'how things are done' might itself become a problem when it can be exploited and evolution in means cannot alone compensate for that effect.

An example outlining the interdependence of means and ways is the concept of network-centric warfare which “focuses on the combat power that can be generated from the effective linking or networking of the warfighting enterprise” [36]. The approach of translating informational superiority into combat advantages within the respective theatre in a rapid fashion relies on the description of the battlefield as a system-of-systems, enabling commanders to effectively control forces distributed across the theatre and enabling them to ‘act as one’. To realize this approach, means needed to be brought into compliance for example by upgrading their communication equipment, new elements for command-and-control needed to be established to handle the increased workload on higher levels, and processes for conducting operations needed to be reorganized to reflect the underlying optimization. The implementation is reliant on changes for both means and ways to yield its added value. The sole introduction of improved or new Intelligence, Reconnaissance, Surveillance (ISR) assets can bring better information, but does not tackle the necessity to have this information readily available in the field or shared with the relevant operators to direct action based upon them. On the other hand, centralizations in the command structure without the information and infrastructure to effectively steer assets in the field can have negative effects on the performance.

The existence of interdependencies and their inherent influence on the principal validity and efficiency of new materiel and non-materiel approaches raises the issue of how to assess these relationship in the decision-making process. New materiel acquisitions and developments need to be judged in light of their operational performance under the current ways, while changes in doctrine and other non-materiel parameters need to be compliant with the abilities of assets and personnel.

In addition to the inherent interdependencies between ends, means, and ways, enemy behaviour and the phrasing of ends as quasi-permanent as opposed to achievable goals provides additional challenges [37]. Based on the aforementioned information it can be stated that**:**

Observation 1.2: The changes in operational behavior in conjunction with the alternation of capabilities are crucial to analyze the effectiveness of new assets and technologies.

1.3 Defense Acquisitions and Investments

The conjoint consideration of means and ways is embedded in the Defense Acquisition System (DAS), which is governed by the standing Department of Defense (DoD) Directive 5000.01 [38]. The directive is issued by Under Secretary of Defense for Acquisition and Sustainment, who oversees the DAS, and has last been revised on September 9, 2020.

The stated overarching "objective of the DAS is to support the National Defense Strategy through the development of a more lethal force based on U.S. technological innovation and a culture of performance that yields a decisive and sustained U.S. military advantage" [38]. It takes the environment and ends as given from higher level guidance and pursues avenues with regards to means and ways. While acquisitions have an inherent focus on the means, the most recent revisions of the directive acknowledge the interdependence of means and ways for gaining the highest efficiency possible.

Demands are raised for the enhancement of the conduction of System-of-Systems (SoS) Analysis and overall data-driven approaches in the process. In this context the SoS Analysis shall "identify operational gaps and develop SoS employment concepts in order to develop system capabilities that improve the warfighters' ability to execute critical mission threads" [38]. This stipulation addresses the inherent need to combine the assessment of means and ways with respect to the performance in an operational environment.

In accordance with this the employment of performance-based acquisition strategies is explicitly stipulated. This requires "a strategy that supports an acquisition approach structured around the results to be achieved as opposed to the manner by which the work is to be performed" [38]. This includes the consideration of non-traditional solutions that can fulfil the requested objectives and achieve the ends in the given environment but might not necessarily be an evolution of currently employed approaches. Overall, it can be stated that**:**

Observation 1.3: the Department of Defense provides scope to evolve the defense acquisition process towards a more computationally-enhanced, capability-based and result-oriented process.

1.4 Principal Gap

Based on the initial observations made in CHAPTER 1 as observations 1.1, 1.2, and 1.3, this research aims to address the lack of sufficiency in current methods and approaches to consider both means and ways side-by-side. This main gap is formalized as follows:

Gap 1: The existing capabilities to parameterize the ways in addition to the means are insufficient to conduct holistic studies to comprehensively explore the design space.

In order to contribute to a solution that allows conducting future studies in a comprehensive manner, existing capabilities and methods need to be augmented or revised to meet the demands put forward by these new challenges.

1.4.1 Methodology to Cover the Gap

The augmentation of existing means can be accomplished by creating a new methodology taking into account the state-of-the-art approaches utilized in the acquisition process, analyzing the critical elements and preserve their content, and infusing the necessary changes into the process. Before proceeding, it should be noted that such a new methodology needs to satisfy multiple general requirements in order to be suitable for implementation: Structured, Modular, Quantifiable, and Representative.

The methodology needs to qualify as structured in a sense that it transparently and traceably outlines the process to ensure repeatability. While the methodology is formulated and demonstrated in the progress of this study, the added value of its creation ultimately rests in the possibility to apply it to relevant cases. Especially with regards to the scenario formalization that enables the inclusion of multiple scenarios alongside each other, the process needs to follow certain standardized guidelines to ensure its applicability.

In addition, it needs to be modular in order to be adaptable to a variety of operational scenarios. Due to the variability in comprehensiveness and complexity of the infused problem objectives, the expected variability in fidelity of the assessments required to produce a scenario necessitates a broadly applicable methodology. The method needs to be able to accommodate to this diverse perspective and continue to work under the various circumstances.

Third, it needs to include quantified metrics, stating that the outputs and results contain a dimension relevant for decision-making. It needs to include metrics that allow a comparison on a numeric scale, although the resolution for that scale depends on the attainable level of fidelity. This means depending on the accuracy of the analysis in the specific case various approaches such as discrete scales or a tiered ranking will be employed.

Lastly, the methodology needs to be representative, claiming that it can provide meaningful results. This means that the results created through this approach need to show an internal validity relative to each other so that the relationship of compared results sufficiently resembles real world results. This does not necessarily require the resemblance in absolute values as the results are based on models and simulations; absolute values can usually also not be verified when the real-world values cannot be obtained in a quantitative fashion.

1.5 Research Objective

Summarizing the discussion so far, we are facing a highly uncertain future military operating environment with a multitude of diverse challenges. These create a security environment that, with unchanged aspirations, will require means and ways to be critically reviewed and adjusted to stand the test of these new and changing threats.

As the consideration of means and ways is highly multi-dimensional, the existing approaches are often coupled or integrated and cannot be sufficiently judged in isolation. Existing options for changes in means and ways could include the development of new assets, or shifting away from 'the way things are done'. To identify the appropriate methodology for means and ways consideration, a holistic approach must be used to build this methodology.

The crucial element for these considerations is the ability to conduct a comprehensive exploration of the options available, the identification of feasible combinatorial approaches and a systematic assessment of their performance and efficiency. This study places its scope on the ability to merge different operational requirements into a framework that allows a joint assessment of materiel and non-materiel approaches. Subsequently, the following overall research objective is defined to guide this study:

Research Objective: Develop a methodology that considers diverse operational requirements and operational ways in a parameterized fashion within a system-of-system analysis in the early stages of the acquisition process.

1.6 Research Approach

In order to realize the research objective, a comprehensive literature survey has been conducted prior to the realization of the new methodology. Before presenting the details of the survey in CHAPTER 2 to CHAPTER 4, the following subsection outlines the overall approach of this research to provide the reader with the context in which this work was developed. Following the literature review and the formal layout of the methodology laid out in CHAPTER 5, validating experiments and a full demonstration of the methodology are provided in CHAPTER 6 to CHAPTER 8. Finally, the policy implications and final conclusions are presented in CHAPTER 9 and CHAPTER 10, respectively.

1.6.1 Logical Approach

To address the research objective, this research started with an in-depth analysis of the status quo and how defense acquisition decisions are made today in order to determine the points of infusion for adjustments to close the gap. This analysis yields additional observations and complements the identified main gap (gap 1) with three additional gaps to be addressed in the process. Subsequently, the work can be structured into three work streams: scenario formalization and modularization, the definition of the design and options space, and the analysis environment. Figure 2 shows an excerpt of the overall logical flow diagram outlining the logical connections between the aforementioned work streams. The comprehensive logical diagram of this dissertation can be found in APPENDIX A.

The first work stream on the formalization and modularization of scenarios, the core element of this thesis, is motivated by the need to consider various ways to mirror multi-mission, multi-scenario suitability. It started with an analysis of the Defense Acquisition System and its individual components, as described in detail in CHAPTER 2. With scenarios being currently considered part of the problem definition, even before different ways and means are introduced, the variation of scenarios needs to be placed early in the process. After identifying a suitable position in the process for implementation, research focused on the search for an elementary definition approach, a process to define elements and interfaces of scenarios allowing a structured and modular integration in the subsequent steps. The process identified was originally developed for classical systems design and has thus been adjusted to meet the needs of this methodology. Subsequently, this adjusted process was tested experimentally to ensure its operability, as presented in CHAPTER 6.

As second work stream, the definition of the design and options space, is addressed in order to merge the variation of means with the alternation of ways and accommodate for the implications yielding from the step. The literature review focused on the analysis of the formalized process to comprehensively categorize and describe different materiel and non-materiel approaches, as described in detail in CHAPTER 3. Confronted with the extensive number of categories embedded in the overall process, a first scoping decision for this research has been made to focus on doctrinal aspects for the parameterization of ways. Subsequently, the definition of both doctrinal aspects and materiel approaches was explored separately and jointly. Of particular interest was the process of identifying feasible and infeasible approach combinations across the respective domains and options. Deciding on the usage of literature-based subject-matter expertise for this element, the structural decision to formalize these decisions could be made and experimentally tested to ensure the proper classification in the process, as presented in CHAPTER 7.

Finally, as third work stream, considerations have been made with respect to the analysis environment, as described in detail in CHAPTER 4. Driven by the multi-dimensionality of the problem and the desire to enable the methodology to provide a comprehensive initial analysis, the current usage of computational capabilities was analyzed with regards to their suitability for the required process. It has been concluded, as the subsequent chapters will show, that for this methodology modelling and simulation needs to be low-fidelity in order to assess the design and options space in a timely manner. Considering subsequently the various options for modelling types, it has further been determined that Discrete Event modelling should be pursued. While this is especially true in context of the other two work streams and given that the methodology augments the existing process, it should be noted that this decision satisfies a sufficiency criterion with regards to the level of fidelity required at a minimum.

After pursuing the work streams separately, they culminate with the formulation of the overall research hypothesis and equivalency conjecture. These enable the structural creation of the methodology, summarized in the following section and outlined in detail in CHAPTER 5, and subsequent to the aforementioned experimental validations, an application demonstration of the full methodology, as presented in CHAPTER 8.

Figure 2: Logical Flowchart of the Dissertation

1.6.2 Proposed Methodology

Based on the logical approach, the following methodology, as representation of the Capabilities Based Assessment (CBA), is summarized, and presented in detail in CHAPTER 5. The methodology is divided into three parts that reflect the different functional analyses within the CBA. Figure 3 shows a flowchart of the entire methodology including its division into the three parts and the corresponding steps.

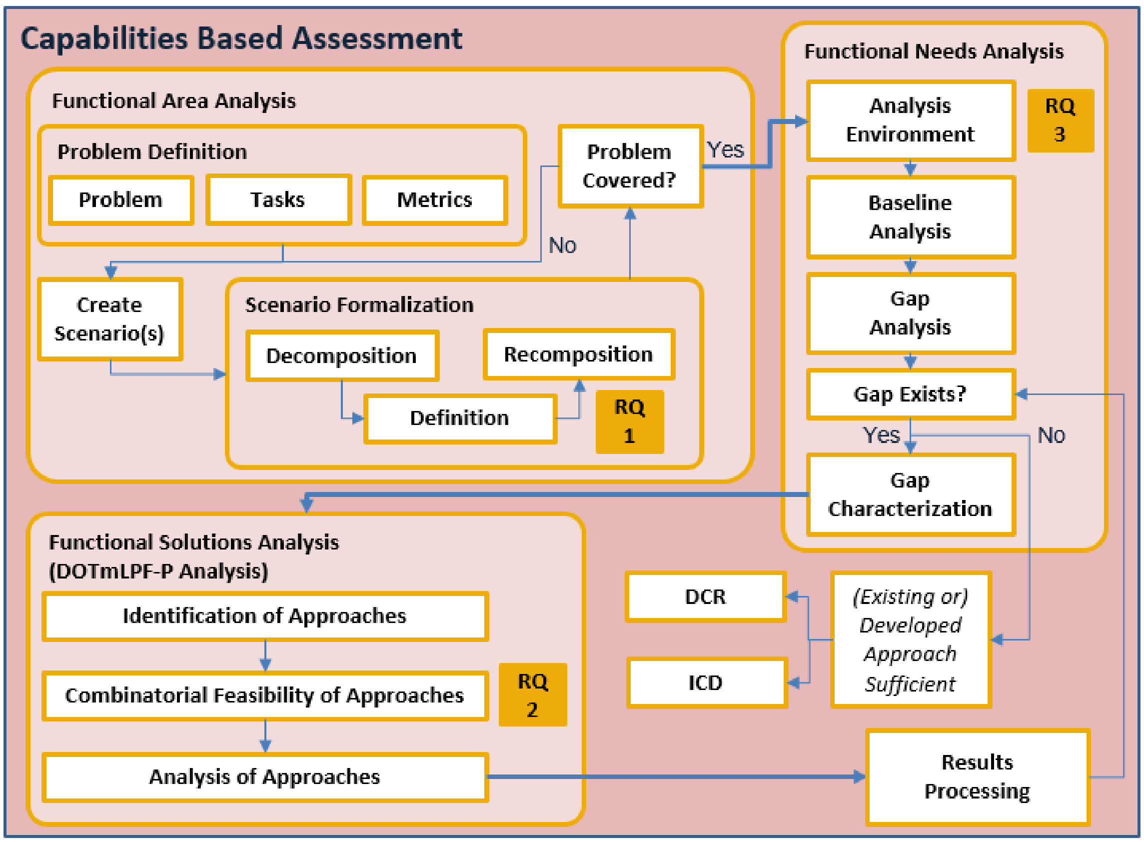


Figure 3: Methodology Flowchart within the Capabilities Based Assessment

In the first part, the problem is defined, and the corresponding scenarios are created. The problem definition kicks off the methodology and can be performed with various levels of abstraction based on a multitude of standards. It sets up the general goal for the CBA by providing the problem statement, either including either specific target metrics to satisfy or more abstract guidance (to be later translated into quantitative measures throughout the CBA). The general requirements which define the problem were set by the applied case study which will be described in the following section. As mentioned before, the critical element of scenario formalization and modularization occurs already at this level and influences the remaining process onward. This part's deliverable is an assessment of whether the defined scenarios are sufficient for the to-be-assessed problem. Part 1 represents the Functional Area Analysis.

In the next part, the analysis environment is introduced into the process and baseline and gap analyses are performed. As baseline analysis, a status-quo case with open-source data is introduced and utilized to ensure the representativeness of the analysis environment. This allows for subsequent computational simulations to be performed with 'internal cohesion' as a multitude of case is considered vis-à-vis the baseline. The subsequent gap analysis then translates the previously established goals into clear targets in the context of the analysis. If goals are only provided in an abstract manner, i.e. no clear gap-yielding target metrics are provided a priori, target performance and demands are adjusted here to translate these goals into clear quantities. This part concludes with the stipulation that gaps exist and characterizes them. Part 2 represents the Functional Need Analysis.

Finally, in the last part, possible approaches are identified and analyzed in order to find solutions that would cover the established gap or gaps. As mentioned in the previous section, here the combinatorial nature of various alternatives and the consideration of their interdependence comes into play. After the feasibility of approaches is established, they are simulated in the selected analysis environment to gather the data on the metrics of interest. These results are then processed in order to make the final determination that an existing gap is not covered, and to conclude the CBA. Part 3 represents the Functional Solutions Analysis.

1.6.3 Proposed Case Study

In order to provide an applied context for the new methodology presented throughout this research, and to experimentally validate the new elements to be introduced into the defense acquisition process, a case study is introduced. While the two validation experiments and the full methodology demonstrations use different experimental inputs, they are each a derivative of a shared case and utilize the same testbed that has been developed since 2017 within the Aerospace Systems Design Laboratory (ASDL) in partnership with the Australian Department of Defence's Defense and Science Technology Group and the United States Navy's Office of Naval Research.

The created background deals with the performance of Humanitarian Aid and Disaster Relief (HADR) operations by the Australian Military in the South East Pacific. The forces respond to a catastrophic event, such as a cyclone, hitting the island nations of Fiji and Vanuatu. Due to the damage caused by this natural catastrophe, the local infrastructure is overwhelmed or destroyed and cannot cope with the urgent demand for immediate support to ensure the survival of the affected population. Thus, the nations rely on immediate foreign aid which in this region is provided by Australia.

The aid is provided by a multi-facetted operation. Operated from regional bases in Australia, inter-theater strategic airlift transports equipment and personnel to a forward operating base to be established at an international airport within the affected theater, and subsequently continues to sustain the base and its operations. On site, intra-theater operations include aerial assessment of the theater as well as vertical airlift assets operating the logistics to transport aid packages to the population. The operation itself is limited to a 5-day time window.

The baseline validation data have been taken from actual operations performed as response to Cyclone Winston hitting Fiji, and Cyclone Pam hitting Vanuatu in 2016 and 2015, respectively. The gaps within the CBA are derived by the demand for improved vertical airlift and aerial assessment capabilities. Additional details and specific setups will be provided throughout CHAPTER 6 to CHAPTER 8 in the context of the experiments and full demonstration.

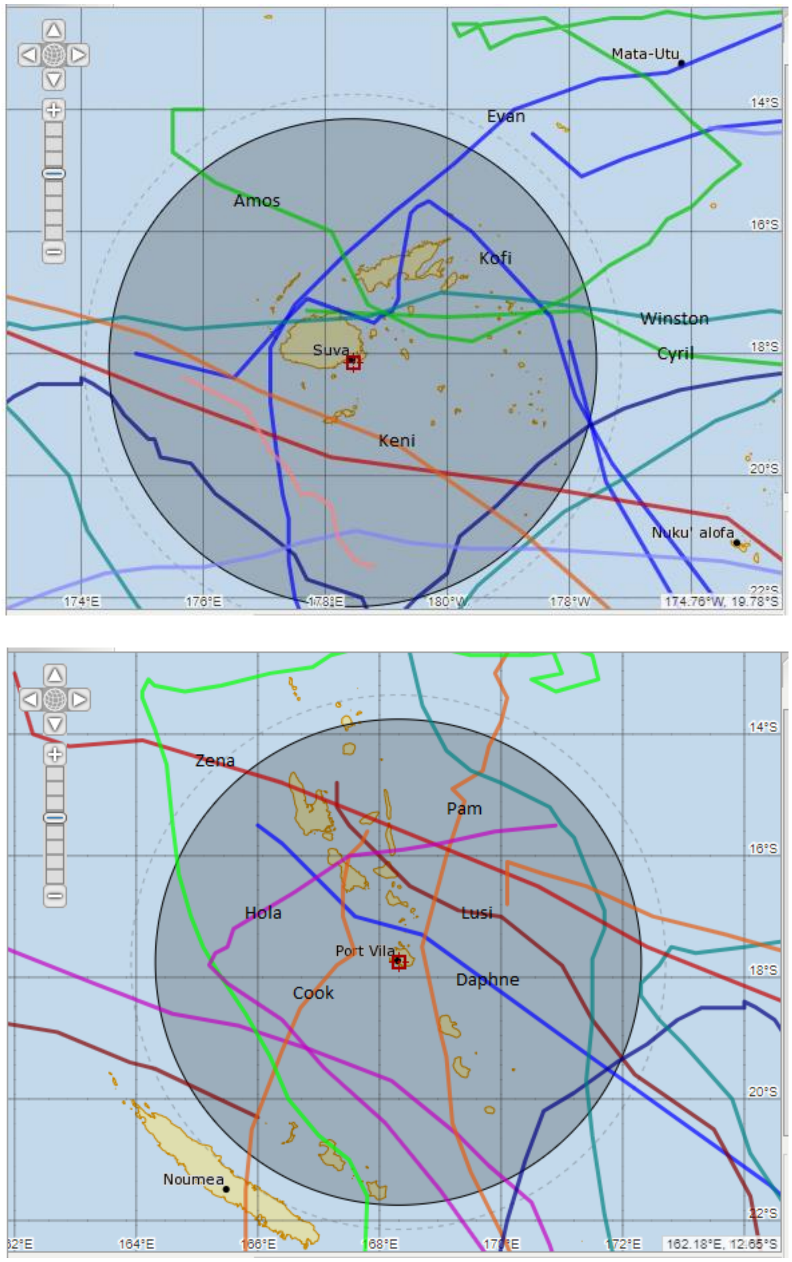


Figure 4: Map of Fiji and Vanuatu including various hurricanes

CHAPTER 2. THE DEFENSE ACQUISITION PROCESS

Following the provision of the introduction and motivation of this research in the previous chapter, the next three chapters present background knowledge based on the conducted literature survey and formulate the research along the three different work streams. This chapter starts the process by discussing the defense acquisition process to embed the problem into the proper context.

2.1 Defense Acquisition System

The Defense Acquisition System (DAS) is the structural and regulatory foundation governing defense acquisition. It consists of three distinct elements: The requirements-driving Joint Capabilities Integration and Development Systems (JCIDS), the funding-acquiring Planning, Programing, Budget and Execution (PPBE) process, and the management-providing Defense Acquisitions Process (DAP). The elements provide for the identification of required capabilities based on the needs, the obtainment of funding for intended acquisitions, and for a structured approach to implement the actual acquisitions. While certain steps within the overall DAS need to be taken sequentially, the three elements are interacting with, and are dependent on, each other as illustrated in Figure 5. In the following subsections, the relevant information for the DAP and JCIDS are provided, while the PPBE is excluded from the scope of this study.

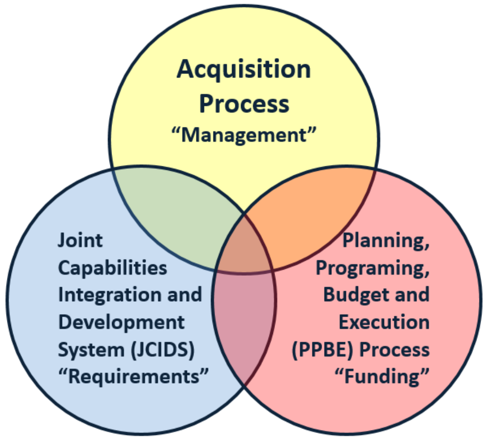


Figure 5: Defense Acquisition System (Adapted from [39])

2.1.1 Defense Acquisition Process and Major Capability Acquisitions

The Defense Acquisition Process (DAP) is governed by DoD Instruction 5000.02 [38], and supported by the Adaptive Acquisition Framework (AAF) that allows the classification and the distinction between different types of acquisitions [40]. Within DAP, the most common and 'default' process is the Major Capability Acquisitions process, which follows an unspecialized and traditional approach. Alternative approaches are defined for rapid (less than two years) and mid-tier (two to five year) processes, as well as specialized acquisitions such as software, business systems and services.

In addition to the character of the acquisition, the funding levels and importance are considered for the classification towards a certain path and to decide the level of oversight that is provided on a certain program. Three acquisitions categories (ACAT) are defined based on research and development (R&D) investments and procurement value (in FY20 constant dollars) [41]:

- ACAT I: R&D of more than $524M and total procurement $3.065B
- ACAT II: R&D of more than $200M and total procurement $920M
- ACAT III: Less than ACAT II

The Major Capability Acquisitions process is governed by DoD Instruction 5000.85 [41], and separated into 5 phases as shown in Figure 6:

- Materiel Solution Analysis (MSA)
- Technology Maturation & Risk Reduction (TMRR)
- Engineering & Manufacturing Development (EMD)
- Production & Deployment (P&D)
- Operations & Support (O&S)

Each phase of the process has its own objectives and requirements that need to be satisfied in milestone reviews prior to proceeding to the next phase [42].

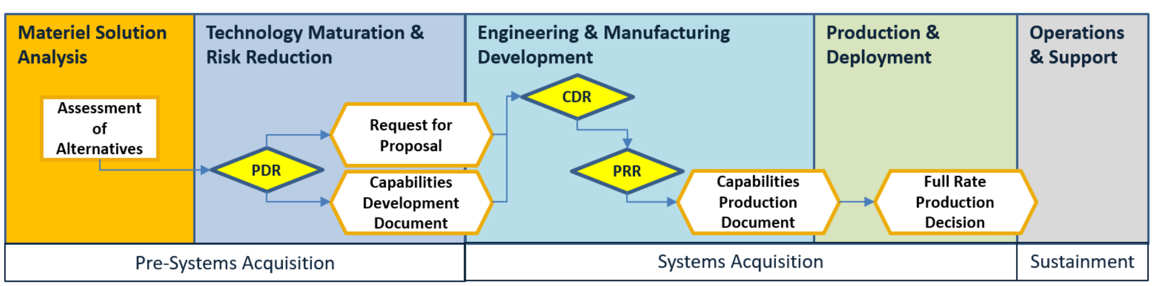


Figure 6: Major Capability Acquisitions Process (Adapted from [43])

The first two phases, MSA and TMRR, are building on a pre-process Material Development Decision (MDD) and are dealing with pre-systems acquisition considerations. The MSA conducts the traditional Assessment of Alternatives (AoA), before commencing the TMRR. The TMRR itself includes a comprehensive risk analysis and determines a set of technologies that satisfy the capability requirements, ultimately leading to the creation of the Capabilities Development Document (CDD) enabling the inclusion of commercial actors through a Request for Proposal (RFP). The third and fourth phase, EMD and P&D, accompany the actual development and acquisition of a physical system, while the fifth phase, O&S, moves the acquisition into sustained operations. Overall, it can be stated that**:**

Observation 2.1.1: The DAP does not include the consideration of different operational approaches or non-materiel dimensions in general. It operates based on an already-developed ICD and already-made MDD, thus the decision to pursue materiel solutions has already been made. As the traditional AoA happens at this step, it is constrained to materiel alternatives.

2.1.2 Joint Capabilities Integration and Development System

The Joint Capabilities Integration and Development System (JCIDS) overlaps with the first two pre-systems acquisition phases of the DAP. Moreover, it also encompasses as first step the DAP-preceding Capabilities Based Assessment that contains the analysis driving the system requirements, as shown in Figure 7. The objective of the JCIDS is "to ensure the capabilities required by the joint warfighter are identified, along with their associated operational performance criteria (requirements), in order to successfully execute the missions assigned." [39] Overall, it can be stated that**:**

Observation 2.1.2: The JCIDS includes the critical component of considering means and ways within the Capabilities Based Assessment as it considers capabilities broadly with materiel and non-materiel dimensions.

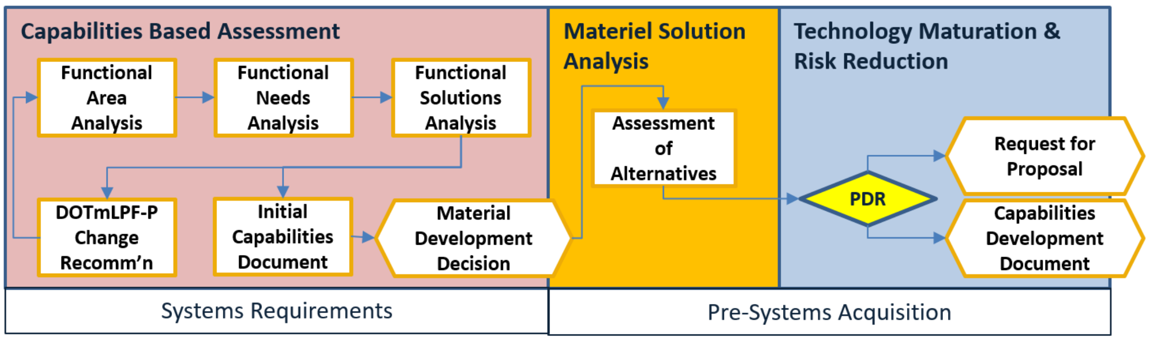


Figure 7: Joint Capabilities Integration and Development System (JCIDS) Process (Adapted from [43])

2.2 Capabilities Based Assessment & Functional Analyses

The Capabilities Based Assessment (CBA) provides the analysis for a given problem of various materiel or non-materiel solutions and recommendations on which options shall be pursued. Goal of the CBA is the identification and validation of capability gaps and subsequent discovery and analysis of solutions through the following objectives [39]:

- "Define the mission;
- Identify capabilities required;
- Determine the attributes/standards of the capabilities;
- Identify gaps;
- Assess operational risk associated with the gaps;
- Prioritize the gaps;

- Identify and assess potential non-materiel solutions;
- Provide recommendations for addressing the gaps."

The process derives its inputs from high-level strategic guidance, such as NMS[31], NDS[1], and NSS[30] considers various approaches and generates solutions for the identified to-be-solved problem. Within the process, three different functional analyses are performed consecutively: Functional Area Analysis (FAA), Functional Needs Analysis (FNA), and Functional Solutions Analysis (FSA). The CBA can conclude with two separate outcomes: The issuance of a DOTmLPF-P Change Recommendation (DCR), which would suggest a materiel or non-materiel solution and trigger an iteration of the process to consider the changes, or the creation of an Initial Capabilities Document (ICD) and subsequent Material Development Decision (MDD) to pursue the development of the capability through the subsequent DAP. The schematic of the CBA process is shown in Figure 8.

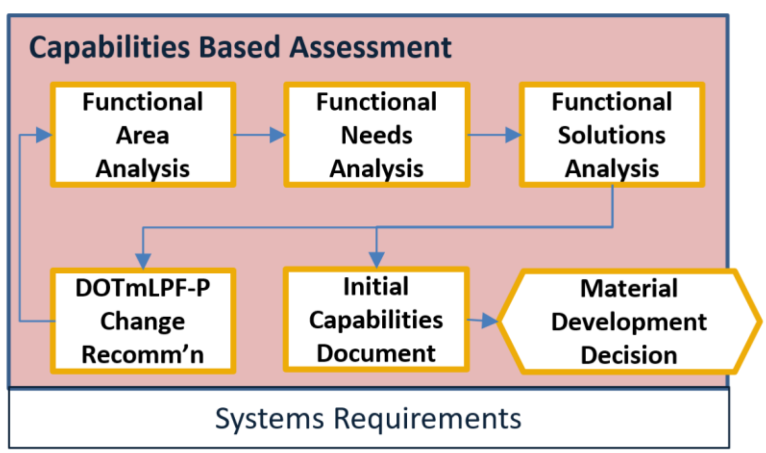


Figure 8: Capability-Based Assessment Process (Adapted from [43])

2.2.1 Functional Area Analysis

The FAA is the initial step of the CBA that considers strategic guidance and that identifies specific problems. Each problem yields capabilities that need to be achieved in order to solve the issue, which are subsequently translated into a set of certain operational tasks to be performed under specified conditions. The conditions are derived from alternative concepts of operations (CONOPS), providing representative scenarios that allow the definition of acceptable performance and thus quantifiable goals that can be met [44].

2.2.2 Functional Needs Analysis

The FNA is the intermediate step of the CBA that provides an assessment of existing and foreseeable military capabilities with regards to the required capabilities identified in the FAA [44]. The process identifies capability gaps based on the ability or inability to perform in an adequate manner in the given scenarios; the respective metrics are established in the preceding FAA.

If a capability gap is discovered, the FNA proceeds to analyze in detail what impact this gap has and characterizes it. Hereby, the FNA can classify the gap in certain ways. It can state a complete inability to achieve an intended effect due to existing capabilities being unusable to address new or evolved threats. Also, a partial inability applicable only under certain conditions indicating a lack of proficiency can be found. Lastly, either a general ability to perform but an inability driven by insufficiency with respect to available forces, or an existing but foreseeably limited ability due to respective assets reaching the end of its lifespan can be established. Relating capability gaps to the priority of the objective they fail to address the attribution of priority to the capability gaps themselves. For certain inabilities, the assessment of multiple scenarios is necessary to test multiple conditions and avoid misclassification based on a singular favorable or unfavorable scenario.

2.2.3 Functional Solutions Analysis

The FSA is the final step of the CBA and it aims to generate solutions for the gaps identified in the FNA. In order to assess possible approaches, ideas for materiel and non-materiel approaches need to be collected. These different approaches are then analyzed with regards to whether they can cover or at least reduce a gap, yielding one or multiple possible solutions; each solution consists of one or multiple of the collected approaches [44] [45].

If multiple possible solutions are identified, the FSA provides recommendations for how to address the gap. To issue such a recommendation, the established parameters from the FAA needs to be reviewed and a measure of effectiveness (MoE), in addition to the measures of performance (MoP), must be established. The MoE does not only take into account to which degree the objectives have been satisfied, but also what efforts need to be undertaken to reach that point; the latter applies especially to fiscal considerations. In summary, it can be stated that:

Observation 2.2: The Functional Area Analysis and Functional Needs Analysis translate high-level strategic information and conclusions into the acquisition process, while the Functional Solution Analysis introduces alternative non-materiel and materiel approaches and assesses them in relation to the preceding information.

2.3 Gap

Combining the observations made in CHAPTER 1 and CHAPTER 2 as observations 2.1.1, and 2.1.2, the gap addressing the enhancement of the consideration of ways can be formalized as follows:

Gap 2: The existing functional analysis process demands a standardized and comparable approach but does not inherently manage the diversity of operational requirements or scenarios investigated conjointly.

The gap addresses the need for diversification of the investigated scenarios, while maintaining a quasi-singular process. This means that the expansion of scenarios cannot just yield a multiplication of the entire process, but rather that multi-scenario capability needs to become an inherent step of the CBA.

2.3.1 Derivation of Research Question

When considering multiple scenarios to cover a wide range of operational requirements, the approach can be faced with a diverse set of tasks, metrics and structures. These need to be translated into a form where their infusion into the same environment becomes possible and an inter-scenario analysis feasible. The identification of standard elements within the scenarios includes the vertical and horizontal modularization, the specification of sequences of events, and the interfaces between modules and sequences. Relating the developed methodology requirements to this gap, the approach needs to qualify as structured and modular. This allows the formulation of a research question corresponding to gap 2 as follows:

Research Question 1: How can elements of an operational scenario be standardized to enable dynamic exploration of the design space?

2.4 Requirements, Functional, Logical, Physical (RFLP) Process

In order to address the research question formulated at the end of the previous section, and subsequently develop a corresponding hypothesis, the study considers elementary definition approaches and for such leans into Systems Engineering (SE) and adapts the Requirements, Functional, Logical, Physical (RFLP) process utilized for system design tasks.

2.4.1 Systems Engineering and System Design Background

SE is a complex engineering activity that addresses problems on the system level in order to enable the development of complex products and the solution of complicated problems. In order to approach problems on a system level, ‘system thinking’ or hierarchization needs to be applied [46][47]. This means moving from the general to the particular to comprehend a system and move in the opposite direction to integrate the various elements into its combined shape [48]. The process is supported by modelling on the various levels that compartmentalize the behavior of elements of the complex system [49].

The SE approach enables the separation of aspects to address multivariate interests, allowing the involvement of different stakeholders in areas relevant for their interests and applicable to their expertise. Furthermore, it is compliant with the separation of design work into disciplinary teams and their subsequent multi-disciplinary recombination.

The RFLP process, schematically shown in Figure 9 following the common SE V-Model, implements the general SE approach in more detailed fashion. It's separated into distinct directional phases: Top-to-bottom decomposition (system analysis), and bottom-up recomposition (system integration).

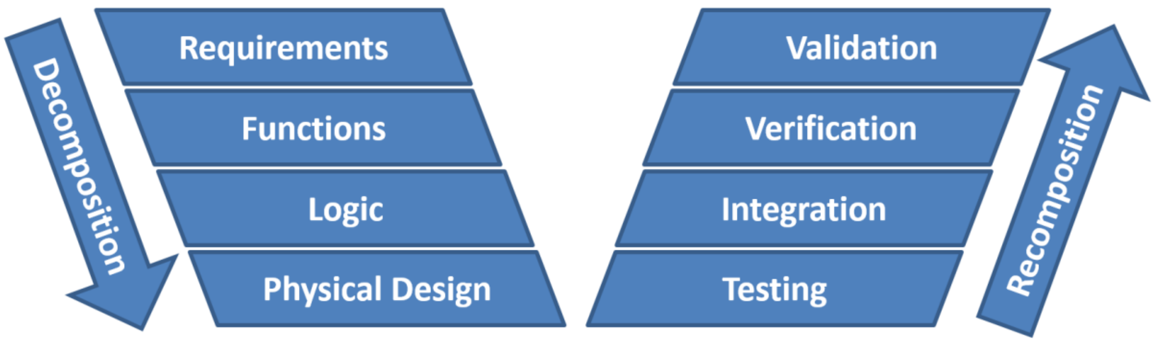


Figure 9: Schematic Overview of the RFLP Process (Adapted from [46])

2.4.2 Decomposition

The decomposition part, or analysis, approaches the system theoretically to describe it extensively on four levels [46].

Requirements define the parameters that ensure the system meets its mission and purpose, including which objectives it shall achieve and top-level goals relating to the necessity of the system. They are usually provided as textual descriptions and include targets that need to be achieved.

Functions are operations performed by the system that contribute to the fulfillment of the requirements. It can be subdivided into main and sub-functions, whereby main functions remain on the critical path towards the requirements and sub-functions contribute to the performance of the functions. The functions include performance characteristics that are related to the established targets.

Logic outlines the components of the system functions, including a sequence of actions, description of behavior and interactions of components and functions through interfaces.

Physical design describes real world solutions for the required components that satisfy the decomposed specifications. It stipulates which products, tools, and parts can be used to create the physical system with characteristics that relate to the previously established performance metrics; usually this includes multiple available options for consideration.

2.4.3 Recomposition

The recomposition part, or integration, performs various steps to virtually assemble the system in four steps analogous to the previously described decomposition steps [46].

Testing includes the inspection of physical components for fulfillment of the established specifications. Integration applies the interface connections between different components. Verification assesses whether the connected components perform the functions required. Validation assesses whether the requirements are satisfied according to customer needs and specifications.

An example use case is the use of the process in a specific tool environment towards an Unmanned Aerial System (UAS) [50]. In this case, the combination of a multicopter with a flying wing is investigated. Key drivers for considering the suitability of this concept aerodynamic efficiency, stability in flight, propulsion, and use of commercial off-the-shelf components. Using an integrated platform environment, multiple models can be developed in parallel using other resources to evaluate key performance indicators: lift to drag ratio, thrust to weight ratio, mechanical design feasibility, space allocation, mission capabilities, and total cost. Figure 10 shows how the decomposition and recomposition steps of the RFLP process are applied to this example case, as well as sample modelling visualizations.

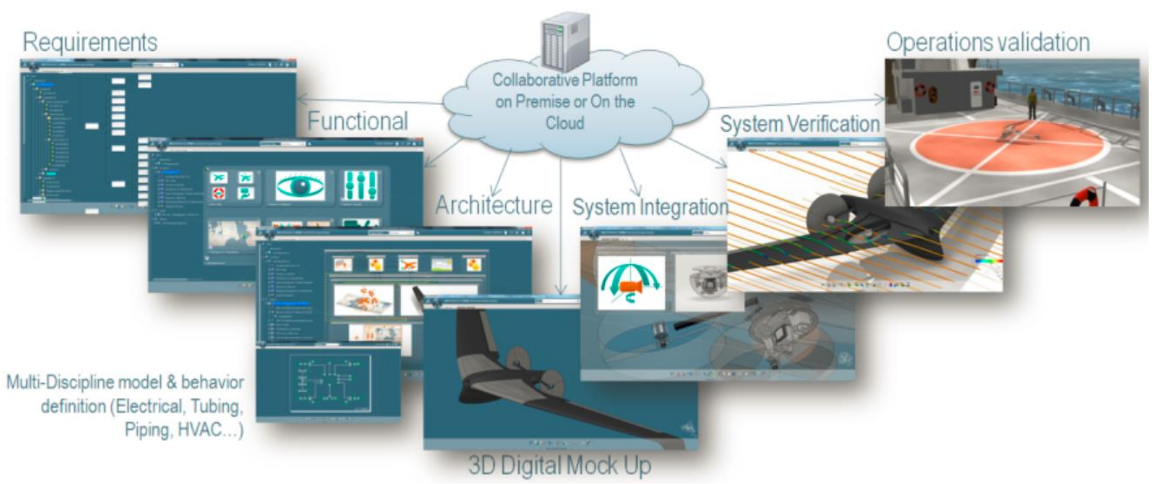


Figure 10: Environment Example showing RFLP Implementation of Sample Case [50]

2.4.4 Formalization in Architecture Environments

With the RFLP process able to provide the starting point, the question of relating both the required-input as well as the generated-output scenario information to other defense processes arises. The Department of Defense has developed an suitable architecture framework, the Department of Defense Architecture Framework (DoDAF), that formalizes the conceptualization of systems [51]. It includes description and documentation of elements and relationships, and provides for standardized communication between stakeholders through the creation of view points filtering information in different contexts.

Before describing the DoDAF, the following definitions are provided for clarity [52]**:**

- “Architecture: fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution
- Architecture framework: conventions, principles and practices for the description of architectures established within a specific domain of application and/or community of stakeholders
- Architecture view: work product expressing the architecture of a system from the perspective of specific system concerns

DODAF itself was developed as overarching, comprehensive framework and conceptual model for architecture development. It prescribes standards across the various DoD domains and is integrated in the JCIDS and DAS process. The models in DODAF base on a coherent overall model and common data structure, but break-down into different view points for different perspectives with a variable level of detail.

Figure 11 shows an overview over the structure and categories of the various viewpoints embedded in DODAF. Two different dimensions of categories are differentiated: One the one hand, a separation into Standard, Data, and All Views is made. Standard Views reflect the stakeholder diversity with tailored elements to the respective needs, while Data Views specifically focus on data relationships and alignment structures. All Views then provide the 'big picture' context required to assess the overall situation. On the other hand, within these categories, different views are available focusing on areas Capability, Operation, System Engineering, Services, and Systems. Lastly, specific Project Views are available that some adjust aforementioned views for the purpose of managing defense acquisitions. Figure 12, Figure 13, Figure 14, and Figure 15 show sample views of some of the operational and overall views.

In the context of this research, DODAF can be used to both gain the information to set up the scenarios for subsequent application of a methodology, as well as to document the problem definition and scenario formalization phase. The standard is integrated into other processes in the DAS and enables the gathering the necessary information about elements, relationships, and interfaces that are required for the adjust RFLP process. As this formalization standard is used across the DoD based on already documented subject-matter expert work, the step of formatting this information for use within the methodology can benefit from these synergies. Conversely, the results produced through the process of scenario formalization can be documented through DODAF and utilized by others, especially in processes immediately following the CBA.

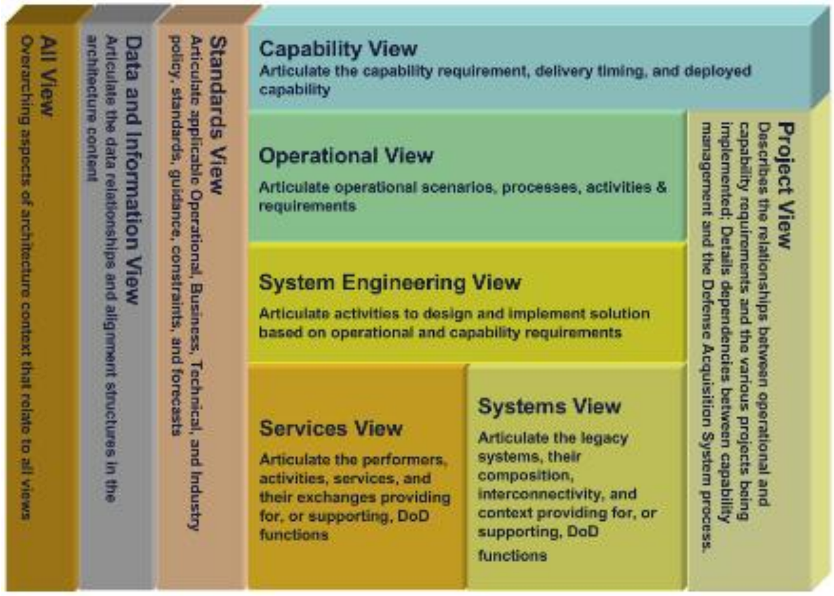


Figure 11: Structure and Categories of DODAF Views [51]

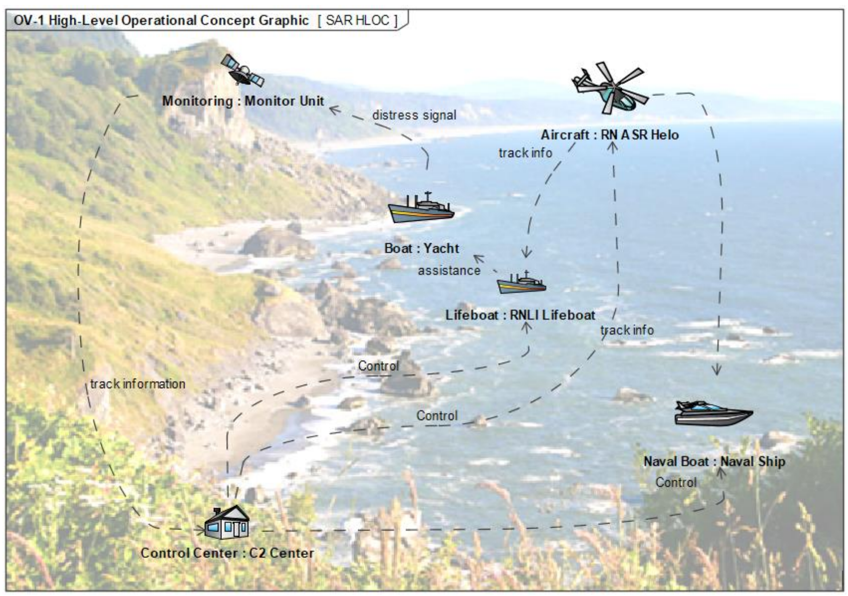


Figure 12: Sample DODAF OV-1 View [53]

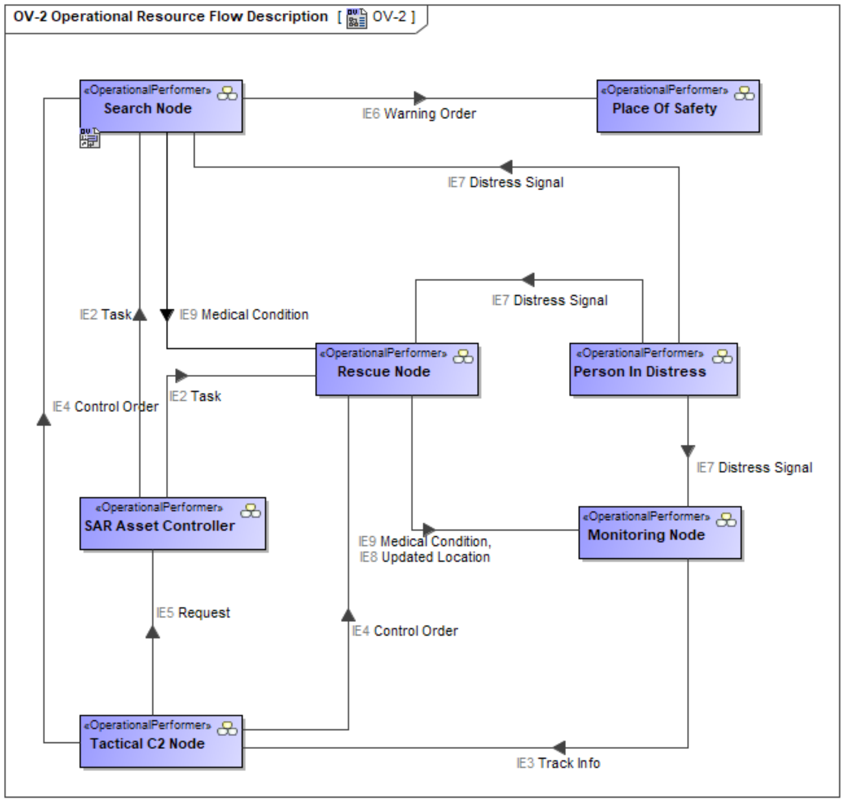


Figure 13: Sample DODAF OV-2 View [53]

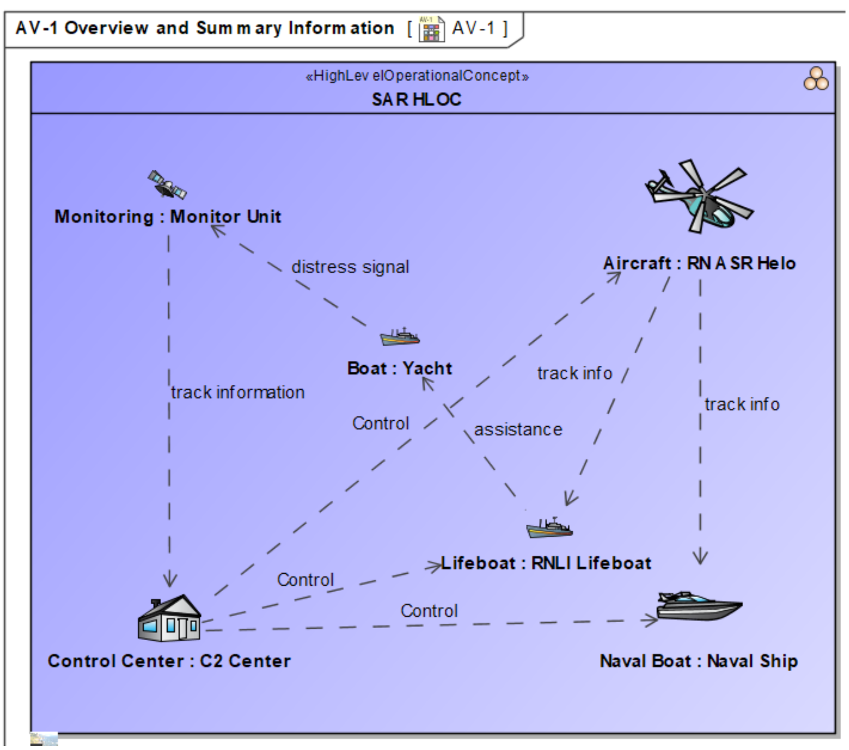


Figure 14: Sample DODAF AV-1 View [53]

#	Exchange ID	Operational Exchange Item	Sending Operational Performer	Receiving Ope
1	OE1	IE6 Warning Order	Search Node	Place Of Sa
2	OE2	IE9 Medical Condition	Search Node	Rescue Nod
3	OE3	IE7 Distress Signal	Person In Distress	Rescue Nod
4	OE4	IE7 Distress Signal	Person In Distress	Monitoring N
5	OE5	IE4 Control Order	Tactical C2 Node	Rescue Nod
6	OE6	IE3 Track Info	Monitoring Node	Tactical C2 I
7	OE7	IE4 Control Order	Tactical C2 Node	Search Nod
8	OE8	IE5 Request	Tactical C2 Node	SAR Asset C
9	OE9	IE2 Task	SAR Asset Controller	Rescue Nod
10	OE12	IE2 Task	SAR Asset Controller	Search Nod
11	OE13	IE7 Distress Signal	Person In Distress	Search Nod

Figure 15: Sample DODAF OV-3 View [53]

2.5 Conclusion

In this chapter, the first part of the literature survey dealing with the defense acquisition system, and its various elements has been presented, the gap with regards to the considerations of ways in the process been identified and formalized, and the initial stage of a solution in the form of the RFLP process been identified.

2.5.1 Formulation of Research Hypothesis

Comparing the outlined RFLP process with the previously described CBA, similarities of the different steps can be seen and the fundamental approach of hierarchization in both processes be identified. While the nature of the system design process enables a comparison between RFLP and the general CBA process, the comparison with the scenario considerations within the CBA in the research question at hand is more difficult. It requires the elevation of the process from the definition of the system level towards both the definition and operational conduct at the SoS level. Based on these considerations, the following hypothesis with respect to research question 1 is formalized:

Hypothesis 1: If the RFLP process is utilized as the adjusted elementary definition approach and alternative scenarios are decomposed into elements and interfaced, then a standardized and modular approach can be produced.

CHAPTER 3. MATERIEL AND NON-MATERIEL DIMENSIONS

This chapter continues the literature survey by shifting the focus from the scenarios, towards the means and ways as material and non-materiel dimensions of an overall design and solutions space.

3.1 DOTmLPF-P Analysis

Based on the previously introduced CBA and especially FSA that considers various approaches, DOTmLPF-P as a term describes the entire spectrum of materiel and non-materiel dimensions; it stands for doctrine, organization, training, materiel, leadership and education, personnel, facilities, and policy. According to the Defense Acquisition University [54], the dimensions are defined as follows:

- “Doctrine: the way we fight (e.g., emphasizing maneuver warfare, combined air-ground campaigns)
- Organization: how we organize to fight (e.g., divisions, air wings, Marine-Air Ground Task Forces)
- Training: how we prepare to fight tactically (basic training to advanced individual training, unit training, joint exercises, etc.).
- materiel: all the “stuff” necessary to equip our forces that does not require a new development effort (weapons, spares, test sets, etc. that are “off the shelf” both commercially and within the government)
- Leadership and education: how we prepare our leaders to lead the fight (squad leader to 4-star general/admiral - professional development)

- Personnel: availability of qualified people for peacetime, wartime, and various contingency operations
- Facilities: real property, installations, and industrial facilities (e.g., government owned ammunition production facilities)
- Policy: DoD, interagency, or international policy that impacts the other seven non-materiel elements."

Due to the comprehensiveness of the dimensions, CBA including a DOTmLPF-P analysis requires the collection of large sets of data that allow an adequate assessment of the various approaches. Based on the CBA User Guide [55], however, the overall process is a mainly traditional and paper-based, founded on literature and policy review and subject-matter expert (SME) input. Important to note is that the process not only includes SMEs on the respective CBA team, but SME dispatched and responsible to other organizations and units.

3.1.1 Limitations and Shortcoming

The diversity of factors included in a CBA can make the process of managing the information challenging to manage [56]. While obtaining the information for each dimension is not difficult, establishing metrics suitable to draw conclusions and create rankings proves to be challenging. This applies especially when comparing materiel solutions with the remaining non-materiel dimensions. Mitigating efforts include for example the creation of portfolio frameworks that aggregate sparse information "related by a common theme" [55] and aim to institutionalize that part of the process. However, these steps remain scattered efforts and have not reached the level of an integrated and rigorous CBA framework yet that would be required to address the issues holistically [57]. In summary, it can be stated that:

Observation 3.1: The DOTmLPF-P analysis produces various possible approaches towards addressing identified capability gaps in the respective dimensions, but lacks sufficient interdimensional comparisons and subsequent comprehensive interconnected feasibility and efficiency assessments.

3.2 Prioritization & Research Scope

While the consideration of interdimensional comparisons, in a parameterized fashion within a system-of-system analysis, is included in the methodology objective of this study, conducting an entire CBA across all domains is not feasible within the scope of this work. However, as the aim is to develop a general methodology that can ultimately be applied more broadly, the selection of a single non-materiel domain in combination with the materiel spectrum will suffice as it presents the necessary intra- and inter-dimensional relationships.

In order to make this selection, the guidance of the Joint Chiefs of Staff (JCS) with regards to the JCIDS [45] is consulted to identify the most relevant non-materiel dimension. Within that, the dimensions are prioritized in the following order:

1. "changes to the existing doctrine, organization, and education;
2. changes to policy guidance, including force posture;
3. changes to personnel, including staffing, skill levels, and unit composition;

4. product improvements to existing materiel and facilities;
5. adopting interagency or foreign-supplied materiel approaches;
6. potential international cooperative developments;
7. new materiel starts."

Following this prioritization, the set of non-materiel dimensions for consideration in this study is reduced to doctrine, organization, and education. Considering the three dimensions, doctrine can be described as the primary driver of operational ways with organization and education being subsidiary to doctrine. Leadership and education in the military-hierarchical context relates to doctrine as distributing sufficient understanding and enhancing the degree of proper implementation of doctrine. Organization has a direct dependence on doctrine as the formation of units is driven by doctrine-defined objectives and goals; thus, it could only be subsequently included as an additional dimension in an expanded non-binary framework succeeding the to-be-developed methodology.

Thus, for the purpose of this study, **doctrinal aspects are selected as non-materiel dimension for the parameterization of ways.**

3.3 Doctrine

Doctrine is defined by the DoD as "fundamental principles that guide the employment of United States military forces in coordinated action toward a common objective and may include terms, tactics, techniques, and procedures" [58].

3.3.1 Levels of Doctrine

Doctrine can be separated onto different levels, following the levels of warfare established in the Doctrine for the Armed Forces of the United States, as shown in Figure 16: Strategic, Operational, and Tactical [31]. It should be noted at this point that the exact terminology for and within the different branches might vary from the joint documentation. While there is no finite distinction between the different levels, compartmentalization allows the implementation and execution of doctrine on different levels of command and forces. The exact nature of doctrine for the different levels depends on the nature of the respective mission.

Strategic doctrine provides for the formalization of the ends in a military context and focuses on the employment of instruments of power on a global or theater level [31]. For each branch of the armed forces, general warfighting principles are laid out in strategic doctrine. While changes and updates in wording are frequently made to the respective documents, their core remains more or less unchanged as they reflect the end goals. If development occurs, they are almost always evolutionary in nature and gradual over time.

Operational doctrine links the strategic and tactical level by establishing specific goals and tasks in accordance with the strategic objectives [31]. Given a certain mission, operational doctrine outlines the planning and allocation of resources.

Tactical doctrine is the most specific guidance provided to commanders and operators in the field and prescribes the employment of forces, their arrangement in relation to each other, and their use for engagement [31].

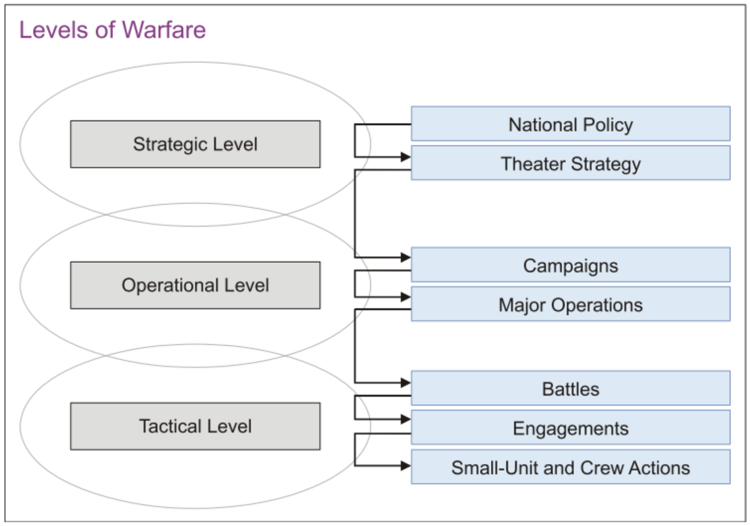


Figure 16: Levels of Warfare [31]

3.4 Gap

The various elements of the DOTmLPF-P analysis cover a diverse range of factors critical to success for the overall mission investigated in a CBA. However, these attributes are neither fully separated nor are the lines between the categories fully binary. Even though there are clear definitions and aspects that have a predominant nature, changes made to a specific approach can lead to a reclassification within multiple dimensions. This situation produces interdependencies between the dimensions, leading to the situation that certain options exclude changes in different positions or limit the variability for these. These interdependencies increase with increasing complexity of the problem and while they are extensive for the full analysis, they are occurring already on the doctrinal-and-materiel-only scope.

Based on these considerations and the observations made in CHAPTER 2 and CHAPTER 3 as observations 2.2 and 3.1, the gap addressing the requirement to deconflict the design and options space can be formalized as follows:

Gap 3: The operational design space needs to be properly constrained to provide a meaningful and credible basis for subsequent exploration.

3.4.1 Derivation of Research Question

The operational design space referred to in gap 3 requires formalization in order to be infused in the computational analysis. Information about doctrine or non-materiel approaches in general occur in a format readily available for comparison with materiel approaches or quantifiable in general. In addition to identification, the question of feasibility is raised to determine if a viable alternative can be identified in conjunction with other alternations. Relating the developed methodology requirements to this gap, the approach needs to qualify as representative and quantifiable. This allows the formulation of a research question corresponding to gap 3 as follows:

Research Question 2: How can the feasible operational approaches, including and beyond the current approach, be identified?

In order to address this research question and subsequently develop a corresponding hypothesis, the following two sections consider the quantification of doctrine and doctrinal interdependencies.

3.5 Quantification of Doctrine

The quantification of doctrinal approaches has been extensively addressed by Steven A. Tangen in the thesis for a methodology for the quantification of doctrine and materiel approaches in a CBA [59], which enabled the parameterization of doctrine in such a way that it becomes comparable to materiel parameters. Similar to the approach of this study, the thesis focuses on doctrine as representative for non-materiel dimensions and quantifies it into tangible metrics for comparison. The collection of input is achieved through SME knowledge, obtained by extensive case-specific review of literature and publications.

Tangen developed methodology subsequently has been applied and showcased on a single-domain, single-objective, single-asset case study, the development of a Hunter/Killer UAV [59]. Variations have been tested in selected operational doctrine aspects (such as patrol patterns) and materiel technology-driven parameters (such as sensor range or cruise speed). The various approaches have been structured into matrices of alternatives, where for each dimension various options are listed.

While the groundwork for the assessment of combinations of different alternatives has been laid in existing work, it’s important to acknowledge this as ‘first step’ towards addressing larger gaps in the current state-of-the-art. In the context of this study, elements of the methodology relating to the quantification of doctrine will be incorporated and tested on a larger scale.

In addition, the main objective of the previous case did not necessitate the analysis of interdependencies and subsequent constraining of design space, which is the focus of the currently discussed gap and research question.

3.6 Doctrinal Interdependencies

Doctrinal interdependencies and incompatibilities occur in complex missions. The utilization of different types of assets for common goals in the same operation requires joint approaches; for modelling and simulation, it requires the harmonization of characteristics to be treated as similar asset type. Missions with multiple, potentially competing, objectives yield interdependencies between the various goals and require the definition of overall performance metrics to accommodate for this.

Interdependencies and incompatibilities of various doctrinal aspects constrain the operational design space. Requiring that certain attributes must align or preventing certain combinations effectively limits variability of approach combinations. Under these circumstances, simple combinatorial logic applied to alternative elements that has been in previous studies inevitably produces impossible cases.

The constraints possibly yielding interdependencies and incompatibilities need to be identified before infusion into modelling and simulation environments. While the environment can recognize certain types of faulty cases whose erroneous nature is incompatible with the flow of the simulation, others can go unnoticed depending on the type of the infeasibility. To enable simulations, models often require simplifications and assumptions, which can lead to the environment treating erroneous cases as real ones to produce an output. These outputs, compared to other valid ones, can be within a reasonable range, making their detection in later stages more difficult, or out of bound. Overall, the simulation of detectable infeasible alternatives consumes time and resources through the need for manual troubleshooting of errors, while undetectable infeasible alternatives infuse false outcomes into the analysis and can bias overall results.

3.7 Conclusion

In this chapter, the second part of the literature survey dealing with the materiel and non-materiel dimensions of the overall design and solutions space has been presented. Moreover, the gap with regards to the required deconfliction has been identified and formalized, and the necessary considerations setting up the inclusion into the methodology been made.

3.7.1 Formulation of Research Hypothesis

Building upon the outlined considerations, the need for an a priori identification of feasible combinatorial approaches through the detection and elimination of infeasible ones can be established. Similar to the identification of the approaches in the first place, this process needs to be educated by SME knowledge, either through experience or literature review.

Following the utilization of matrices of alternative, the creation of matrices of relationship is proposed. These matrices take into account the identified dimensions and require the classification of their relation in a quantified way; categories would need to be specified, for example as (i) no interdependency/independent from each other, (ii) weak interdependency, (iii) strong interdependency, and (iv) (possible) impermissibility. Subsequently, alternative combinations with different levels of incompatibility are eliminated from further consideration. Based on these considerations, the following hypothesis with respect to research question 2 is formalized:

Hypothesis 2: If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations from further consideration.

CHAPTER 4. EXPLORATION OF THE DESIGN AND OPTIONS SPACE

This chapter finishes the literature survey by picking up the various work streams that provide the multitude of options of different types and providing the necessary context for the structured exploration of the design and options space.

4.1 Design Space Exploration

Design Space Exploration (DSE) “refers to the activity of exploring design alternatives prior to implementation” [60]. This process includes the collection of alternatives, the identification of feasible options and their analysis with respect to a certain objective. In order to collect the available options, the respective design space needs to be characterized with dimensions and parameters along which changes can be made.

Depending on the number of identified dimensions (variables) and the resolution within these dimensions (number of options per variable), the DSE attains highly multi-dimensional character and yields a high number of alternative combinations that require analysis. The extent rapidly overwhelms manual assessment capabilities, and quickly even provides challenges for computational approaches. In addition, complex spaces might yield incompatibilities and interdependencies between different dimensions that need to be considered.

In the context of this study, DSE is considered from two different viewpoints: the materiel perspective, and the operational or non-materiel perspective. The first represents the more classical design space, often used in engineering problems, the variation of means such as different assets or technologies. The latter considers the impact of alternate ways by exploring the impact of different operational decisions.

4.1.1 Traditional Analysis of Alternatives

The traditional Analysis of Alternatives (AoA) is a means-oriented process performed in the pre-system acquisition phase of the JCIDS after the creation of an Initial Capabilities Document (ICD) and the Material Development Decision (MDD). It has been developed and established under the classical paradigm of evolution-oriented acquisition processes with its inherent drive towards and preference for the enhancement of existing assets or the development of new assets as successors to existing ones [61]. While this process is not directly applicable to the identified core of this research, the CBA, understanding its limitations and shortcomings is critical to improve the current overall process.

4.1.1.1 Limitations and Shortcomings

AoA in a broader sense is a formalized requirement in military and civil acquisition processes to satisfy formal requirements with regards to the consideration of alternatives. The formal nature demands actual physical assessment processes and does not include stipulations to be complemented or replaced by computational avenues. The consequence of this is high costs to conduct a proper AoA and thus an affordability hurdle only met by large scale programs [62]. While, in principle, an AoA is advisable for every acquisition program and even small volume programs if executed to the highest efficiency can produce significant improvements, the process is not necessarily performed extensively for all programs.

A consequence of the evolution-oriented design of the AoA process is its focus on conventional solutions and improvements that omit revolutionary 'game changing' approaches through an overly constrained design space [62]. Based on the design-biased performance characteristics as foundation of the analysis, alternatives that can provide the higher-level capabilities in different ways cannot reach through due to their incompatibility with the assessment process.

In addition, the Government Accountability Office assessing the AoA's conducted by the DoD [62] found that the selection decisions based on current AoA protocol yields delays and cost overruns in later stages of the acquisition process. During the AoA, according to the assessment, the actual need is not properly addressed in the analysis which causes the deficiencies to show during subsequent steps where adaptive and compensatory action is more costly and time-consuming. In summary, it can be stated that:

Observation 4.1.1: The traditional procurement process does not utilize the opportunities of design space exploration to its full extent. The currently performed assessments of alternatives show insufficient structure and relative weight to serve their crucial role in the acquisition process, preventing the proper analysis of asset effectiveness.

4.1.2 Comprehensive Evaluation of Alternatives

A comprehensive evaluation of alternatives (EoA) needs to be employed to address the shortcomings of the traditional AoA. Comprehensive in that context implies not only the consideration of a high number of alternatives, but also the consideration of capabilities over detailed performance requirements.

Several methodologies such as the Integrated Product and Process Development (IPPD) [63] include an approach that abstracts the necessary steps for this kind of decision support and allow the creation of an specialized EoA process. In case of IPPD, a systematic establishment of the need, problem definition and establishment of the value (evaluation parameters) precedes the generation and alternatives evaluation before a decision can be made.

Independent of the methodology, the high number of cases demands the utilization of computational means. First, the analysis of individual cases needs to be shortened by using modelling and simulation as opposed to conventional analysis. It generally requires additional time for setting up or creating the necessary environment, but drastically reduces the time spent on individual cases. In addition to that, if the dimensionality and run time constraints do not allow the assessment of all relevant cases, surrogate modelling techniques need to be employed to create an analytical model of the entire design space. In summary, it can be stated that:

Observation 4.1.2: The multi-dimensionality caused by the breadth of independent variables in the process demands the utilization of computational means to enable assessments with reasonable time and resources.

4.2 Conducting a Capabilities Based Assessment (CBA)

Before proceeding to a survey of available computational means, this section establishes the connection between the abstract approach of the exploration of the design and options space, the comprehensive evaluation of alternatives under consideration, and its specific relevance for the conduction of a Capabilities Based Assessment (CBA).

Fundamentally, a CBA is conducted through an interactive process between a core study group and a stakeholder working group in a limited time frame [55]; the generic workflow is shown in Figure 17: Task Relationships and Overlap for a CBA [55]Figure 17. Personnel for the core study group can be recruited from across the organization or on a contract basis from outside but is generally considered primarily committed to the CBA and its mission. In contrast, the members of the stakeholder working group are representatives from entities within the organization that have a varying degree of interest in the CBA and its outcome; they act as ambassadors of their home unit and are monitoring the CBA with respect to the interests of their unit. This situation can make the process subject to 'departmental politics'.

This tension-prone relationship also creates circumstances where the selection of staff and their corresponding affiliation, as well as procedural steering decisions throughout the process can pre-determine or at least influence the outcome of the CBA irrespective of the formal steps and their respective results. Given the flexible nature of CBA structure, enabling the process to be performed manually without any required utilization of computational means or modelling and simulation, a subsequent ability to 'shape the process to your liking' based on stakeholder interests not necessarily committed to the CBA mission can be observed. In summary, it can be stated that:

Observation 4.2.1: The formal guidance for the CBA still heavily relies on manual work by subject-matter experts, and does not yet require or formalize the use of computational models and simulations.

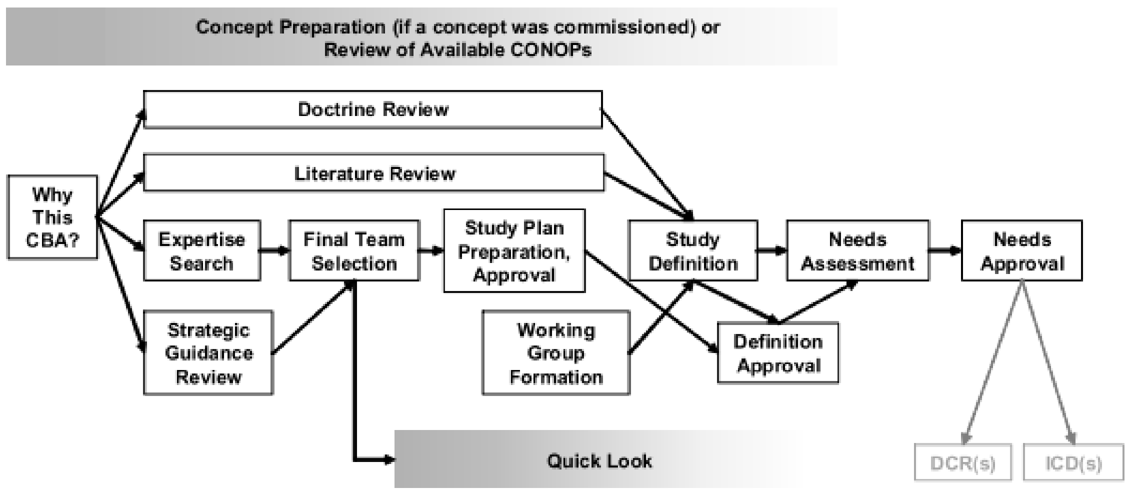


Figure 17: Task Relationships and Overlap for a CBA [55]

4.2.1 Motivation for Process Enhancement

The CBA shows improvement potential through the infusion of computational means both with regards to increasing the objectivity and expanding its comprehensiveness.

First, a decoupling of the input from subject-matter experts, both from the core study group as well as from the stakeholder working group, from the generation of results enables the 'best of both worlds'. Knowledge from staff of different entities, as well as from uninvolved experts through reports and documentation can still be accessed and utilized. Due to a decoupled and subsequently formalized transition structure, the potential for unnecessary down-scoping and steering (i.e. ‘playing the system’) of individual members decreases.

Second, the use of computational means, especially such with low time-per-case load and potential for a high volume of cases, allows to expand the number of cases or approaches to be considered which further reduces the need for limitations. The employment of low fidelity modelling and simulation that satisfies requirements established in section 1.4.1 provides a pathway for a comprehensive exploration of the design and options space. While the results might require additional analysis due to the inherent inaccuracy, it still enables an open-ended initial assessment process that can guide the subsequent decision-making with an objective data foundation. In summary, it can be stated that:

Observation 4.2.2: The separation of subject-matter input and creation of results could enhance the objectivity of the CBA process.

4.3 Existing Environments for Military Simulations

Computational models in general are utilized for the assessment of scenarios in lieu of physical experiments. They are built when real-world elements are either impossible to conduct, at all or under the necessary controlling conditions, or their execution in sufficient quantity is too expensive. In a military context, the considerations are known as war gaming, whereby the level of fidelity is a driving factor for affordability and extent; high fidelity environments yield detailed results, but are computationally expensive and resource consuming. Nonetheless, for military planning and campaign simulations often a detail-oriented approach is required to satisfy the needs.

Examples for existing environments are the Synthetic Theater Operations Research Model (STORM) of the U.S. Navy and the Advanced Framework for Simulation, Integration and Modeling (AFSIM) of the U.S. Air Force. Both environments are able to conduct in-depth analysis of military strategy and operations and attempts have been made to adapt them for rapid assessment purposes that would be required for the consideration of acquisition alternatives [64][65].

4.3.1 Limitations and Shortcomings

Scenario building currently requires extensive work by SME's for setting up the required parameters [64]. Tailored towards military strategy and operations of various scales, experience is deemed key for making sure the model is as reflective of real-world behavior as possible. Furthermore, this experience needs to be matched with the ability to translate knowledge into computational language, which can further complicate and prolong the process.

For detailed high-fidelity studies, significant computational powers are required and considerable run times even for single simulations are the norm [64]. The level of fidelity automatically drives models to certain modelling types and the underlying environments to certain complexity.

In addition, most war games require human involvement at certain steps for critical decisions [64]. This means that even highly sophisticated scenarios include decisions that are made by high-level commanders or officials and are thus difficult to anticipate and to predetermine. While some war games are conducted as completely manual tabletop exercise, even hybrid approaches require human input. Besides the significant effect on the run time of computational models, the availability of suitable participants for a simulation is a severe constraint. Individuals suitable for the role of the decision maker usually tend to have little availability for extensive simulations and games even with only single cases. All these factors limit the number of available scenarios and scenarios that can simulated. In summary, it can be stated that:

Observation 4.3.1: The modelling and simulation of military operations is currently employed as supplementary element for purposes of planning and gaming.

Observation 4.3.2: Current modelling and simulation capabilities are predominantly high-fidelity and do not allow the simulation of a large set of missions in a timely manner.

4.4 Gap

Considering the observations made in CHAPTER 4 as observations 4.1.1, 4.1.2, 4.2.1, 4.2.2, 4.3.1, and 4.3.2, the gap requiring the paradigm of low-fidelity modelling and simulation as necessity for the scope of our analysis can be formalized as follows:

Gap 4: Low-fidelity modelling and simulation needs to be employed to allow the consideration of alternative scenarios and mission variations in a timely manner.

The stipulation towards low-fidelity modelling and simulation is a direct consequence of our scope towards early high-level considerations and the need to tackle the multi-dimensionality and quantity of options.

4.4.1 Formulation of Research Question

When simulating a large amount of cases with varying attributes, available time and resources quickly become critical. The type of model built, method of simulation used and level of fidelity applied in combination with the available computational power drives the runtime of the overall simulation. Even with the use of surrogate models, the number of cases that need to be run to construct these surrogates must be appropriate with respect to the complexity of the scenario. The complexity of the scenario is determined by the probabilistic uncertainties inherent to operational events and the influence of stochasticity on the simulated behavior. The level of fidelity of the modelling and simulation approach needs to reflect this complexity to properly address the multidimensionality of the problem and avoid oversimplifications and suppression of stochastic effects through enabling assumptions. Relating the developed methodology requirements to this gap, the approach needs to qualify as representative. This allows the formulation of a research question corresponding to gap 4 as follows:

Research Question 3: How should the modelling of operational scenarios be structured such that elementary interfaces and behavior are supported?

4.5 Modelling and Simulation Options

In order to address this research question, the study considers modelling and simulation options. To guide this part of the study, taking into account the results of the previous work streams, the following specific research questions can be formulated:

Research Question 3.1: Which modelling type is compatible with the decomposition and recomposition approach applied to operational scenarios?

Based on the reviewed literature and previous studies for similar problems, the following techniques are considered: Agent Based Simulation (ABS), Discrete Event Simulation (DES), and System Dynamics (SD). The approaches vary with respect to their complexity and resolution and are shown in comparison in Figure 18. In order to decide on an approach suitable for the purpose of this study, all three techniques are assessed and compared.

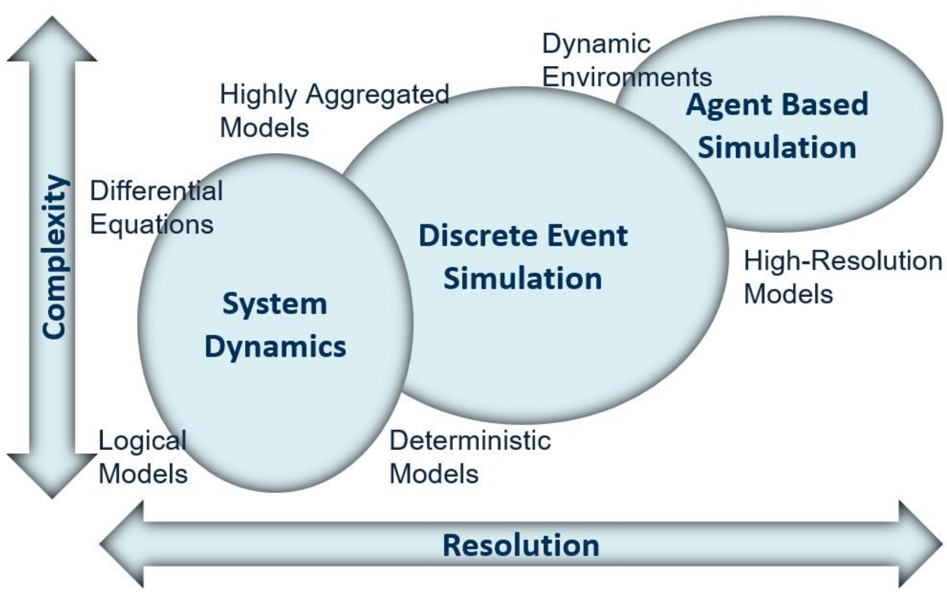


Figure 18: Comparison of Modelling and Simulation Options (Adapted from [66])

4.5.1 Agent Based Simulation

ABS is a complex technique most notably used in game theory and SoS design [67], which focuses on agents as driving force of the simulation [68]. Each agent is described by its own attributes and characteristics, its relationship towards other agents and the goals it is pursuing. This yields individual distinguishable behavior guard railed in the simulation by simulation rules and constraints [67][69]. The 'bottom-up' setup of ABS without requiring a central authority and the ability to 'let the scenario play out' with stochastic effects, makes it well-suited to study emergent behavior. It can yield overall scenario performance and tracks each individual agent through the scenario.

A downside of ABS is, compared to DES and SD, the high computational demand it raises due to its complexity [70]. The coding of the individual agents provides a certain flexibility with regards to the level of detail [71]; this applies to both the initial attributes and the information gained from the simulation. If an ABS is considered, a careful assessment in comparison to DES needs to be undertaken. A simple or highly-reduced ABS can deteriorate into a quasi-DES, in which a proper DES with its advantages should be used in the first place.

In a military context, this approach can provide valuable insights when the required level of fidelity demands the consideration of individual distinguishable behavior of units and the related stochastic effects related, such as for engagements on the mission level [70].

4.5.2 Discrete Event Simulation

DES is a technique often attributed to manufacturing or logistic problems [72], which focuses on entities, events and sequences over time within a simulation [68][73]. Entities are moved through different states within the simulation, requiring certain events to occur in order to proceed. The simulation can consider probabilistic effects by allowing conditionality of the occurrence, timing, and duration of certain events. Depending on the setup of the model, it can operate it a flexible 'bottom-up' fashion or stringent 'top-down'.

Compared to ABS and SD, it requires less computational resources than ABS but more than SD. However, it is unable to reach the level of complexity for individual behavior achieved by ABS. DES model probabilistic effects related to events, while ABS can include stochastic behavior of its agents (and indirectly events as they are driven by the agents themselves). As already mentioned previously, a careful tradeoff between ABS and DES is advised with regards to the problem at hand.

In a military context, this approach is valuable for logistic simulations in general, but also abstracted high-level operational questions if a low level of fidelity is sufficient. The latter is the case for the exploration of a multitude of options, that can be followed by the in-depth verification of few or a single option.

4.5.3 System Dynamics

SD is a technique frequently employed in engineering disciplines [67], addressing problems of dynamic nature with a high-level focus on the effects of interactions [74]. Its simulations are characterized by interdependence, mutual interaction, information feedback, and circular causality [75]. It follows a predetermined scheme based on flow chart and equations, thus operates strictly ‘top-down’.

In a military context, this approach is applicable to strategic training policy design and analysis, answering ‘what if’ questions, and organizational planning [74].

4.5.4 Hybrid Approaches

Different modelling approaches can also be employed together in a hybrid manner. With increasing dimensionality and complexity of models, the overall simulation can be compartmentalized, and distinctly different approaches applied for sub-models providing the interfaces are compatible and the information exchanged is coordinated.

4.5.5 Comparative Assessment of Approaches

Comparing the outlined techniques with the RFLP process and the adjustment considerations made, ABS and DES can be identified as generally suitable to proceed with, while reservations exist for SD with regards to the consideration of probabilistic and stochastic effects. Equivalent structures for the implementation of the logical and physical can be identified for both methods: Agents and entities represent the general physical layer, agent behavior and discrete sequences translate the logical layer. The functional layer is represented through discrete events and states in DES and is embedded in agent types and their respective goals in ABS. However, the overall similarity with DES is higher as they both include the layering as structural elements, while the implementation in ABS requires conversion into agent-related characteristics. With regards to the computational requirements, DES is preferable to ABS to increase the caseload that can be considered for simulation.

4.6 Conclusion

In this chapter, the last part of the literature survey dealing with the background for for the structured exploration of the design and options space has been presented, the gap with regards to the needed paradigm of low-fidelity modelling and simulation been identified and formalized, and the applicable modelling and simulation techniques been analysed.

4.6.1 Formulation of Conjecture

It concludes with the assessment that the discrete event modelling and simulation approach reflects the inherent structure of decomposed and recomposed scenarios, and will be utilized for the remainder of this research. The high-level nature of the CBA and its position in the early stages of the defense acquisition process allow the prioritization of the structural compatibility and decreased computational demand of the DES with the RFLP approach over the flexibility advantage of ABS.

Furthermore, the satisfaction of the goals pursued with the establishment of the methodology in this research remains undisturbed by the literature-based selection of DES. With the overall to define a structured approach that does not require the limitation, but enables the comprehensive exploration of the design and option space, DES strikes the necessary balance and maintains the edge over the computationally-intense ABS. In addition, it should be repeated that due to its location in the overall process traditional or high-fidelity means can be employed as additional (and traditional process-trusted) verification following the methodology process. Based on these considerations, the following conjecture with respect to research question 3 is formalized:

Conjecture 3: If discrete event simulations are utilized to model an operational scenario as a whole, then the structure and characteristics of decomposed operational scenarios is properly represented.

4.6.2 Lack of Experimental Validation Option

Before proceeding beyond the literature survey and applying the conjecture, it needs to be stated that an experimental verification of the conjecture is infeasible. By the nature of the setup of discrete event simulations, it will yield conclusive, or indistinguishably conclusive-appearing, results irrespective of the probabilistic parameters implemented; an emergence of stochasticity-influenced individual behavior of actors would not occur.

It should be noted that the conjecture does not imply an imperative of the utilization of DES, but rather a qualified enabling decision for the progress of this study. Depending on the nature of other problems this research, and especially the methodology described in the following chapter, can be applied to, each technique or a hybrid form of them can be utilized if suitable.

CHAPTER 5. METHODOLOGY STRUCTURE

Previous chapters have introduced the motivation and the literature background setting up the different work streams and the overall objective of this research. In addition, a formalization of the research through the formulation of specific gaps and questions has been conducted, which will be used the following chapters to successively close the gaps. In this chapter, a comprehensive methodology is formulated that accomplishes the research objective. Before discussing the three parts of the methodology in detail, additional background towards its creation is provided.

5.1 Background

5.1.1 Review of Existing Methodologies

Before proceeding further in the formulation of the methodology, a review containing the assessment of existing methodologies introduced by relevant academic studies relating to the gaps of this research is presented. While the selected theses all make contributions to the main gap, they have a varying impact on the subsequent gaps 2 to 4; an overview including their impact on the gaps is shown in Table 1.

Patrick T. Biltgen developed a methodology for capability-based technology evaluation for SoS [76] that is addressing the human-in-the-loop problem through intelligent agents (so called 'Meta General') that are able to simulate tactical and strategic decisions by themselves. These agents make their decisions based on predefined alternatives and given preferences.

Steven A. Tangen, as already discussed in Section 3.5, developed a methodology for the quantification of doctrine and materiel approaches in a CBA [59], laying important ground work for the parameterization of doctrine in such a way that it becomes comparable to materiel parameters. While the methodology provides a starting point for this study to tackle gap 4, the focus on the quantification leaves open the question of combinatorial feasibility and the proper constraining of the operational design space.

Kelly A. Griendling developed the Architecture-based Technology Evaluation and Capability Tradeoff (ARCHITECT) method that enhances the CBA through the structured inclusion of executable architectures [77]. The work of this thesis on these architectures provides meaningful contributions towards the mitigation of gap 3 and it is utilized in this study with regards to the modelling and simulation environment.

Mahmoud A. Abdelaal developed a methodology for determining critical decision points through analysis of wargame data that enhances the proficiency of simulated course of action decisions [78]. Tackling the computational representation of principally human-driven decisions, the thesis takes existing war game data, identifies battlefield heuristics, and establishes recognizable patterns through critical decision points.

Seth E. Gordon developed the Stochastic Agent Approach (SAA) for mission effectiveness that translates decisions into probability-driven coefficients for simulations purposes [79]. The thesis contributes a small-scope high-fidelity approach to inform new representations on mission-level activities and is deemed applicable with a high degree of universality regarding methods, tools, and scenarios.

Biltgen, Abdelaal and Gordon all provide extensive insight and solution approaches towards the problem of the computational simulation of human-driven decisions. While the theses provide knowledge for consideration in this work, their focus is outside of the scope identified for this study.

Steven C. Chetcuti developed a framework for developing executable architecture for aerial intelligence surveillance and reconnaissance SoS through Systems Dynamics (SD) that enables the analysis of means and ways trades across the DOTmLP-P spectrum in support of CBA [80]. Addressing a similar problem as this study, the focus of this thesis lies towards a comprehensive analysis of the entire materiel and non-materiel spectrum for a given problem on a high-level, enabling the employment of SD (which is discarded for the purpose of this study in a later stage) and does not address the diversity in operational requirements.

Griendling and Chetcuti both provide extensive research on executable architectures in the context of the research scope and offer a framework that can be translated towards addressing gap 2 in the progress of this study.

Mackenzie H. K. Lau developed a methodology exploring employment concepts in engagement to enhance quantitative technology evaluation [81]. This thesis provides insights into the representation, generation, and evaluation of alternative ways and links the corresponding considerations with other areas of research.

Raffaele Gradini developed a methodology enabling science and technology investment trade-offs showcased for ship and naval technology [82]. Providing the means-focused counterpart to this more way- and environment-oriented research, this thesis utilizes scenario parameter variation to challenge technologies in different circumstances with the goal of identifying robust solutions.

It should be noted that none of the relevant academic studies provides significant contributions to gap 2 and the consideration of diverse operational requirements.

Table 1: Overview over Relevant Existing Methodologies and their Impact on the Identified Gaps

	Gap 1	Gap 2	Gap 3	Gap 4
Biltgen [76]	Contributions	Out of scope	Out of scope	Mentioning
Tangen [59]	Contributions	Out of scope	Contributions	Mentioning
Griendling [77]	Contributions	Mentioning	Mentioning	Contributions
Abdelaal [78]	Contributions	Out of scope	Mentioning	Mentioning
Gordon [79]	Contributions	Out of scope	Out of scope	Mentioning
Chetcuti [80]	Contributions	Mentioning	Out of scope	Contributions
Lau [81]	Contributions	Mentioning	Contributions	Mentioning
Gradini [82]	Contributions	Mentioning	Out of scope	Contributions

5.1.2 Objective and Hypothesis

Research Objective: Develop a methodology that considers diverse operational requirements and operational ways in a parameterized fashion within a system-of-system analysis in the early stages of the acquisition process.

In order to satisfy the research objective, it is required to address the variations in means and ways in order to enable decision making on acquisitions. Most critical aspect is the consideration of a multitude of scenarios in a conjoint process, as the lack of in-depth discussion in current methods and approaches considering both means and ways side-by-side has been identified as the main gap (gap 1).

To address this, the following methodology introduces the involvement of diverse operational requirements expressed through multiple scenarios. The inclusion of these multi-scenario, multi-mission aspects and the corresponding establishment of metrics for inter-scenario comparisons widens the scope towards an integrated analysis. Furthermore, the research considers incompatibilities and interdependencies in the alternative selection process to produce proper constraints for the operational design space. While studying alternative options in a compartmentalized manner streamlines the process through parallelization of tasks, it raises the aforementioned issues that need to be mitigated when introducing complex problems. By addressing these issues, we provide for the closure or mitigation of the gap through the ability to simulate and subsequently analyze alternative concepts of operations (CONOPS). Based on the presented research, preliminary assessments of the mitigation steps required, and requirements to address the gap, there can be a formalization of the following research hypothesis:

Overall Research Hypothesis: If the operational design space is formalized considering interdependencies and constraints, and operational scenarios defined on an elementary level, then feasible alternative concepts of operations can be rapidly composed, infused into low-fidelity modelling and simulation and subsequently analyzed with various approaches.

As outlined in the discussion in CHAPTER 4 and specifically included in the overall research hypothesis, an intentional choice is made to utilize low-fidelity modelling and simulation. In the early stage of the acquisition process, the comprehensive exploration is prioritized over detailed results. The latter can be obtained subsequently through traditional means or high-fidelity approaches.

5.1.3 Equivalency Conjecture

The formulated methodology performs the established and broadly utilized process of a CBA. Commencing with a problem definition and consideration of necessary tasks to be performed to solve the problem or fulfil the objectives, it ultimately produces an analysis considering various approaches to educate decisions on which kind of avenues to pursue. The experiments presented in CHAPTER 6 and CHAPTER 7 validate key functionalities of newly-infused or adapted elements of this process.

However, it won't be possible to compare the outcome of experiments to the same process performed in a traditional setting due to the limitations outlined throughout this study. The improvements towards the state-of-the-art are nonetheless established through derivation from the overall hypothesis. Through experimentation, this study defines and verifies an approach to properly constrain the operational design space for the parameterization of ways as well as the ability to rapidly and conjointly consider alternative CONOPS and draw overall conclusions. Thus, the following equivalency conjecture has been formalized:

Equivalency Conjecture: The methodology executes the steps of a Capabilities Based Assessment (CBA), starting with the correct inputs and yielding the same outputs. Given the success of the separate experiments validating the newly-infused or adapted elements of the process, a successful execution of the methodology enables

a CBA considering the comprehensive design space through low-fidelity modelling and simulation. Thus, it satisfies the overall research objective.

5.1.4 Limitations

Before proceeding to the development steps, the limitations of the methodology need to be stated. First, the methodology is input sensitive. The CBA as process itself, as mentioned earlier, is highly flexible and is not regulated into a strict formal nature. Subsequently, the methodology preserves this flexibility, stays intentionally general, and does not overly constrain the possible problems to which it can be applied. As consequence, the user needs to ensure quality of preparatory work and inputs in order to provide meaningful contribution to the defense acquisition process.

Second, the utilization of the RFLP process limits the upward mobility along the level of scope. Specific missions, engagement, and other lower-level scopes can be easily managed, while it is not suitable for entire campaigns or theater assessments. Applying the technique to top-level scopes can strain the methodology to the point of results being no longer meaningful due to the lack of reflection of the inherent parameters such as increased decision freedom of individuals or changing environmental parameters that have not been accounted for. However, this limitation is in line with the scope of the utilization of one or multiple scenarios for specific cases within the CBA.

Third, the combinatorial feasibility of alternatives can get increasingly complex and multi-dimensional depending on the applied level of detail, and the scope of DOTmLPF-P dimensions considered. With increasing numbers of parameters, the time required for deconfliction can increase exponentially along with the increased caseload to be assessed subsequently. These factors need to be considered when creating the overall time plan for a specific CBA to be conducted.

Lastly, as it applied to all computational designs of experiments and building upon the previous consideration, the quantity of parameters and options can strain the computational capabilities available to a user. While low-fidelity simulations open up the quantity of cases that can be assessed compared to its alternatives, there is still a consideration to be made how many cases can be assessed with the means available.

5.2 Development Steps

Having provided the background for the methodology and discussed its structure, this section outlines the development needed from the starting points provided at the conclusion of the literature reviews in CHAPTER 2 and CHAPTER 3 towards their integration into the methodology in the following section.

5.2.1 Modification of the RFLP Process

Based on the discussion outlined in Section 2.5 with regards to the scenario formulization, the following hypothesis has been formalized:

Hypothesis 1: If the RFLP process is utilized as the adjusted elementary definition approach and alternative scenarios are decomposed into elements and interfaced, then a standardized and modular approach can be produced.

The RFLP systems design process was identified as a suitable structure to achieve the scenario modularization part contributing to the research objective. However, the still inherent specificity towards engineering systems needs to be resolved for it to become applicable to this research. While parallels can be drawn from an operational scenario towards a system, a transition of the logic towards the proper terminology needs to occur. Thus, to relate the RFLP process to the issue of scenario formalization, the different levels of analysis need to be adjusted towards operational design considerations. Table 2 shows the transition relationship outlined in this section, while Figure 19 presents an example of the RFLP decomposition used for the following experiments. As example for a full decomposition including different logical elements, the detailed steps for the case study can be found in APPENDIX B.

Table 2: RFLP transition from systems design to the adjusted process

	Systems Design	Adjusted Process
Scenario	-------------------	Capability Demand
Requirement	Goals	Mission Purpose, Objectives
Function	Operations Performed	Mission Components, defined by operational segments
Logic	Components	Sequential Tasks, influenced by non-materiel aspects
Physical	Physical Parts	Geography & Resources

5.2.1.1 Scenario

Prior to the presumably first element of requirements, we address the scenario or more previse its objective. The original process itself is started by external input, e.g. the desire to build a system that can accomplish a certain goal. As important distinction, this process outlines a singular path to accomplish it. In the context of this research and the CBA in general, the RFLP process needs to be triggered as well. However, the overall goal or objective of the CBA itself is not equal to the one applied to the RFLP process. The CBA process is focused an acquisition problem, or prior to that the assessment of materiel and non-materiel approaches to avoid costly acquisitions. The demanded capabilities need to be related to an actual use case. Thus, the adjusted process is initialized with the creation of overall scenarios that derive from the capability and translate it into one or multiple problem statements cover the use cases of the capability.

5.2.1.2 Requirements

As next step and first of the original RFLP process, requirements are defined. Requirements serve as top-level goals defining the purpose and necessity of a system, or in this adjusted case the scenario. All requirements need to be satisfied in order to fulfill the capability. Satisfaction of a criteria, or sufficiency, is related to fulfilling certain target metrics associated with a requirement. Depending on the initial guidance that starts the process, such metrics can be predefined or need to be derived through a quantification process at this stage. In addition, varying with the context of the actual CBA, these requirements can be limited to a binary definition (satisfied/not satisfied), or extended towards a more granular classification (different levels of performance).

Furthermore, it’s important to note the step of quantification that occurs at this level. Given the computational simulations that rely on input and outputs in discrete, categorical, or continuous forms, the satisfaction of requirements need to fit that scheme as well. This means irrespective of whether satisfaction of requirements is binary or associated with certain levels of performance, the thresholds need to be associated with metrics and corresponding quantities. In the context of the case study, examples for such requirements metrics are ‘5000 packages need to be delivered to the population by 5 days’, ‘50% of the population in need needs to be serviced after 5 days’, or ‘3 days into the operation at least 2500 packages need to be delivered’.

In the context of the Requirements level, it is important to note that the meaning and extent changes significantly between system design and the adjusted process. Requirements in the traditional systems sense usually occur in high numbers and flow down through the entire decomposition process. Thus, they can be prominently traced at any level as they are detailed enough so that they can be associated with lower entities in the process. Through the adjustment process and transition towards scenario formalization, the meaning shifts towards higher-level objectives that need to be satisfied. Hereby, objectives are kept to a minimum number. Enablers of the objectives, i.e. elements that need to be satisfied in order for an objective to be fulfilled, are addressed on the functions level in the adjusted process.

The extent of requirements to be considered is important to evaluate the necessity of a complex process such as RFLP, and whether the problem is compact enough so that a traditional manual process can suffice. In the system design process, the value of utilizing the RFLP process and Model-Based Systems Engineering (MBSE) in general unfolds with the increasing number of requirements to be considered and tracked. Thus, with increasing complexity the value of this approach increases to the point of being required to handle the process. The case study in this dissertation demonstrates the scalable process in its detailed steps, and provides the guidance for its application for more complex and comprehensive problems.

5.2.1.3 Functions

Functions originally describe the operation performed by a system. In the adjusted context towards a scenario, this level corresponds to top-level mission components that perform separate operations necessary to fulfil the requirements. Each function deals with a separate task, and can be considered/simulated separately, although they might be sequentially dependent on each other and transition from one to another. While all requirements can be considered critical, functions can be separated into mandatory and supporting ones. The latter are performed to enhance the overall target metrics, i.e. either contribute to their satisfaction or improvement, but are not necessary for performance. The important distinction for functions is that they are associated with performance metrics that either directly constitute the aforementioned top-level targets or express a contribution towards them.

5.2.1.4 Logic

On the logical level, the system would be separated into components that are attributed with specific behavior and interaction with each other through interfaces. In the adjusted context, it describes the sequence of subordinate tasks and events within a mission component (vignettes). An important element of the logic is the manifestation of decision-making as it is influenced by the non-materiel dimension of the problem. In addition, logic would also need to tackle the prioritization and distribution of shared resources utilized for different functions; this would make the different functions interdependent on each other, whereby their individual performance is connected to the performance of other functions.

5.2.1.5 Physical

Lastly, the physical design of a system includes the specification of actual physical building blocks and parts. For scenarios, the physical structure lays out the geography of the theater of operations, as well as the physical resources available.

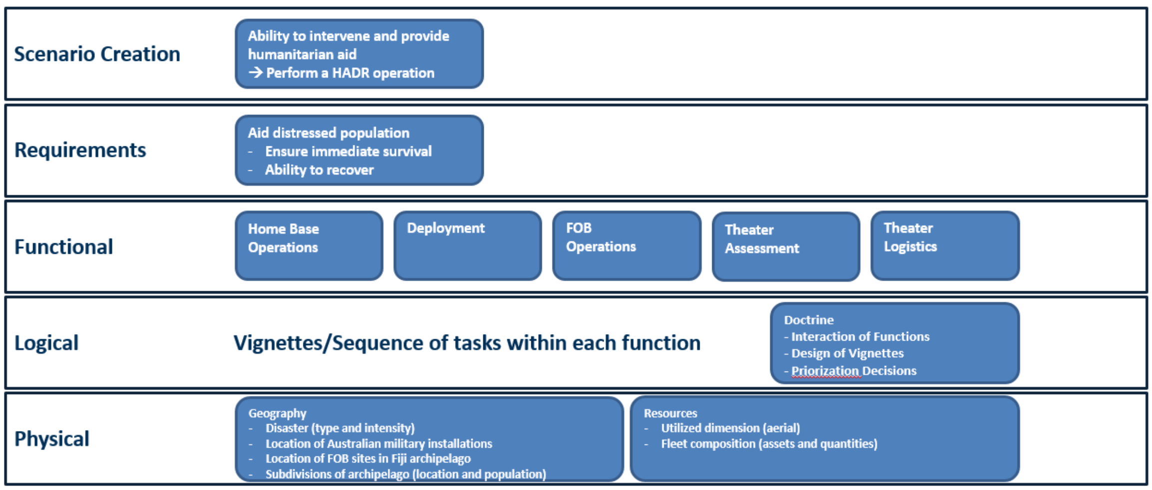


Figure 19: Sample RFLP Decomposition

5.2.1.6 Recomposition

Having outlined the various steps of the decomposition, the most critical element in the adjusted process, the redefined recomposition part is addressed here as well. The extent of the recomposition process is driven by the level of complexity in the problem overall and its formalization in the decomposition. The complexity is reflected by the amount of elements on each level, and the excess of their interfaces amongst each other.

The classical defense acquisition examples such as the underlying case study of this dissertation remain fairly manageable in this regard. However, the consideration of complex technologies such as Artificial Intelligence (AI) or Autonomy or an increased scope in operational consideration from the mission to campaign and theater level would put higher demands and likely more iterations on this part of the process.

Initially, testing is performed to ensure that the formalized information representing the physical layout can interface and interact with each other in an analytical environment. Most important aspect here is that all information is provided for the higher elements, and an iterative return to the testing phase can become necessary if a lack of information occurs subsequently. In the adjusted process, the testing focusses on ensuring the correct translation of physical and geographical information into the selected environment. In the simulation process, the relationships amongst each other drive the performance of the entire operation. A simple example of such interaction is the correct definition of various locations in the theater in a universal coordinate system that can be translated into distances. The latter is the relevant parameter for assets moving between locations, and the corresponding time and paths it will need to take. In an applied manner, the testing can occur in the simulation environment by focusing on elements of the scenario and run test simulations, and subsequently expand the scope in steps towards the full scale.

In the integration stage, the logic elements or tasks are put into relationship with each other. It's assessed whether the transition between tasks is functional, all necessary information is present from the previous level, and sequences can be successfully completed. In the adjusted process, integration ensures that all implemented logical elements are populated by the physical and geographical elements established and tested before. Similarly, to the testing phase, integration occurs step-by-step to ensure that possible definition errors or lacking information can be traced and corrected. The steps can either be built up sequentially or bundled in blocks if a parallelized process occurs.

As verification, its analyzed whether the mission components themselves produce the required outputs. Given a successful completion of the previous steps, the verification can focus on performance metrics being produced and proper transition between functions is occurring. At this stage of the adjusted process, various vignettes and sequences are functional and produce credible outcomes. Subsequently, they form a combined function that produces quantified performances that is again assessed for credibility and representativeness. In addition, functions can sequentially depend on each other, so a similar process as for integration needs to reoccur on this elevated level.

In the final validation step, its assessed whether the requirements of the mission are satisfied, and the overall construct has successfully fulfilled the mission purpose.

5.2.2 Creation of Matrices of Alternatives and Relationships

Based on the discussion outlined in Section 3.7 with regards to the operational design space, the following hypothesis has been formalized:

Hypothesis 2: If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations from further consideration.

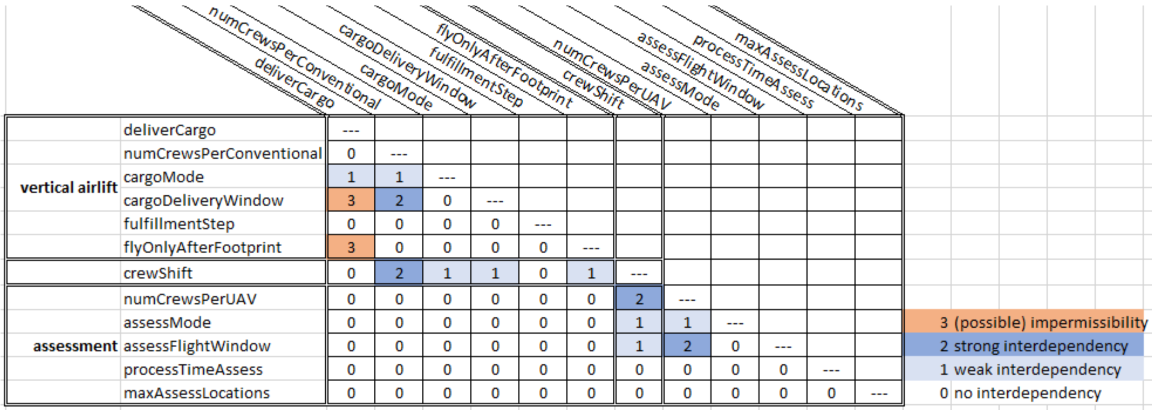
The process to create these matrices follows well-established procedures. For matrices of alternatives, the parameters that are to be varied are identified. Before moving on to the actual alternatives, each parameter is characterized on whether it continuous, discrete, or categorical. For categorical parameters, the alternatives need to be directly identified and listed. For both discrete and continuous parameters, upper and lower boundaries need to be determined. For discrete parameters, in addition, the level of discretization (e.g. nonnegative integer) needs to be specified. This means for discrete parameters we can identify a total number of options, while this is not the case for continuous parameters. When translating the matrix of alternatives into a design of experiments, one thus has the option of selecting a representative subset of discrete parameters but needs to specify the resolution or sampling parameter to produce specific alternatives from a continuous parameter. Optionally, the parameters can be grouped into one or multiple levels of categories that represent their association of an element of a more complex system. Figure 20 presents an example of a matrix of alternatives used for the following experiments.

		type	alternatives
inter-theater	YAMB130	discrete	0,2
	YAMB17	discrete	2,3,4,5,6
intra-theater vertical airlift	rc_cargo_num	discrete	2,3,4,5,6
	rc_cargo_type	categorical	MRH-90,CH-47,UH-60,V-22, V-280
intra-theater assessment	uav_assess_num	discrete	0,2,3,4
	uav_assess_type	categorical	Stalker,Bat,RQ-21
	rc_assess_num	discrete	0,1
	rc_assess_type	categorical	AP-3C

Figure 20: Sample Matrix of Alternatives

Once the matrix of alternatives is produced, it can be expanded into a relationship matrix. Structurally, the list of parameters forms both rows and columns that allow the definition of the relationship with each parameter among each other in a lower-hand triangle. Before conducting the relationship analysis and definition itself, a classification nomenclature needs to be set. This is a contextual decision driven by what level of detail is required in a given CBA. For example, the following classification can be used, and is applied to the following experiments: (i) no interdependency/independent from each other, (ii) weak interdependency, (iii) strong interdependency, and (iv) (possible) impermissibility.

The classification of the relationship of parameters is a subject-matter expertise driven process. Either the operator or the study team jointly possesses the necessary expertise, or decision are justified on a literature basis; the latter option is used in this research. When making the determination for two parameters, all possible alternatives need to be taken into account and the strictest classification be assigned for a parameter overall. At this point, the matrix can be expanded into an additional level of detail, breaking down certain parameter into separate rows and columns representing the options. An advantage of this approach is that all the relevant relationship information remains in one place, and for parameters whose options yield different interdependencies the matrix is not over constraining. However, this approach can quickly increase the size of the matrix to excessive levels that might not aid clarity in manual or human-interaction steps of its use. Figure 23 presents an example of a matrix of alternatives used for the following experiments.



		deliverCargo	numCrewsPerConventional	cargoMode	cargoDeliveryWindow	fulfillmentStep	flyOnlyAfterFootprint	crewShift	numCrewsPerUAV	assessMode	assessFlightWindow	processTimeAssess	maxAssessLocations
vertical airlift	deliverCargo	---											
	numCrewsPerConventional	0	---										
	cargoMode	1	1	---									
	cargoDeliveryWindow	3	2	0	---								
	fulfillmentStep	0	0	0	0	---							
	flyOnlyAfterFootprint	3	0	0	0	0	---						
	crewShift	0	2	1	1	0	1	---					
assessment	numCrewsPerUAV	0	0	0	0	0	0	2	---				
	assessMode	0	0	0	0	0	0	1	1	---			
	assessFlightWindow	0	0	0	0	0	0	1	2	0	---		
	processTimeAssess	0	0	0	0	0	0	0	0	0	0	---	
	maxAssessLocations	0	0	0	0	0	0	0	0	0	0	0	---

3	(possible) impermissibility
2	strong interdependency
1	weak interdependency
0	no interdependency

Figure 21: Sample Relationship Matrix

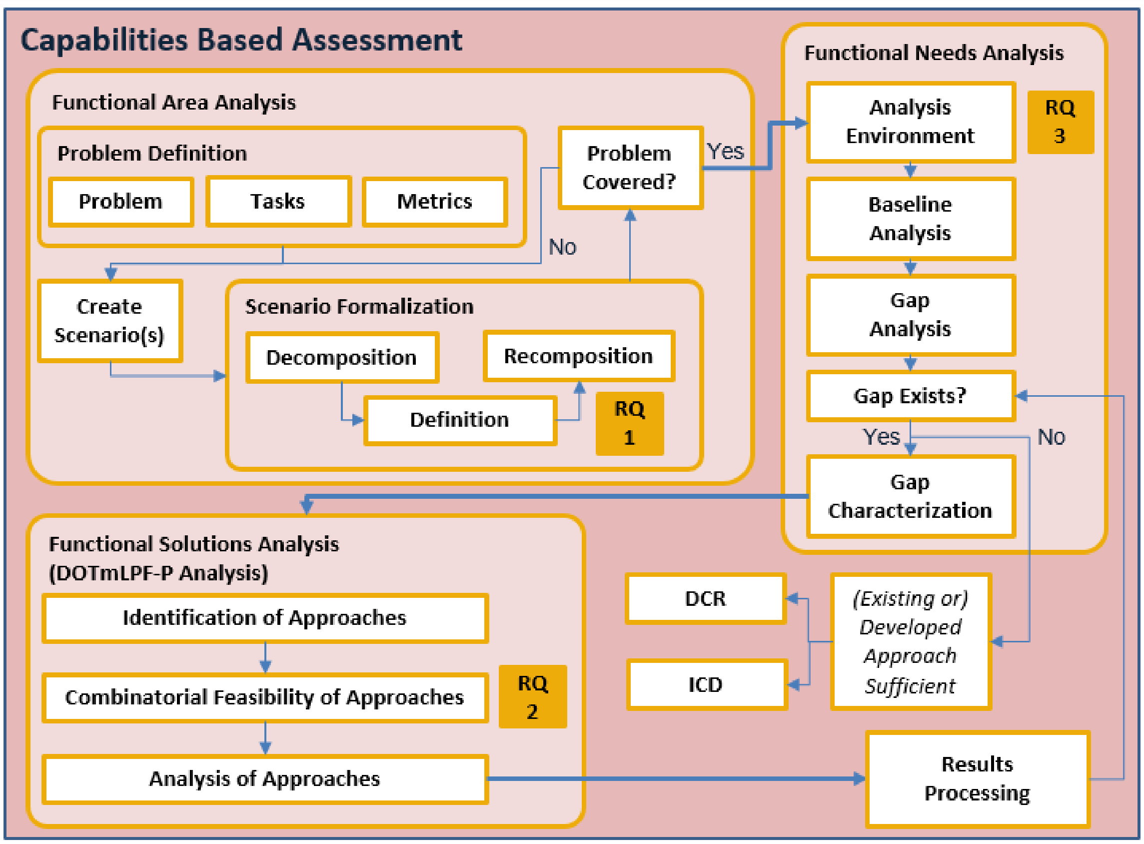


Figure 22: Methodology Flowchart within the Capabilities Based Assessment

5.3 Part 1: Functional Area Analysis

Steps 1 and 2 form the equivalent of a Functional Area Analysis (FAA) performed in the CBA.

5.3.1 Step I: Problem Definition

The first step is the definition of the problem that needs to be solved. The problem itself can be given externally as initialization of the process or extracted from high-level strategic guidance via an exploratory process. This step formalizes the problem into standardized tasks and corresponding requirement metrics. The tasks describe the required or aimed-for capabilities and objectives, while the metrics allow the quantitative evaluation of performance and effectiveness in later stages. The step overall provides a quantification of relevant parameters that sets up a structured solution-finding process. The creation of this initial documentation requires subject-matter expertise or extensive literature review.

To summarize, for step I the outputs are a problem description, tasks and metrics.

5.3.2 Step II: Scenario Formalization

The second step of the methodology is the formalization of the scenarios which address the needs of the defined problem. This includes building a sufficient set of scenarios fully covering the tasks outlined in the problem definition. Full coverage in this context means they provide appropriate conditions around the testable metrics from the defined tasks to be performed; one (dominant) scenario can be used, or multiple ones if necessary.

In order to maintain a cohesive flow through the successive steps of the methodology, the formalization needs to take place through a standardized process. This is necessary as these scenarios represent diverse operational requirements that will be assessed in a shared framework. For this methodology, the standardized process is an adjusted version of the RFLP process, as surveyed in Section 2.4 and to be formalized in CHAPTER 6.

The step commences with a verification that all the scenarios are properly addressing the problem as defined in the previous step. If that this cannot be verified and deficiencies are detected, the process of generating the scenarios needs to be repeated before proceeding to the next step.

To summarize, for step II the inputs are the problem description, tasks and metrics developed in step I and the output is a standardized formulation of one or multiple scenarios.

5.4 Part 2: Functional Needs Analysis

Steps 3 and 4 form the equivalent of a Functional Need Analysis (FNA) performed in the CBA.

5.4.1 Step III: Analysis Environment

The third step of the methodology is the creation or selection of a modelling environment able to analyze the scenarios. The step itself is subdivided into three parts: the selection of a modelling technique, the consideration and determination of a modelling tool, and the creation of the actual specific environment. For this methodology, in order to be compatible with the standardized RFLP process, a pre-selection towards a discrete event simulation is made, as established in Section 4.6.

However, while this determination is made based on the conjecture established in aforementioned section, it's not mandatory to proceed on this path. Based on the discussion provided in Section 0, the identification of a suitable modelling technique can be performed on a scenario-specific basis and expanded to a more complex modelling technique to ensure that it can tackle the characteristics of the scenario and generate meaningful outputs towards the required metrics. Subsequently, a modelling tool that can support the chosen technique needs to be identified from among the tools available to the operator; the availability of tools can be constrained by a variety of reasons such as legal accessibility/user constraints or fiscal procurement limitations. With a tool selected, the actual environment capable of processing the required inputs such as the formalized scenarios can be coded.

To summarize, for step III the inputs are the metrics defined in step I and the standardized scenario formulations developed in step II, and the output is a modelling environment.

5.4.2 Step IV: Baseline and Gap Analysis

The fourth step of the methodology is performing a baseline and gap analysis. For the baseline analysis, a simple scenario is selected to benchmark the selected environment. This scenario is infused into the developed environment and simulated. In the context of this step, 'infusion' describes the process of utilizing the standardized scenario formulation populating the environment, while ‘simple’ requires the absence of a capability gap and a reasonable way of validating the simulation results such as the comparison with real world data. Alternatively, a baseline can also be selected based on parameters that have been performed in a real operation, irrespective of whether such a scenario already includes gaps. This is especially useful if the CBA and methodology are performed due to dissatisfaction with an operational performance that triggered the process in the first place. The baseline scenario can be a part of the already developed set or it can be created ad hoc – provided it follows the same formalization step and it is related to the respective matter; it can also be a simplification of an already existing scenario.

Subsequently, an assessment of the remaining scenarios is conducted with the aim to identify performance gaps. Based on the requirement metrics from step 1, the gaps can be detected through comparison of these metrics with the simulated performance. This assessment gives the ground for the characterization of gaps that describe the deficiencies with regards to the required capabilities. Alternatively, the process of gap analysis and characterization can be combined by raising the requirements on the performance of the baseline scenario in order to achieve generally improved performance. In this case, the quantification of the new target metrics need to be performed at this point. This is especially useful if the methodology is conduced with only a single, or small number of scenarios. If no gaps are detected or established within the initialization loop of the methodology then the process would stop and deem the existing approaches sufficient.

To summarize, for step IV the <u>inputs</u> are the metrics defined in step I, the standardized scenario formulations developed in step II, and the modelling environment defined in step III, and the <u>output</u> is are the characterized gaps.

5.5 Part 3: Functional Solutions Analysis

Steps 5 to 7 form the equivalent of a Functional Solutions Analysis (FAA) performed in the CBA.

5.5.1 Step V: Identification of Approaches

The fifth step of the methodology is the identification of alternative approaches. These approaches characterize the design space, both in a non-materiel operational and material context. Based on the standardized scenario formulation, dimensions can be identified and for each dimension alternatives selected in the context of the identified gaps based on subject-matter expertise or literature review. The collection of these results are documented in multiple dimension-specific morphological matrices.

To summarize, for step V the <u>inputs</u> are the standardized scenario formulations developed in step II and the characterized gaps identified in step IV and the <u>outputs</u> are the alternative approaches.

5.5.2 Step VI: Combinatorial Feasibility of Approaches

The sixth step of the methodology is the assessment of combinatorial feasibility of the approaches to properly constrain the design space. As previously discussed in Section 3.6, with increasing operational complexity incompatibilities and interdependencies occur that constrain certain combinations of alternatives from different dimensions. This step is performed through the establishment of relationship matrices that allow the documentation of relationships and, based on their respective strength under the applied level of scrutiny, their subsequent detailed analysis or exclusion from the pool of feasible approaches if necessary.

To summarize, for step VI the inputs are the alternative approaches found in step V and the outputs are the feasible approach combinations.

5.5.3 Step VII: Analysis of Approaches

The seventh step of the methodology provides for the analysis of approaches. Based on the quantity of considered scenarios and feasible approaches identified in combination with the available time and resources, a design of experiment (DoE) is devised and successively infused into the simulation. In the context of this step, 'infusion' described the consideration of the various alternatives as defining elements of simulation cases.

If the multidimensionality and quantity of scenarios does not allow the simulation of all relevant alternatives in a full-factorial DoE, surrogate models are constructed to reflect the entirety of the constrained design space.

To summarize, for step VII the inputs are the requirement metrics defined in step I, standardized scenario formulations developed in step II, the modelling environment defined in step III and the feasible approach combinations identified in step VI and the outputs are the performance metrics and, if necessary, representations of the design space through surrogate models.

5.5.4 Step VIII: Gap Reassessment & Approach Selection

The eighth and final step of the methodology is the reassessment of the gaps. Based on the results of the analysis and the ability to analytically assess the entirety of the design space, either through full-factorial results or surrogate model representation, multivariate analysis and profiling can be conducted for an overall comparison between the required performance and the measured performance within the different cases.

If the gaps are not closed, when none or only some required performance metrics are met, the process loops back to the gap characterization at the end of step IV and/or the identification of approaches at step V.

If the gaps are closed and the performance in the respective cases is sufficient, the process proceeds to preparing the selection of approaches by compiling a list of possible satisfactory approaches. If there is still a high quantity of approaches at this point that does not allow immediate decision-making to occur, a prioritization based on the decision-maker or stakeholder preferences can be conducted.

To summarize, for step VIII the inputs are the requirement metrics defined in step I, the characterized gaps identified in step IV and the performance metrics and general representations of the design space and the outputs are the clarification on gap satisfaction and possibly prioritization of alternatives.

With the conclusion of step VIII, the full methodology unfolds its potential as a process aiding the decision-making in the CBA and DAS. Throughout the process, criteria’s have been established and mapped against relevant influencing factors. Thus, criteras and factors are available in a structured manner that allow the proper education of decision makers prior to making their decisions. Furthermore, it enables the application of decision-making techniques that would consider preferences and criteria weightings, and subsequently provide ranked recommendations. The latter steps being particularly useful to be applied by a moderating leader that needs to take into account different stakeholder interests.

Figure 23 depicts the information flow between the different steps of the methodology. Table 3 relates the various steps of the methodology to both the formal CBA steps, as well as the corresponding elements of the IPPD process.

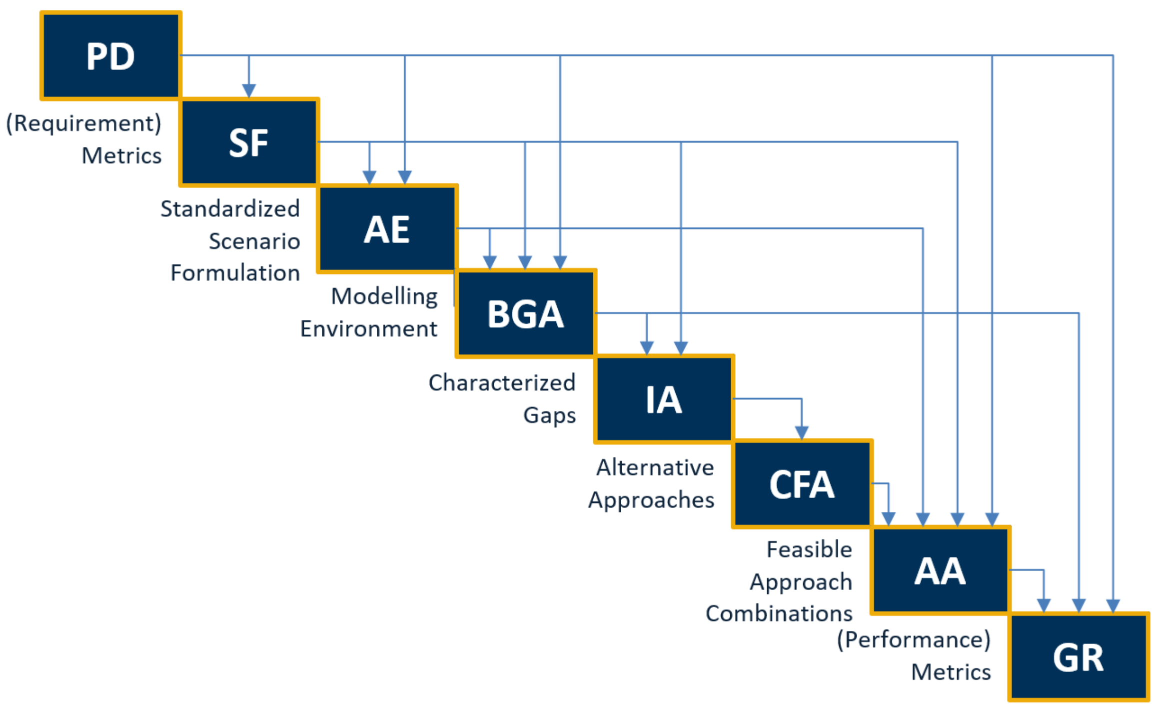


Figure 23: Methodology Information Flow

Table 3: Steps of the Methodology in relation to CBA and IPPD

Step		Relation to CBA	Relation to IPPD
I	Problem Definition	FAA	Establish the Need
II	Scenario Formalization		Define the Problem
III	Analysis Environment	FNA	Establish Value
IV	Baseline and Gap Analysis		
V	Identification of Approaches	FSA	Generate Feasible Alternatives
VI	Combinatorial Feasibility of Approaches		
VII	Analysis of Approaches		Evaluate Alternatives
VIII	Gap Reassessment & Approach Selection	------	Make Decision

CHAPTER 6. SCENARIO MODULARIZATION

This chapter describes the experimental validation of hypothesis 1 that, based on the discussion outlined in Section 2.5 with regards to the scenario formulization, it has been formalized as follows:

Hypothesis 1: If the RFLP process is utilized as the adjusted elementary definition approach and alternative scenarios are decomposed into elements and interfaced, then a standardized and modular approach can be produced.

6.1 Approach

To validate hypothesis 1, the objective of the experiment is to ensure coherent simulation results across multiple scenarios proofing that a structured and modular approach has been created. Thus, it needs to be verified that the conducted approach not only provides instructions on how to introduce scenarios into modelling and simulation, but that is also formally standardizes the process in a transparent manner to speed up repeatability. The crucial elements of the methodology utilizing scenarios and mitigating inherent bottleneck contribute to its usefulness and overall importance in future application.

6.2 Experiment

The experiment follows the background and structure of the case study introduced in Section 1.6.3. A 5-day immediate HADR mission needs to be performed in different scenarios under consideration. The setup of the experiment is to apply the RFLP process in its version as adjusted through the development outlined in Section 5.2.1 to a set of selected scenarios. Through this, the decomposition, interfacing and recomposition process is formalized and documented as an architecture in a suitable format prior to the infusion into an environment. Subsequently, the architecture is infused into the environment, simulations are conducted, and results are obtained.

6.2.1 Design

In this experiment, and applicable to the following experiment and case study, the Australian Armed Forces react to various HADR scenario within the South East Pacific. A cyclone of high intensity hits an independent Pacific Island nation, overwhelms national response capabilities, and leads to a request for help to Australia. The Australian Armed Forces are tasked to respond and react with a HADR operation launched from an Air Force Base on the east coast of Australia, the RAAF Amberley in the southwest of Queensland.

To provide for strategic airlift from Australia towards a location suitable to serve as Forward Operating Base within the theater, 2 C-17 and 2 C-130 are mobilized to operate for an initial operation period of 5 days. For the inter-theater deployment, with regards to personnel and equipment transport, the first priority is placed on transporting the personnel who will establish a forward presence, subsequently the unmanned aerial assessment capabilities, thirdly the vertical airlift capabilities before entering the continuous supply operation sustaining the overall operation. The five days period for the operation reflects an initial and immediate response to a disaster in a remote location that relies solely on aerial inter-theater operations. During this time, the focus is on supplying aid necessary for the survival of the impacted population (such as potable water, basic food, emergency medication, and simple shelter material). After this initial period, depending on the extent of the disaster and the ability of local authorities to recover, a more tailored operation would commence. This would include reconstruction efforts that can also be delivered via external maritime-based aid (that takes longer to reach the theater); however, operations outside of the five-day time window is not dealt in this thesis.

For the intra-theater operations, 3 MRH-90 helicopters are deployed for logistical operations as well as 4 Stalker UAV's and 1 AP-3C fixed-wing aircraft for the theater assessment. While the AP-3C can self-deploy and fly from Australia to the theater, the other assets - including the necessary equipment and personnel for operations – are transported through the strategic airlift. Using the path of the cyclone striking the theater, locations are designated with levels of presumed severity of impact based on the distance of the location to the center of the storm (with shorter distances yielding higher priority), and the time when the storm reached the location (with earlier time yielding higher priority). This designation is used to allocate assessment flights surveying the locations and determining the actual severity of impact. Subsequently, this information is used to estimate how much of the population is in need of imminent aid. It's furthermore used to determine the allocation of logistical flights with actual aid, whereby an equal distribution across impacted locations is ensured as well.

As for the scenario, the variable element in this experiment, the island nations of Fiji and Vanuatu are considered as theaters. Each of these archipelago nations have been hit by multiple cyclones in the past, and the storm paths of six cyclones per archipelago are considered as disaster event.

Figure 24 shows maps of both archipelagos including the paths of the selected storms. While only cyclones Winston in Fiji in 2016, and Pam in Vanuatu in 2015, had reached sufficient intensity to cause significant and response-triggering damage. Climate change predictions show that in the future more storms will reach the critical levels of intensity [83]. Therefore, this experiment simulates all storms with a severe intensity of varying extent. In addition, the experiment considers not only a preferred location, but also an alternative one for the Forward Operating Bases in each theater that could become necessary if the preferred location survivability during the storm is over estimated.

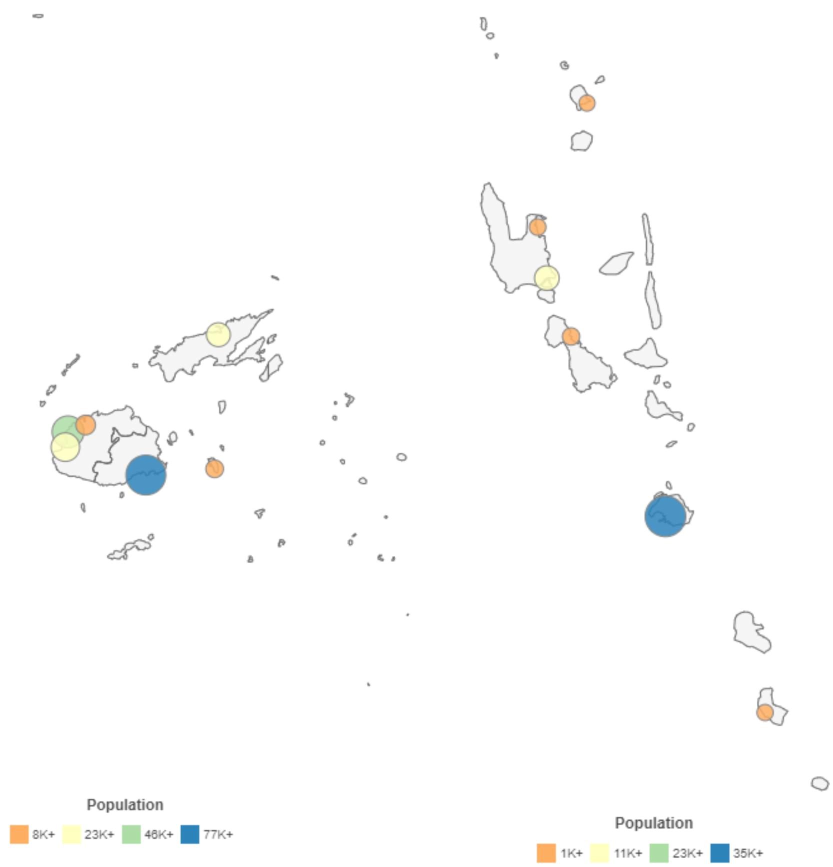


Figure 24: Maps of Fiji (left) and Vanuatu (right) including Population Concentrations [84][85]

In addition to that, the experiment diversifies the scenarios by artificially changing the geographic location of both theaters across the South East Pacific, and by varying levels of population density. Figure 25 shows the implemented artificial relocation pattern for the Fiji example. In the figure, purple needles represent the actual location of a Forward Operating Base and the green needles their artificial alternatives.

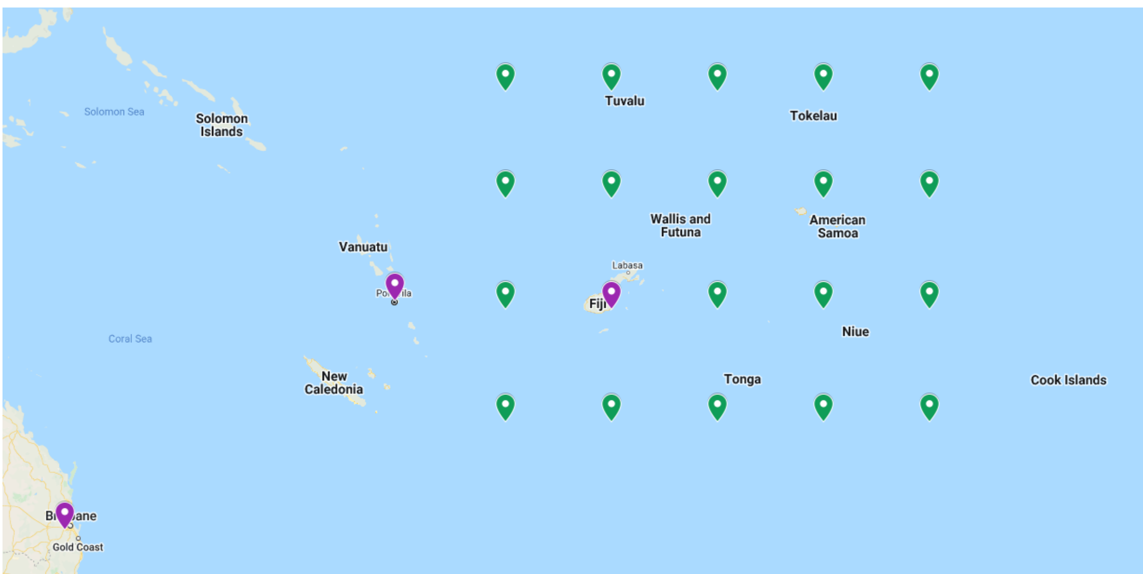


Figure 25: Map of the South East Pacific indicating Original Locations of Bases in Australia, Vanuatu, and Fiji (purple) as well as Artificial Relocation Pattern of Fiji (green)

6.2.2 RFLP Decomposition

Based on the design of the experiment, the scenario is subjected to the RFLP process; the result is visualized in Figure 26. As overall scenario, the 'ability to intervene and provide humanitarian aid' is identified with the corresponding singular requirement ‘aiding the distressed population’ by ensuring their immediate survival and their ability to recover. Due to the scope of the mission, the latter is limited to ensuring their ability, but not necessarily providing for recovery or reconstruction. In order to satisfy the requirement, five different functions need to be performed: operations at the regional home base, deployment into the theater, operations at the local base (including its establishment), assessment of the theater, and performing deliveries within the theater. It should be noted at this point that the fourth function, assessing the theater, could be considered as optional. While its performance benefits the operation and aids in the achievement of target metrics, producing results at all is not contingent on this function. Each function is subsequently decomposed into logical elements, vignettes forming a sequence of tasks that form the function. This level also includes the specification of doctrinal levers. Lastly, the physical layer is formed by the varying geography and allocation of resources to the operation.

The full decomposition including the different logical elements that are not listed here can be found in APPENDIX B.

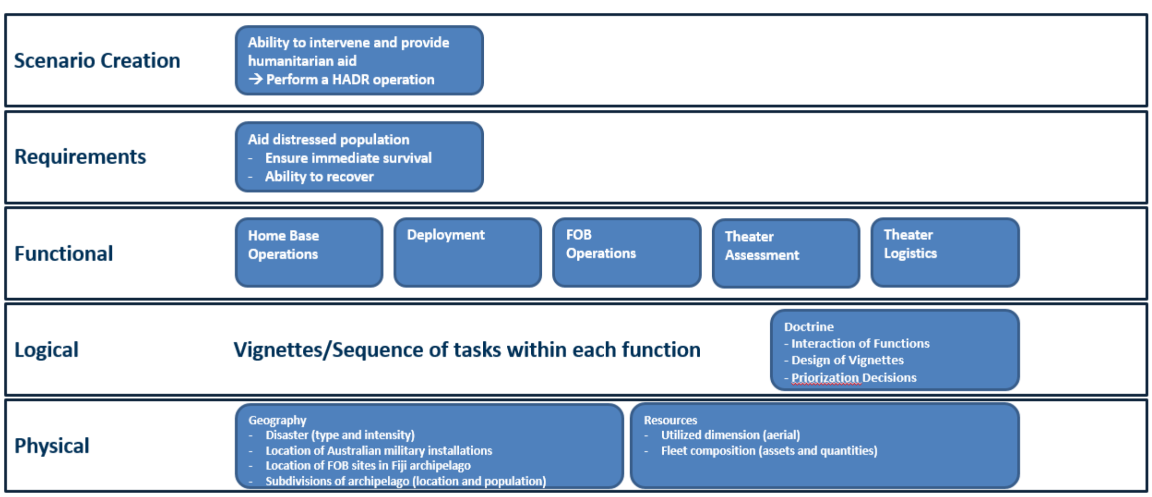


Figure 26: RFLP Decomposition of the Case Studies

6.2.3 Implementation

To reflect the experiment, the statistical analysis software JMP [87] was used to create a full-factorial design of experiments with a total of 11,520 cases. The formalized parameters as outlined previously can be found in Table 4. The experimental parameters are then infused into the Python testbed [88] environment and results are created; the testbed environment and the additional inputs into the simulation are discussed in the following section. Following the generation of results, JMP again is used to analyze the data and create visualizations.

Table 4: Design of Experiments for Scenario Modularization Validation

Parameter	Alternatives	
	#	Description
Theater	2	**<u>Fiji</u>**, Vanuatu
Storm	6	Fiji: **<u>Winston</u>**, Evan, Keni, Amos, Kofi, Cyril Vanuatu: Hola, Cook, Zena, Pam, Lusi, Daphne
Storm Destruction Radius	3	Fiji: **<u>50</u>**, 60, 70; Vanuatu: 60, 70, 80 [km]
Local Base Location	2	Fiji: **<u>Suva</u>**, Macuata; Vanuatu: Port Vila, Luganville
Initial Availability of Aid	2	**<u>0</u>**, 500 [# of packages]
Artificial Relocation Patterns		
Latitude Shift	4	-5, **<u>0</u>**, 5, 10 [°]
Longitude Shift	5	-5, **<u>0</u>**, 5, 10, 15 [°]
Population Scaling	4	**<u>100</u>**, 110, 125, 150 [%]

6.3 Testbed Environment

Before proceeding to the results of the experiments, this section introduces and describes the testbed environment used for all case studies. The environment is under development since 2017 within the Aerospace Systems Design Laboratory (ASDL) in partnership with the Australian Department of Defence's Defense and Science Technology Group and the United States Navy's Office of Naval Research [89][90][91][92][93]. The environment stage used for this research is able to simulate the scenario with the following major elements:

- Inter-theater Strategic Airlift
- Theater Aerial Assessment with Unmanned Aerial Assets
- Intra-theater Aerial Logistics (Cargo Distribution) with Vertical Airlift Assets
- Limited Base and Ground Operations

In addition, it should be noted that the most recent expansion of the environment also supports the inclusion of maritime operations [94], especially maritime-based (complementing land-based) aerial assessment and logistical operations, and allows the simulation of extended operations. It worth noting that the inter-theater part of the environment is capable of performing more complex agent-based simulation of deployment between global, regional (Australia), and local bases with varying and optimized routing logics.

6.3.1 Original Selection Design

Based on the original considerations for an analysis environment presented in CHAPTER 4, and a similar context for the original study preceding this research, multiple options for were considered: Python [88], NetLogo [95], SimEvents [96], FLAMES [97], and Simio [98]. An overview of the options and the considered attributes is provided in Table 5. It should be noted that in the original context the possibility of expanding from a

DES towards a hybrid DES-ABS was considered as an attribute. Python and NetLogo are open-access applications that allow the flexible creation of models, both being applicable to the problems considered. While Python enables both DES and ABS through its setup packages, NetLogo is exclusively built for ABS. SimEvents is an extension to the commercial product MATLAB, providing solid DE capabilities, but is not suitable for AB approaches, and nor it is easily applicable to the considered problems. FLAMES and Simio are commercial products, whereby the first is often used for military applications and the latter is utilized in an industrial context. Both environments enable both DE and AB simulations. With regards to the commercial products, only SimEvents via MATLAB is readily available to the author.

Table 5: Considered Testbed Environments

	Accessi-bility	Applica-bility	Adapti-bility	Discrete Events	*Agent Based*	Level of Effort
Python [88]	Good	Good	Good	Good	*Fair*	Fair
NetLogo [95]	Good	Good	Good	Poor	*Good*	Fair
SimEvents [96]	Fair	Fair	Poor	Good	*Poor*	Fair
FLAMES [97]	Poor	Good	Fair	Fair	*Good*	Poor
Simio [98]	Poor	Fair	Good	Good	*Fair*	Poor

Following these considerations, the utilization of a self-built environment in Python has been selected for this research. It should be noted that the military simulation environments mentioned in CHAPTER 4, namely AFSIM [99] and STORM [64][65], have not been considered due to their access restrictions.

6.3.2 Required Inputs

In order to infuse the designs of experiments into the environment, the case file created by the JMP software is exported as CSV file. Table 6 presents the comprehensive list of input parameters that are used for various case studies in this research, while Table 7 presents the baseline parameters used in the case studies if the respective parameter is not subject to a variation in the design of experiments.

Table 6: Testbed Input Parameters

Parameter	Additional Description
Scenario Aspects	
Theater	Theater for operations, associated with locations and their population
Storm	Storm name, associated with path
Storm Destruction Radius	Radius around the path, driving the prioritization of locations
Local Base Location	Location used as Forward Operating Base
Initial Availability of Aid	Designation on whether initial aid material is available on site (quantity of packages)
Latitude Shift	Degrees latitude for shift of coordinates
Longitude Shift	Degrees longitude for shift of coordinates
Population Scaling	Percentage scaling for increase of population numbers

Table 6: Testbed Input Parameters (continued)

Materiel Aspects	
C-17 Quantity	Number of strategic airlift assets of the type C-17
C-130 Quantity	Number of strategic airlift assets of the type C-130
Vertical Airlift Asset Type	Type of vertical airlift assets
Vertical Airlift Asset Quantity	Number of vertical airlift assets
Unmanned Assessment Asset Type	Type of unmanned assessment assets
Unmanned Assessment Asset Quantity	Number of unmanned assessment assets
Conventional Assessment Asset Type	Type of fixed-wing assessment assets
Conventional Assessment Asset Quantity	Number of fixed-wing assessment assets
Doctrinal Aspects	
Vertical Airlift Cargo Delivery Mode	Utilization of external, internal, or dual loading capacity
Crews per Conventional Asset	Number of full crews assigned to each vertical airlift and fixed-wing assessment asset
Cargo Flight Types	Designator on whether single or multiple locations are serviced on a single cargo flight; for multiple locations, only applicable if load remains and further designation on whether proximity (closest) or priority (next reachable on priority list) is used to determine additional ones required
Cargo Flight Time Window	Operation conducted either only during the day, or day-and-night

Table 6: Testbed Input Parameters (continued)

Local Fulfillment Steps	Designation of how much of the percentage need of a single location can be fulfilled before deprioritization up to the uniform fulfillment of the need across all reachable locations
Asset-Footprint Operations Mode	Designator on whether operations can be conducted by assets prior to the arrival of their footprint (full ground infrastructure)
Duration of Crew Shifts	Duration of the shift of an individual crew, in [h]
Crews per Unmanned Asset	Number of full crews assigned to each unmanned asset
Assessment Flight Types	Designator on whether single or multiple locations are serviced on a single assessment flight; for multiple locations, further designation on whether proximity (closest) or priority (next reachable on priority list) is used to determine additional ones
Assessment Flight Time Window	Operation conducted either only during the day, or day-and-night
Assessment Processing Time	Duration between landing of an assessment asset and the availability of the gathered information for operational consideration
Assessment Consecutive Location Maximum	Maximum number of locations that can be assessed on a single flight

Table 7: Baseline Parameters for Case Studies (labeled bold in tables for designs of experiments)

Parameter	Attribute	
Scenario Aspects		
Theater (2 baseline theaters)	**Fiji**	Vanuatu
Storm	**Winston**	Pam
Storm Destruction Radius	**50** [km]	60 [km]
Local Base Location	**Suva**	Port Vila
Initial Availability of Aid	**0** [# of packages]	
Materiel Aspects		
Operating C-17	**2**	
Operating C-130	**2**	
Vertical Airlift Asset Type	**MRH-90**	
Vertical Airlift Asset Quantity	**3**	
Unmanned Assessment Asset Type	**Stalker**	
Unmanned Assessment Asset Quantity	**4**	
Conventional Assessment Asset Type	**AP-3C**	
Conventional Assessment Asset Quantity	**1**	
Doctrinal Aspects		
Vertical Airlift Cargo Delivery Mode	**Both** (External and Internal)	
Crews per Conventional Asset	**2**	
Cargo Flight Types	**Multiple Locations by Proximity**	
Cargo Flight Time Window	**DayNight**	
Local Fulfillment Steps	**10** [%]	
Asset-Footprint Operations Mode	**Yes**	
Duration of Crew Shifts	**12** [h]	
Crews per Unmanned Asset	**2**	
Assessment Flight Types	**Multiple Locations by Proximity**	
Assessment Flight Time Window	**Day**	
Assessment Processing Time	**3** [h]	
Assessment Consecutive Location Maximum	**4**	

While most parameters are designators or quantities that are directly read into the simulation, some scenario aspects as well as the asset type designators, trigger references to additional files with secondary input data. For each theater, a list of considered locations within the theater along with their reference coordinates (latitude, longitude) and population number is required. In this research (and the general use of the environment), township-equivalent level for both Fiji (Tikina) and Vanuatu (Area) are used with data obtained from a collection website accessing various government statistic data [100]. These levels are used to mirror the fact that deliveries of aid are distributed to mid-size population centers first, and subsequently distributed by local means to individual houses or people; deliveries to villages or settlements only occur if they aren't close or part of a larger structure, e.g. on very small inhabited islands. In order to simulate a specific storm, a list of coordinates with points listed in temporal order is required. For this research, the data has been obtained from the Australian Bureau of Meteorology [86] with lists of storm points also being time-equidistant. The intensity of the storm is controlled through the storm destruction radius parameter. As for the specification of local bases, a secondary list specifying the location, runway length, and total aircraft capacity is required; the data utilized for this research can be found in Table 8. With regards to the various asset types, different kind of inputs specifying their performance characteristics and operational constraints are required. Table 9, Table 10, and Table 11 present these parameters for strategic airlift, vertical airlift, and assessment assets, respectively.

Table 8: Specification of the Regional and Local Bases for the Case Studies

Theater	Location	Latitude [°]	Longitude [°]	Runway Length [ft]	Aircraft Capacity [-]
Australia	Amberley	-27.6406	152.7119	9997	10
Fiji	Suva	-18.0433	178.5592	6129	5
Fiji	Macuata	-16.4667	179.3397	3521	5
Vanuatu	Port Vila	-17.6992	168.3197	8530	5
Vanuatu	Luganville	-15.5058	167.2214	6523	5

Table 9: Vehicle Parameters for Strategic Airlift Assets

Parameter	Unit	C-17	C-130 J30
Range (at 65t payload)	km	5185.6	n/a
Range (at 28t payload)	km	10463.8	n/a
Range (at 16t payload)	km	n/a	3148.4
Cruise Speed	km/h	833.4	644.5

Table 10: Vehicle Parameters for Vertical Airlift Assets

Parameter	Unit	**MRH-90**	CH-47	UH-60	V-22	V-280
Footprint Volume *	% C-17	**0.5**	1	0.5	0.5	0.5
Vehicle Volume *	% C-17	**0.5**	1	0.5	n/a	n/a
Internal Load Capacity	# Pkg	**20**	80	20	36	20
External Load Capacity	# Pkg	**18**	108	54	90	72
Fuel Consumption	liter/h	**1250**	1590	1360	1290	875
Range	km	**800**	740	600	1628	1480
Combat Radius	km	**380**	250	295	360	465
Cruise Speed	km/h	**260**	300	280	500	520
Cruise Speed (Sling Load)	km/h	**200**	220	220	400	400
Setup Time	h	**4**	12	6	1	1
Flight Setup Time	h	**1**	3	2	3	2

Table 10: Vehicle Parameters for Vertical Airlift Assets (continued)

Unload Cargo Time	h	**0.5**	1.5	1	1	1
Flight Time between Maintenance	h	**5**	5	5	7	7
Time for Maintenance	h	**4**	4	4	4	3

* The volume metrics are simplified for this environment towards the utilized assets C-17 and C-130; 50% of C-17 cargo load is equated to 100% of a C-130 cargo load.

Table 11: Vehicle Parameters for Unmanned (and Conventional) Assessment Assets

Parameter	Unit	**Stalker**	Bat	RQ-21A	AP-3C
Setup Time	h	**0.5**	6	4	2
Footprint Size	m	**n/a**	6.1x2.5 x2.5	3.0x2.5 x2.5	-
Footprint Volume	m3	**n/a**	38.125	18.75	-
Vehicle Size	m	**5x1.5 x1.5**	5x1.5 x1.5	5x1.5 x1.5	n/a
Vehicle Volume	m3	**11.25**	11.25	11.25	n/a
Operators (/Crew)	-	**1**	2	2	10
Link Range	km	**60**	130	93	n/a
Combat Radius	km	**n/a**	n/a	n/a	2200
Fuel Consumption	liter/h	**0.5**	0.8	0.4	2556
Range	km	**444**	2164	1601	6500
Cruise Speed	km/h	**55**	120	100	560
Flight Setup Time	h	**0.5**	0.5	0.5	1
Flight Time between Maintenance	h	**12**	12	12	10
Time for Maintenance	h	**2**	2	2	2

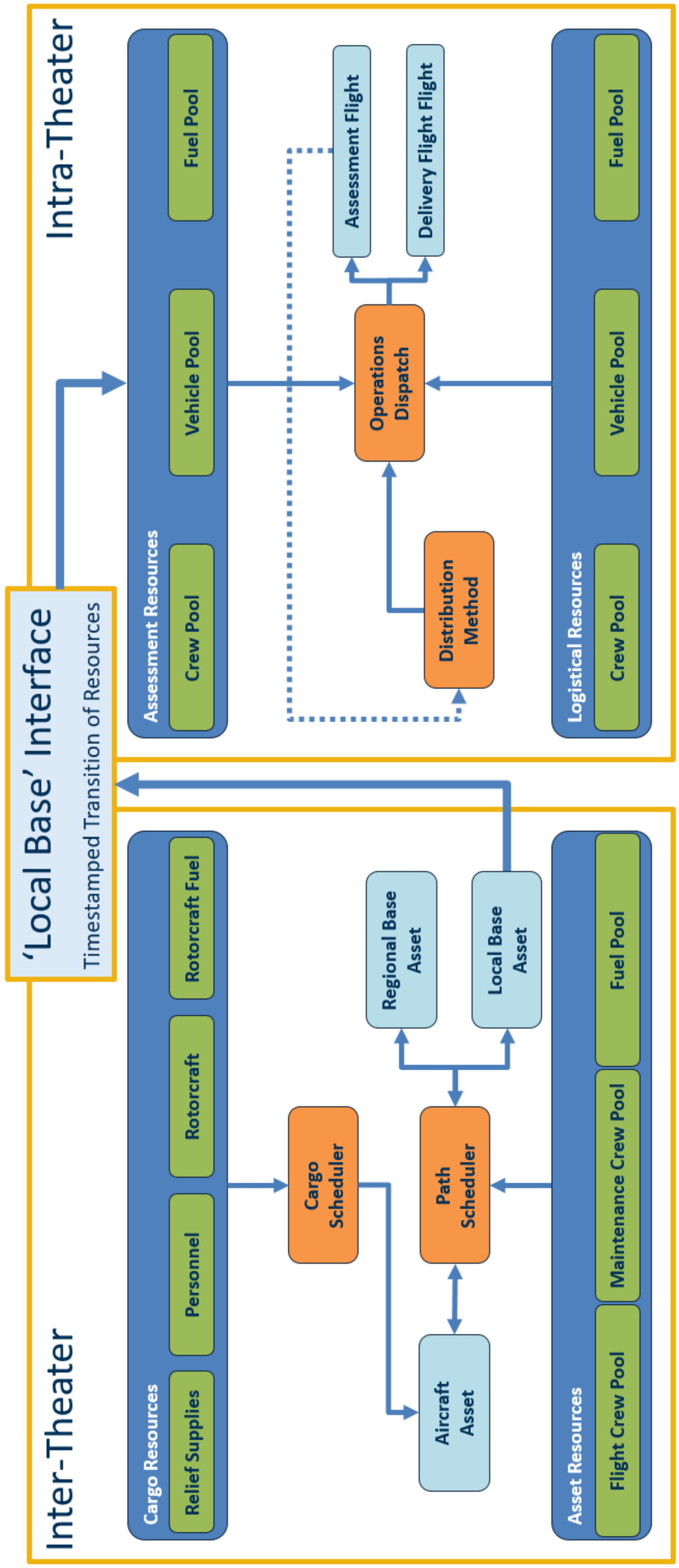


Figure 27: Summarized Logical Flowchart of the Scenario

6.3.3 Logical Structure

The environment strictly separates operations into inter-theater and intra-theater operations, and transitions information between the elements through a 'local base interface'; Figure 27 shows the summarized logical flow of the scenario. The comprehensive logical diagram for the simulation in the testbed environment can be found in APPENDIX C. The local base interface consists of case-specific csv files that outline the time-stamped arrival of inter-theater assets and specify their respective load, thus initializing them to be in the theater and accessible to the intra-theater operations. Embedded within each simulation is a data processing phase that takes into account the various inputs and generates relevant simulation objects, events, and secondary parameters before executing the actual case simulation. The input and overall output data, handled as csv input file with data in columns and cases in rows, is centralized and accessed from the same location; each sub-simulation can generate detailed case-specific output data in excess of the overall output.

6.3.3.1 <u>Inter-Theater Strategic Airlift</u>

The inter-theater simulation initializes the available assets and relevant bases for a specific case. Initially, the assets are at the regional base and are subject to group operations prior to their transit towards the theater. On the ground, maintenance and crew requirements are checked before considering an asset for a flight. If the maintenance requirements are satisfied, i.e. the flight in question is within the maintenance time window, the aircraft moves towards refueling and loading, The loading is performed based upon the priority of cargo, and scheduled according to the available ground personnel (and stock) resources. If maintenance is necessary, the simulation considers the available maintenance resources and schedules it before clearing the aircraft for the subsequent aforementioned steps. If, after the aircraft is ready for the flight, the crew requirements are satisfied, i.e. an available crew can perform the flight without violating scheduled/rest requirements, the flight is taking-off after regular airport operations (checks, taxing, etc.). The flight between bases is simulated in accordance with the performance characteristics of the respective aircraft. Upon landing, an immediate unloading of the aircraft is performed and resources transitioned to the intra-theater simulation. After that, the rerouting back to the regional base follows a similar, albeit reduced, logic as outlined before.

6.3.3.2 Intra-Theater Assessment

The intra-theater simulation for the assessment of the theater initializes the available assessment assets and performs successive assessment flights until all impacted locations, or all locations that can be reached with the available assets, have been assessed. Due to the size of the UAV and the self-deployment of the fixed-wing assets, those tasked to perform assessments are usually initialized at the same time early in the overall operation after the arrival of the flight carrying all unmanned assets and the ground infrastructure and personnel (footprint) for all assessment assets. It should be noted that the intra-theater assessment is the only element within the environment operating a possibly heterogeneous fleet, considering both conventional fixed-wing and unmanned assets, for the same purpose. Based on the geographical details of the theater and storm, the locations are prioritized to gain information about more and earlier affected areas first. In order to schedule an assessment flight, maintenance criterions are checked to determine whether the asset is able to fly. If maintenance is required, the asset is blocked for the necessary time and then reconsidered for flights at a later point in time. Once an asset is cleared to be operated, crew constraints are checked. For conventional assets, as well as for strategic and vertical airlift, the requirement is that the whole mission under consideration needs to be performed within the crew's schedule. For unmanned assets, however, a crew change can occur during the flight so flights are less constrained in that regard, as long as crew schedules follow on each other. If both criterions are satisfied, and the time of operation is in the permissible time window for operations, a flight is launched. For the specific determination of locations, initially, the next priority location is assigned. If assets are set to assess multiple locations, additional location are added to the flight plan, either based on proximity or priority, as long as the overall flight including return is still possible or the maximum number of locations per flight is reached.

Once an asset has returned from an assessment flight, the 'gathered information' about the locations is used to update the information about level of need for locations. The assumptions of a uniform need across the affected areas are corrected using discovered information. This corrective step can be delayed to reflect the required processing time to translate visual information in the corresponding data.

6.3.3.3 Intra-Theater Logistics with Vertical Airlift

Figure 28 shows an overview over the logical decision-making process with regards to the intra-theater logistics operations using vertical airlift assets. The simulation initializes the available assets and performs successive delivery flights until the 5-days window ends, or until all impacted locations have fully satisfied needs.

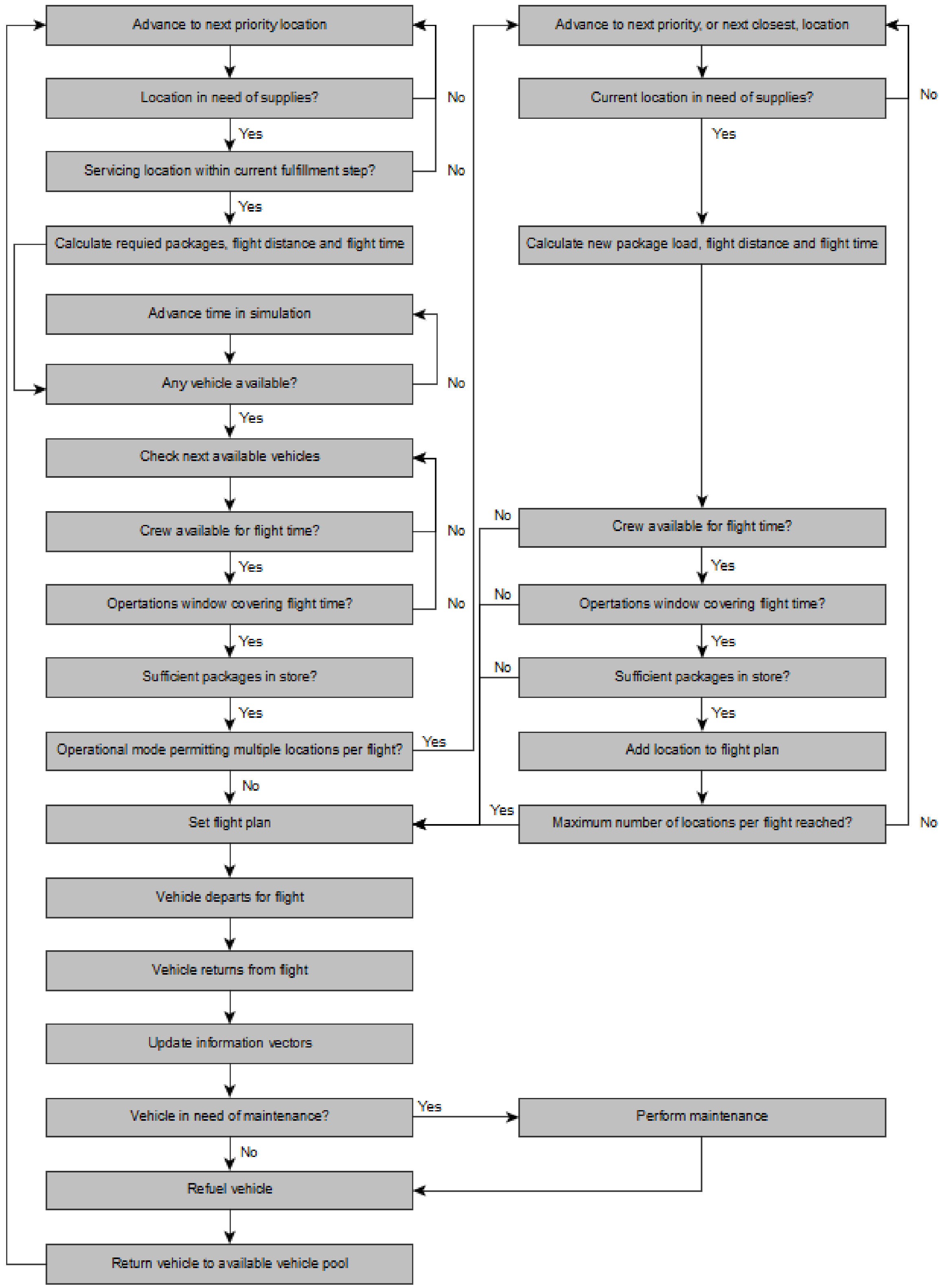


Figure 28: Logical Flowchart of the Simulated Decision-Making for Intra-Theater Logistical Operations utilizing Vertical Airlift Assets

Due to the size of the assets and the fact that multiple flights are needed to carry assets and footprints, they are initialized at different times into the operation. Depending on operational parameters, the asset is required to wait for the footprint to arrive as well if it is carried on a separate flight, or it can operate immediately. Similar to other assets, in order to schedule a delivery flight, maintenance criterions are checked to determine whether the asset is able to fly. If maintenance is required, the asset is blocked for the necessary time and then reconsidered for flights at a later point in time. Once an asset is cleared to be operated, resource and crew constraints are checked. The requirement is that the whole mission under consideration needs to be performed within the crew's schedule, as well as that sufficient fuel for a full refill of the assets tank, and enough aid packages are available. Aid packages are simplified metrics assumed to provide the necessary aid for 25 people in immediate need, and are transported through the strategic airlift to be stocked at the Forward Operating Base. The environment allows the assumption that the theater, as a measure of local preparedness reflected as a scenario parameter, is initially stocked with a number of packages (allowing immediate delivery operations) or even sufficiently stocked (allowing de-prioritization of aid packages delivery in the strategic airlift).

The determination of the load of an asset is driven by an operational parameter dependent on the use of internal and/or external loading capabilities. For the specific determination of locations, besides the prioritization of locations, the simulation considers a fulfillment step that requires locations to be served by multiple flights only up to a certain point of need. This allows an even distribution of aid across the theater on a continuous basis. For example, if the fulfillment threshold is set to 10%, no additional flights to a location are assigned if it has passed the threshold unless all other impacted locations that can be reached by the available assets have already reached the threshold; if that's the case, the threshold is raised to 20% and operations continue. For flights, taking this into account, the next priority location is assigned. If the full package load of a single flight exceeds the entire need of the location, the remainder of the load has a relevant quantity, and an extension wouldn't exceed the permissible time window, then additional locations can be added to the flight plan, either based on proximity or priority, as long as the overall flight including return is still possible. This option is especially relevant for the delivery to very small remote locations as opposed to more densely-populated areas where an immediate satisfaction wouldn't occur.

Based on these considerations, flights are launched. Upon arrival at the location, they are unloaded for a certain amount of time before it returns to base, or proceeds on its flight plan. Upon return, the process is reiterated.

6.3.4 Provided Outputs

After all cases have been simulated, an overall output file in CSV format is created containing the cases as rows, and both input and output parameters as columns. Table 12 presents the comprehensive list of output parameters that are used for various case studies in this research. A detailed step-by-step process of the simulation in the testbed environment for a sample case can be found in APPENDIX D.

Table 12: Testbed Output Parameters

Parameter	Additional Description
Inter-Theater	
Number of C-130 flight to Fiji	Number of flights performed between the regional base and the local base in the theater by C-130 assets
Number of C-17 flights to Fiji	Number of flights performed between the regional base and the local base in the theater by C-17 assets
Number of packages received in Fiji	Total number of aid packages transported from the regional base to the local base in the theater
Timestamp of Asset Arrivals	Time of arrival of a specific number of assets (time of unloading from strategic airlift) Milestone Steps: 3, 5
Timestamp of Footprint Arrivals	Time of arrival of a specific number of footprints (time of unloading from strategic airlift) Milestone Steps: 3, 5
Timestamp of Packages Arrivals	Time of arrival of a specific number of aid packages at the local base (time of unloading from strategic airlift) Milestone Steps: 1, 1000, 5000, 10000, 20000
Intra-Theater Vertical Airlift	
Number of packages delivered	Total number of aid packages delivered to the population
Timestamp of Packages Deliveries	Time of delivery of a specific number of aid packages to the population in the theater (time of unloading at location) 1, 1000, 2000, 5000, 10000

Table 12: Testbed Output Parameters (continued)

Cargo delivery flight time [h]	Total flight time of vertical airlift assets for operations within the theater
Number of cargo flights	Total number of cargo flights performed by the vertical airlift assets
Number of locations delivered to	Number of locations that have received aid packages during the operation
Amount of Population Serviced	Number of individuals serviced with aid packages during the operation (directly dependent on the number of packages)
Intra-Theater Assessment	
Time to complete assessments [min]	Time of completion of the assessment of locations within range of the assessment assets
Assessment flight time [h]	Total flight time of assessment assets for operations within the theater
Number of assessment flights	Total number of assessment flights performed by the assessment assets
Number of locations assessed	Number of locations that have been assessed during the operation

6.4 Results

For the scope of this experiment, the analysis is focused on the mission-critical ‘packages delivered’ parameter, as well as noteworthy behaviors for the ‘number of strategic airlift flights to the theater’, and for ‘time of delivery of 1000 packages’ in relation to the ‘distance between Amberley and the Forward Operating Base’. For an in-depth view of the results, for the subsequent visualizations presented in Figure 29, Figure 30, and Figure 31, the data has been filtered to the Fiji theater, a 50km storm radius, no initial availability packages, and an original 100% population scale. With this filter, when observing the data for different storms, it can be found that the simulation yields that for Keni and Amos the mission termination criteria (satisfaction of the full need within the scenario) is triggered, with 161 and 1213 packages in total. Thus, to maintain a comparable view as these cases are not challenging the overall requirements, the storms Amos and Keni have been excluded. The full results of this experiment as scatterplot overview visualizations can be found in APPENDIX E.

Figure 29 shows the number of packages delivered (on the y-axis) versus distance between Amberley and the FOB (on the x-axis), grouped by different local bases (on the top x-axis) and selected storms (on the right y-axis). It should be noted that the artificial geographical shifts in latitude and longitude have been converted into the critical parameter of distance between the regional base in Australia and the Forward Operating Base that changes with the geographical shift. The pattern we can observe here is a generally reduced number of packages delivered in total with increasing distance to Australia. Also, the different storms yield different patterns that are consistent with the geographical relation of their path towards the impacted areas; with the shift of more impacted areas away from the respective FOB, the flights consume more time than if a proximity of the base to these areas is given.

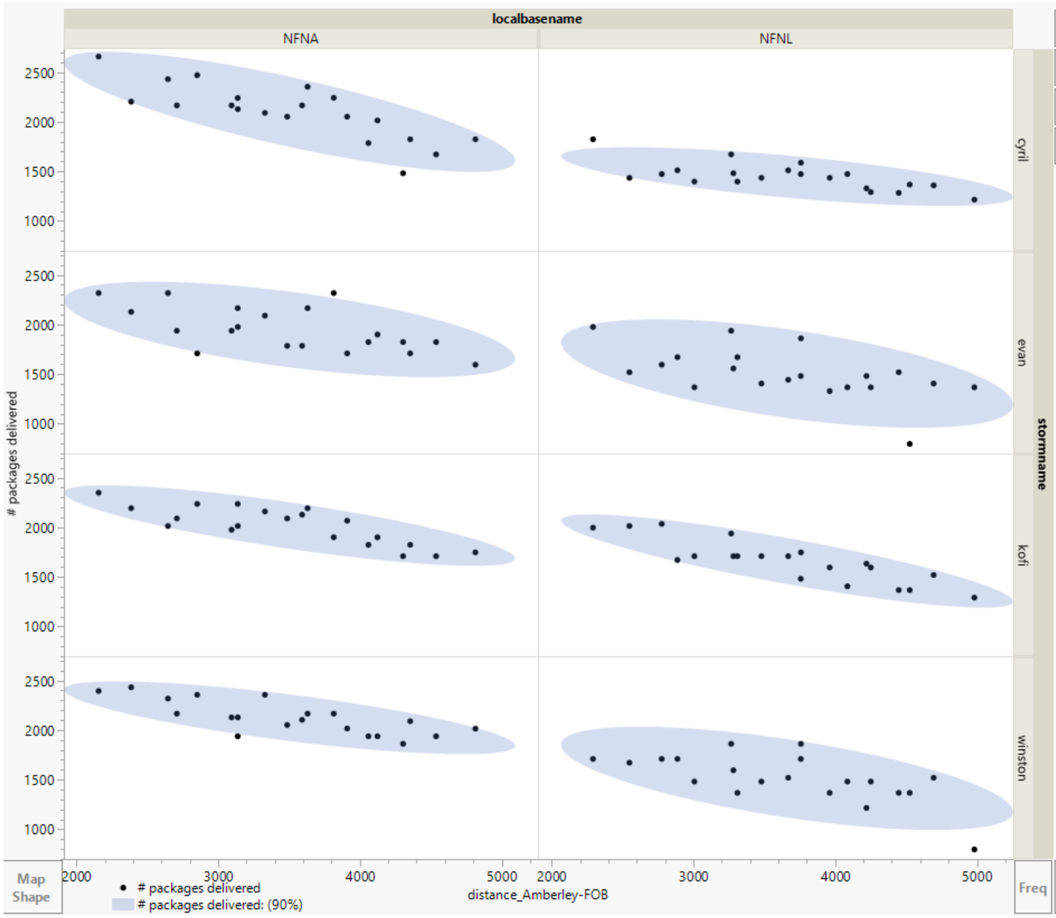


Figure 29: Visualization of number of packages delivered (Y) versus distance between Amberley and the FOB (X), grouped by different local bases (X) and selected storms (Y), for the Fiji theater

Figure 30 shows the number of strategic airlift flights to the theater (on the y-axis) versus distance between Amberley and the FOB (on the x-axis), grouped by different local bases (on the top x-axis) and selected storms (on the right y-axis). While we can observe a similar behavior for the distance, i.e. a reduction of flights during the five days due to increasing distance, no significant distinction occurs between storms or bases.

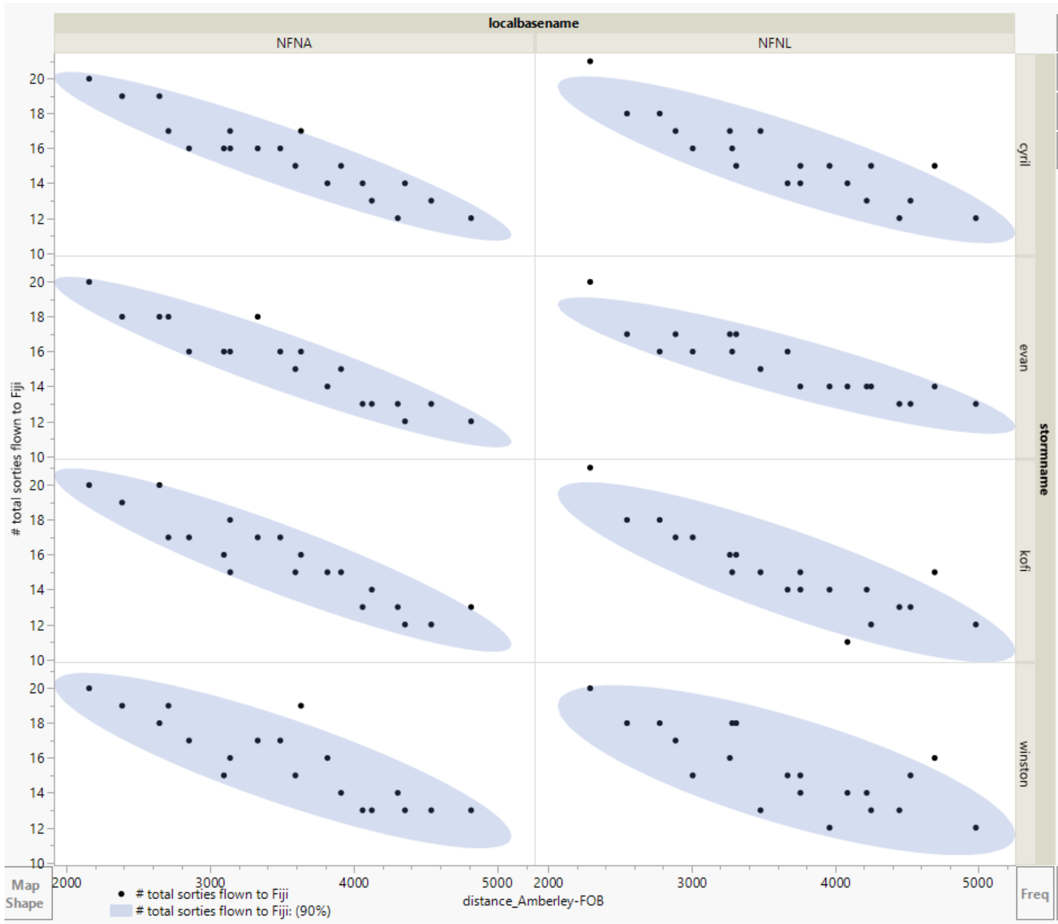


Figure 30: Visualization of number of strategic airlift flights to the theater (Y) versus distance between Amberley and the FOB (X), grouped by different local bases (X) and selected storms (Y), for the Fiji theater

Figure 31 shows the time of delivery of 1000 packages, a ‘milestone parameter’ (on the y-axis) versus distance between Amberley and the FOB (on the x-axis), grouped by different local bases (on the top x-axis) and selected storms (on the right y-axis). Here, we can observe an inverted but similar behavior for the distance, where the accomplishment of the milestone gets delayed due to the slower speed of the operation.

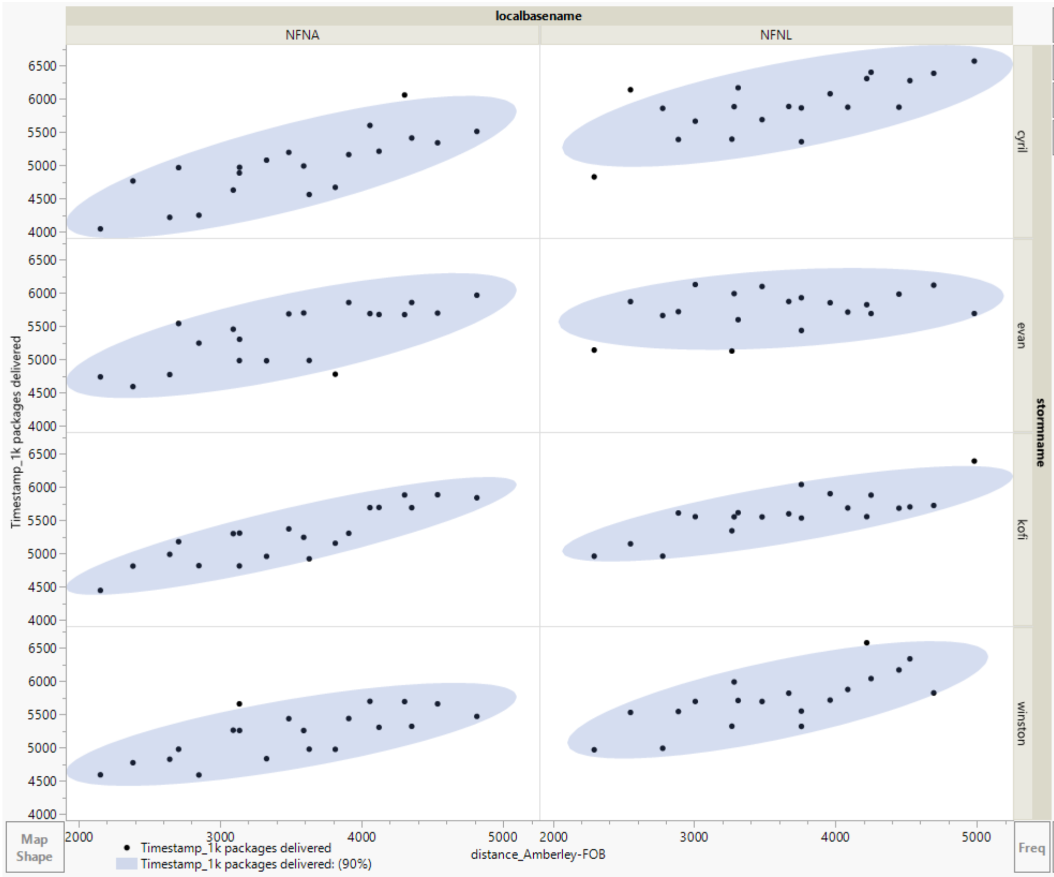


Figure 31: Visualization of time of delivery of 1000 packages (Y) versus distance between Amberley and the FOB (X), grouped by different local bases (X) and selected storms (Y), for the Fiji theater

6.5 Conclusion

In the previous sections of this chapter, the approach and the experiment used to validate the hypothesis with regards to the Scenario Modularization has been presented, along with the results of it’s execution. To enable this, and subsequent experiments, the testbed environment that is utilized throughout this research has been described. Before drawing conclusions, hypothesis 1 is evaluated:

Hypothesis 1: If the RFLP process is utilized as the adjusted elementary definition approach and alternative scenarios are decomposed into elements and interfaced, then a standardized and modular approach can be produced.

Looking at the previously presented results of the experiment, it can be stated that hypothesis 1 has been validated. The goal of the experiment was to apply the adjusted RFLP process to multiple scenarios with variations across the domains and to bring them into a shared framework. The execution, represented by the results in the previous section, shows that the produced setup infused into an environment yields conclusive results. The results confirmed trends we would expect when comparing the different scenarios in a thought or manual assessment process. The fact that this experiment can produce these results, and its position in the overall methodology serve as validation for the functioning of this step and the proof of the hypothesis.

CHAPTER 7. DESIGN AND OPTIONS SPACE

This chapter describes the experimental validation of hypothesis 2 that, based on the discussion outlined in Section 3.7 with regards to the operational design space, has been formalized as follows:

Hypothesis 2: If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations from further consideration.

7.1 Approach

In order to validate hypothesis 2, the objective of the experiment is to verify the necessity of relationship analysis to detect interdependencies and possible impermissibilities as a prerequisite for the large-scale consideration of materiel and doctrinal approaches. Given the multi-dimensionality and different types of input parameters in relation to a variety of output parameters in an experimental setting, the approach not only needs to be able to guide the operator during the non-computational part of the analysis of alternatives within the methodology, but also identify the need for deconfliction (exclusion of alternatives) in case of impermissibilities of conjoint options in the process. The assessment of the operational behavior under consideration of combinatorial doctrinal and materiel approaches within the proper quantification of approaches yields the proof for sufficient representativeness of the selected approaches.

7.2 Experiment

The experiment follows the background and structure of the case study introduced in Section 1.6.3. A 5-day immediate HADR mission for a specific scenario needs to be performed considering various materiel and doctrinal approaches. The setup of the experiment is to apply the matrix creation process outlined in Section 5.2.2 to the selected materiel and doctrinal options. Through this, the process of quantification and deconfliction of alternatives is formalized and documented as a step within the overall methodology. This experiment is limited to a separate but comprehensive analysis of the respective dimensions; the inter-dimensional analysis is performed as part of the full methodology demonstration in the following chapter. Subsequently, the alternative cases are infused into the environment, simulations are conducted and results are obtained.

7.2.1 Design

In this experiment, the Australian Armed Forces react to a cyclone striking the nation of Fiji. The cyclone follows path and intensity of the events with Cyclone Winston in 2016, as displayed in Figure 32, which overwhelmed the local infrastructure and made external aid necessary. The Australian Armed Forces are reacting with a HADR operation launched from an Air Force Base on the east coast of Australia, the RAAF Amberley in the southwest of Queensland.

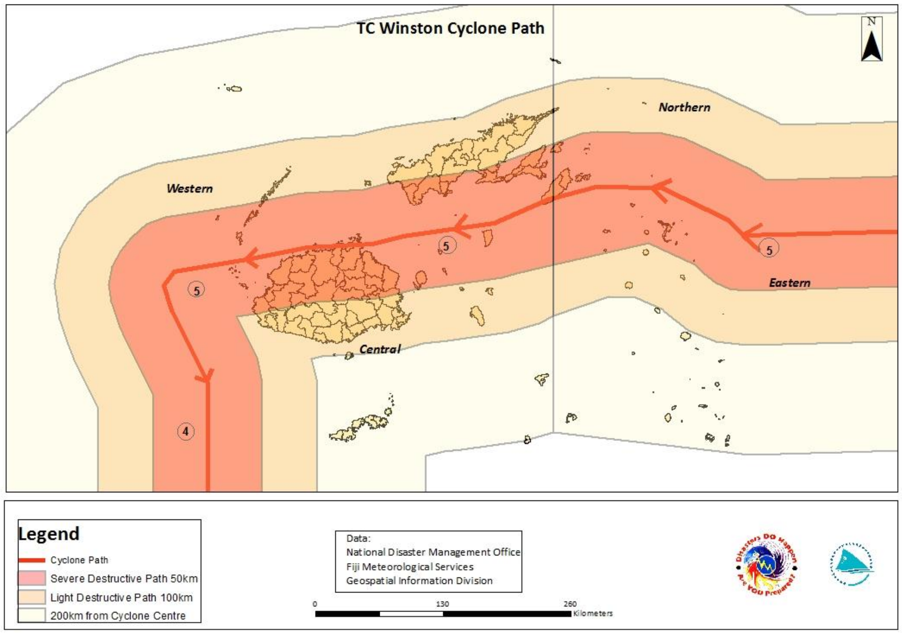


Figure 32: Storm Path of Cyclone Winston through Fiji in 2016 [101]

As for materiel variations, for the required strategic airlift from Australia, 2 C-130's operate alongside a varying number from 2 to 6 C-17's. For the intra-theater operations, first for vertical airlift assets, a number of assets ranging between 2 and 6 is deployed with types including MRH-90, CH-47, UH-60, V-22, and V-280. The first three assets are regular helicopters with MRH-90 and UH-60 similar in size, and the CH-47 a large dual-rotor helicopter. V-22 and V-280 are tiltrotor assets that can self-deploy from Australia to Fiji, and only require the strategic airlift of their footprint. Second, for assessment assets, either 0, or 2 to 4 unmanned drones are considered of the types Stalker, Bat, and RQ-21. In addition, the presence, or the lack, of a single self-deployable AP-3C fixed-wing assessment aircraft is considered.

For the variation in doctrinal approaches, multiple factors are perturbated. With regards to the operations of the vertical airlift assets, the operational mode of cargo loading, the number of crews per asset, the option and type of multi-location flights, the time window for operations, the fulfillment considerations for deliveries, and the possibility of initial operations without footprint are altered. Concerning the assessment assets, the number of crews per asset, the option and type of multi-location flights, the time window for operations, the processing time for the gathered data, and the number of possible consecutive locations during a flight are altered. Applicable to both types of assets, the duration of the crew shifts is changed. The detailed description of these parameters has been already previously introduced in Table 6 in Section 6.3.2.

7.2.2 Matrices of Alternatives and Relationships

Based on the design of the experiment, matrices of alternatives and relationships are established; the result for the matrices alternatives are shown in Figure 33 and Figure 34, the matrices of relationships in Figure 35 and Figure 36. Matrices are formed separately for materiel and doctrinal approaches.

The matrices of alternatives are a formalization based on the available options, or the scope of consideration. The relationship matrices require subject-matter expertise, either by the operator themselves or based on literature and document analysis. For this experiment, the following interdependencies of factors with each other with regards to the operational performance are stipulated:

- The number and type of deployed vertical airlift assets is strongly interdependent with the number of strategic airlift assets. Given the limited time window and the priority of assets within the inter-theater deployment, an increasing number of to-be-deployed assets takes up resources that delay or become unavailable for lower priority items including aid packages.

- The number of unmanned and conventional assessment assets are weakly interdependent as their purpose is the same and they contribute to the same relevant performance metric, and subsequently dilute the ability for a materiel analysis of these assets if used as a heterogeneous fleet.
- Depending on the operational circumstances, the specific alternatives of the operational mode of cargo loading and the time window for cargo operations can be combinatorically impermissible. If external load is exclusively or also used for cargo delivery, operations during night time require expanded infrastructure on the ground (such a lighted area) as opposed to day time operations.
- Depending on the operational circumstances, the specific alternatives of the operational mode of cargo loading and the operational option to operate early without a footprint present can be combinatorically impermissible. If the crew assisting with loading an external load is not present, present ground personnel might not be qualified in handling that assistance for early operations.
- For vertical airlift assets, the number of crews per asset is strongly interdependent with the time window for operations. A low number of crews can constrain the operability of assets to not be able to accomplish day and night operations, and subsequently mislabel the performance metrics of such simulations.
- Similarly, for both vertical airlift and assessment assets, the number of crews per asset is strongly interdependent with the crew shift durations. A low number of crews with short shifts can constrain the operability of assets, while a high number of crews with

long shifts overstaffs the operation in that regard and does not provide additional benefit.

The aforementioned list is limited to strong interdependencies and possible impermissibility's, as well as weak interdependencies that are considered in the progress of this experiment.

		type	alternatives
inter-theater	YAMB130	discrete	0,2
	YAMB17	discrete	2,3,4,5,6
intra-theater	rc_cargo_num	discrete	2,3,4,5,6
vertical airlift	rc_cargo_type	categorical	MRH-90,CH-47,UH-60,V-22, V-280
	uav_assess_num	discrete	0,2,3,4
intra-theater	uav_assess_type	categorical	Stalker,Bat,RQ-21
assessment	rc_assess_num	discrete	0,1
	rc_assess_type	categorical	AP-3C

Figure 33: Matrix of Alternative for Materiel Experiment

		type	alternatives (considered)
	deliverCargo	categorical	Both,External,Internal
	numCrewsPerConventional	discrete	1,2,3
vertical airlift	cargoMode	categorical	MultipleProx,Single,MultiplePrio
	cargoDeliveryWindow	categorical	Day,DayNight
	fulfillmentStep	continuous	0.05,0.1,0.2
	flyOnlyAfterFootprint	categorical	0,1 (No, Yes)
	crewShift	continuous	8,10,12
	numCrewsPerUAV	discrete	1,2,3
	assessMode	categorical	MultipleProx,Single,MultiplePrio
assessment	assessFlightWindow	categorical	Day,DayNight
	processTimeAssess	continuous	2,3
	maxAssessLocations	discrete	4,5,6

Figure 34: Matrix of Alternatives for Doctrinal Experiment

		YAMB130	YAMB17	rc_cargo_num	rc_cargo_type	uav_assess_num	uav_assess_type	rc_assess_num	rc_assess_type
inter-theater	YAMB130	---							
	YAMB17	0	---						
intra-theater vertical airlift	rc_cargo_num	2	2	---					
	rc_cargo_type	1	2	0	---				
intra-theater assessment	uav_assess_num	0	0	0	0	---			
	uav_assess_type	0	0	0	0	0	---		
	rc_assess_num	0	0	0	0	1	0	---	
	rc_assess_type	0	0	0	0	0	0	0	---

- 3 (possible) impermissibility
- 2 strong interdependency
- 1 weak interdependency
- 0 no interdependency

Figure 35: Relationships Matrix for Materiel Experiment

		deliverCargo	numCrewsPerConventional	cargoMode	cargoDeliveryWindow	fulfillmentStep	flyOnlyAfterFootprint	crewShift	numCrewsPerUAV	assessMode	assessFlightWindow	processTimeAssess	maxAssessLocations
vertical airlift	deliverCargo	---											
	numCrewsPerConventional	0	---										
	cargoMode	1	1	---									
	cargoDeliveryWindow	3	2	0	---								
	fulfillmentStep	0	0	0	0	---							
	flyOnlyAfterFootprint	3	0	0	0	0	---						
	crewShift	0	2	1	1	0	1	---					
assessment	numCrewsPerUAV	0	0	0	0	0	0	2	---				
	assessMode	0	0	0	0	0	0	1	1	---			
	assessFlightWindow	0	0	0	0	0	0	1	2	0	---		
	processTimeAssess	0	0	0	0	0	0	0	0	0	0	---	
	maxAssessLocations	0	0	0	0	0	0	0	0	0	0	0	---

- 3 (possible) impermissibility
- 2 strong interdependency
- 1 weak interdependency
- 0 no interdependency

Figure 36: Relationships Matrix for Doctrinal Experiment

7.2.3 Implementation

To reflect the experiment, the statistical analysis software JMP [87] was used to create a full-factorial design of experiments with a total of 6,000 (including 125 vertical airlift and 18 assessment combinatorial cases) and 104,976 cases for materiel and doctrinal aspects, respectively. The formalized parameters as outlined previously can be found in Table 13 and Table 14. The experimental parameters are then infused into the Python [88] testbed environment and results are created; the testbed environment and the additional inputs have been introduced in Section 6.3. Following the generation of results, JMP again is used to analyze the data and create visualizations.

Table 13: Materiel Design of Experiments for Design and Options Space

Parameter	Alternatives	
	#	Attribute
Operating C-17	5	**2**, 3, 4, 5, 6
Operating C-130	1	**2**
Vertical Airlift Asset Type	5	**MRH-90**, CH-47, UH-60, V-22, V-280
Vertical Airlift Asset Quantity	5	2, **3**, 4, 5, 6
Unmanned Assessment Asset Type	3	**Stalker**, Bat, RQ-21A
Unmanned Assessment Asset Quantity	4	0, 2, 3, **4**
Conventional Assessment Asset Type	1	**AP-3C**
Conventional Assessment Asset Quantity	2	0, **1**

Table 14: Doctrinal Design of Experiments for Design and Options Space

Parameter	Alternatives	
	#	Attribute
Vertical Airlift Cargo Delivery Mode	3	External, Internal, **Both**
Crews per Conventional Asset	3	1, **2**, 3
Cargo Flight Types	3	Single Location, **Multiple Locations by Proximity**, Multiple Locations by Priority
Cargo Flight Time Window	2	Day, **DayNight**
Local Fulfillment Steps	3	5, **10**, 20 [%]
Asset-Footprint Operations Mode	2	**Yes**, No
Duration of Crew Shifts	3	8, 10, **12** [h]
Crews per Unmanned Asset	3	1, **2**, 3

Table 14: Doctrinal Design of Experiments for Design and Options Space (continued)

Assessment Flight Types	3	Single Location, **<u>Multiple Locations by Proximity</u>**, Multiple Locations by Priority
Assessment Flight Time Window	2	**<u>Day</u>**, DayNight
Assessment Processing Time	2	2, **<u>3</u>** [h]
Assessment Consecutive Location Maximum	3	**<u>4</u>**, 5, 6

7.3 Results

This section presents the results of the materiel and doctrinal experiment separate from each other. In addition, each experiment is sub-divided between vertical airlift and assessment assets as known cross-asset type interdependencies have been identified. Subsequently, the visualizations are filtered to the respective baselines of the non-assessed elements. The detailed results in this experiment are scoped to focus on the interdependencies and possible impermissibilities identified in Section 7.2.2. The full results of this experiment as scatterplot overview visualizations can be found in APPENDIX E.

7.3.1 Materiel Experiment

Figure 37 shows the time of delivery of different numbers of packages (on the y-axis) versus the number of utilized vertical airlift assets (on the x-axis), grouped by the total number of utilized strategic airlift assets (on the top x-axis) and the different vertical airlift asset types (on the right y-axis). The different reference number for the operational milestones include the first (blue), 1000th (red), 2000th (green), 5000th (purple), and 10000th (brown) package.

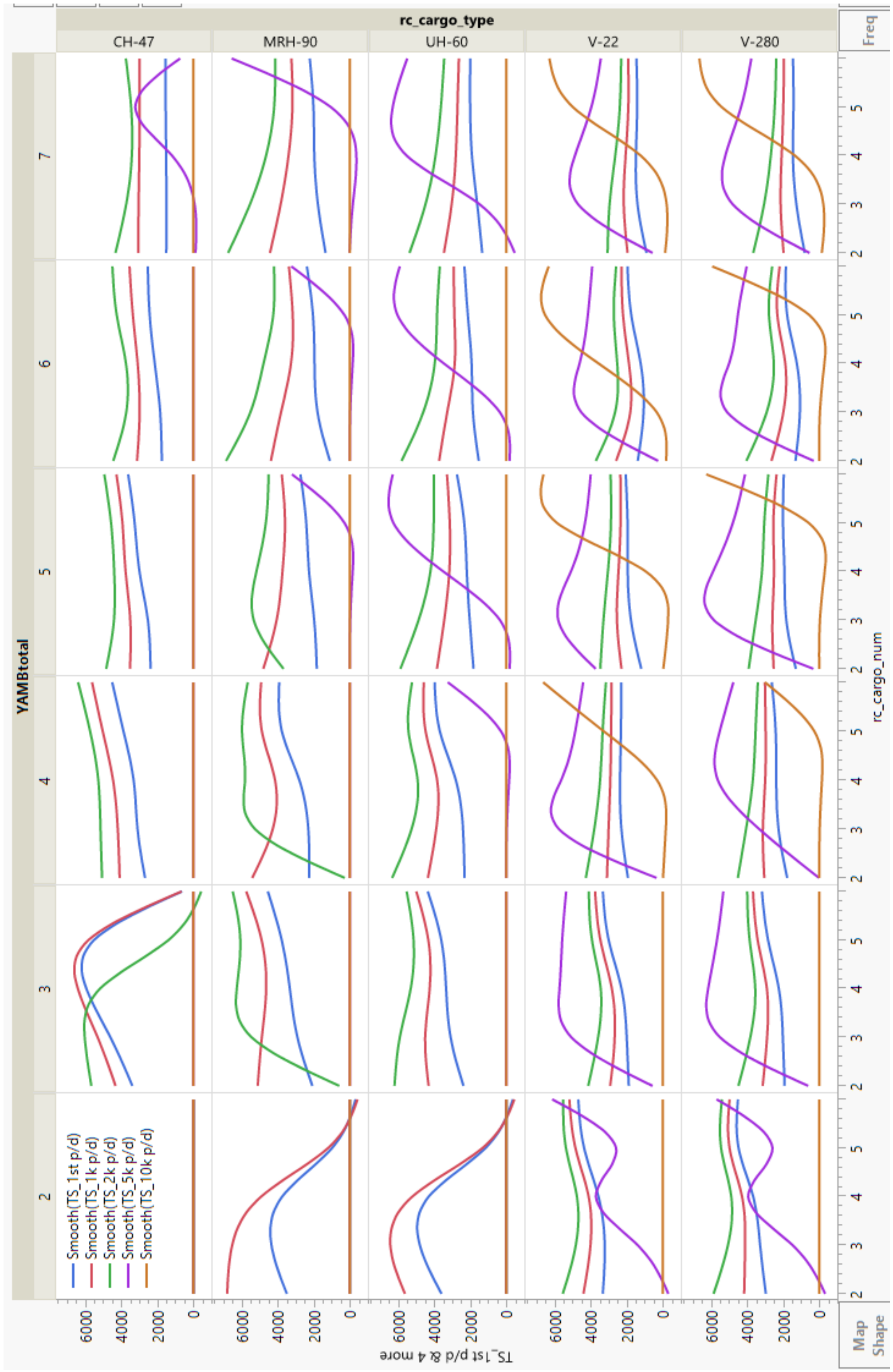


Figure 37: Visualization of time of delivery of different numbers of packages (Y) versus number of utilized vertical airlift assets (X), grouped by number of strategic airlifts assets used (X) and vertical airlift assets types (Y)

It’s important to note that the respective case points have been connected with an interpolant, and that zero values (or lack of a line) express that the milestone has not been reached. For the observation of the figure, recalling the vehicle and footprint volumes provided in detail in Table 10 in Section 6.3.2, most assets and their footprint can be delivered on a single C-17 flight (occupying each 50% of the cargo volume) or two C-130 flights. However, the CH-47 requires a full C-17 for the asset (which cannot be transported on a C-130), while the V-22 and V-280 assets can self-deploy (thus only requiring the footprint to be airlifted into the theater). These considerations drive the strong interdependence between type and number of utilized strategic and vertical airlift assets.

Overall, we can observe that the milestone 1, 1000, and 2000 packages are more or less consistently reached. Each with variations in time being traceable to a reduction through increased number of vertical airlift (providing faster operations) and strategic (providing for earlier start of operations) assets. This reduction only occurs when both numbers are increased, but they stall if only one of them is increased indicating that overburdening the strategic airlift with too many vertical airlift assets has a stagnating or even negative impact on the operational performance. In addition, it should be noted that this statement does not hold for strategic airlift fleets with the minimum of only 2 C-130 (and no C-17’s) and assets that require strategic deployment.

For the milestone of 5000 packages, we can observe a varying behavior of the parameters. For assets requiring strategic deployment, the milestone can only be reached for a high number of both strategic and vertical airlift assets. Assets that are able to self-deploy can reach the milestone already with a mid-size deployed fleet and a small strategic airlift fleet, and see subsequent time reductions if either parameter is increased. However, for a very strong imbalance as seen for a minimal strategic airlift fleet and maximized deployed fleet, a time increase can again be observed indicating overburdening the deployment. The 10000 packages milestone displays similar behavior to the 5000 package milestone across the board, although in a shifted fashion.

In summary, the non-linear behavior that can be traced back to the a priori identified interdependency can be identified from this detailed visualization. It shows the impacted performance of extreme cases making it questionable whether they would be considered feasible in an operational sense, and not just their ability to be physically executed.

7.3.2 Doctrinal Experiment

7.3.2.1 Aid Delivery Operation

Figure 38 shows the number of packages delivered (on the y-axis), grouped by the operational mode of cargo loading and the time window options for cargo operations (on the x-axes). The individual performances are driven by the specified input metrics, i.e. a higher internal loading capacity and faster speed without external load yields better results, while the slower speed of external loading with the combined capacity of internal and external loading is the preferred option. However, the use of external loading at all requires the theater to be suitable for this kind of operations. The landing areas need to be sufficiently large to support the dropping of the load, and landing next to it. In addition, it needs be considered whether these areas need to be secured by ground personnel to accommodate for sudden movement by crosswinds during the landing that could cause harm to bystanders, especially given a scenario with a population in desperate need of the aid. This factor becomes even more critical when operations are extended into the night, which shows slight performance improvements, but requires the ability of the assets to conduct the landing operation in darkness to illuminated areas or using special equipment.

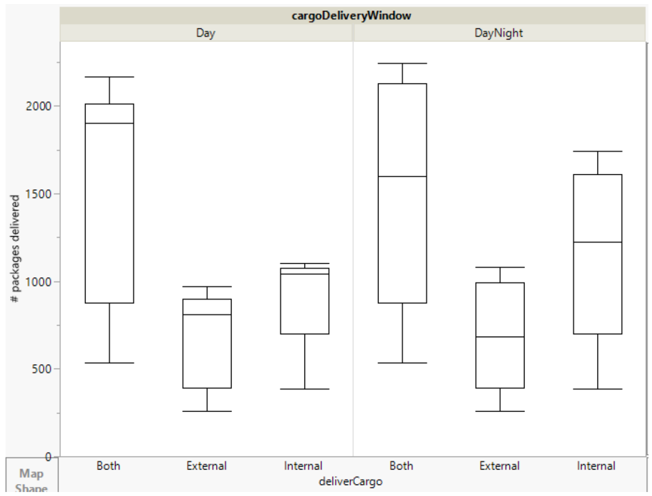


Figure 38: Visualization of the number of packages delivered (Y), grouped by the operational mode of cargo loading and the time window options for cargo operations (X)

Figure 39 shows the number of packages delivered (on the y-axis), grouped by the operational mode of cargo loading and the operational option to operate early without a footprint (on the x-axes). Previously, a possible impermissibility has been identified, between the operational mode of cargo loading and whether an asset that has been deployed is able to start operating without its full footprint. The latter designation asks the question whether looking into this possibility is worth it, presuming a required deviation from protocol of operating with ground infrastructure, or allowing the cross-use of footprints within a homogenous fleet. However, the results show that the performance differences are negligible across the board.

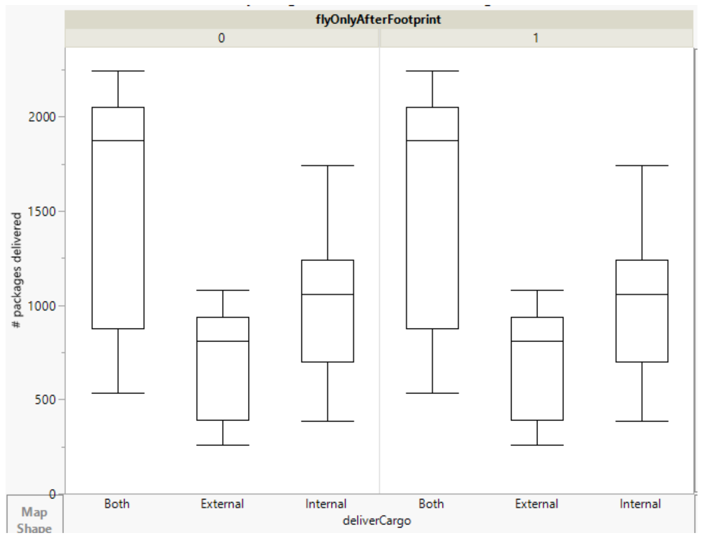


Figure 39: Visualization of the number of packages delivered (Y), grouped by the operational mode of cargo loading and the operational option to operate early without a footprint (X)

Figure 40 shows the number of packages delivered (on the y-axis), grouped by the number of crews assigned to each asset and the time window options for cargo operations (on the x-axes). It can be seen that the adding of additional crews has an initial significant positive effect from 1 to 2, and subsequently not harmful to slightly positive effect from 2 to 3. However, the interdependent expansion of operations into the night only yields positive effects for crews of 2 and 3 as a single crew is mostly constrained by their schedule.

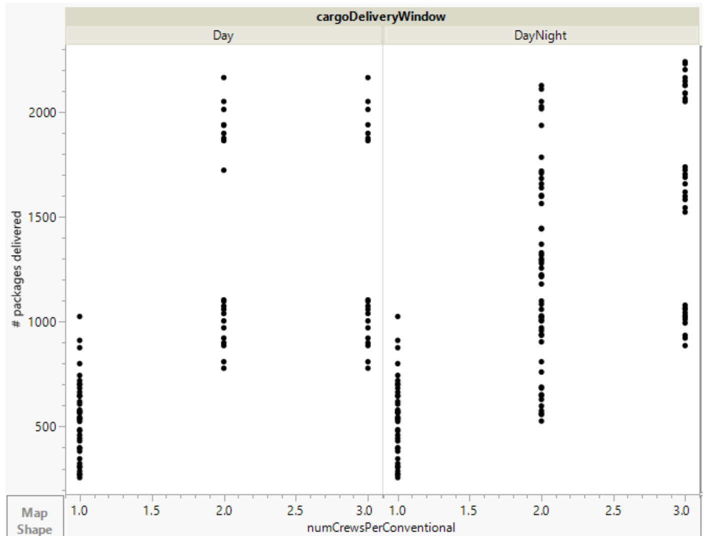


Figure 40: Visualization of the number of packages delivered (Y), grouped by the number of crews assigned to each asset and the time window options for cargo operations (X)

Figure 41 shows the number of packages delivered (on the y-axis), grouped by the duration of an individual crew shifts and the number of crews assigned to each asset (on the x-axes). For a single crew operating each asset, we can observe the expectable negative effect of the reduction of crew shifts on the operational performance as the available time for flights is directly reduced. For three crews, that would have either back-to-back shifts or overlapping ones, no performance difference can be observed. The biggest tradeoff can be derived from the assignment of two crews, where the average performance doesn't change between 8 and 10 hour shifts and an increase can only be observed for 12h shifts.

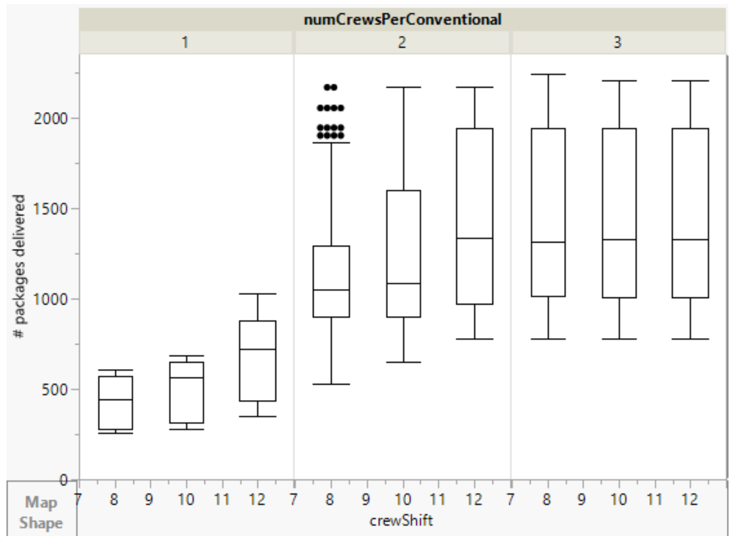


Figure 41: Visualization of the number of packages delivered (Y), grouped by the duration of an individual crew shifts and the number of crews assigned to each asset (X)

7.3.2.2 Theater Assessment Operation

Figure 42 shows the required time to complete the assessment (on the y-axis), grouped by the duration of an individual crew shifts and the number of crews assigned to each asset (on the x-axes). Across all the different numbers of crews assigned there is a difference in average performance between 8h shifts on the one side, and 10h or 12h shifts on the other side. While the spread of packages delivered increases for 12h shifts including better performances, it's nonetheless noteworthy that the average time remains constant overall. While a strong interdependency has been identified a priori, the results clarify that the effects might be negligible.

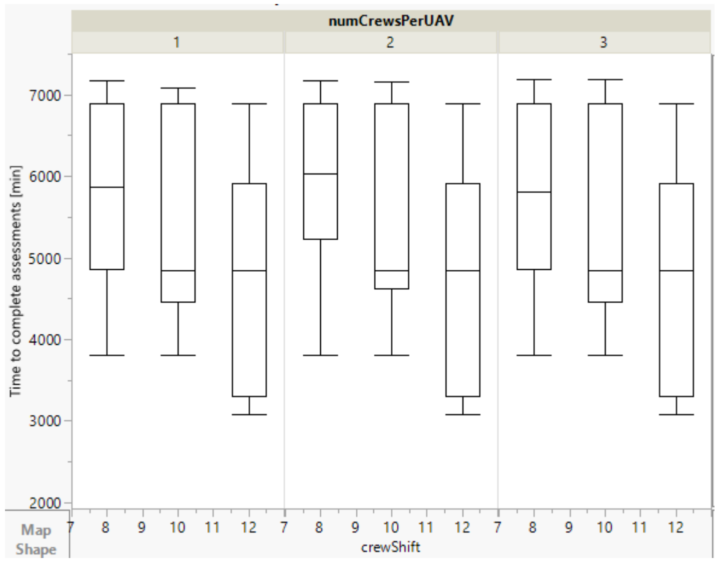


Figure 42: Visualization of the required time to complete the assessment (Y), grouped by the duration of an individual crew shifts and the number of crews assigned to each asset (X)

7.4 Conclusion

In the previous sections of this chapter, an approach and experiment to validate the hypothesis with regards to the Design and Options Space has been presented, along with the results of its execution. This approach was tested in the experiment using the same testbed environment as with the previous experiment and subsequent case study. Before drawing conclusions, reviewing the formalized hypothesis 2 to be evaluated:

Hypothesis 2: If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations from further consideration.

Looking at the previously presented results of the experiment, showing the usefulness of relationship metrics, it can be stated that hypothesis 2 has been validated. The goal of the experiment was to utilize the matrices of alternatives and relationships in order detect interdependencies and possible impermissibilities. With their showcased detection abilities, it makes clear their necessity, especially for relationship analysis, a process with a large number of cases. Through the execution of the experiment, we could observe that a priori identified interdependencies play a significant role in driving the performance results. In addition, the possible infeasibility of combinations of approaches, despite individual approaches being all feasible, has been demonstrated.

CHAPTER 8. FULL METHODOLOGY DEMONSTRATON

This chapter presents a full demonstration of the entire methodology, utilizing the overall case study in a scoped manner. The key parts of the methodology, and how they differentiate it from established processes, have been presented and validated in detail in the previous CHAPTER 6 and CHAPTER 7. Based on these validations, a demonstration case study is conducted to show the satisfaction of the research objective:

Research Objective: Develop a methodology that considers diverse operational requirements and operational ways in a parameterized fashion within a system-of-system analysis in the early stages of the acquisition process.

Before entering the three different parts of the methodology in the applied case, the case study is introduced with a motivational statement, background information on the utilized scenarios, and their suitability for the demonstration of the methodology.

8.1 Case Study Introduction

8.1.1 Mission

The acquisition-driven motivation for this demonstration case study is the performance of different types of vertical airlift assets while operating within a theater. The assets are conducting a Humanitarian Aid and Disaster Relief (HADR) operation in different scenarios.

8.1.2 Scenario Background

The scenario for this demonstration case study follows the background and structure of the case study introduced in Section 1.6.3 and incorporates similar scopes as in the previous experiments. While the problem statement is provided as part of the actual methodology, this subsection addresses the necessary background of the scenario. The island nations of Fiji and Vanuatu are considered as theaters. Each of these archipelago nations have been hit by multiple cyclones in the past, with cyclones Winston in Fiji in 2016 and Pam in Vanuatu in 2015 having reached sufficient category 5 intensity within reach of the respective archipelago to cause significant and response-triggering damage; the archipelagos and paths of the storms are displayed in Figure 43.

Cyclone Winston hit the Fiji archipelago as category 5 tropical cyclone [102]. The path of the storm cut right through the center of the archipelago, putting densely populated areas in proximity to the storm center and its destructive power. Fiji consists of 332 islands of whom 110 are inhabited. The population is around 900,000 people, of whom 87% live on the two main islands Viti Levu and Vanua Levu, and 75% on the coasts of Viti Levu [84]. The disaster hit almost 350,000 people living in the country, killing at least [103]. Besides financial and other support by the Australian Government, the Australian Defence Forces provided operational capabilities within 24h. These efforts included the deployment of forces with more than 200 personnel to be temporarily operating out of the main airport in Fiji, permanent back-and-forth flights of one C-17 aircraft for relief supply delivery, and immediate financial aid worth $26.1million [104]. As forces in Fiji, a P-3 Orion aircraft was used for aerial assessments, while MRH-90 helicopters were used for the distribution of aid [104].

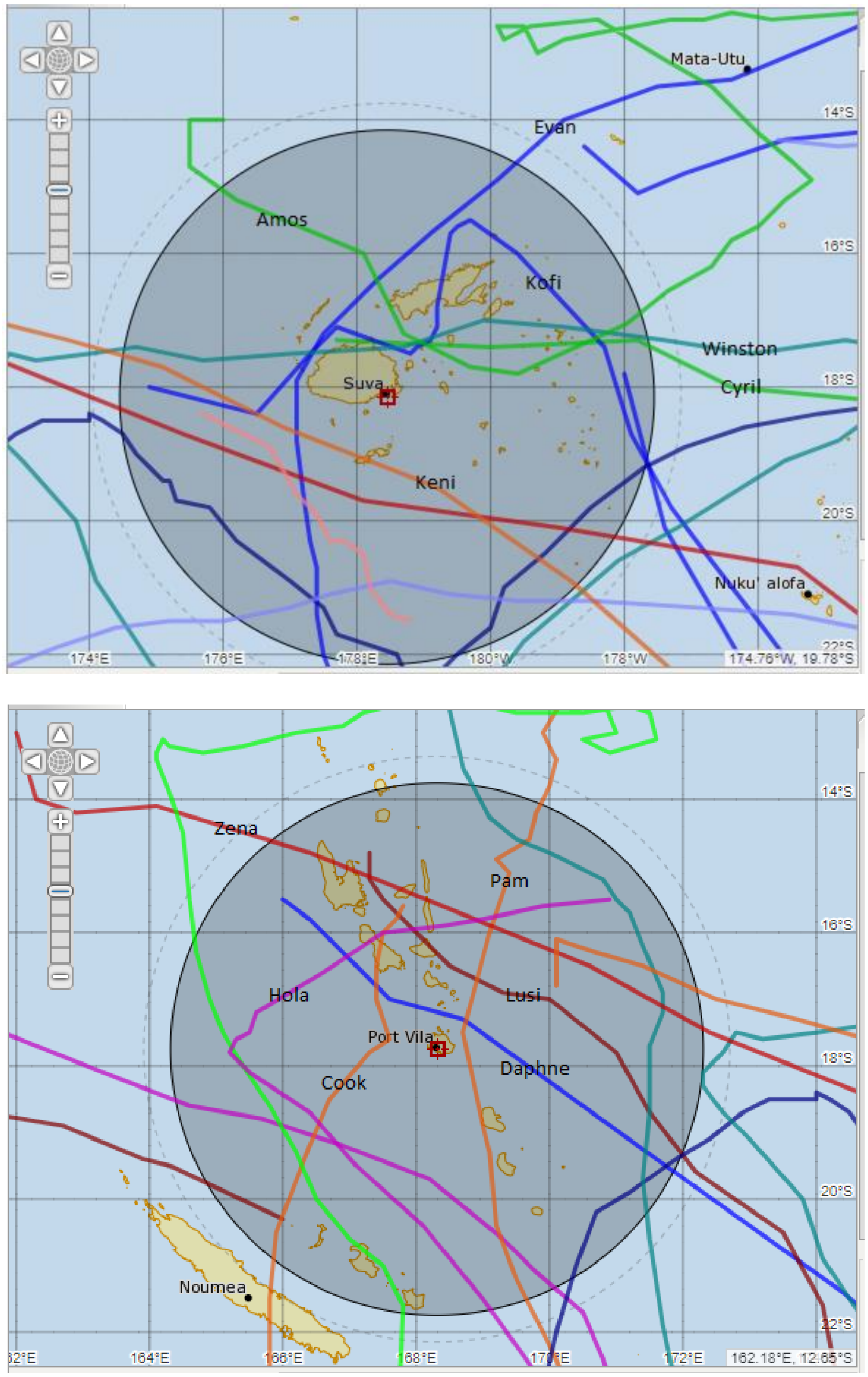


Figure 43: Maps of Fiji and Vanuatu including Various Hurricane Paths [86]

Similarly, a year earlier, Cyclone Pam hit the Vanuatu archipelago as category 5 [105]. The path through the country impacted all of Vanuatu's provinces, and caused major damages in the direct proximity of its capital. Vanuatu consists of 80 islands and a population of approximately 270,000 people [85]. The disaster impacted an estimated total of 166,600 people which constitutes more than half of the country's population [105]. Australia also provided a variety of aid, ranging from financial aid to deployment of forces within 36h [106]. The operation included 500 personnel as well as 182t of relief supply.

8.1.3 Suitability

HADR operations abroad are usually conducted by armed forces utilizing military assets that are designed and acquired for a different purpose. Often, they are the only choice to provide relief when existing civilian structure is destroyed or inoperable, and a robust and independent organizational structure is needed for immediate aid and initial recover. This type of operations contain elements relevant to traditional military operations: the need for rapid deployment into a theater with limited logistical support available, operating in a potentially dull-and-dirty environment, and the necessity to accomplish a mission goal within a short time frame.

In addition, HADR missions are suitable for the demonstrating a CBA and this methodology as ample public data is available on them and the nature of their operation requires the consideration of improvement potential across the available dimensions. While military helicopters, aircraft and the corresponding operational schemes are effective and often the only choice, HADR operations cannot rely on their operational requirements being considered in an asset development process. The opportunity to choose from amongst existing materiel capabilities and to adjust the way operations are conducted in order to maximize the efficiency is crucial to achieving improvements for operational performance and ensure the success of such operations.

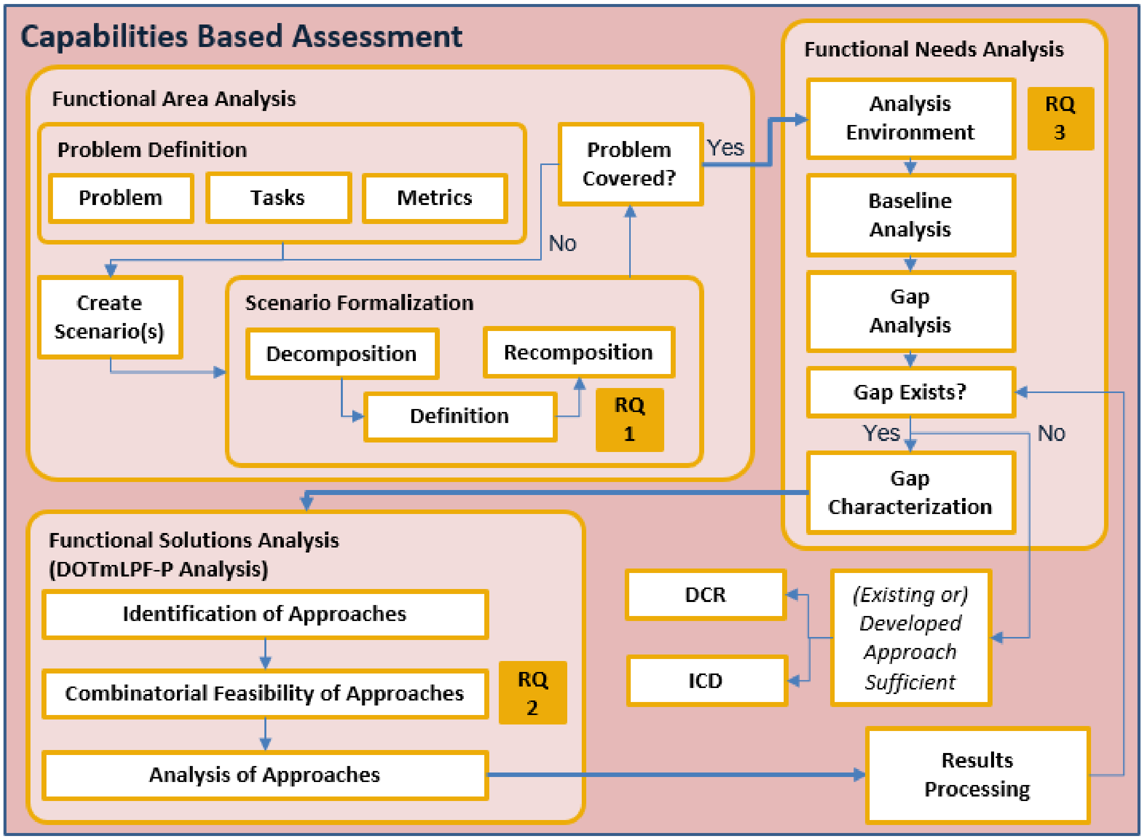


Figure 44: Methodology Flowchart within the Capabilities Based Assessment

8.2 Part 1: Functional Area Analysis

8.2.1 Step I: Problem Definition

Based on the provided mission statement, the problem definition and overall scope is for the Australian Defence Forces to provide humanitarian aid to an underserved remote area in the immediate aftermath of an emergency situation. Local infrastructure is deemed insufficient for the duration of the operations so the mission in its entirety needs to be supported by the deployed forces themselves.

Subsequently, the following tasks and metrics are formalized in Table 15 and Table 16, respectively. It should be noted that the metric of interest 'population serviced with aid' is directly correlated to the simulation-generated 'number of packages delivered', but allows to put the performance in a relative perspective.

Table 15: Tasks from Problem Definition

Assemble and prepare forces in homeland for deployment
Deploy forces into the theater (including equipment, personnel, and aid material) and sustain their operation
Establish a presence in the theater enabling forces to operate within the theater
Assess the theater to gain information about the impact of the disaster in various locations
Deliver aid to locations within the theater

Table 16: Metrics from Problem Definition

Metrics of Interest
Number of packages delivered
Population serviced with aid
Number of delivery flights
Total delivery flight time [h]
Time of delivery of specific numbers of packages (milestone parameters)
Secondary auxiliary metrics
Ratio of number of packages delivered over delivery flight time [#/h]
Ratio of number of packages delivered over number of utilized assets

8.2.2 Step II: Scenario Formalization

Based on the defined problem, especially the scope of an Australian-operated HADR operation abroad, two scenarios are identified to be utilized in the progress of this demonstration case study: the events around the cyclones Winston in Fiji in 2016 and Pam in Vanuatu in 2015. A detailed description of the general layout of the scenarios has been provided in Section 6.2.1. Subsequently, the scenario options are formalized in Table 17, and utilized for the entirety of the remaining process.

Table 17: Scenario Options from Scenario Formalization

Parameter	Attributes	
Original parameters utilized for the design of experiments (in Part 3)		
Theater	Fiji	Vanuatu
Storm	Winston	Pam
Storm Destruction Radius	50 [km]	60 [km]
Local Base Location	Suva	Port Vila
Initial Availability of Aid	0 [# of packages]	
Derived (or reference) parameters		
Distance of Local Base from Australia	2852 [km]	1945 [km]
Total population in need [103][105]	350,000	166,600

Following the selection of the scenarios, the adjusted RFLP approach is applied to decompose scenarios along the layered dimensions. A detailed description of the process has been provided in Section 6.2.2, and the results are displayed in Figure 45.

The full decomposition including the different logical elements that are not listed here can be found in APPENDIX B.

The formalization of the scenarios and the inference that the selected scenarios covers the breadth of the required mission and defined problem concludes the first part of the methodology, and the Functional Area Analysis that it represents.

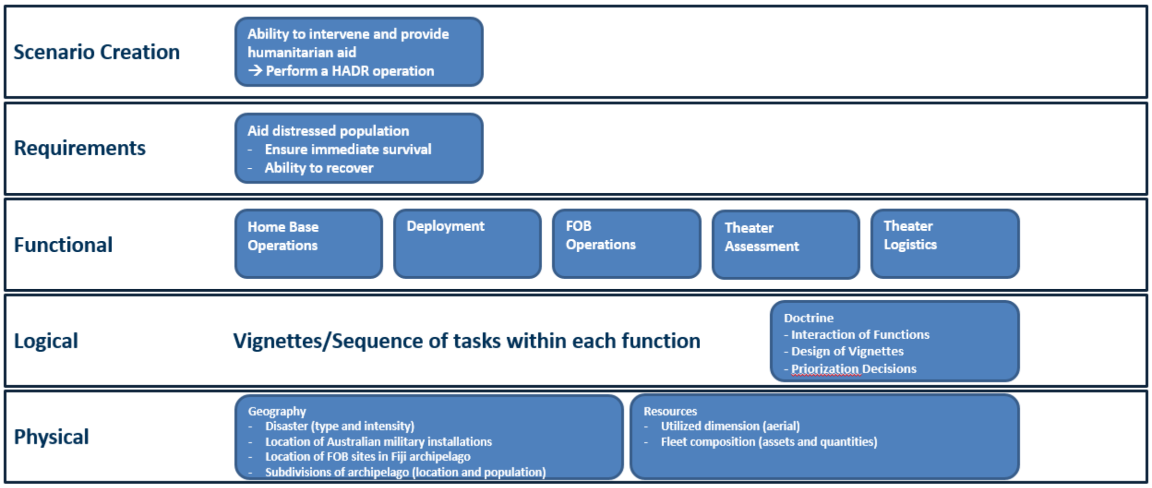


Figure 45: RFLP Decomposition from Scenario Formalization

8.3 Part 2: Functional Needs Analysis

8.3.1 Step III: Analysis Environment

As analysis environment, the Python testbed environment introduced and described in Section 6.3 is utilized. It conducts discrete event simulations reflecting the scenarios formalized in Step II and generating results for the metrics of interest established in Step I.

Figure 46 and Figure 47 show the storm path and the subsequent classification and prioritization of locations performed by the analysis environment for the previously established scenario in Fiji and Vanuatu, respectively.

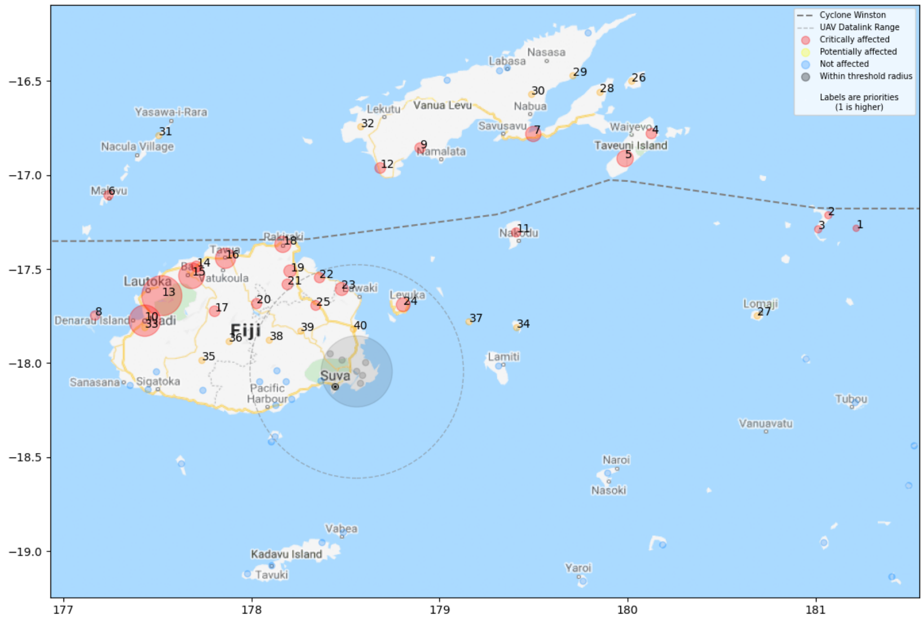


Figure 46: Map of Fiji with the Classification and Prioritization conducted by the Testbed Environment

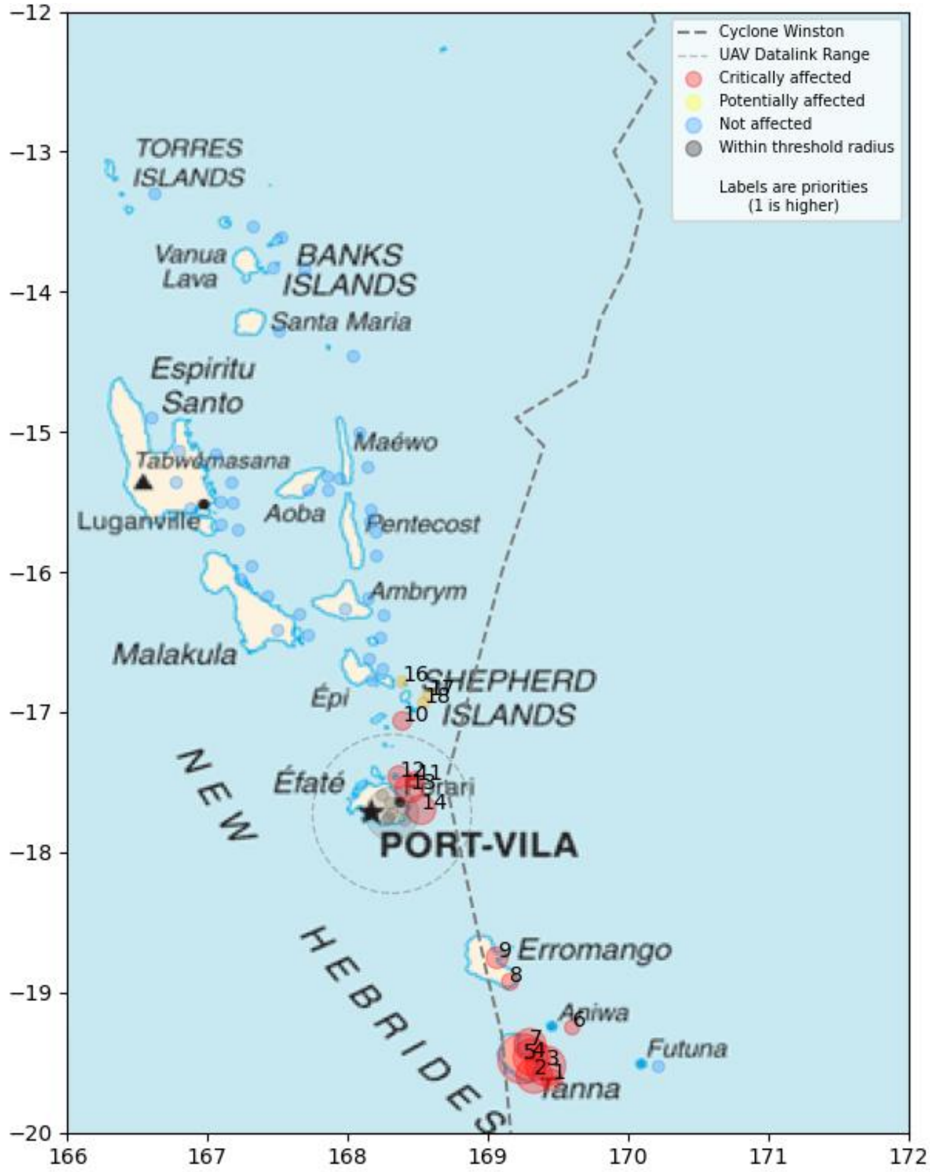


Figure 47: Map of Vanuatu with the Classification and Prioritization conducted by the Testbed Environment

8.3.2 Step IV: Baseline and Gap Analysis

As baseline case, in line with the considerations for previous experiments, 2 C-17 and 2 C-130 are mobilized to operate for the strategic airlift, 3 MRH-90 helicopters are deployed for logistical operations, and 4 Stalker UAV's and 1 AP-3C fixed-wing aircraft for the theater assessment. The case is infused into the analysis environment for each theater, and the results are presented in Table 18.

Table 18: Performance Parameters from Baseline Analysis

	Fiji	Vanuatu
Number of packages delivered	2,736	1,869
Population serviced with aid	54,720	37,380
Ratio of population serviced over total population in need	15.2%	22.4%
Number of delivery flights	72	52
Total delivery flight time [h]	92	92
Time of delivery of the 1st package	1d 3h	1d 3h
Time of delivery of 1,000 packages	1d 20h	2d 0h
Time of delivery of 2,000 packages	3d 23h	Not reached
Time of delivery of 5,000 packages	Not reached	Not reached
Time of delivery of 10,000 packages	Not reached	Not reached

By assessing the performance of the baseline, the process moves on to the second part of this step and into the gap analysis. In this demonstration case study, the gaps are formalized by target performance metrics not met by the baseline analysis. This approach combines gap analysis and characterization as it directly translates guidance into quantified parameters. Given the baseline performance in the different theaters, Fiji is identified as the more demanding environment and two improvement requests, of slight and strong magnitude, are established to form the gap; the formalized target performance metrics are displayed in Table 19.

The conclusion that a gap exists, and its formalized characterization concludes the second part of the methodology, and the Functional Needs Analysis it represents.

Table 19: Target Performance Parameters (for the Fiji theater) from Gap Analysis

	Slight Improvement	Strong Improvement
Number of packages delivered	5,000	9,000
Population serviced with aid	100,000	180,000
Ratio of population serviced over total population in need	27.8%	50.0%

8.4 Part 3: Functional Solutions Analysis

8.4.1 Step V: Identification of Approaches

For the identification of approaches, the possible materiel and doctrinal alternations based on scenario decomposition, fleet availability, and technology improvements are determined. Following the comprehensive assessments made during the experiment for the design and options space, a full-factorial design of experiments with a total of 54,000is created (with 2 theaters, 125 materiel, and 216 doctrinal combinatorial cases). This is displayed in Table 20 and Table 21. The materiel and doctrinal assessment parameters which form part of the operation but not of the scope of the approaches are kept at the previously established baseline. It should be noted that while the materiel aspects of the

DoE are identical to the one for vertical airlift assets used in the experiment for the design and options space, this demonstration case study crosses all materiel with doctrinal approaches, including those that have not been performed yet.

Table 20: Materiel Aspects of Design of Experiments for Demonstration Case Study

Parameter	Alternatives	
	#	Attribute
Operating C-17	5	**2**, 3, 4, 5, 6
Operating C-130	1	**2**
Vertical Airlift Asset Type	5	**MRH-90**, CH-47, UH-60, V-22, V-280
Vertical Airlift Asset Quantity	5	2, **3**, 4, 5, 6

Table 21: Doctrinal Aspects of Design of Experiments for Demonstration Case Study

Parameter	Alternatives	
	#	Attribute
Vertical Airlift Cargo Delivery Mode	3	External, Internal, **Both**
Crews per Conventional Asset	2	**2**, 3
Cargo Flight Types	3	Single Location, **Multiple Locations by Proximity**, Multiple Locations by Priority
Cargo Flight Time Window	2	Day, **DayNight**
Local Fulfillment Steps	3	5, **10**, 20 [%]
Asset-Footprint Operations Mode	2	**Yes**, No
Duration of Crew Shifts	1	**12** [h]

8.4.2 Step VI: Combinatorial Feasibility of Approaches

Based on the design of the experiment developed in the previous step, matrices of alternatives and relationships are established; the result for the matrices are shown in Figure 48 and Figure 49.

	type	alternatives (considered)
YAMB130	discrete	0,2
YAMB17	discrete	2,3,4,5,6
rc_cargo_num	discrete	2,3,4,5,6
rc_cargo_type	categorical	MRH-90,CH-47,UH-60,V-22, V-280

Figure 48: Materiel Matrix of Alternative from Combinatorial Feasibility

deliverCargo	categorical	Both,External,Internal
numCrewsPerConventional	discrete	1,2,3
cargoMode	categorical	MultipleProx,Single,MultiplePrio
cargoDeliveryWindow	categorical	Day,DayNight
fulfillmentStep	continuous	0.05,0.1,0.2
flyOnlyAfterFootprint	categorical	0,1 (No, Yes)
crewShift	continuous	8,10,12

Figure 49: Doctrinal Matrix of Alternative from Combinatorial Feasibility

		YAMB130	YAMB17	rc_cargo_num	rc_cargo_type	deliverCargo	numCrewsPerConventional	cargoMode	cargoDeliveryWindow	fulfillmentStep	flyOnlyAfterFootprint	crewShift
materiel	YAMB130	---					3 (poss.) impermissibility					
	YAMB17	0	---				2 strong interdependency					
	rc_cargo_num	2	2	---			1 weak interdependency					
	rc_cargo_type	1	2	0	---		0 no interdependency					
doctrinal	deliverCargo	0	0	0	1	---						
	numCrewsPerConventional	0	0	0	0	0	---					
	cargoMode	0	0	0	1	1	1	---				
	cargoDeliveryWindow	0	0	0	3	3	2	0	---			
	fulfillmentStep	0	0	0	0	0	0	0	0	---		
	flyOnlyAfterFootprint	0	0	0	0	3	0	0	0	0	---	
	crewShift	0	0	0	0	0	2	1	1	0	1	---

Figure 50: Relationship Matrix from Combinatorial Feasibility

Figure 50 shows the established relationship matrix. The intra-dimensional relationships (top-left, and bottom-right triangles of the figure) have been already analyzed for the experiment for design and options space, as outlined in detail in Section 7.2.2, and are added here without further discussion. In this demonstration case study, however, the process needs to be expanded to the inter-dimensional interdependencies and possible impermissibility's (bottom-left rectangle of the figure). Given the scope of the demonstration case study, a single possible impermissibility is identified between the type of vertical air lift asset used and the time window for operation. Hereby, it needs to be taken into account whether the asset is actually equipped to fly operations at night, generally, and given the scenario-related surrounding infrastructure. While the assets under consideration are all generally available in versions equipped for nighttime operations, a technological analysis is still performed to investigate the performance impact. To conclude Step VI,

Table 22 shows a list of the identified interdependencies and possible impermissibility's, and summarizes the assessment made for them.

Table 22: List of identified interdependencies and possible impermissibility's, including the respective assessment for consideration

First Parameter	Second Parameter	Classification	Assessment
Intra-Dimensional Materiel			
number and type of deployed vertical airlift assets	number of strategic airlift assets	Strong Interdependent	Perform manual comparative analysis.
Intra-Dimensional Doctrinal			
operational mode of cargo loading	time window for cargo operations	Possible Impermissibility	Treat as permissible in scenarios.
operational mode of cargo loading	operational option to operate early without a footprint	Possible Impermissibility	Effects negligible, thus filter alternatives to single baseline for second parameter.
number of crews per conventional asset	time window for cargo operations	Strong Interdependent	Exclude combination '1 crew/day&night' from consideration as unrealistic.
number of crews per conventional asset	crew shift durations	Strong Interdependent	Maintain as part of analysis.
Inter-Dimensional			
Cargo asset type	Time window for cargo operations	Possible Impermissibility	Perform technology analysis.

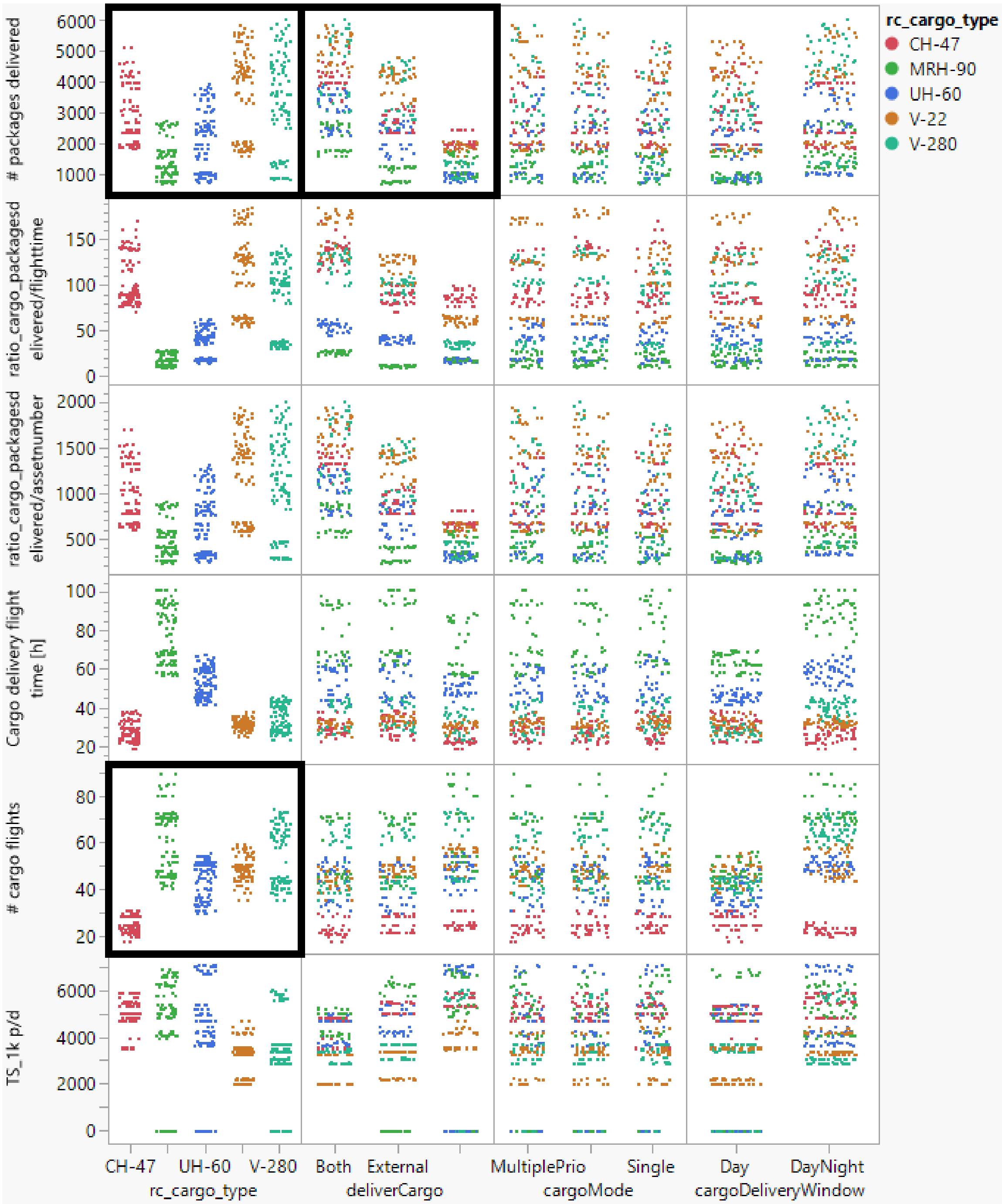


Figure 51: Scatterplot overview visualization of the results of the Demonstration Case Study for the Fiji theater, including highlighted areas

8.4.3 Step VII: Analysis of Approaches

In Step VII, we utilize the analysis environment to execute simulations of the design of experiments and compare the results for our metrics of interest.

8.4.3.1 Initial Overall Analysis

As first step in the analysis, a 'big picture' plot containing all cases to be considered is created. Due to the multi-dimensionality of the problem, with each data point being an extensive vector of input and output information, it is not possible to visualize all information at once. However, through the use of multiple plots and filters, we can tailor a suitable overview visualization towards the gap we are trying to close. In this research, scatterplots are used containing outputs of interest on the y-axis, and inputs of interest on the x-axis. Within each field of the plots, data points are shown that group together dependent on pairwise parameters.

Figure 51 present a scatterplot overview visualization of selected output parameters (on the y-axis) in contrast to the selected materiel and doctrinal input parameters (on the x-axis) for the Fiji theater whereby the quantitative materiel baseline of 3 vertical airlift assets and 4 strategic airlift assets is kept constant. As established in the previous subsection, and applied to all figures in this subsection, the parameter 'operational option to operate early without a footprint' has been eliminated and coded to the footprint being required for operations. The technology analysis with regards to 'time window for cargo operations' is conducted with all but one plot including a differentiation of the parameter. Given the overall similar behavior patterns between the theaters, and the fact that the gap requirements are formulated for the Fiji theaters, the following analysis will focus only on this scenario. The full results of this experiment can be found in APPENDIX E.

The presented scatterplot visualization shows interesting behavior that requires further investigation. While the subsequent analysis is structurally driven by the layout of the experiment and the gap parameters to be assessed, the overview analysis nonetheless sets the tone for identifying overall trends. Three sub-plots as highlighted in Figure 51 are subsequently subjected to a closer look.

Figure 52 as a zoomed plot of the top-left highlight shows the numbers of packages delivered (on the y-axis) versus types of vertical airlift assets (on the x-axis). Given the constant quantities with varying types of materiel assets, we can identify the overall trend of deployed assets (CH-47, MRH-90, UH-60) reaching a significantly lower maximum than self-deployable assets (V-22, V-280). However, all assets show a wide stretch and share similar performance regions along it, implying that additional non-materiel parameters play a key role to shape the operational outcome. Within the deployed assets category, the UH-60 performs generally better than the MRH-90, with the CH-47 showing a wide stretch of results. For self-deployable assets, a large share of cases falls into the same region as deployable assets, implying that certain conditions need to be met in order for them to unfold high performance.

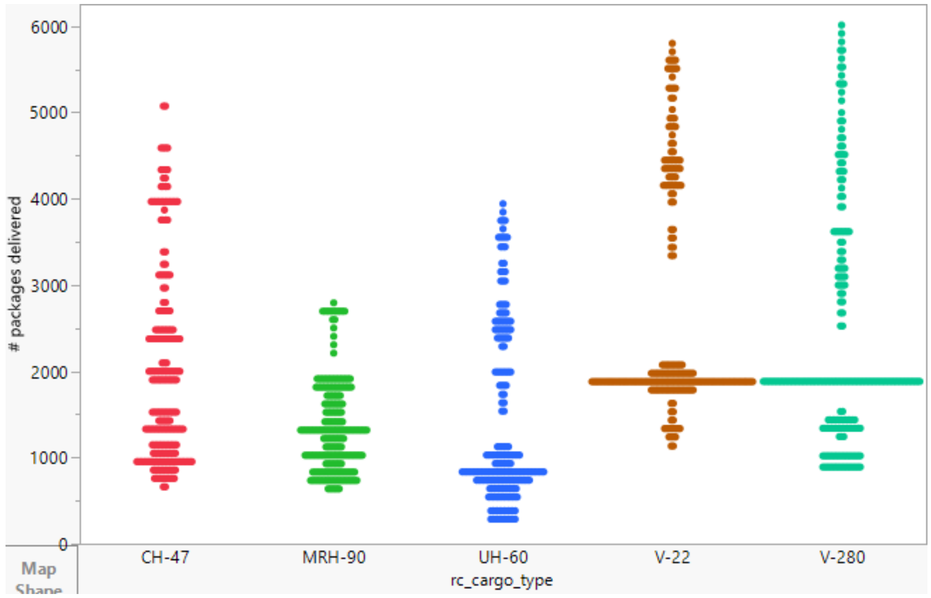


Figure 52: Visualization of the numbers of packages delivered (Y) versus type of vertical airlift asset (X)

Figure 53 as a zoomed plot of the bottom-left highlight shows the numbers of total cargo flights (on the y-axis) versus types of vertical airlift assets (on the x-axis), with data points colored by types of vertical airlift assets. Given the geographical layout of the Fiji theater that does not include many affected regions out of range of any asset, the respective numbers of flights can be generally correlated to performance metrics. In this context, longer ranges yield fewer flights, and for assets with similar ranges, faster cruise speeds yields more flights. Depending on the value of the stakeholders placed on diversity of deliveries, i.e. the distribution of aid across a large amount of locations, these considerations can become critical in an early stage. Most noteworthy at this point is the significantly low number of flights of CH-47 across all cases.

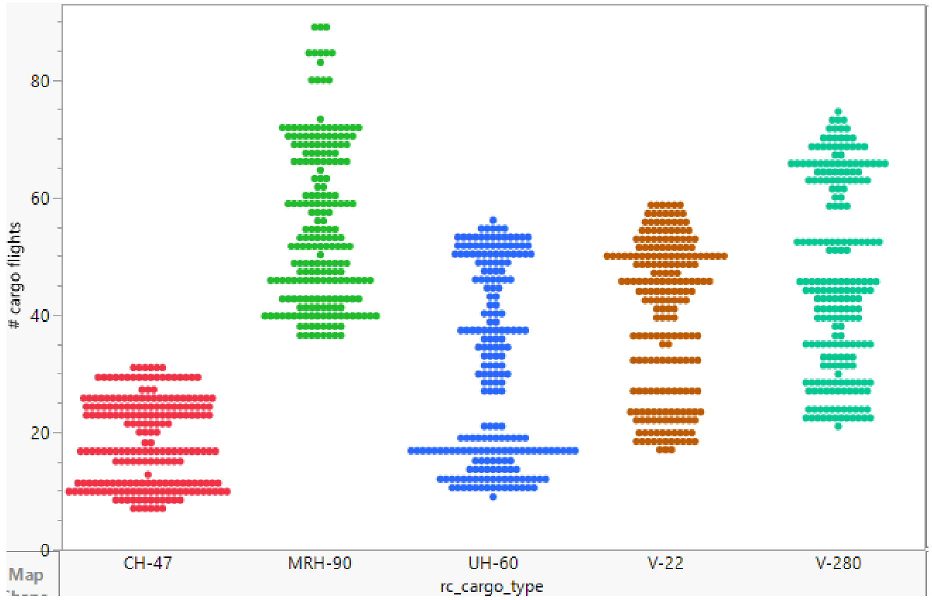


Figure 53: Visualization of the numbers of cargo flights performed (Y) versus type of vertical airlift asset (X)

Figure 54 as a zoomed plot of the top-right highlight shows the numbers of packages delivered (on the y-axis) versus operational mode of cargo loading (on the x-axis), with data points colored by types of vertical airlift assets. It can be observed that Dual and External loading share a large overlap of performance, although Dual can reach higher numbers under certain conditions. In addition, Dual can reach similar numbers over a wide range of assets, while high performance for all types is limited to self-deploying assets. However, it again can be observed that a large share of cases across all types fall into the same performance region, implying that specific other parameters need to align in order for good and high performance to unfold in the simulation.

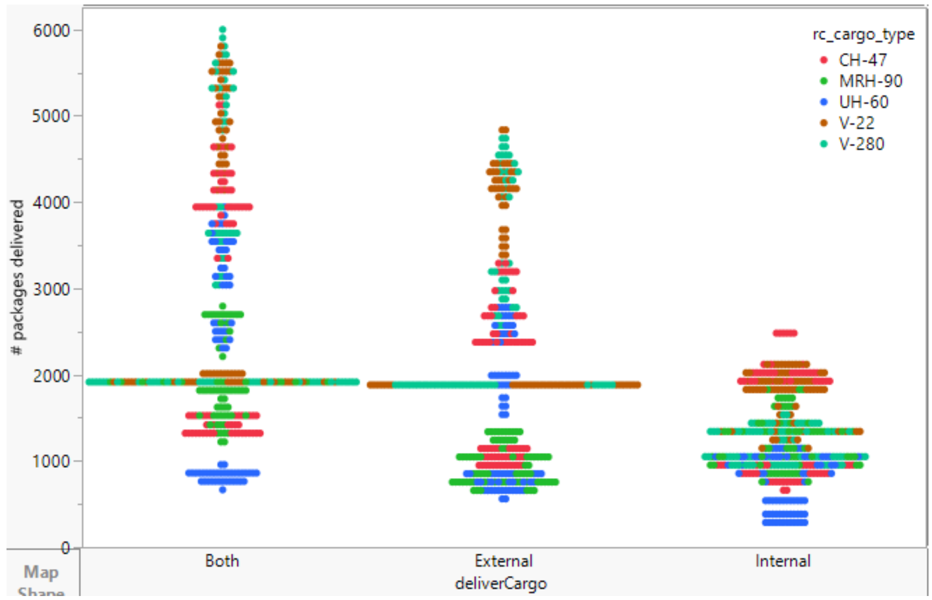


Figure 54: Visualization of the numbers of packages delivered (Y) versus operational mode of cargo loading (X); data points colored by types of vertical airlift assets

8.4.3.2 Gap-Oriented Step-By-Step Analysis

Having assessed the generated data in general in the initial overall analysis, we now recall the gap to be assessed. As established in Section 8.3.2, we would like to achieve a slight and strong improvement to 5,000 and 8,000 total packages delivered, respectively. Based on the prioritization between materiel and non-materiel aspects in the JCIDS and CBA process, we take different steps until we reach the goal of satisfaction. Figure 55 shows a logical diagram of the steps of the gap-oriented detailed analysis.

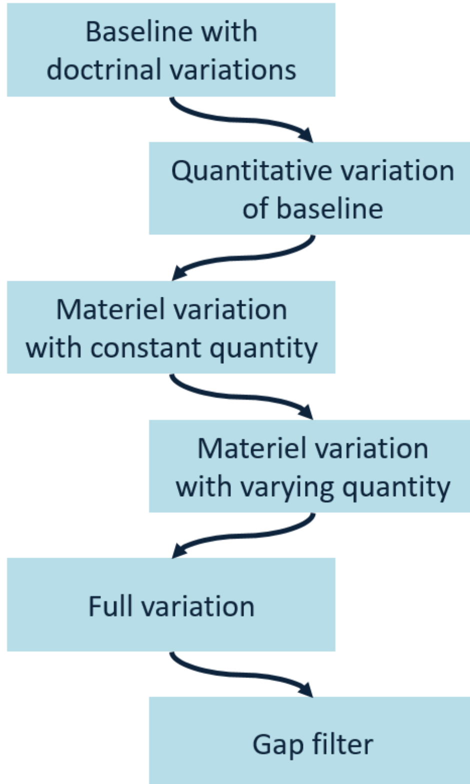


Figure 55: Logical Diagram of Gap-Oriented Analysis Approach

First, we are looking at our baseline and consider non-materiel doctrinal changes. This equates to using resources in similar quantities, but trying out different ways to optimize results. Second, we are staying with similar type of resources but consider deployment of increasing quantities. This would require more effort by the operator, but avoids utilization of new or different types of assets that likely would need to be procured.

Third, stepping towards materiel variations, we revert to baseline quantities with the deployment of different types of assets. Hereby, new assets would be required but once in the arsenal, similar efforts with regards to deployment and personnel would be considered. Fourth, we then assess materiel variations in varying quantities. Fifth, this materiel variation is combined with the full non-materiel variation to investigate the entire design space. As last step, a gap filter is applied limiting assessed options to those meeting the hard gap criterias.

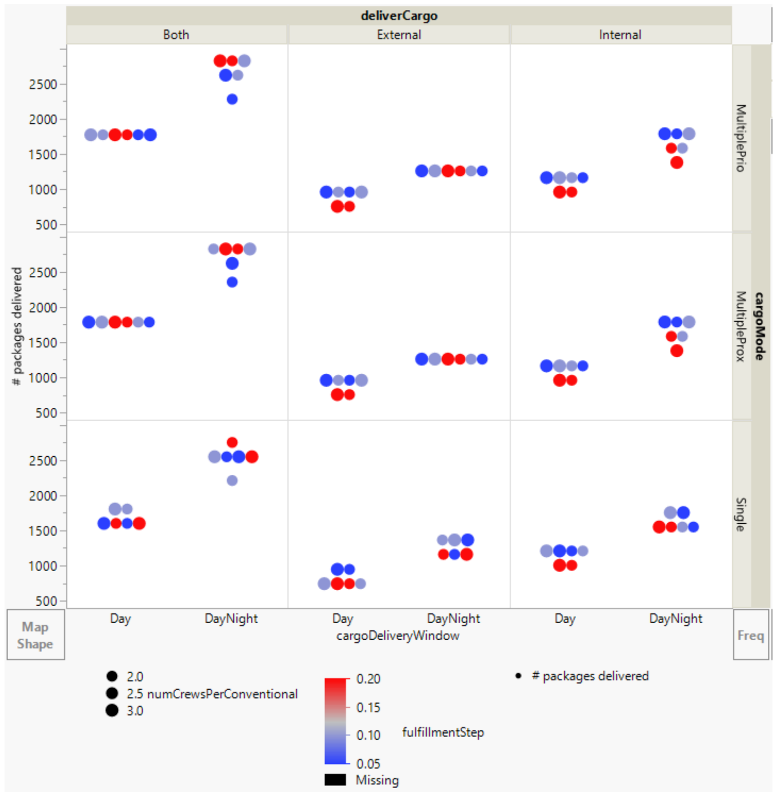


Figure 56: Visualization of the numbers of packages delivered (Y) versus time window for cargo operations (X), grouped by the operational mode of cargo loading (X) and cargo flight types (Y); data points sized by number of crews per asset, and colored by local fulfillment steps

To start the gap-oriented analysis, an investigation of the established baseline with the MRH-90 asset under doctrinal variations is performed. Figure 56 shows the numbers of packages delivered (on the y-axis) versus time window for cargo operations (on the x-axis), grouped by the operational mode of cargo loading (on the top x-axis) and cargo flight types (on the right y-axis), with data points sized by number of crews per asset, and colored by local fulfillment steps. The baseline doctrinal parameters are reflected in the left column, center row, right entries.

It can be observed that the baseline already provides maximum performance for the materiel baseline. In addition, we see that the local fulfillment step (reflected by different data point colors) does generally not have an effect on the overall performance; this parameter is subsequently eliminated and coded to 10% for the remainder of the analysis.

With the sole adjustments to doctrinal parameters not sufficient for an increase in operational performance, an investigation into quantitative variation of the MRH-90 baseline asset is conducted. Figure 57 shows the numbers of packages delivered (on the y-axis) versus operational mode of cargo loading (on the x-axis), grouped by the number of strategic airlift assets (on the top x-axis) and number of vertical airlift assets (on the right y-axis), with data points colored by time window for cargo operations. Besides the displayed parameters, the various options for ‘number of crews per asset’ and ‘cargo flight types’ are included as undifferentiated data points. For these two doctrinal parameters, one can observe that comparison of respective cases cluster amongst each other indicate a lack of impact on the performance parameter displayed. The pattern between the operational modes of cargo loading remains constant across the board, although with different intensities, with dual loading yielding the best results, over only internal loading, and lastly external loading only. Most significantly, one can observe an increased impact in the number of strategic airlift assets with an increased number of vertical airlift assets. Furthermore, the addition of vertical airlift assets without increasing strategic airlift capacity only benefits the performance initially before the effect remains stagnant. Referring to the established gaps, one can observe that only a large quantity of both strategic and vertical airlift assets, combined with around-the-clock operations, can reach the slight improvement gap.

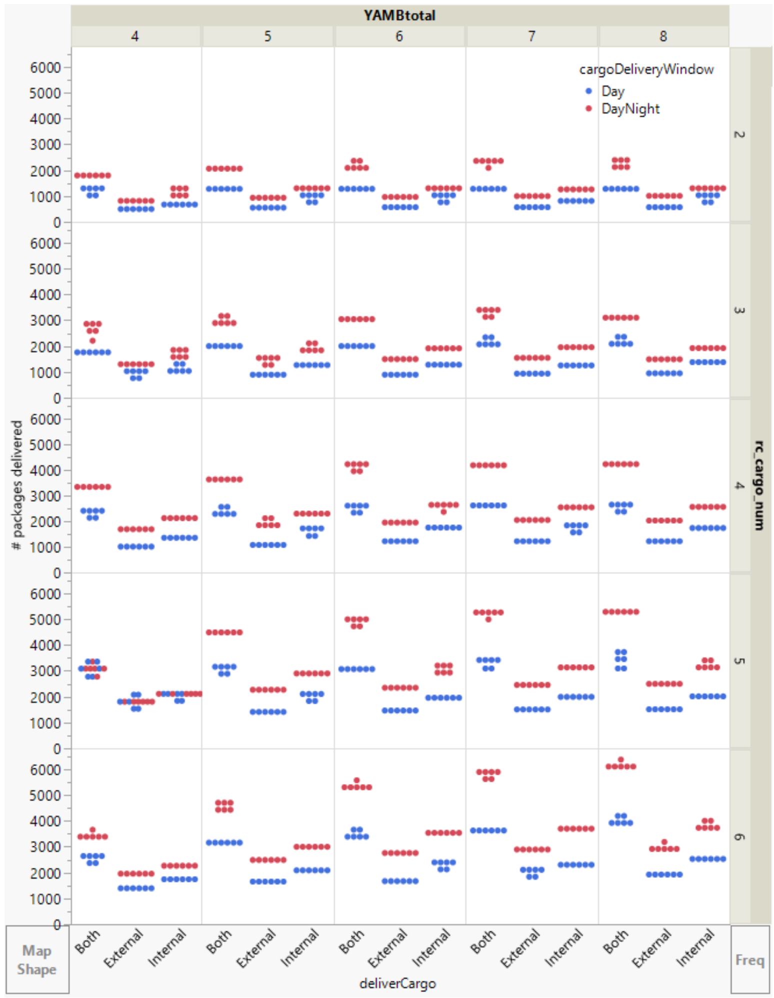


Figure 57: Visualization of the numbers of packages delivered (Y) versus operational mode of cargo loading (X), grouped by number of strategic airlift assets (X) and number of vertical airlift assets (Y); data points colored by time window for cargo operations

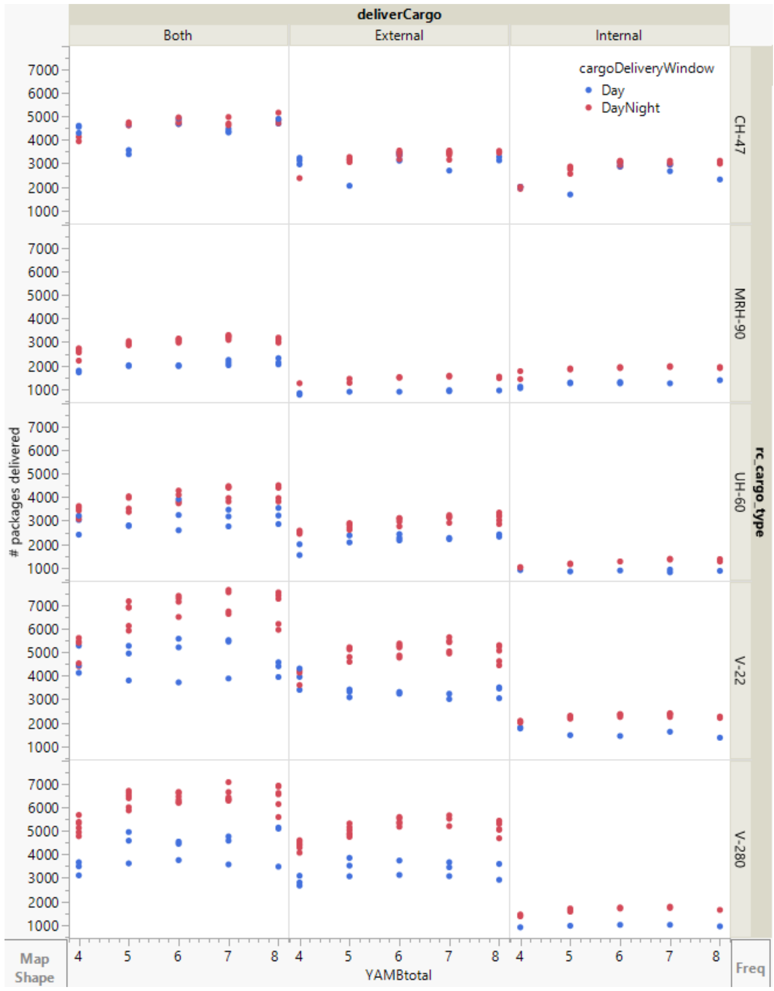


Figure 58: Visualization of the numbers of packages delivered (Y) versus number of strategic airlift assets (X), grouped by operational mode of cargo loading (X) and types of vertical airlift assets (Y); data points colored by time window for cargo operations

Based on the observations so far, the analysis moves towards the inclusion of alternative materiel options and assesses the performance of various asset types in the same quantity (3 assets). Figure 58 shows the numbers of packages delivered (on the y-axis) versus number of strategic airlift assets (on the x-axis), grouped by the operational mode of cargo loading (on the top x-axis) and types of vertical airlift assets (on the right y-axis), with data points colored by time window for cargo operations. Having introduced different asset types, one can observe that self-deployable tiltrotor assets can close the slight improvement gap consistently with day-and-night operations and either only-external or dual loading; in case of the V-22, the gap can also be closed with day time operations and dual loading. However, conventional helicopters still can not close the gap with the fixed quantity.

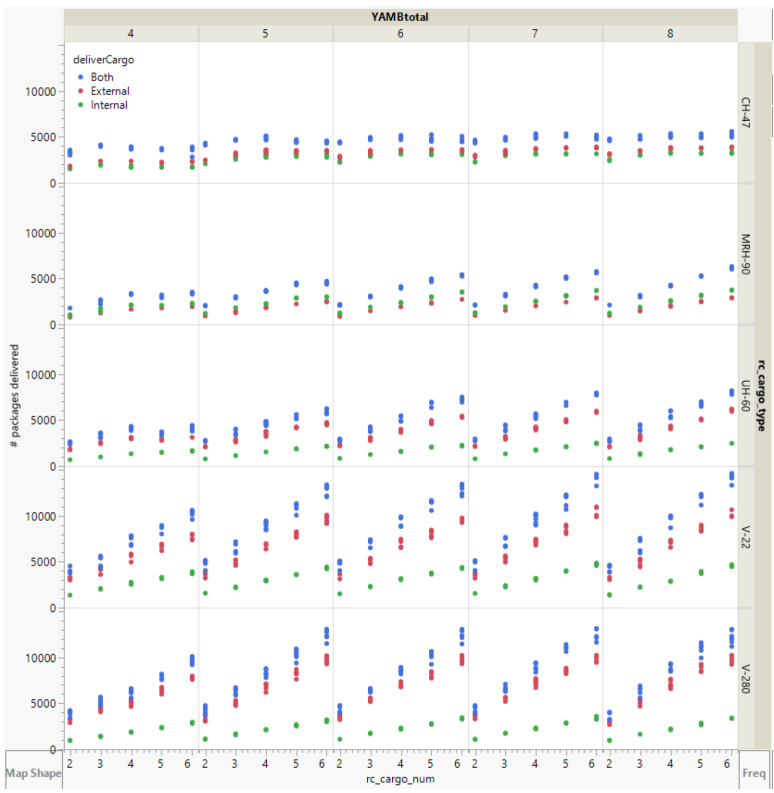


Figure 59: Visualization of the numbers of packages delivered (Y) versus number of vertical airlift assets (X), grouped by number of strategic airlift assets (X) and types of vertical airlift assets (Y); data points colored by operational mode of cargo loading

Subsequently, an analysis of different quantities is performed. Figure 59 shows the numbers of packages delivered (on the y-axis) versus number of vertical airlift assets (on the x-axis), grouped by the number of strategic airlift assets (on the top x-axis) and types of vertical airlift assets (on the right y-axis), with data points colored by operational mode of cargo loading. It should be noted that the parameter ‘time window for cargo operations’ is kept constant at Day-and-Night, but its alternative does not cause any pattern changes. It can be observed that the CH-47 consistently does not close the slight improvement gap. As already assessed previously, the MRH-90 is able to do so only with large quantities of both strategic and vertical airlift assets. However, the UH-60 reaches the slight improvement gap target with a lower number of assets, both with regards to vertical and strategic airlift. As for the tiltrotor assets, they consistently close the gap and, through an increase in deployment numbers, approach or reach the strong improvement gap.

Based on the previous observations, the analysis can be concluded by focusing on the varying numbers of different vertical airlift assets combined with the relevant doctrinal parameters. Figure 60 shows the numbers of packages delivered (on the y-axis) versus time window for cargo operations (on the x-axis), grouped by the number of vertical airlift assets (on the top x-axis) and operational mode of cargo loading (on the right y-axis), with data points colored by types of vertical airlift assets. It should be noted that the data points include all quantities of strategic airlift assets, while the number of crews per asset has been fixed to 2 and the cargo flight type set to multiple by proximity. This visualization shows that internal cargo loading cannot close the slight performance gap in any configuration, while other loading types show similar success patterns. It also confirms the importance of being able to operate around-the-clock in order to being able to improve performance.

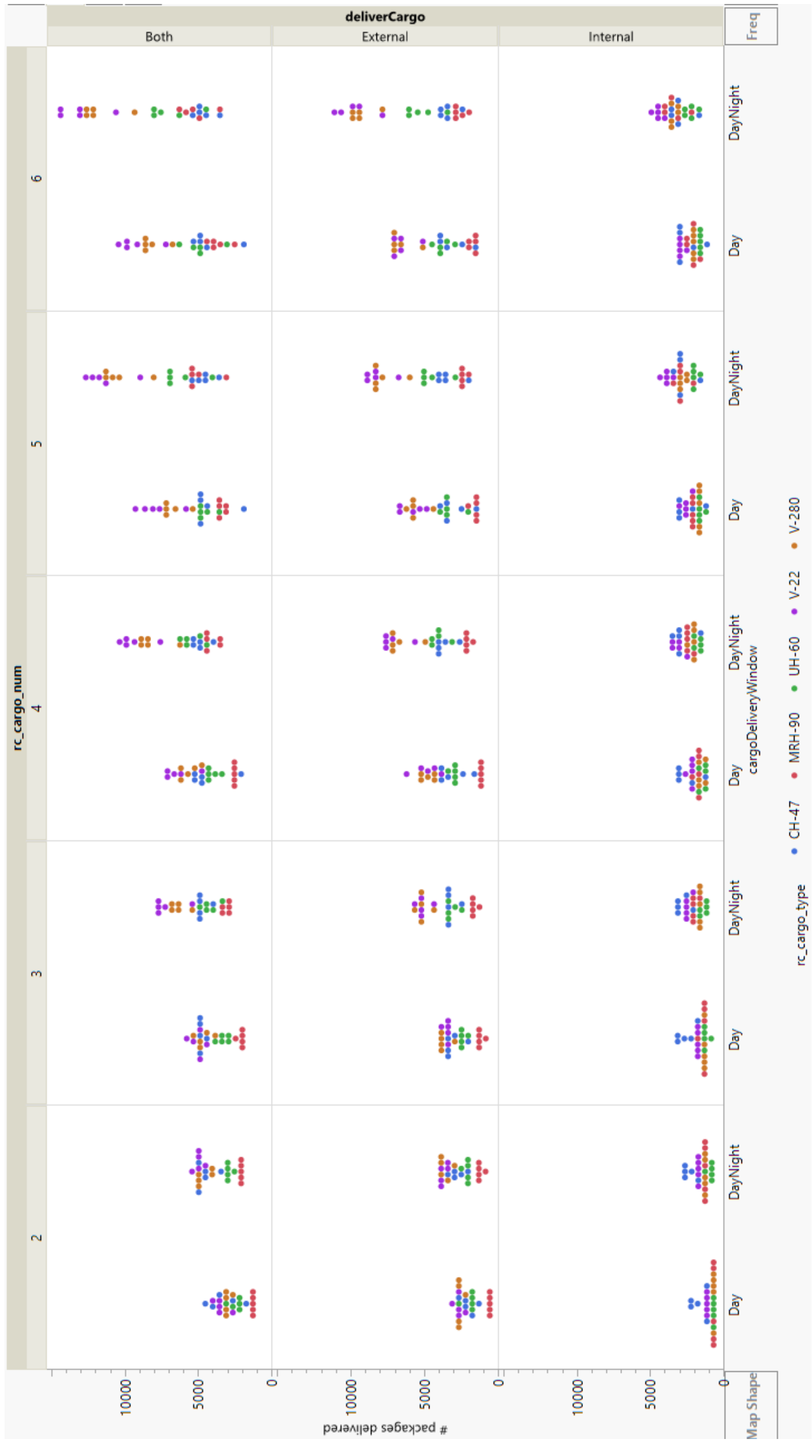


Figure 60: Visualization of the numbers of packages delivered (Y) versus time window for cargo operations (X), grouped by number of vertical airlift assets (X) operational mode of cargo loading (Y); data points colored by types of vertical airlift assets

In order to transition to the gap reassessment, doctrinal options are reduced to the baseline with the exception of the time window for cargo operations. Figure 61 shows the numbers of packages delivered (on the y-axis) versus number of vertical airlift assets (on the x-axis), grouped by the number of strategic airlift assets (on the top x-axis) and types of vertical airlift assets (on the right y-axis), with data points colored by time window for cargo operations.

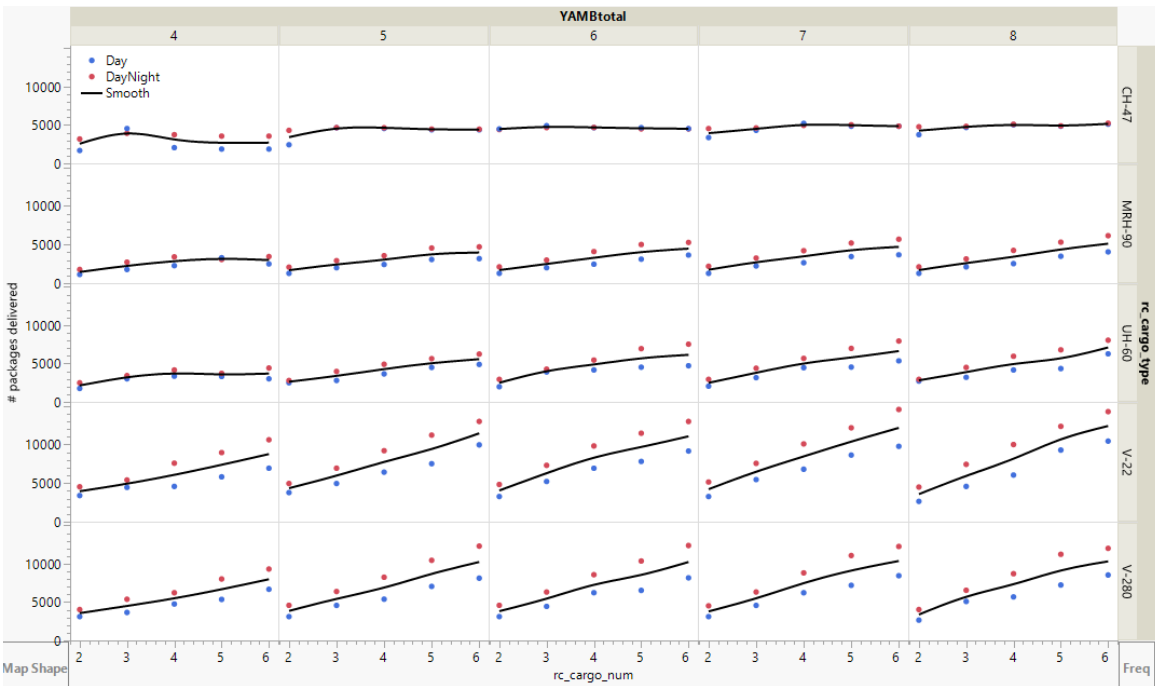


Figure 61: Visualization of the numbers of packages delivered (Y) versus number of vertical airlift assets (X), grouped by number of strategic airlift assets (X) and types of vertical airlift assets (Y); data points colored by time window for cargo operations

8.4.4 Step VIII: Gap Reassessment & Approach Selection

Having concluded the analysis in Step VII and identified options for gap closure, we can formalize and finalize this in Step VIII. Identical in layout to the concluding figure of the previous subsection, Figure 62 and Figure 63 filter the approaches towards satisfaction of the gaps by limiting data points to the delivery of 5000 and 9000 packages or more, respectively, pursuant to the slight and strong improvement requirements.

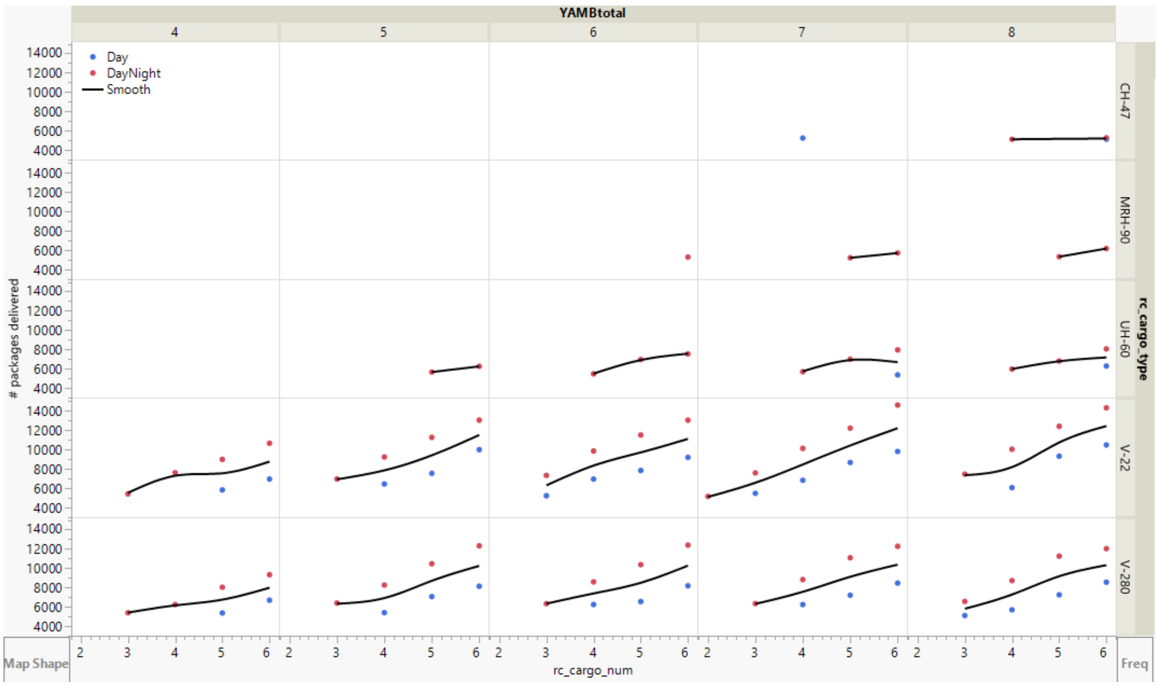


Figure 62: Visualization for slight improvement gap closure of 5000+ packages delivered (Y) versus number of vertical airlift assets (X), grouped by number of strategic airlift assets (X) and types of vertical airlift assets (Y); data points colored by time window for cargo operations

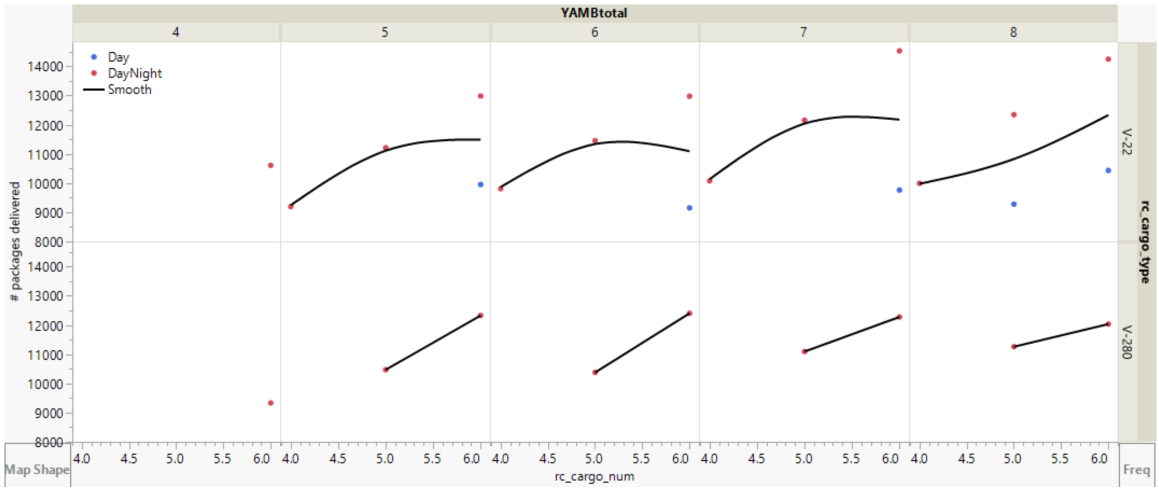


Figure 63: Visualization for strong improvement gap closure of 9000+ packages delivered (Y) versus number of vertical airlift assets (X), grouped by number of strategic airlift assets (X) and types of vertical airlift assets (Y); data points colored by time window for cargo operations

Before selecting approaches, it should be highlighted that across all presented figures in the analysis in Step VII, the different options for the time window for operations showed a significant performance difference. As can be expected for prolonged operations, the performance increases with extension into the night time.

Table 23 shows the final results of the methodology, presenting the enhanced performance alternatives that close the respective gaps and provide for an approach to be selected moving forward. The selection of candidates is principally based on the identification from different asset types that can close the gap with minimal deployment numbers, for each possible time window of cargo operation. This group of candidates has been cross-complemented with different flocks of assets of equal numbers for comparison. One can observe that the MRH-90 and UH-60 can close the sight improvement gap with different amounts of assets, although only the UH-60 can close it with day time operations.

The V-22 and V-280 can close both gaps in both operational modes with the same number of assets for each type, although the V-22 shows slightly better performance in each case comparison.

As for the actual selection of an approach, if the CBA would be performed with sole reliance on this process, the next step would be to perform either manual decision-making based on the provided table or proceed to a TOPSIS analysis. However, as the methodology is an augmentation of an overall process and based on low-fidelity modelling and a large caseload, the demonstration case study concludes with the identification of principal candidates that are subsequently presented to decision maker or subject matter experts.

Table 23: Enhanced Performance Alternatives from Approach Selection

	Total number of strategic airlift assets	Number of vertical airlift assets	Type of vertical airlift asset	Time window for cargo operations	Number of packages delivered	Population serviced with aid	Ratio of population serviced over total population in need	Number of delivery flights	Total delivery flight time [h]	Time of delivery of the 1st package	Time of delivery of 1,000 packages	Time of delivery of 2,000 packages	Time of delivery of 5,000 packages
Baseline	4	3	MRH-90	DayNight	2736	54720	15.2%	72	92	1d 3h	2d 24h	n/r	n/r
Slight Improvement			UH-60		3449	68980	19.7%	47	59	1d 8h	2d 14h	3d 10h	n/r
			V-22		5411	108220	30.9%	44	30	1d 2h	2d 7h	2d 19h	4d 15h
			V-280		5390	107800	30.8%	59	41	1d 8h	2d 1h	2d 18h	4d 19h
		5	V-22	Day	5818	116360	33.2%	48	33	1d 6h	2d 6h	2d 15h	4d 10h
			V-280		5370	107400	30.7%	59	40	1d 6h	2d 6h	2d 17h	4d 13h
	6	4	UH-60	DayNight	5476	109520	31.3%	74	92	0d 19h	1d 19h	2d 11h	4d 18h
			V-22		9811	196220	56.1%	79	52	0d 13h	1d 5h	1d 14h	2d 21h
			V-280		8593	171860	49.1%	94	62	0d 13h	1d 6h	1d 17h	3d 6h
		6	MRH-90		5282	105640	30.2%	139	179	0d 16h	2d 2h	2d 17h	4d 20h
	7		UH-60	Day	5372	107440	30.7%	73	94	0d 17h	1d 18h	2d 14h	4d 15h
Strong Improvement	4		V-22	DayNight	10610	212200	60.6%	85	57	1d 2h	1d 23h	2d 11h	3d 8h
			V-280		9336	186720	53.3%	103	69	0d 23h	2d 2h	2d 14h	3d 13h
	5		V-22	Day	9954	199080	56.9%	79	55	0d 13h	1d 10h	1d 16h	3d 6h
			V-280		8141	162820	46.5%	89	62	0d 12h	1d 10h	1d 17h	3d 9h

CHAPTER 9. POLICY IMPLICATIONS

Before concluding this thesis, this chapters addresses the policy implications of this work. In addition to the impact on making actual acquisition decisions for which this methodology has been developed, this research also reaches into the area of policy-making and shaping the framework and guidelines that define the defense acquisition system in the first place.

9.1 Impact of Scenario Variation Capability

The ability to take multiple scenarios and break them down into a shared framework allows to gain comparable data on all of them. Modelling and simulation is used in policy analysis and planning to search for underlying themes in relevant scenarios. Changing some variables while keeping others constant enables the identification of trends and developments based on a variety of factors, and provides for the identification of critical or major influences. Similarly to systems-of-systems analyses, the ability to expand the dimensionality to include multiple relevant scenarios enhances the quality and quantity of possible conclusions to be drawn.

In addition, the decomposition of scenarios and subsequent operations into a decision flow tree required for discrete event simulation also allows for the in-depth analysis of options and considerations along each step of the way. The application of the RFLP process with its hierarchically-organized elements and interfaces enables the tracking of metrics at any step of the process, not just in overall performance. As exemplified by the use of milestone metrics in the previous case study, one can observe each branch and node of an operation in order to find bottle necks, resiliencies, and negligible factors.

9.2 Hybrid Adoption with Human Operators

The methodology and general concepts outlined in this research can be adopted in a hybrid manner with human operators to become applicable to higher levels of scope. As a stand-alone approach, the process is subject to the limitations outlined in Section 5.1.4 that include the loss of meaningfulness of results when inherent parameters such as increased decision freedom of individuals is not reflected. However, when the critical decisions are made by human with the relevant expertise this limitation can be resolved.

The important factor that maintains the aforementioned limitation is the ability to quantify a parameter or decision, and subsequently provide alternative pathways as well as relationships and impact of these options. If parameters that can't be quantified needs to be included in order to maintain the representativeness of the overall process, it can be replaced by a human deciding on these specific factors. While it would impact the comprehensiveness of the process, it expands the applicability of the methodology with results being constrained to the human-designated space.

In order for such an adoption to be feasible, the operation of the analytical process should be transitioned to a dashboard- or interface-model. As the human element represents the actions of a relevant decision-maker, individuals acting in this role need to be either decision-makers themselves, or proxies with sufficient expertise to act in lieu of a decision-maker. The need to involve either group of people constrains the process as the time required for the execution of the analysis becomes a critical factor due to their availability.

Proper interfacing with the human operators can be accomplished through a dashboard or tabletop exercise where an easy transition from inputs to outputs of the process can be designed. Depending on the depth of integration, these environments can be designed to be actually operated by decision-makers themselves, or to simply provide the big picture layout over the analysis process to make the drawing of conclusions, and subsequent testing of reconsideration and rescoping decisions in a rapid fashion possible.

9.3 Future of Wargaming

In the area of wargaming, the methodology can enable a shift away from manual exercises and establish the inclusion of environments that can run different options instantly and produce results on demand for decision-makers to consider. The methodology is well-suited to be integrated in an environment that supports the execution of tabletop exercises or wargames. As discussed in the analysis in the previous chapter, an extensive number of cases is analyzed through the process. These cases consist of input and output vectors, and reflect scenario, materiel, and non-materiel variations that can populate a wargaming or tabletop environment more rapid and exhaustive that traditional approaches.

Taking into account the previously outlined policy implications, their combination with the methodology allows the creation of a gaming environment, replacing analogue elements with computational visualizations and the rapid creation of data reacting to any manual inputs. The interactive nature can speed up the progress of a game, increasing overall efficiency when involving time-constrained actors and freeing up resources for more in-depth analysis of non-covered elements.

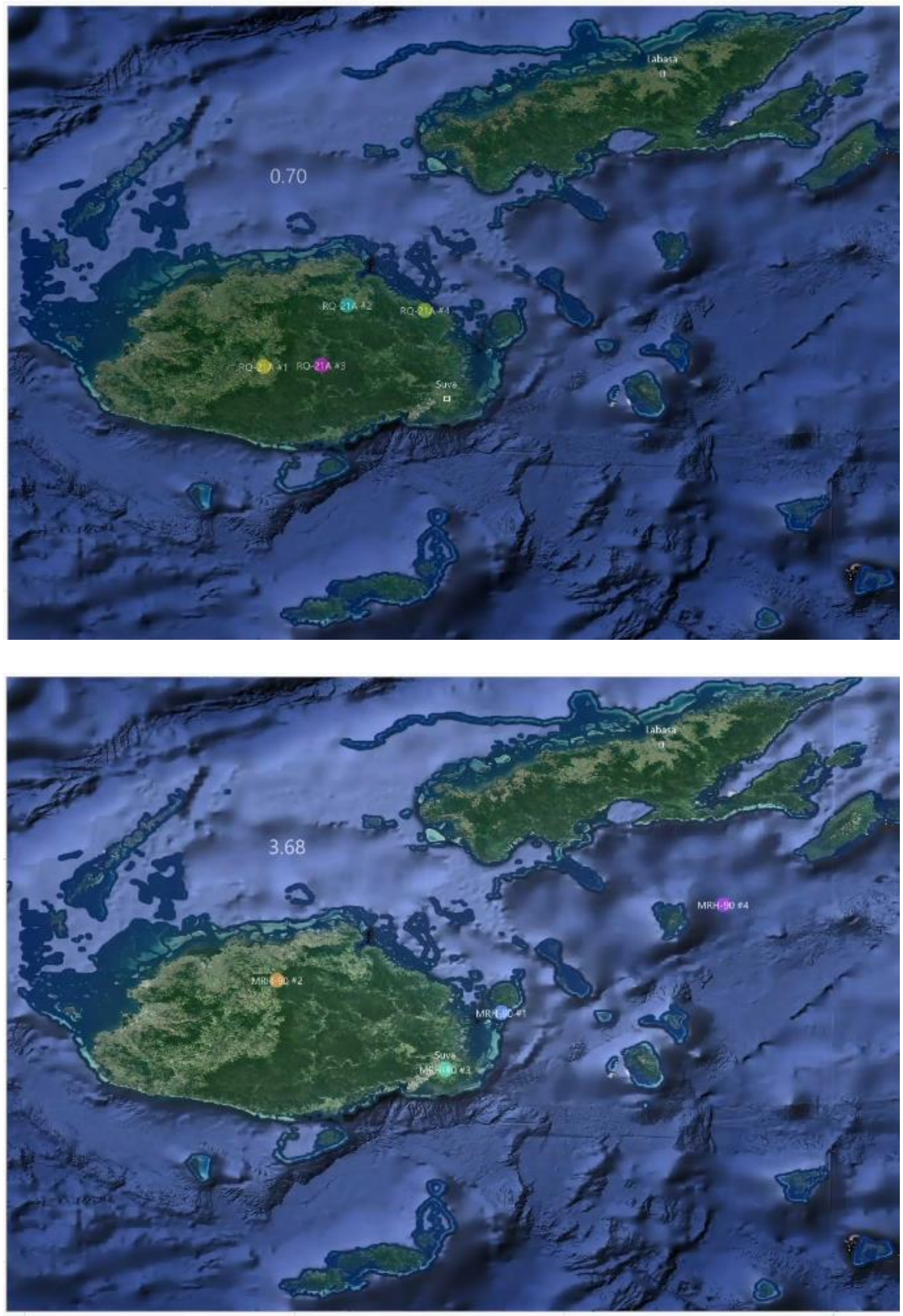


Figure 64: Status visualization of assets during case study operation at specific time steps; early stage with assessment assets (top), mid stage with vertical airlift assets (bottom)

Figure 64 shows a status visualization of the assets position during the case study operation at two specific time steps. The top element is taken at an early stage and shows assessment assets, while the bottom element is taken at a time when vertical airlift asset are out delivering aid. This visualization provides an example of the level of detailed information that can easily be extracted from a low-fidelity simulation and be utilized to showcase information beyond total metrics.

9.4 Application Outlook

Having discussed the policy implications of this methodology, we can revisit the original motivation presented in CHAPTER 1. A deterioration in the security environment through potent non-state actors, terrorist threat, rogue states, and renewed long-term strategic power competition challenges the status quo and the maintenance of unchanged defense objectives. In this section, the possible utilization of this methodology to aid in addressing those challenges is discussed through the presentation of brief potential application cases.

For potent non-state actors, an often debated case is their role in the cyber domain. Capabilities are available to such actors that are sufficient to challenge the ability of state authorities to upkeep a secure environment. This does not only impact the ability of armed forces to maintain the necessary resiliency to perform their missions, but can impact the every day life of societies directly. Examples for both cases are the possible stealing and exploitation of personal data that lets adversaries draw conclusions about military readiness and planning, or the vulnerability of digital management systems for critical infrastructure such as the energy grid. Thus, it becomes necessary to connect those arising new challenges to the existing and procureable capabilities to find the best way to address them. This methodology can include the relevant scenario parameters of unknown adversaries with varying capabilities as scenario options and augment the materiel and non-materiel parameters with additional attributes towards their vulnerability and responsiveness for cyber impacts. Subsequently, the simulation would game out various cases allowing the identification of critical technology reliance to be secured and threshold identification of adversarial capabilities that cannot be tolerated.

When looking at the terrorist threat, we can envision similar examples of instant of challenges demanding an immediate response as has occurred in the past. A prominent past example is the deployment into Iraq and the emergence of improvised explosive devices for which the widely unused Humvee vehicles were not equipped to withstand. In that case, a rapid development process of a new kind of vehicle had to be initiated. Such sitatuations where the creativity of terrorist is employed to challenge existing military capabilities in a asymetric manner are likely to reoccur. For example, a peacekeeping operation in an area with a active terrorist threat can be challenged by the hostiles gaining access to chemical weapons. This would be a game changing development putting imminent requirements on the mission to address that threat and adjust or enhance the equipment. The methodology process can be used to combine the comprehensive assessment of the available landscape with the requirement and scenario options to point to solutions. It can furthermore identify the failure of being to address the challenge in a conventional procurement and development with its inherent time constraints, and raise the demand for a solution outside of the regular process.

The challenges from rogue states are characterized by their inability so fundamentally challenge the persistence of the homeland society itself, but rather their destabilizing effects on regions, the imminent threat they pose to allies, as well as their reach to forces stationed abroad. A potential example to consider the interconnection of available means and ways would be the closure of the Strait of Hormuz by Iran. When weighing whether to force an opening of the strait against a (potentially-now but in the scenario) presumed-then nuclear power, alternative options can be explored through scenario variation in combination with possible assets to be utilized. In this context, the threat situation, preparedness of forces, suitability of available assets can be simulated considering alternative ways of air and land transport replacing the maritime corridor.

When dealing with long-term, strategic power competition with adversaries such as China and Russia, the methodology can unfold its potential to consider a wide range of technologies and their impact on the balance of power and active and potential battle fields. For example adversarial and national advances in military applications for autonomy, robotics, artificial intelligence, hypersonics, and nanotechnology can be considered under various scenarios and vis-à-vis existing and to-be-procured assets in various domains. This allows the exploration of how technologies can unfold and what security implications can be derived from it. Given the uncertainty on development status and their impact, the ability to consider and game out a high number of options in a large number of dimensions allows for broad consideration and exploration of issues. Another potential application of the methodology is the consideration of changed rules of warfare if international law or treaties governing warfare erode, i.e. when they are not properly followed or outright suspended. Especially a reversion of the long-standing ban of certain kind of weapons can have drastic effects on existing capabilities that would need to be compensated in order to uphold or strengthen posture.

In conclusion, this methodology has broad application potential in the military domain beyond the developed-for acquisition process. The structure to consider means and ways in a conjoint manner supports the big picture analysis of how to address the changing security environment. The modularity of the methodology further allows to consider the various challenges outlined above in conjunction with each other to reflect the reality that the different threats need to be addressed within the overall unified military force structure.

CHAPTER 10. CONCLUSIONS

This chapter concludes the research performed for this doctoral thesis. Before closing with future work and general research conclusions, it first retraces the logical steps of the research performed, summarizes the methodology.

The thesis started with an analysis of the changing future operating environment and how its consequences are currently addressed, and what changes need to be made to the state of the art to cope with new realities. Based on initial general observations and to establish a scope for the contributions this thesis is providing, a principal gap (gap 1) in the acquisition process has been identified and connected to a research objective that guides this work.

Table 24 guides through the initial process of literature surveys and corresponding observation that allowed the formalization of gaps that this research aimed to close.

Once the gaps and possible solution approaches were identified, the research could be structured into research questions to be answered and corresponding hypotheses to be tested. In the document, this process occurred immediately after the identification of the respective gap. Table 25 guides the reader through the structuring process that enabled validation of the developed elements and the creation of the methodology.

Table 24: Summary of Observations & Gaps, and their location in the document

Label	Observation/Gap	Section
Gap 1	**The existing capabilities to parameterize the ways in addition to the means are insufficient to conduct holistic studies to comprehensively explore the design space.**	**1.4**
Obs. 1.1	The changing operating environment puts more diverse demands on existing and future assets.	1.1
Obs. 1.2	The changes in operational behavior in conjunction with the alternation of capabilities are crucial to analyze the effectiveness of new assets and technologies.	1.2
Obs. 1.3	The Department of Defense provides scope to evolve the defense acquisition process towards a more computationally-enhanced, capability-based and result-oriented process.	1.3
Gap 2	**The existing functional analysis process demands a standardized and comparable approach but does not inherently manage the diversity of operational requirements or scenarios investigated conjointly.**	**2.3**
Obs. 2.1.1	The DAP does not include the consideration of different operational approaches or non-materiel dimensions in general. It operates based on an already-developed ICD and already-made MDD, thus the decision to pursue materiel solutions has already been made. As the traditional AoA happens at this step, it is constrained to materiel alternatives.	2.1.1
Obs. 2.1.2	The JCIDS includes the critical component of considering means and ways within the Capabilities Based Assessment as it considers capabilities broadly with materiel and non-materiel dimensions.	2.1.2

Table 24: Summary of Observations & Gaps, and their location in the document (continued)

Gap 3	**The operational design space needs to be properly constrained to provide a meaningful and credible basis for subsequent exploration.**	**3.4**
Obs. 2.2	The Functional Area Analysis and Functional Needs Analysis translate high-level strategic information and conclusions into the acquisition process, while the Functional Solution Analysis introduces alternative non-materiel and materiel approaches and assesses them in relation to the preceding information.	2.2
Obs 3.1	The DOTmLPF-P analysis produces various possible approaches towards addressing identified capability gaps in the respective dimensions, but lacks sufficient interdimensional comparisons and subsequent comprehensive interconnected feasibility and efficiency assessments.	3.1
Gap 4	**Low-fidelity modelling and simulation needs to be employed to allow the consideration of alternative scenarios and mission variations in a timely manner.**	**4.4**
Obs. 4.1.1	The traditional procurement process does not utilize the opportunities of design space exploration to its full extent. The currently performed assessments of alternatives show insufficient structure and relative weight to serve their crucial role in the acquisition process, preventing the proper analysis of asset effectiveness.	4.1
Obs. 4.1.2	The multi-dimensionality caused by the breadth of independent variables in the process demands the utilization of computational means to enable assessments with reasonable time and resources.	4.1
Obs. 4.2.1	The formal guidance for the CBA still heavily relies on manual work by subject-matter experts, and does not yet require or formalize the use of computational models and simulations.	4.2
Obs. 4.2.2	The separation of subject-matter input and creation of results could enhance the objectivity of the CBA process.	4.2

Table 24: Summary of Observations & Gaps, and their location in the document (continued)

Obs. 4.3.1	The modelling and simulation of military operations is currently employed as supplementary element for purposes of planning and gaming.	4.3
Obs. 4.3.2	Current modelling and simulation capabilities are predominantly high-fidelity and do not allow the simulation of a large set of missions in a timely manner.	4.3

Table 25: Summary of Research Steps, and their location in the document

Label	**Objective, Questions, Hypotheses/Conjecture**	**Section**
Objective	**Develop a methodology that considers diverse operational requirements and operational ways in a parameterized fashion within a system-of-system analysis in the early stages of the acquisition process.**	1.5
Question 1	**How can elements of an operational scenario be standardized to enable dynamic exploration of the design space?**	2.3
Hypothesis 1	If the RFLP process is utilized as the adjusted elementary definition approach and alternative scenarios are decomposed into elements and interfaced, then a standardized and modular approach can be produced.	2.5
Question 2	**How can the feasible operational approaches, including and beyond the current approach, be identified?**	**3.4**
Hypothesis 2	If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations from further consideration.	3.7

Table 25: Summary of Research Steps, and their location in the document (continued)

Question 3	**How should the modelling of operational scenarios be structured such that elementary interfaces and behavior are supported?**	4.4
Question 3.1	Which modelling type is compatible with the decomposition and recomposition approach applied to operational scenarios?	4.5
Conjecture 3	If discrete event simulations are utilized to model an operational scenario as a whole, then the structure and characteristics of decomposed operational scenarios is properly represented.	4.6
Overall Hypothesis	**If the operational design space is formalized considering interdependencies and constraints, and operational scenarios defined on an elementary level, then feasible alternative concepts of operations can be rapidly composed, infused into low-fidelity modelling and simulation and subsequently analyzed with various approaches.**	5.1
Equivalency Conjecture	The methodology executes the steps of a Capabilities Based Assessment (CBA), starting with the correct inputs and yielding the same outputs. Given the success of the separate experiments validating the newly-infused or adapted elements of the process, a successful execution of the methodology enables a CBA considering the comprehensive design space through low-fidelity modelling and simulation. Thus, it satisfies the overall research objective.	5.1

In order to tackle the research objective, and guided by the logical approach towards the identified gaps, a methodology has been devised that represents the Capabilities Based Assessment (CBA) and augments it in order to incorporate a formalized approach for multi-scenario consideration, and structured approach identification and deconflicton. It leverages the advantages of low-fidelity modelling and simulation through the employment of discrete event models that are in line with the infused scenario decomposition.

The methodology provides for a three-part process that reflect the different functional analyses within the CBA. Figure 65 shows a flowchart of the entire methodology including their division into the parts and the corresponding steps. Based on a mission statement that initiates the process, the methodology exercises through the various steps in order to define the problem with its various aspects such as targets, metrics, scenarios, and status quo performance, before characterizing the gaps and analyzing solution approaches.

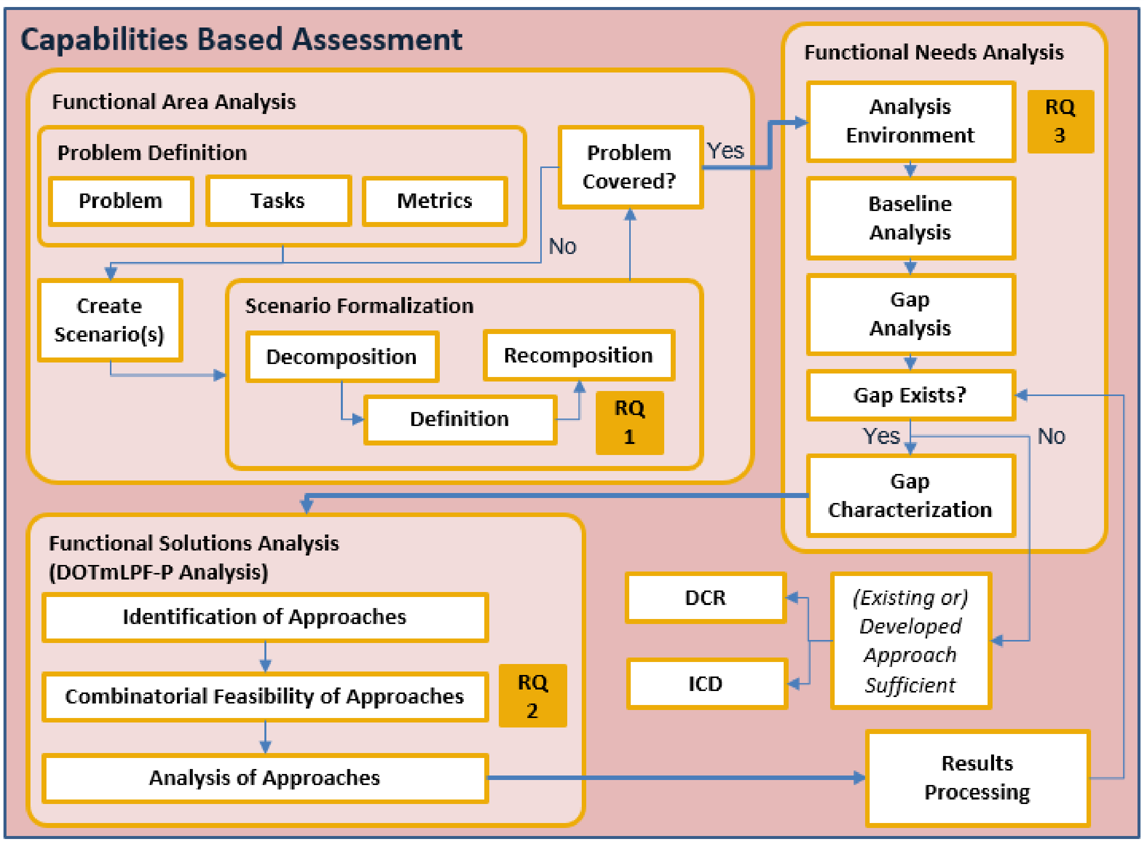


Figure 65: Methodology Flowchart within the Capabilities Based Assessment

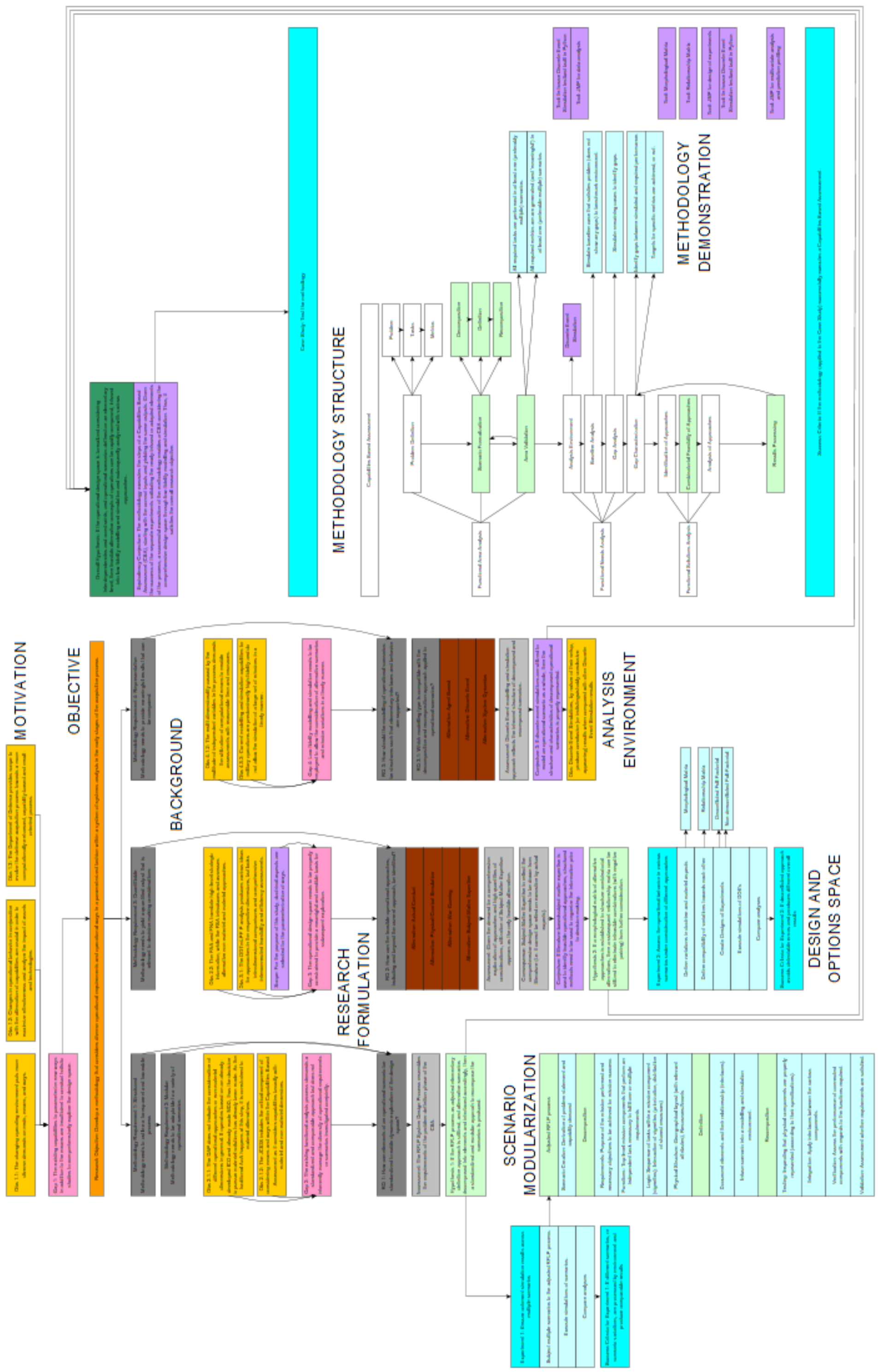
Core element of the development of the methodology is the introduction of an adjusted RFLP approach that allows the decomposition of operational scenarios in a standardized fashion. Scenarios are taken from sources of varying structure, and subjected to a process that describes them in its elements and connections among each other. The multi-level hierarchical approach introduces the comparability of scenarios of different types that are required to perform a CBA with the necessary scope.

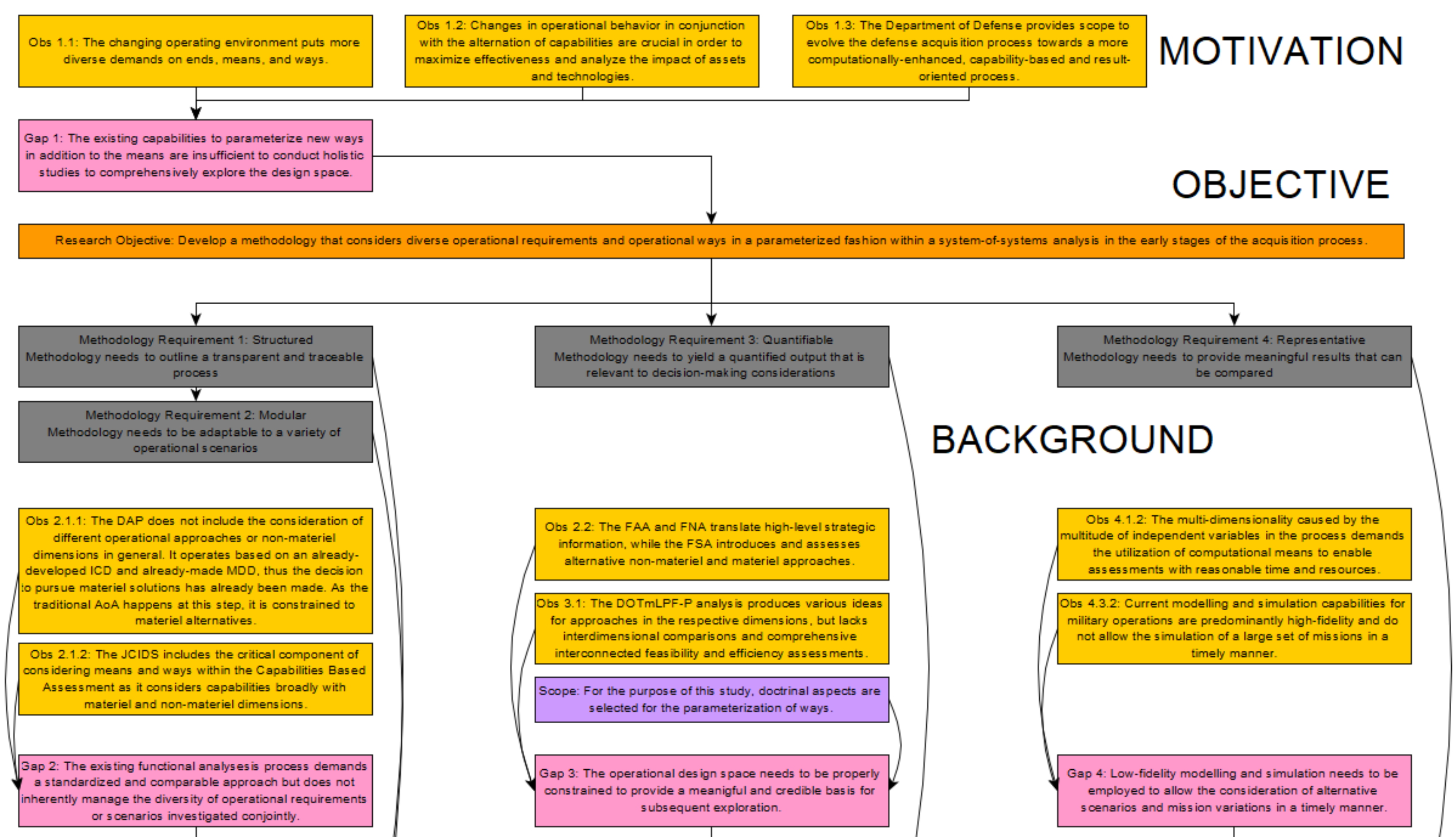
The newly developed elements of the methodology that expand the traditional CBA process have been thoroughly assessed and experimentally validated, before the methodology was applied to a demonstration case study that showcased its process in the entirety. As result, an initial request made with regards to the identification of better performing vertical airlift assets could be translated through the methodology into recommendations of approaches that satisfy the required demand.

In the future, this methodology can be employed not only for the scope presented in the demonstration with a focus on materiel and doctrinal approaches but expand into additional or all dimensions of the DOTmLPF-P analysis. Similarly, the materiel aspects can be further refined to include sub-iterations on the assessment of different technology investments expanding the horizon of alternatives in a structured manner. In addition, an additional overarching iteration dealing with the analysis of ends in addition to means and ways can be integrated. If the outcome of the process that considers all available options does not yield satisfying results, the question arises of whether the laid-out goals that derive from the desired ends are achievable in the first place. Given the adaptability of the methodology towards more complex problems, it is intended to enhance CBA conducted moving forward. In conjuction, in-depth further development can be performed on the topic of employed modelling types and simulations. While the discrete event approach has been identified as most suitable for the large case load and exploration goals, the utilization of hybrid modelling types that combine advanced elements from other methods without requiring excessive computational resources appears promising. Finally, while this methodology is developed for the defense acquisition process and focused on the needs for military operations, leveraging the capabilities of low-fidelity modelling and simulation is not limited to this domain and can be expanded into broader applications.

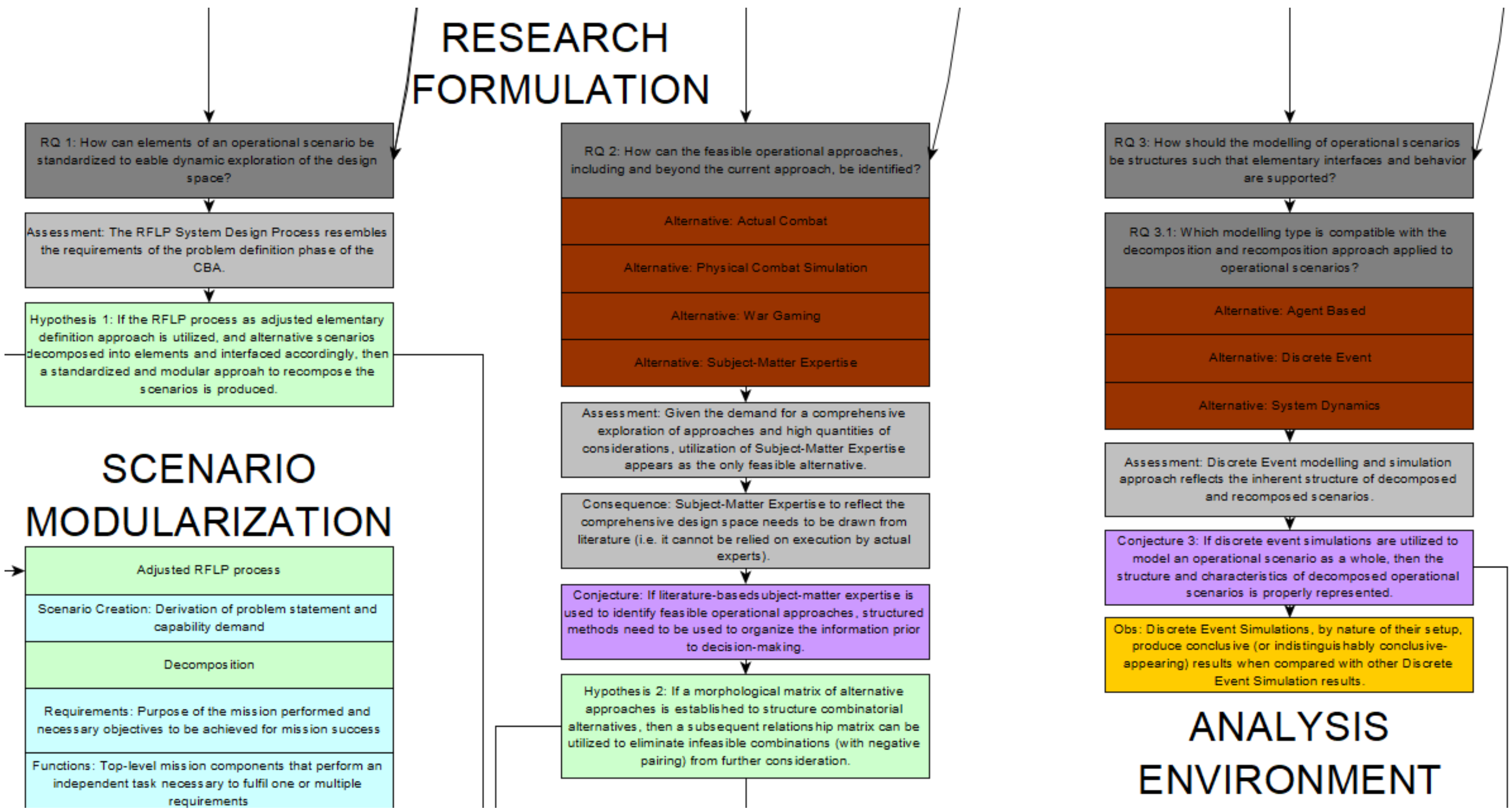
In conclusion, this thesis contributed a standardized way for scenarios being transitioned from architectures into modelling and simulation and affects an increased understanding of scenario structure and composition for comparisons and inter-scenario considerations. Leveraging low-fidelity modelling for rapid exploration of high number of alternatives with combined means and ways provides for an optimized simulation performance in the early stages of the acquisition process and enables the systematic and comprehensive consideration of the design and options space available. In conjuction with that, it provides for a pathway to address the operational complexities and improves the quality of quantification of materiel and non-materiel dimensions by ensuring the consideration of interconnectivity and interdependencies in different operational approaches. Overall, the methodology provides an integrated process to parameterize ways, define the operational design space and combine it with diverse operational requirements for subsequent analysis.

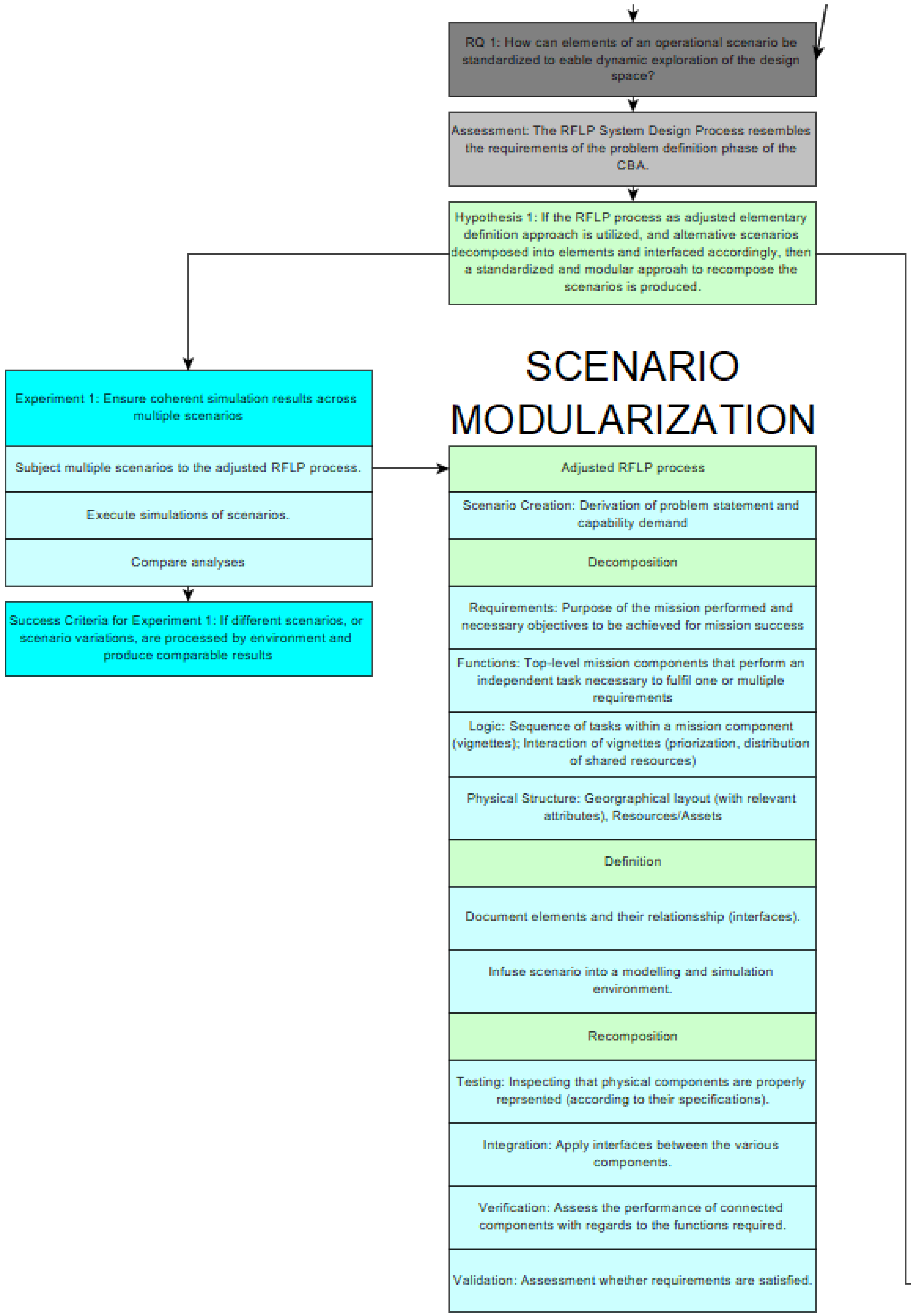
APPENDIX A. COMPREHENSIVE LOGICAL DIAGRAM OF THE DISSERTATION

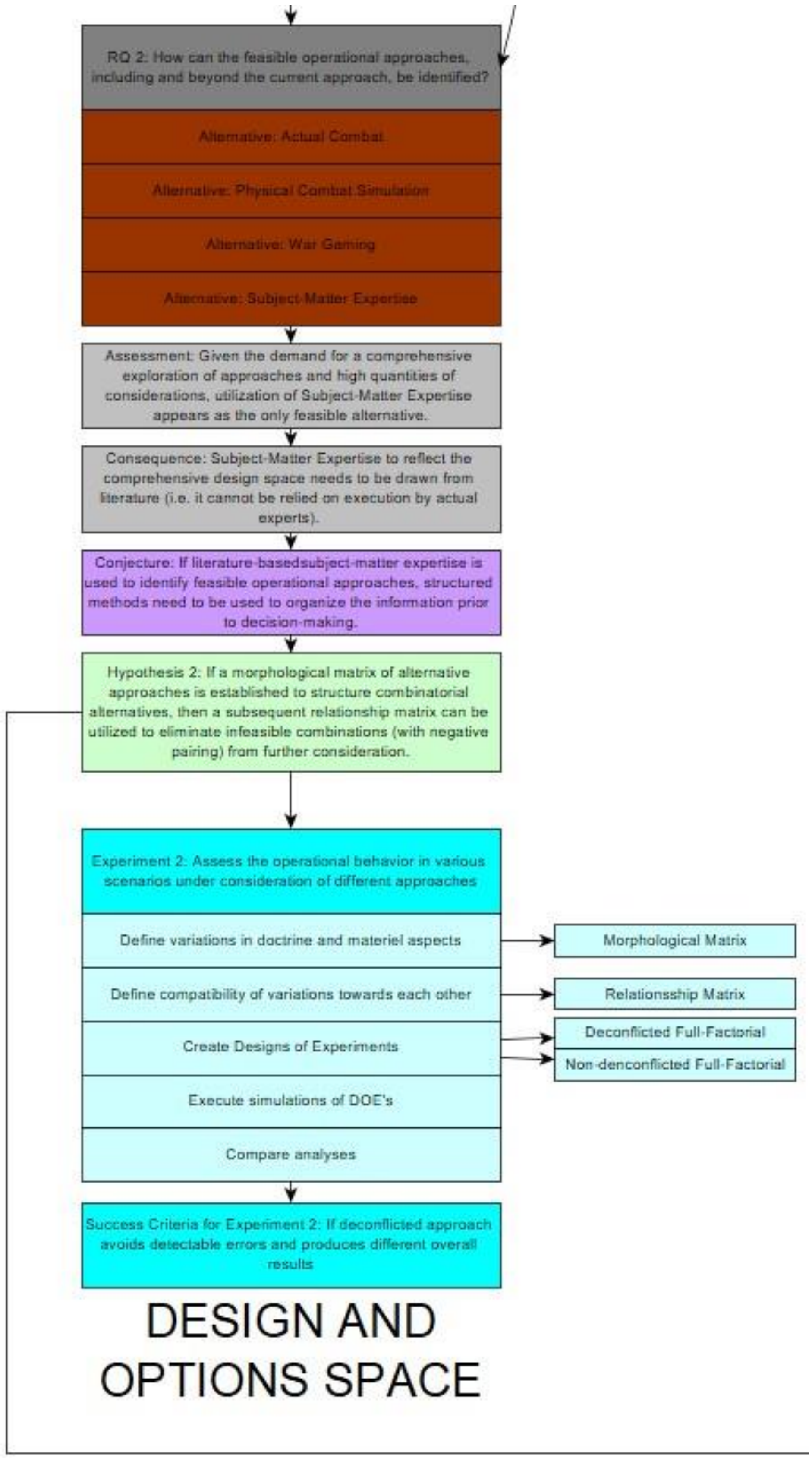


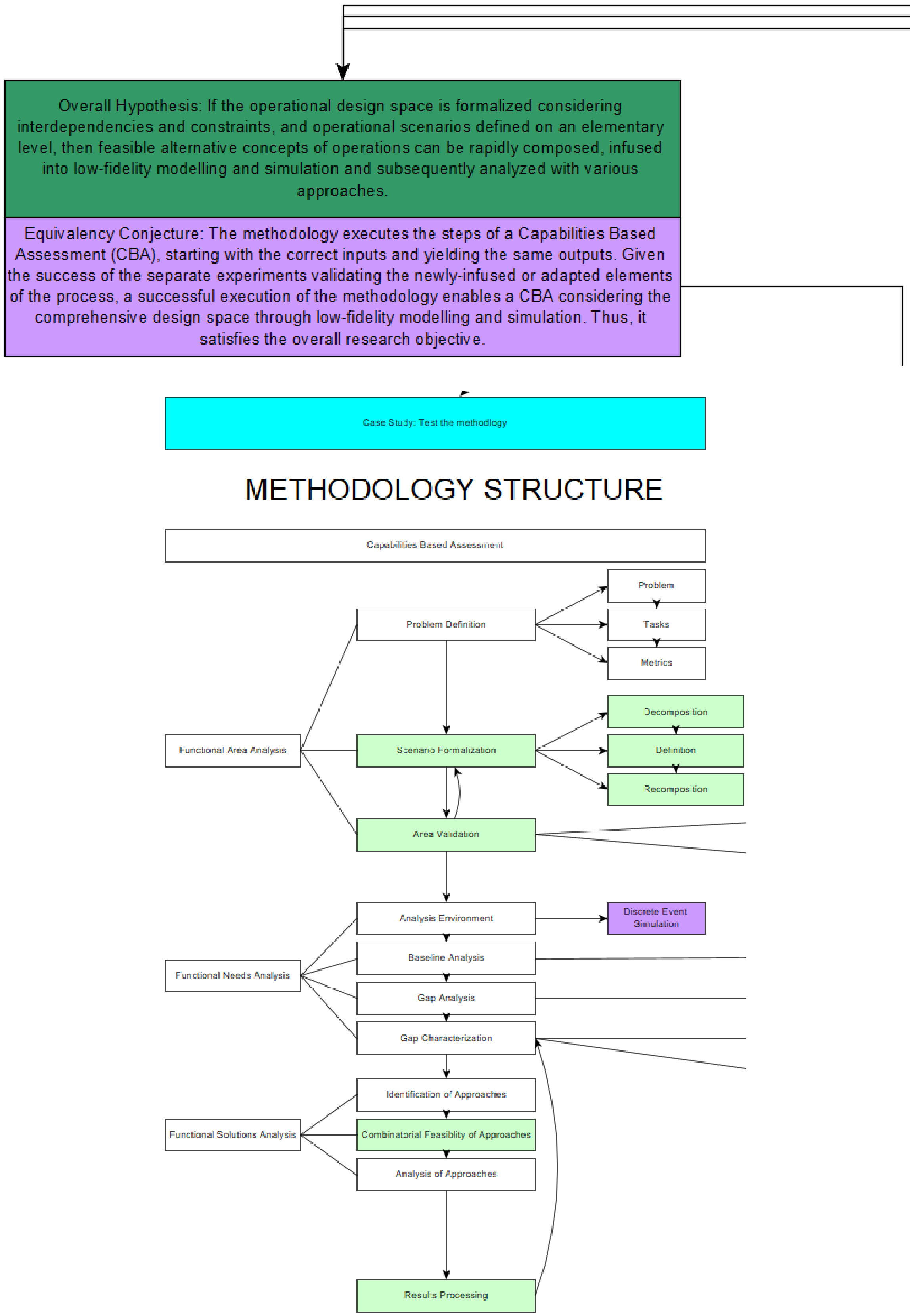


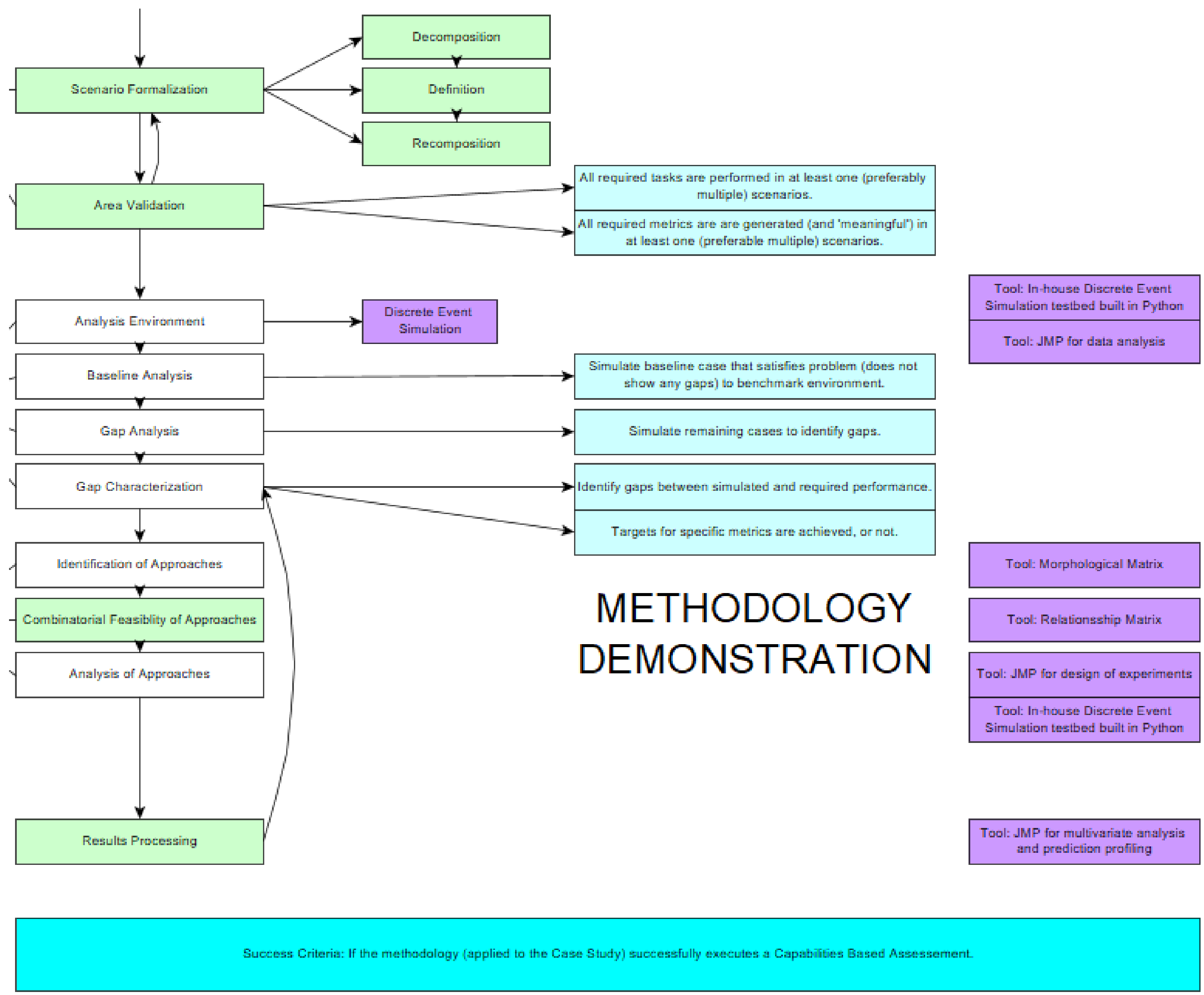
MOTIVATION
Obs 1.1: The changing operating environment puts more diverse demands on ends, means, and ways.
Obs 1.2: Changes in operational behavior in conjunction with the alternation of capabilities are crucial in order to maximize effectiveness and analyze the impact of assets and technologies.
Obs 1.3: The Department of Defense provides scope to evolve the defense acquisition process towards a more computationally-enhanced, capability-based and result-oriented process.
Gap 1: The existing capabilities to parameterize new ways in addition to the means are insufficient to conduct holistic studies to comprehensively explore the design space.
OBJECTIVE
Research Objective: Develop a methodology that considers diverse operational requirements and operational ways in a parameterized fashion within a system-of-systems analysis in the early stages of the acquisition process.
Methodology Requirement 1: Structured
Methodology needs to outline a transparent and traceable process
Methodology Requirement 2: Modular
Methodology needs to be adaptable to a variety of operational scenarios
Methodology Requirement 3: Quantifiable
Methodology needs to yield a quantified output that is relevant to decision-making considerations
Methodology Requirement 4: Representative
Methodology needs to provide meaningful results that can be compared
BACKGROUND
Obs 2.1.1: The DAP does not include the consideration of different operational approaches or non-materiel dimensions in general. It operates based on an already-developed ICD and already-made MDD, thus the decision to pursue materiel solutions has already been made. As the traditional AoA happens at this step, it is constrained to materiel alternatives.
Obs 2.1.2: The JCIDS includes the critical component of considering means and ways within the Capabilities Based Assessment as it considers capabilities broadly with materiel and non-materiel dimensions.
Gap 2: The existing functional analysesis process demands a standardized and comparable approach but does not inherently manage the diversity of operational requirements or scenarios investigated conjointly.
Obs 2.2: The FAA and FNA translate high-level strategic information, while the FSA introduces and assesses alternative non-materiel and materiel approaches.
Obs 3.1: The DOTmLPF-P analysis produces various ideas for approaches in the respective dimensions, but lacks interdimensional comparisons and comprehensive interconnected feasibility and efficiency assessments.
Scope: For the purpose of this study, doctrinal aspects are selected for the parameterization of ways.
Gap 3: The operational design space needs to be properly constrained to provide a meaningful and credible basis for subsequent exploration.
Obs 4.1.2: The multi-dimensionality caused by the multitude of independent variables in the process demands the utilization of computational means to enable assessments with reasonable time and resources.
Obs 4.3.2: Current modelling and simulation capabilities for military operations are predominantly high-fidelity and do not allow the simulation of a large set of missions in a timely manner.
Gap 4: Low-fidelity modelling and simulation needs to be employed to allow the consideration of alternative scenarios and mission variations in a timely manner.


RESEARCH FORMULATION
RQ 1: How can elements of an operational scenario be standardized to eable dynamic exploration of the design space?
Assessment: The RFLP System Design Process resembles the requirements of the problem definition phase of the CBA.
Hypothesis 1: If the RFLP process as adjusted elementary definition approach is utilized, and alternative scenarios decomposed into elements and interfaced accordingly, then a standardized and modular approah to recompose the scenarios is produced.
SCENARIO MODULARIZATION
Adjusted RFLP process
Scenario Creation: Derivation of problem statement and capability demand
Decomposition
Requirements: Purpose of the mission performed and necessary objectives to be achieved for mission success
Functions: Top-level mission components that perform an independent task necessary to fulfil one or multiple requirements
RQ 2: How can the feasible operational approaches, including and beyond the current approach, be identified?
Alternative: Actual Combat
Alternative: Physical Combat Simulation
Alternative: War Gaming
Alternative: Subject-Matter Expertise
Assessment: Given the demand for a comprehensive exploration of approaches and high quantities of considerations, utilization of Subject-Matter Expertise appears as the only feasible alternative.
Consequence: Subject-Matter Expertise to reflect the comprehensive design space needs to be drawn from literature (i.e. it cannot be relied on execution by actual experts).
Conjecture: If literature-basedsubject-matter expertise is used to identify feasible operational approaches, structured methods need to be used to organize the information prior to decision-making.
Hypothesis 2: If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations (with negative pairing) from further consideration.
RQ 3: How should the modelling of operational scenarios be structures such that elementary interfaces and behavior are supported?
RQ 3.1: Which modelling type is compatible with the decomposition and recomposition approach applied to operational scenarios?
Alternative: Agent Based
Alternative: Discrete Event
Alternative: System Dynamics
Assessment: Discrete Event modelling and simulation approach reflects the inherent structure of decomposed and recomposed scenarios.
Conjecture 3: If discrete event simulations are utilized to model an operational scenario as a whole, then the structure and characteristics of decomposed operational scenarios is properly represented.
Obs: Discrete Event Simulations, by nature of their setup, produce conclusive (or indistinguishably conclusive-appearing) results when compared with other Discrete Event Simulation results.
ANALYSIS ENVIRONMENT


RQ 1: How can elements of an operational scenario be standardized to eable dynamic exploration of the design space?
Assessment: The RFLP System Design Process resembles the requirements of the problem definition phase of the CBA.
Hypothesis 1: If the RFLP process as adjusted elementary definition approach is utilized, and alternative scenarios decomposed into elements and interfaced accordingly, then a standardized and modular approah to recompose the scenarios is produced.
SCENARIO MODULARIZATION
Experiment 1: Ensure coherent simulation results across multiple scenarios
Subject multiple scenarios to the adjusted RFLP process.
Execute simulations of scenarios.
Compare analyses
Success Criteria for Experiment 1: If different scenarios, or scenario variations, are processed by environment and produce comparable results
Adjusted RFLP process
Scenario Creation: Derivation of problem statement and capability demand
Decomposition
Requirements: Purpose of the mission performed and necessary objectives to be achieved for mission success
Functions: Top-level mission components that perform an independent task necessary to fulfil one or multiple requirements
Logic: Sequence of tasks within a mission component (vignettes); Interaction of vignettes (priorization, distribution of shared resources)
Physical Structure: Georgraphical layout (with relevant attributes), Resources/Assets
Definition
Document elements and their relationsship (interfaces).
Infuse scenario into a modelling and simulation environment.
Recomposition
Testing: Inspecting that physical components are properly reprsented (according to their specifications).
Integration: Apply interfaces between the various components.
Verification: Assess the performance of connected components with regards to the functions required.
Validation: Assessment whether requirements are satisfied.


RQ 2: How can the feasible operational approaches, including and beyond the current approach, be identified?
Alternative: Actual Combat
Alternative: Physical Combat Simulation
Alternative: War Gaming
Alternative: Subject-Matter Expertise
Assessment: Given the demand for a comprehensive exploration of approaches and high quantities of considerations, utilization of Subject-Matter Expertise appears as the only feasible alternative.
Consequence: Subject-Matter Expertise to reflect the comprehensive design space needs to be drawn from literature (i.e. it cannot be relied on execution by actual experts).
Conjecture: If literature-basedsubject-matter expertise is used to identify feasible operational approaches, structured methods need to be used to organize the information prior to decision-making.
Hypothesis 2: If a morphological matrix of alternative approaches is established to structure combinatorial alternatives, then a subsequent relationship matrix can be utilized to eliminate infeasible combinations (with negative pairing) from further consideration.
Experiment 2: Assess the operational behavior in various scenarios under consideration of different approaches
Define variations in doctrine and materiel aspects
Morphological Matrix
Define compatibility of variations towards each other
Relationsship Matrix
Create Designs of Experiments
Deconflicted Full-Factorial
Non-denconflicted Full-Factorial
Execute simulations of DOE's
Compare analyses
Success Criteria for Experiment 2: If deconflicted approach avoids detectable errors and produces different overall results
DESIGN AND OPTIONS SPACE


Overall Hypothesis: If the operational design space is formalized considering interdependencies and constraints, and operational scenarios defined on an elementary level, then feasible alternative concepts of operations can be rapidly composed, infused into low-fidelity modelling and simulation and subsequently analyzed with various approaches.
Equivalency Conjecture: The methodology executes the steps of a Capabilities Based Assessment (CBA), starting with the correct inputs and yielding the same outputs. Given the success of the separate experiments validating the newly-infused or adapted elements of the process, a successful execution of the methodology enables a CBA considering the comprehensive design space through low-fidelity modelling and simulation. Thus, it satisfies the overall research objective.
Case Study: Test the methodlogy
METHODOLOGY STRUCTURE
Capabilities Based Assessment
Problem
Problem Definition
Tasks
Metrics
Decomposition
Functional Area Analysis
Scenario Formalization
Definition
Recomposition
Area Validation
Analysis Environment
Discrete Event Simulation
Baseline Analysis
Functional Needs Analysis
Gap Analysis
Gap Characterization
Identification of Approaches
Functional Solutions Analysis
Combinatorial Feasiblity of Approaches
Analysis of Approaches
Results Processing



Scenario Formalization
Decomposition
Definition
Recomposition
Area Validation
All required tasks are performed in at least one (preferably multiple) scenarios.
All required metrics are are generated (and 'meaningful') in at least one (preferable multiple) scenarios.
Analysis Environment
Discrete Event Simulation
Tool: In-house Discrete Event Simulation testbed built in Python
Tool: JMP for data analysis
Baseline Analysis
Simulate baseline case that satisfies problem (does not show any gaps) to benchmark environment.
Gap Analysis
Simulate remaining cases to identify gaps.
Gap Characterization
Identify gaps between simulated and required performance.
Targets for specific metrics are achieved, or not.
Identification of Approaches
Tool: Morphological Matrix
Combinatorial Feasiblity of Approaches
Tool: Relationsship Matrix
Analysis of Approaches
Tool: JMP for design of experiments
Tool: In-house Discrete Event Simulation testbed built in Python
METHODOLOGY DEMONSTRATION
Results Processing
Tool: JMP for multivariate analysis and prediction profiling
Success Criteria: If the methodology (applied to the Case Study) successfully executes a Capabilities Based Assessement.

APPENDIX B. FULL RFLP DECOMPOSITION OF THE CASE STUDIES

B.1 Scenario

Ability to intervene and provide humanitarian aid

B.2 Requirements

Aiding the distressed population

B.3 Functions

Operations at the regional home base,

Deployment into the theater,

Operations at the local base (including its establishment),

Assessment of the theater, and

Performing deliveries within the theater

B.4 Logic

B.4.1 Home Base Operations

Removal of Vertical Airlift Asset from Waiting Position (items stored on base)
Removal of Assessment Asset from Waiting Position (items stored on base)
Removal of Aid from Storage

Crew Discharge
Maintenance
Fueling
Cargo Loading
Crew Takeover

Departure of Strategic Airlift Asset (taxing prior to takeoff)
Arrival of Strategic Airlift Asset (taxing after landing)

Departure of Self-Deployable Vertical Airlift Asset (taxing prior to takeoff)

B.4.2 Deployment

Takeoff
Flight (can be subdivided into flight phases)
Landing

B.4.3 Forward Operating Base Operations

Arrival of Strategic Airlift Asset (taxing after landing)
Cargo Unloading
Refueling
Departure of Strategic Airlift Asset (taxing prior to takeoff)

Storage of Aid Received (through strategic airlift)
Storage of Fuel Received (through strategic airlift)

Arrival of Self-Deployable Vertical Airlift Asset (taxing after landing)

Setup of Vertical Airlift Asset
Setup of Vertical Airlift Ground Infrastructure
Setup of Assessment Asset
Setup of Assessment Ground Infrastructure

Initialization of Vertical Airlift Asset
Initialization of Assessment Asset

Vertical Airlift Asset Crew Discharge
Vertical Airlift Asset Maintenance
Vertical Airlift Asset Fueling
Vertical Airlift Asset Cargo Loading
Vertical Airlift Asset Crew Takeover

Assessment Asset Maintenance
Assessment Asset Fueling

Assessment Asset Crew Discharge
Assessment Asset Crew Takeover

Operations Dispatch (scheduling and assignment of flights)

Departure of Vertical Airlift Asset (taxing prior to takeoff)
Departure of Assessment Asset (taxing prior to takeoff)
Arrival of Vertical Airlift Asset (taxing after landing)
Arrival of Assessment Asset (taxing after landing)

Extraction of Intelligence from Assessment Assets

B.4.4 Theater Assessment

Takeoff from Base
Flight to Location
Location Assessment
Flight to Base
Landing at Base

B.4.5 Theater Logistics

Takeoff from Base
Flight to Location
Landing at Location
Unloading at Location
Takeoff from Location
Flight to Base
Landing at Base

B.5 Physical

B.5.1 Geography

Disaster Type
Disaster Extent (e.g. storm path)
Disaster Intensity (e.g. storm destruction radii)

Home Base Location (specified by latitude, longitude)

Forward Operating Base Location (specified by latitude, longitude)

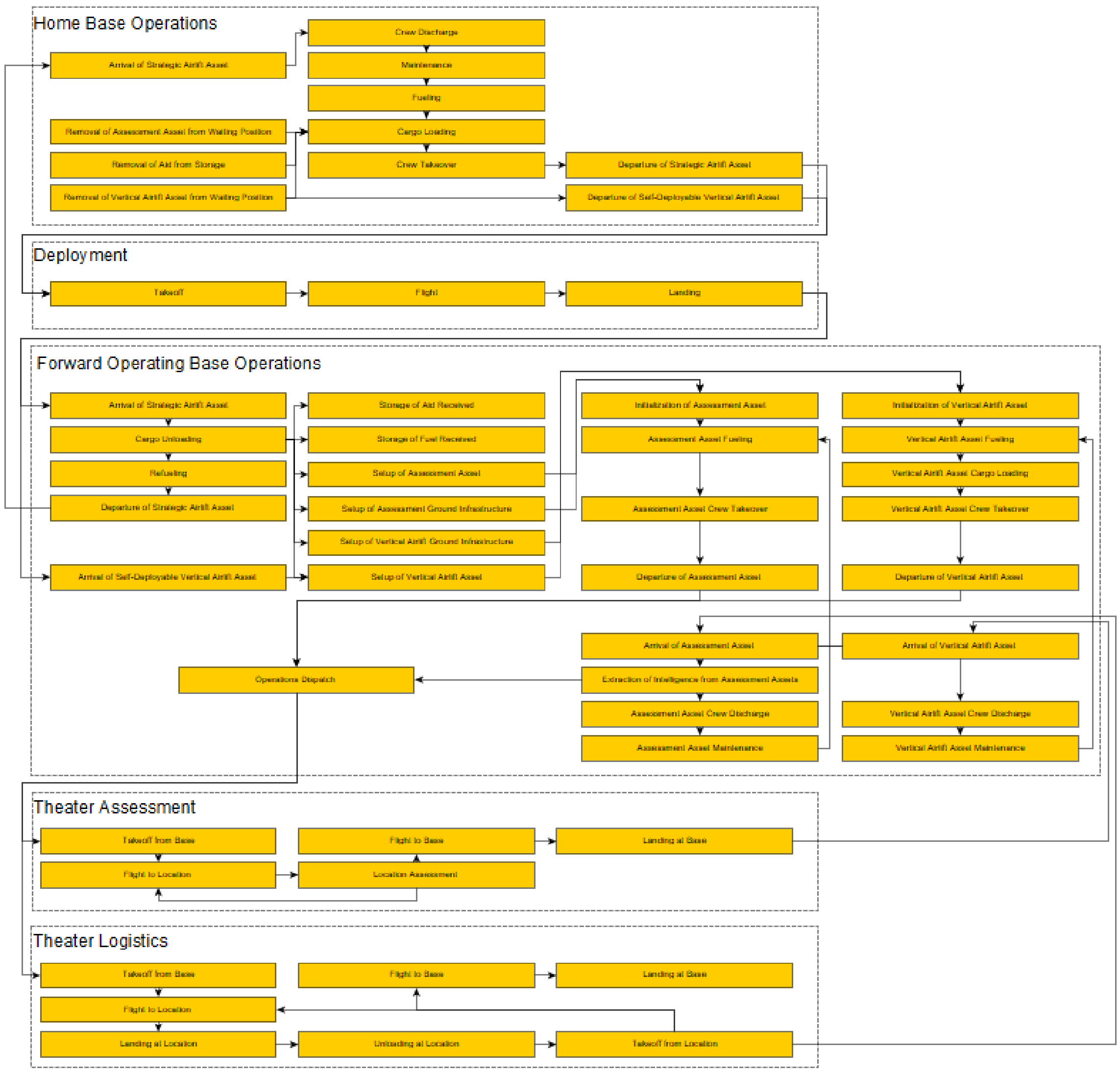
Theater Locations (specified by latitude, longitude, population)

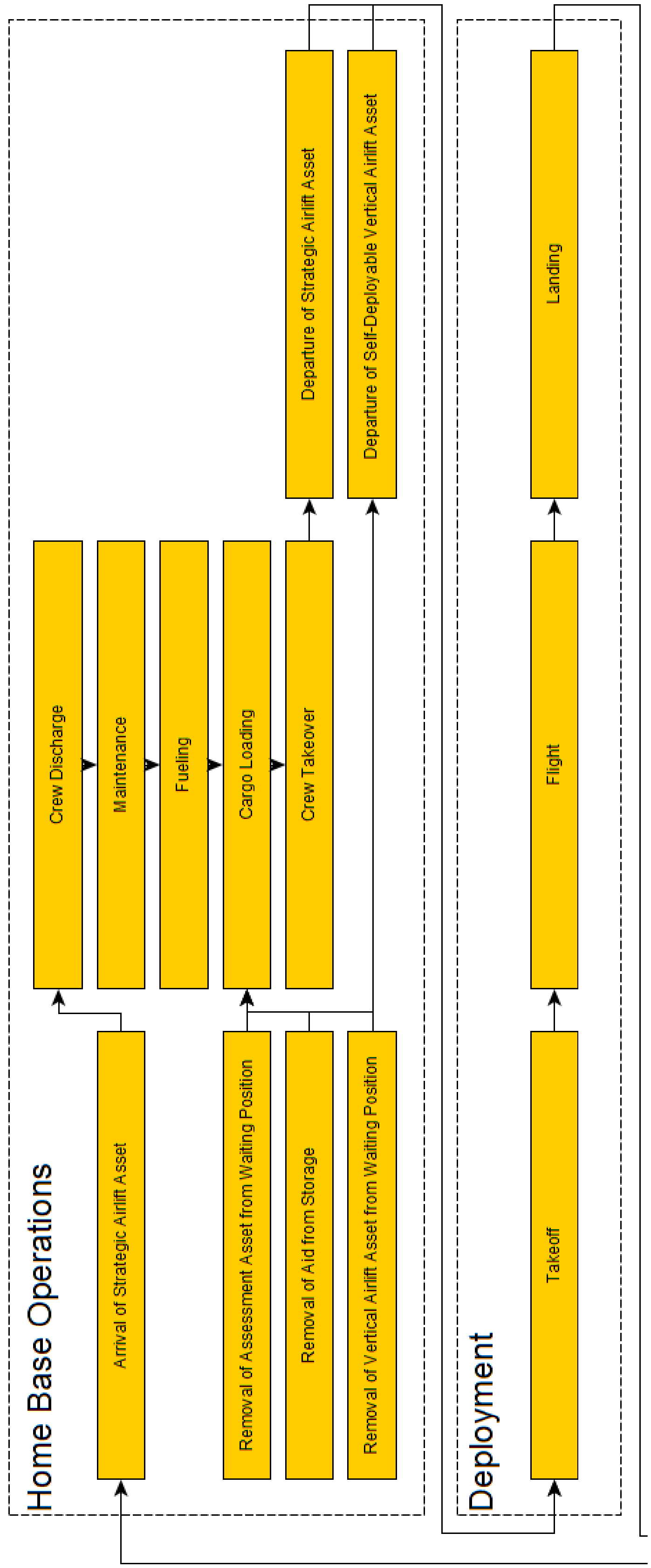
B.5.2 Resources

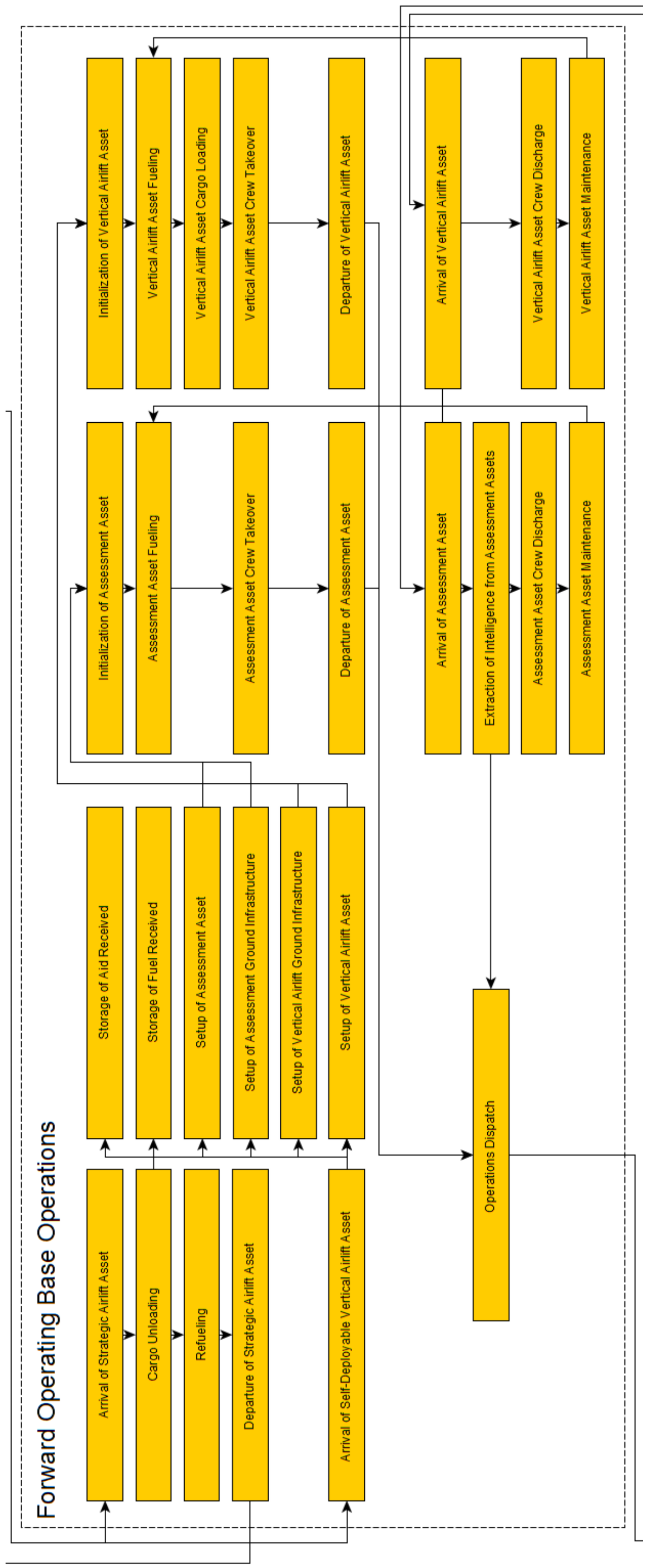
Vertical Airlift Type
Vertical Airlift Quantity

Unmanned Assessment Asset Type
Unmanned Assessment Asset Quantity
Conventional Assessment Asset Type
Conventional Assessment Asset Quantity

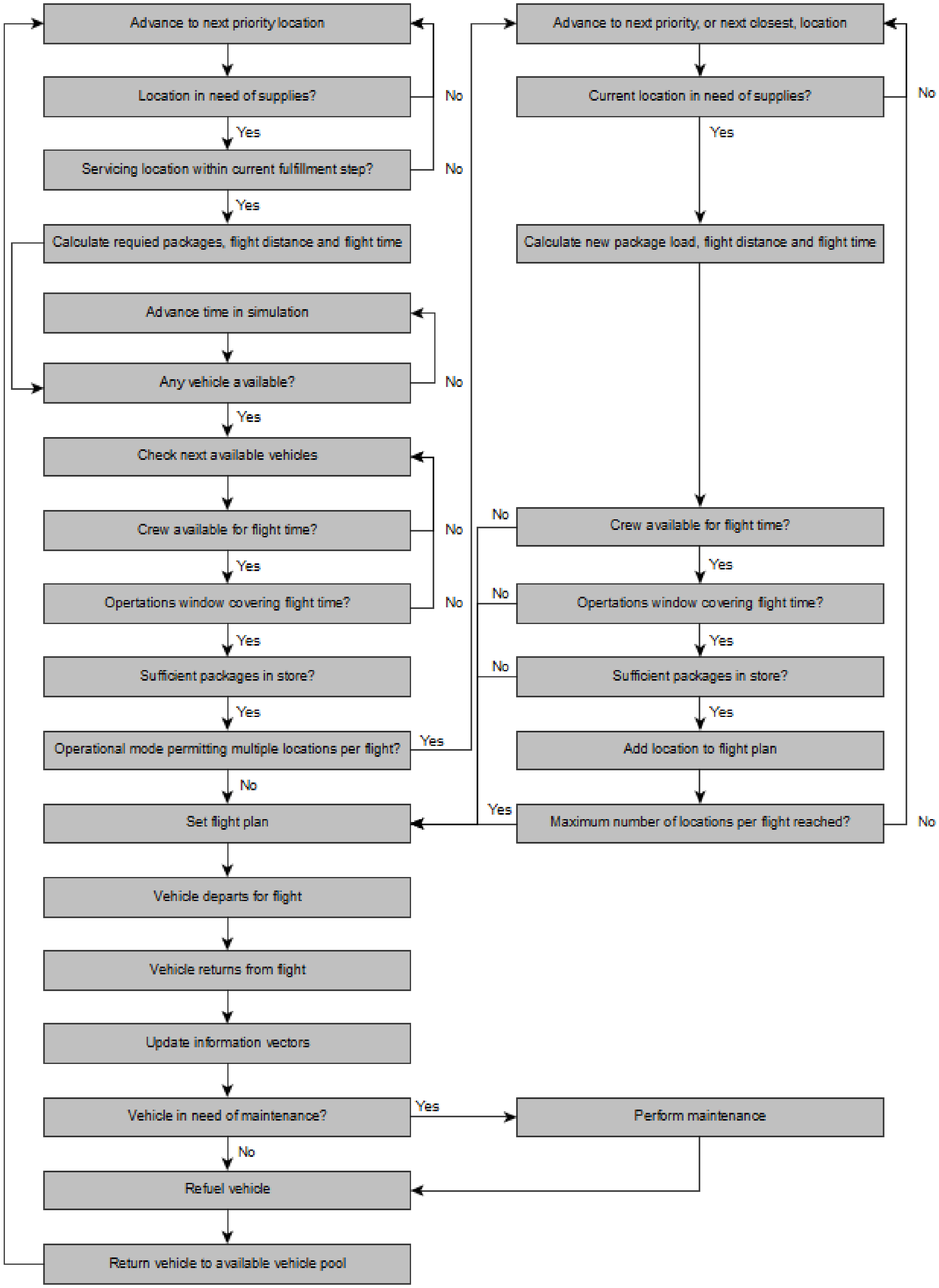
APPENDIX C. COMPREHENSIVE LOGICAL DIAGRAM FOR SIMULATION IN TESTBED ENVIRONMENT

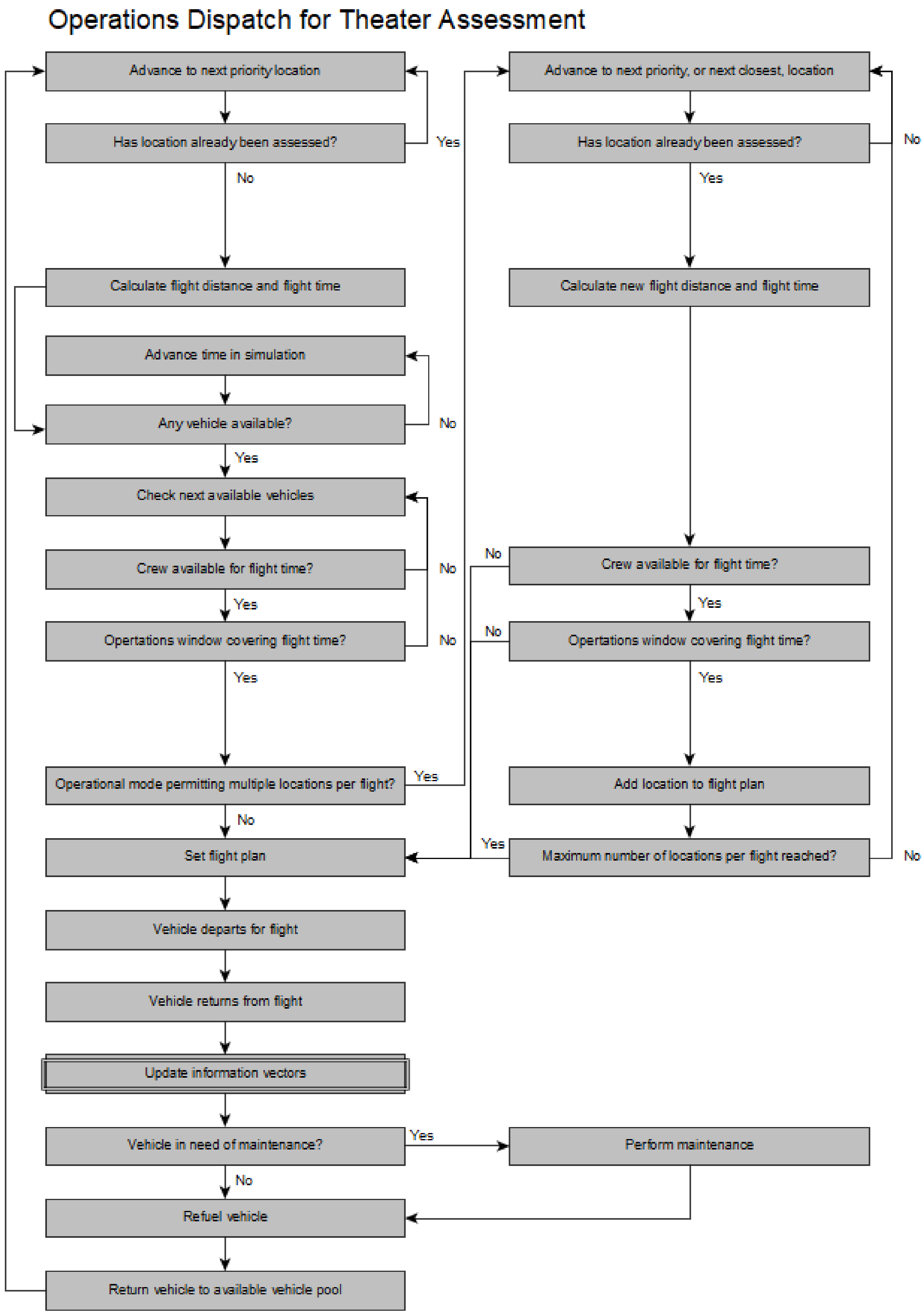



Home Base Operations
Arrival of Strategic Airlift Asset
Removal of Assessment Asset from Waiting Position
Removal of Aid from Storage
Removal of Vertical Airlift Asset from Waiting Position
Crew Discharge
Maintenance
Fueling
Cargo Loading
Crew Takeover
Departure of Strategic Airlift Asset
Departure of Self-Deployable Vertical Airlift Asset
Deployment
Takeoff
Flight
Landing

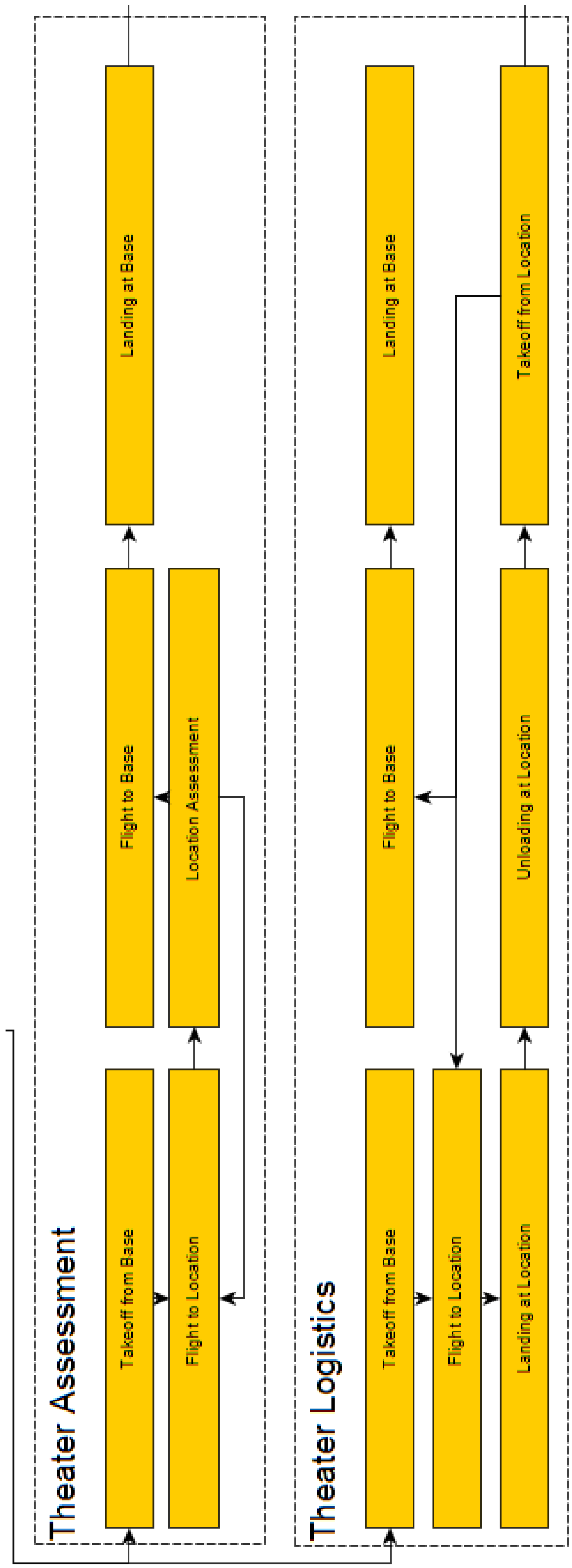

Forward Operating Base Operations
Arrival of Strategic Airlift Asset
Cargo Unloading
Refueling
Departure of Strategic Airlift Asset
Arrival of Self-Deployable Vertical Airlift Asset
Storage of Aid Received
Storage of Fuel Received
Setup of Assessment Asset
Setup of Assessment Ground Infrastructure
Setup of Vertical Airlift Ground Infrastructure
Setup of Vertical Airlift Asset
Operations Dispatch
Initialization of Assessment Asset
Assessment Asset Fueling
Assessment Asset Crew Takeover
Departure of Assessment Asset
Arrival of Assessment Asset
Extraction of Intelligence from Assessment Assets
Assessment Asset Crew Discharge
Assessment Asset Maintenance
Initialization of Vertical Airlift Asset
Vertical Airlift Asset Fueling
Vertical Airlift Asset Cargo Loading
Vertical Airlift Asset Crew Takeover
Departure of Vertical Airlift Asset
Arrival of Vertical Airlift Asset
Vertical Airlift Asset Crew Discharge
Vertical Airlift Asset Maintenance

Operations Dispatch for Theater Logistics





Operations Dispatch for Theater Assessment
Advance to next priority location
Has location already been assessed?
Yes
No
Calculate flight distance and flight time
Advance time in simulation
Any vehicle available?
No
Yes
Check next available vehicles
Crew available for flight time?
No
Yes
Opertations window covering flight time?
No
Yes
Operational mode permitting multiple locations per flight?
Yes
No
Set flight plan
Vehicle departs for flight
Vehicle returns from flight
Update information vectors
Vehicle in need of maintenance?
Yes
No
Refuel vehicle
Return vehicle to available vehicle pool
Advance to next priority, or next closest, location
Has location already been assessed?
No
Yes
Calculate new flight distance and flight time
No
Crew available for flight time?
Yes
No
Opertations window covering flight time?
Yes
Add location to flight plan
Yes
Maximum number of locations per flight reached?
No
Perform maintenance


Theater Assessment
Takeoff from Base
Flight to Location
Location Assessment
Flight to Base
Landing at Base
Theater Logistics
Takeoff from Base
Flight to Location
Landing at Location
Unloading at Location
Takeoff from Location
Flight to Base
Landing at Base

APPENDIX D. DETAILED STEP-BY-STEP PROCESS IN SIMULATION IN TESTBED ENVIRONMENT FOR SAMPLE CASE

C.1 Input Parameter

Theater (2 baseline theaters)	**Fiji**
Storm	**Winston**
Storm Destruction Radius	**50** [km]
Local Base Location	**Suva**
Initial Availability of Aid	**0** [# of packages]
Operating C-17	**2**
Operating C-130	**2**
Vertical Airlift Asset Type	**MRH-90**
Vertical Airlift Asset Quantity	**3**
Unmanned Assessment Asset Type	**Stalker**
Unmanned Assessment Asset Quantity	**4**
Conventional Assessment Asset Type	**AP-3C**
Conventional Assessment Asset Quantity	**1**
Vertical Airlift Cargo Delivery Mode	**Both** (External and Internal)
Crews per Conventional Asset	**2**
Cargo Flight Types	**Multiple Locations by Proximity**
Cargo Flight Time Window	**DayNight**
Local Fulfillment Steps	**10** [%]
Asset-Footprint Operations Mode	**Yes**
Duration of Crew Shifts	**12** [h]
Crews per Unmanned Asset	**2**
Assessment Flight Types	**Multiple Locations by Proximity**
Assessment Flight Time Window	**Day**
Assessment Processing Time	**3** [h]
Assessment Consecutive Location Maximum	**4**

C.2 Printout of Steps of Inter-Theater Simulation

RUNNING INTERTHEATER MODEL
Initializing Crews
Initialization finished

20000 kg FOB supplies & 0 kg of resources delivered by C17_0 at 6.25 hrs
4 Stalker assessment UAV(s) & 20000 kg of resources delivered by C17_1 at 6.5 hrs
0 MRH-90 & 1 footprint delivered by C130_1 at 20.41667 hrs
1 MRH-90 & 0 footprint delivered by C130_0 at 20.667 hrs
Day 1 complete

1 MRH-90 & 1 footprint delivered by C17_1 at 27.75 hrs
1 MRH-90 & 1 footprint delivered by C17_0 at 28.667 hrs
100 people delivered by C130_1 at 39.33 hrs
100 people delivered by C130_1 at 39.33 hrs
16968.56218350546 kg of resources delivered by C130_0 at 43.5833 hrs
Day 2 complete

65000.0 kg of resources & 0 kg of heli fuel delivered by C17_0 at 51.0 hrs
65000.0 kg of resources & 0 kg of heli fuel delivered by C17_1 at 52.0 hrs
16968.56218350546 kg of resources delivered by C130_1 at 65.75 hrs
Day 3 complete

65000.0 kg of resources delivered by C17_0 at 74.416667 hrs
16487.979505454554 kg of resources delivered by C130_0 at 77.5833 hrs
65000.0 kg of resources delivered by C17_1 at 91.5833 hrs
16487.979505454554 kg of resources delivered by C130_1 at 95.91667 hrs
Day 4 complete

65000.0 kg of resources delivered by C17_0 at 107.75 hrs
16968.56218350546 kg of resources delivered by C130_0 at 108.833 hrs
Day 5 complete

RUNS COMPLETE

C17_0 utilization rate = 28.50 %
C17_1 utilization rate = 22.80 %
C130_0 utilization rate = 26.20 %
C130_1 utilization rate = 27.12 %
TOTAL RUN TIME: 2.921875

C.3 Transition Table from Inter- to Intra-Theater Simulation

time [s]	aircraft	load type	asset type	asset quantity	footprint quantity	total payload [kg]	Resources [kg]
16200	AP3C_1	ISR	AP-3C	1	0	28000	0
22500	C17_0	FOB		0	0	20000	0
23400	C17_1	ISR	Stalker	4	1	32000	20000
73500	C130_1	VerticalAirlift	MRH-90	0	1	5000	0
74400	C130_0	VerticalAirlift	MRH-90	1	0	6400	0
99900	C17_1	VerticalAirlift	MRH-90	1	1	11400	0
103200	C17_0	VerticalAirlift	MRH-90	1	1	11400	0
141600	C130_1	People				9000	0
156900	C130_0	Resources				16968.56	16968.56
183600	C17_0	Resources				65000	65000
187200	C17_1	Resources				65000	65000
236700	C130_1	Resources				16968.56	16968.56
267900	C17_0	Resources				65000	65000
279300	C130_0	Resources				16487.98	16487.98
329700	C17_1	Resources				65000	65000
345300	C130_1	Resources				16487.98	16487.98
387900	C17_0	Resources				65000	65000
391800	C130_0	Resources				16968.56	16968.56

C.4 Printout of Steps of Intra-Theater Simulation

Overall Simulation Pre-Processing begun
  Loading storm path coordinates
  Loading Coordinates of Theater Locations
  Creating theater location objects
    Calculating distances
    Calculating sequence of theater locations affected
    Creating list of affected theater locations (less than 50km from the storm path)
    Conducting theater location prioritization
  Pre-processing completed in 0.58 seconds
  Loading vehicle databases
  Formatting inputs from DOE

```
Case-Specific Simulation Pre-Processing begun
  Loading case-specific interface information
     Asset and FootprintAP-3C #1 arriving at 0d 4h 30min
     Asset and FootprintStalker #1 arriving at 0d 7h 35min
     Asset and FootprintStalker #2 arriving at 0d 7h 35min
     Asset and FootprintStalker #3 arriving at 0d 7h 35min
     Asset and FootprintStalker #4 arriving at 0d 7h 35min
     Asset MRH-90 #1 arriving at 0d 20h 25min
     Footprint MRH-90 #1 arriving at 0d 20h 35min
     Asset MRH-90 #2 arriving at 1d 4h 40min
     Footprint MRH-90 #2 arriving at 1d 4h 40min
     Asset MRH-90 #3 arriving at 1d 6h 50min
     Footprint MRH-90 #3 arriving at 1d 6h 50min
     Packages, 565 packages arriving at 1d 21h 10min
     Packages, 2166 packages arriving at 2d 3h 45min
     Packages, 2166 packages arriving at 2d 5h 10min
     Packages, 549 packages arriving at 2d 23h 10min
     Packages, 2166 packages arriving at 3d 1h 5min
     Packages, 549 packages arriving at 3d 16h 40min
     Packages, 2166 packages arriving at 3d 19h 0min
     Packages, 2166 packages arriving at 4d 8h 50min
     Packages, 549 packages arriving at 4d 12h 55min
  Creating vehicle objects
     Vehicle Object for MRH-90 (cargoConventional) created
     Vehicle Object for MRH-90 (cargoConventional) created
     Vehicle Object for MRH-90 (cargoConventional) created
     Vehicle Object for AP-3C (assessConventional) created
     Vehicle Object for Stalker (assessUAV) created
     Vehicle Object for Stalker (assessUAV) created
     Vehicle Object for Stalker (assessUAV) created
     Vehicle Object for Stalker (assessUAV) created
    Calculating required footprint for vehicle selection
    Creating footprint objects
     Footprint Object for MRH-90 (cargoConventional) created
     Footprint Object for MRH-90 (cargoConventional) created
     Footprint Object for MRH-90 (cargoConventional) created
     Footprint Object for AP-3C (assessConventional) created
     Footprint Object for Stalker (assessUAV) created
     Footprint Object for Stalker (assessUAV) created
     Footprint Object for Stalker (assessUAV) created
     Footprint Object for Stalker (assessUAV) created
  Creating pre-processing plot
```

Case Simulation begun
Simulation clock initialized: 0d 0h 0min
Package storage initialized: 0 packages in stock

Simulation clock updated: 0d 4h 30min
Asset arrived
AP-3C self-deployed and is scheduled to initialize at 0d 6h 30min
Footprint arrived
Footprint of AP-3C arrived and is scheduled to initialize at 0d 6h 30min

Simulation clock updated: 0d 6h 30min
AP-3C initialized
- Flights will be assigned after its footprint is initialized
Footprint of AP-3C initialized
AP-3C is being setup for take off at 0d 7h 30min to assess:
- Cikobia
- Mualevu
- Lomaloma
- Cicia

Simulation clock updated: 0d 7h 30min
AP-3C departed from Suva to assess Cikobia
- Scheduled to arrive at 0d 8h 11min

Simulation clock updated: 0d 7h 35min
Asset arrived
Stalker #1 arrived and is scheduled to initialize at 0d 8h 5min
Asset arrived
Stalker #2 arrived and is scheduled to initialize at 0d 8h 5min
Asset arrived
Stalker #3 arrived and is scheduled to initialize at 0d 8h 5min
Asset arrived
Stalker #4 arrived and is scheduled to initialize at 0d 8h 5min
Footprint arrived
Footprint of Stalker arrived and is scheduled to initialize at 0d 8h 5min
Footprint arrived
Footprint of Stalker arrived and is scheduled to initialize at 0d 8h 5min
Footprint arrived
Footprint of Stalker arrived and is scheduled to initialize at 0d 8h 5min
Footprint arrived
Footprint of Stalker arrived and is scheduled to initialize at 0d 8h 5min

Simulation clock updated: 0d 8h 5min
Stalker #1 initialized
- Flights will be assigned after its footprint is initialized
Stalker #2 initialized

- Flights will be assigned after its footprint is initialized
Stalker #3 initialized
- Flights will be assigned after its footprint is initialized
Stalker #4 initialized
- Flights will be assigned after its footprint is initialized
Footprint of Stalker initialized
Footprint of Stalker initialized
Footprint of Stalker initialized
Footprint of Stalker initialized
Stalker #1 is being setup for take off at 0d 8h 35min to assess:
- Nakorotubu
- Sawakasa

Simulation clock updated: 0d 8h 11min
AP-3C arrived at Cikobia and started assessment
- Scheduled to finish at 0d 8h 22min
Stalker #2 is being setup for take off at 0d 8h 41min to assess:
- Ovalau
- Verata

Simulation clock updated: 0d 8h 22min
AP-3C finished assessing Cikobia
- Assessment results will be processed after landing
- Now heading to Mualevu, scheduled to arrive at 0d 8h 25min
Stalker #3 is being setup for take off at 0d 8h 52min to assess:
- Wainibuka
- Matailobau

Simulation clock updated: 0d 8h 25min
AP-3C arrived at Mualevu and started assessment
- Scheduled to finish at 0d 8h 42min
Stalker #4 is being setup for take off at 0d 8h 55min to assess:
- Waimaro

Simulation clock updated: 0d 8h 35min
Stalker #1 departed from Suva to assess Nakorotubu
- Scheduled to arrive at 0d 9h 39min

Simulation clock updated: 0d 8h 41min
Stalker #2 departed from Suva to assess Ovalau
- Scheduled to arrive at 0d 9h 33min

Simulation clock updated: 0d 8h 42min
AP-3C finished assessing Mualevu
- Assessment results will be processed after landing
- Now heading to Lomaloma, scheduled to arrive at 0d 8h 44min

Simulation clock updated: 0d 8h 44min
AP-3C arrived at Lomaloma and started assessment
- Scheduled to finish at 0d 8h 57min

Simulation clock updated: 0d 8h 52min
Stalker #3 departed from Suva to assess Wainibuka
- Scheduled to arrive at 0d 9h 42min

Simulation clock updated: 0d 8h 55min
Stalker #4 departed from Suva to assess Waimaro
- Scheduled to arrive at 0d 9h 52min

Simulation clock updated: 0d 8h 57min
AP-3C finished assessing Lomaloma
- Assessment results will be processed after landing
- Now heading to Cicia, scheduled to arrive at 0d 9h 6min

Simulation clock updated: 0d 9h 6min
AP-3C arrived at Cicia and started assessment
- Scheduled to finish at 0d 9h 20min

Simulation clock updated: 0d 9h 20min
AP-3C finished assessing Cicia
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 0d 9h 53min

Simulation clock updated: 0d 9h 33min
Stalker #2 arrived at Ovalau and started assessment
- Scheduled to finish at 0d 10h 58min

Simulation clock updated: 0d 9h 39min
Stalker #1 arrived at Nakorotubu and started assessment
- Scheduled to finish at 0d 12h 7min

Simulation clock updated: 0d 9h 42min
Stalker #3 arrived at Wainibuka and started assessment
- Scheduled to finish at 0d 11h 31min

Simulation clock updated: 0d 9h 52min
Stalker #4 arrived at Waimaro and started assessment
- Scheduled to finish at 0d 12h 44min

Simulation clock updated: 0d 9h 53min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 0d 12h 53min:

Cikobia
Mualevu
Lomaloma
Cicia

AP-3C is being setup for take off at 0d 10h 53min to assess:
- Wainikeli
- Cakaudrove
- Tunuloa
- Saqani

Simulation clock updated: 0d 10h 53min
AP-3C departed from Suva to assess Wainikeli
- Scheduled to arrive at 0d 11h 24min

Simulation clock updated: 0d 10h 58min
Stalker #2 finished assessing Ovalau
- Assessment transmitted live to the base, results at 0d 13h 58min
- Now heading to Verata, scheduled to arrive at 0d 11h 32min

Simulation clock updated: 0d 11h 24min
AP-3C arrived at Wainikeli and started assessment
- Scheduled to finish at 0d 12h 5min

Simulation clock updated: 0d 11h 31min
Stalker #3 finished assessing Wainibuka
- Assessment transmitted live to the base, results at 0d 14h 31min
- Now heading to Matailobau, scheduled to arrive at 0d 11h 50min

Simulation clock updated: 0d 11h 32min
Stalker #2 arrived at Verata and started assessment
- Scheduled to finish at 0d 13h 58min

Simulation clock updated: 0d 11h 50min
Stalker #3 arrived at Matailobau and started assessment
- Scheduled to finish at 0d 14h 11min

Simulation clock updated: 0d 12h 5min
AP-3C finished assessing Wainikeli
- Assessment results will be processed after landing
- Now heading to Cakaudrove, scheduled to arrive at 0d 12h 8min

Simulation clock updated: 0d 12h 7min
Stalker #1 finished assessing Nakorotubu
- Assessment transmitted live to the base, results at 0d 15h 7min
- Now heading to Sawakasa, scheduled to arrive at 0d 12h 23min

Simulation clock updated: 0d 12h 8min
AP-3C arrived at Cakaudrove and started assessment
- Scheduled to finish at 0d 13h 16min

Simulation clock updated: 0d 12h 23min
Stalker #1 arrived at Sawakasa and started assessment
- Scheduled to finish at 0d 14h 32min

Simulation clock updated: 0d 12h 44min
Stalker #4 finished assessing Waimaro
- Assessment transmitted live to the base, results at 0d 15h 44min
- Now returning to Suva, scheduled to arrive at 0d 13h 41min

Simulation clock updated: 0d 12h 53min
Population in need at Cikobia was updated to 64%
Population in need at Mualevu was updated to 77%
Population in need at Lomaloma was updated to 68%
Population in need at Cicia was updated to 7%

Simulation clock updated: 0d 13h 16min
AP-3C finished assessing Cakaudrove
- Assessment results will be processed after landing
- Now heading to Tunuloa, scheduled to arrive at 0d 13h 22min

Simulation clock updated: 0d 13h 22min
AP-3C arrived at Tunuloa and started assessment
- Scheduled to finish at 0d 14h 10min

Simulation clock updated: 0d 13h 41min
Stalker #4 arrived at Suva

Simulation clock updated: 0d 13h 58min
Stalker #2 finished assessing Verata
- Assessment transmitted live to the base, results at 0d 16h 58min
- Now returning to Suva, scheduled to arrive at 0d 14h 25min

Simulation clock updated: 0d 13h 58min
Population in need at Ovalau was updated to 82%

Simulation clock updated: 0d 14h 10min
AP-3C finished assessing Tunuloa
- Assessment results will be processed after landing
- Now heading to Saqani, scheduled to arrive at 0d 14h 13min

Simulation clock updated: 0d 14h 11min
Stalker #3 finished assessing Matailobau

- Assessment transmitted live to the base, results at 0d 17h 11min
- Now returning to Suva, scheduled to arrive at 0d 14h 54min

Simulation clock updated: 0d 14h 13min
AP-3C arrived at Saqani and started assessment
- Scheduled to finish at 0d 15h 7min

Simulation clock updated: 0d 14h 25min
Stalker #2 arrived at Suva

Simulation clock updated: 0d 14h 31min
Population in need at Wainibuka was updated to 29%

Simulation clock updated: 0d 14h 32min
Stalker #1 finished assessing Sawakasa
- Assessment transmitted live to the base, results at 0d 17h 32min
- Now returning to Suva, scheduled to arrive at 0d 15h 26min

Simulation clock updated: 0d 14h 54min
Stalker #3 arrived at Suva
- Stalker #3 will undergo unscheduled maintenance and will finish at 0d 17h 54min

Simulation clock updated: 0d 15h 7min
AP-3C finished assessing Saqani
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 0d 15h 37min

Simulation clock updated: 0d 15h 7min
Population in need at Nakorotubu was updated to 84%

Simulation clock updated: 0d 15h 26min
Stalker #1 arrived at Suva

Simulation clock updated: 0d 15h 37min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 0d 18h 37min:
Wainikeli
Cakaudrove
Tunuloa
Saqani
AP-3C is being setup for take off at 0d 16h 37min to assess:
- Naviti
- Yasawa
- Malolo

Simulation clock updated: 0d 15h 44min
  Population in need at Waimaro was updated to 14%

Simulation clock updated: 0d 16h 37min
  AP-3C departed from Suva to assess Naviti
    - Scheduled to arrive at 0d 17h 2min

Simulation clock updated: 0d 16h 58min
  Population in need at Verata was updated to 15%

Simulation clock updated: 0d 17h 2min
  AP-3C arrived at Naviti and started assessment
    - Scheduled to finish at 0d 17h 26min

Simulation clock updated: 0d 17h 11min
  Population in need at Matailobau was updated to 19%

Simulation clock updated: 0d 17h 26min
  AP-3C finished assessing Naviti
    - Assessment results will be processed after landing
    - Now heading to Yasawa, scheduled to arrive at 0d 17h 33min

Simulation clock updated: 0d 17h 32min
  Population in need at Sawakasa was updated to 57%

Simulation clock updated: 0d 17h 33min
  AP-3C arrived at Yasawa and started assessment
    - Scheduled to finish at 0d 18h 0min

Simulation clock updated: 0d 17h 54min
  Stalker #3 returned from maintenance and is available for new flights

Simulation clock updated: 0d 18h 0min
  AP-3C finished assessing Yasawa
    - Assessment results will be processed after landing
    - Now heading to Malolo, scheduled to arrive at 0d 18h 16min

Simulation clock updated: 0d 18h 16min
  AP-3C arrived at Malolo and started assessment
    - Scheduled to finish at 0d 18h 30min

Simulation clock updated: 0d 18h 30min
  AP-3C finished assessing Malolo
    - Assessment results will be processed after landing
    - Now returning to Suva, scheduled to arrive at 0d 18h 51min

Simulation clock updated: 0d 18h 37min
Population in need at Wainikeli was updated to 64%
Population in need at Cakaudrove was updated to 54%
Population in need at Tunuloa was updated to 19%
Population in need at Saqani was updated to 13%

Simulation clock updated: 0d 18h 51min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 0d 21h 51min:
Naviti
Yasawa
Malolo
AP-3C is being setup for take off at 1d 5h 0min to assess:
- Nasavusavu
- Vaturova
- Rabi
- Koro

Simulation clock updated: 0d 20h 25min
Asset arrived
MRH-90 #1 arrived and is scheduled to initialize at 1d 0h 25min

Simulation clock updated: 0d 20h 35min
Footprint arrived
Footprint of MRH-90 arrived and is scheduled to initialize at 1d 0h 35min

Simulation clock updated: 0d 21h 51min
Population in need at Naviti was updated to 72%
Population in need at Yasawa was updated to 9%
Population in need at Malolo was updated to 91%

Simulation clock updated: 1d 0h 25min
MRH-90 #1 initialized
- Flights will be assigned after its footprint is initialized

Simulation clock updated: 1d 0h 35min
Footprint of MRH-90 initialized

Simulation clock updated: 1d 4h 40min
Asset arrived
MRH-90 #2 arrived and is scheduled to initialize at 1d 8h 40min
Footprint arrived
Footprint of MRH-90 arrived and is scheduled to initialize at 1d 8h 40min

Simulation clock updated: 1d 5h 0min
AP-3C departed from Suva to assess Nasavusavu

- Scheduled to arrive at 1d 5h 24min

Simulation clock updated: 1d 5h 24min
AP-3C arrived at Nasavusavu and started assessment
- Scheduled to finish at 1d 6h 17min

Simulation clock updated: 1d 6h 17min
AP-3C finished assessing Nasavusavu
- Assessment results will be processed after landing
- Now heading to Vaturova, scheduled to arrive at 1d 6h 20min

Simulation clock updated: 1d 6h 20min
AP-3C arrived at Vaturova and started assessment
- Scheduled to finish at 1d 7h 36min

Simulation clock updated: 1d 6h 50min
Asset arrived
MRH-90 #3 arrived and is scheduled to initialize at 1d 10h 50min
Footprint arrived
Footprint of MRH-90 arrived and is scheduled to initialize at 1d 10h 50min

Simulation clock updated: 1d 7h 36min
AP-3C finished assessing Vaturova
- Assessment results will be processed after landing
- Now heading to Rabi, scheduled to arrive at 1d 7h 44min

Simulation clock updated: 1d 7h 44min
AP-3C arrived at Rabi and started assessment
- Scheduled to finish at 1d 8h 9min

Simulation clock updated: 1d 8h 9min
AP-3C finished assessing Rabi
- Assessment results will be processed after landing
- Now heading to Koro, scheduled to arrive at 1d 8h 25min

Simulation clock updated: 1d 8h 25min
AP-3C arrived at Koro and started assessment
- Scheduled to finish at 1d 8h 56min

Simulation clock updated: 1d 8h 40min
MRH-90 #2 initialized
- Flights will be assigned after its footprint is initialized
Footprint of MRH-90 initialized

Simulation clock updated: 1d 8h 56min
AP-3C finished assessing Koro

- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 1d 9h 13min

Simulation clock updated: 1d 9h 13min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 1d 12h 13min:
  Nasavusavu
  Vaturova
  Rabi
  Koro
- AP-3C will undergo scheduled maintenance and will finish at 1d 11h 13min

Simulation clock updated: 1d 10h 50min
MRH-90 #3 initialized
- Flights will be assigned after its footprint is initialized
Footprint of MRH-90 initialized

Simulation clock updated: 1d 11h 13min
AP-3C returned from maintenance and is available for new flights
AP-3C is being setup for take off at 1d 12h 13min to assess:
- Wainunu
- Vuya
- Bua
- Rakiraki

Simulation clock updated: 1d 12h 13min
Population in need at Nasavusavu was updated to 55%
Population in need at Vaturova was updated to 11%
Population in need at Rabi was updated to 15%
Population in need at Koro was updated to 83%
AP-3C departed from Suva to assess Wainunu
- Scheduled to arrive at 1d 12h 33min

Simulation clock updated: 1d 12h 33min
AP-3C arrived at Wainunu and started assessment
- Scheduled to finish at 1d 13h 32min

Simulation clock updated: 1d 13h 32min
AP-3C finished assessing Wainunu
- Assessment results will be processed after landing
- Now heading to Vuya, scheduled to arrive at 1d 13h 36min

Simulation clock updated: 1d 13h 36min
AP-3C arrived at Vuya and started assessment
- Scheduled to finish at 1d 14h 26min

Simulation clock updated: 1d 14h 26min
AP-3C finished assessing Vuya
- Assessment results will be processed after landing
- Now heading to Bua, scheduled to arrive at 1d 14h 30min

Simulation clock updated: 1d 14h 30min
AP-3C arrived at Bua and started assessment
- Scheduled to finish at 1d 15h 52min

Simulation clock updated: 1d 15h 52min
AP-3C finished assessing Bua
- Assessment results will be processed after landing
- Now heading to Rakiraki, scheduled to arrive at 1d 16h 3min

Simulation clock updated: 1d 16h 3min
AP-3C arrived at Rakiraki and started assessment
- Scheduled to finish at 1d 16h 56min

Simulation clock updated: 1d 16h 56min
AP-3C finished assessing Rakiraki
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 1d 17h 9min

Simulation clock updated: 1d 17h 9min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 1d 20h 9min:
Wainunu
Vuya
Bua
Rakiraki
AP-3C is being setup for take off at 1d 18h 9min to assess:
- Nairai
- Batiki

Simulation clock updated: 1d 18h 9min
AP-3C departed from Suva to assess Nairai
- Scheduled to arrive at 1d 18h 22min

Simulation clock updated: 1d 18h 22min
AP-3C arrived at Nairai and started assessment
- Scheduled to finish at 1d 18h 36min

Simulation clock updated: 1d 18h 36min
AP-3C finished assessing Nairai
- Assessment results will be processed after landing
- Now heading to Batiki, scheduled to arrive at 1d 18h 40min

Simulation clock updated: 1d 18h 40min
AP-3C arrived at Batiki and started assessment
- Scheduled to finish at 1d 18h 49min

Simulation clock updated: 1d 18h 49min
AP-3C finished assessing Batiki
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 1d 18h 59min

Simulation clock updated: 1d 18h 59min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 1d 21h 59min:
Nairai
Batiki
AP-3C is being setup for take off at 2d 5h 0min to assess:
- Nadi
- Nawaka
- Vuda
- Ba

Simulation clock updated: 1d 20h 9min
Population in need at Wainunu was updated to 97%
Population in need at Vuya was updated to 62%
Population in need at Bua was updated to 17%
Population in need at Rakiraki was updated to 87%

Simulation clock updated: 1d 21h 10min
Packages arrived (Quantity: 565)
Package storage updated: 565 packages in stock
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 527.0 packages in stock
MRH-90 #1 will take off at 1d 22h 10min to deliver relief supplies to:
- Nadi: 38 pcks, representing 1 % of the known packages needed
(cumulative known need fulfilled: 1 %)

Simulation clock updated: 1d 21h 59min
Population in need at Nairai was updated to 14%
Population in need at Batiki was updated to 14%
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 489.0 packages in stock
MRH-90 #2 will take off at 1d 22h 59min to deliver relief supplies to:
- Sawakasa: 38 pcks, representing 16 % of the known packages needed
(cumulative known need fulfilled: 16 %)

Simulation clock updated: 1d 22h 10min
MRH-90 #1 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 1d 22h 50min
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 451.0 packages in stock
MRH-90 #3 will take off at 1d 23h 10min to deliver relief supplies to:
- Verata: 38 pcks, representing 48 % of the known packages needed (cumulative known need fulfilled: 48 %)

Simulation clock updated: 1d 22h 50min
MRH-90 #1 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 1 %
- Now returning to Suva, scheduled to arrive at 1d 23h 57min

Simulation clock updated: 1d 22h 59min
MRH-90 #2 departed from Suva to deliver supplies to Sawakasa
- Scheduled to arrive at 1d 23h 14min

Simulation clock updated: 1d 23h 10min
MRH-90 #3 departed from Suva to deliver supplies to Verata
- Scheduled to arrive at 1d 23h 17min

Simulation clock updated: 1d 23h 14min
MRH-90 #2 delivered 38 packages to Sawakasa
- Cumulative known need fulfilled: 16 %
- Now returning to Suva, scheduled to arrive at 1d 23h 59min

Simulation clock updated: 1d 23h 17min
MRH-90 #3 delivered 38 packages to Verata
- Cumulative known need fulfilled: 48 %
- Now returning to Suva, scheduled to arrive at 1d 23h 55min

Simulation clock updated: 1d 23h 55min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 413.0 packages in stock
MRH-90 #3 will take off at 2d 0h 55min to deliver relief supplies to:
- Cikobia: 4 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Mualevu: 33 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Cicia: 1 pcks, representing 25 % of the known packages needed (cumulative known need fulfilled: 25 %)

Simulation clock updated: 1d 23h 57min
MRH-90 #1 arrived at Suva

Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 375.0 packages in stock
MRH-90 #1 will take off at 2d 0h 57min to deliver relief supplies to:
- Lomaloma: 32 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Rabi: 6 pcks, representing 33 % of the known packages needed (cumulative known need fulfilled: 33 %)

Simulation clock updated: 1d 23h 59min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 337.0 packages in stock
MRH-90 #2 will take off at 2d 0h 59min to deliver relief supplies to:
- Wainikeli: 38 pcks, representing 27 % of the known packages needed (cumulative known need fulfilled: 27 %)

Simulation clock updated: 2d 0h 55min
MRH-90 #3 departed from Suva to deliver supplies to Cikobia
- Scheduled to arrive at 2d 2h 23min

Simulation clock updated: 2d 0h 57min
MRH-90 #1 departed from Suva to deliver supplies to Lomaloma
- Scheduled to arrive at 2d 2h 19min

Simulation clock updated: 2d 0h 59min
MRH-90 #2 departed from Suva to deliver supplies to Wainikeli
- Scheduled to arrive at 2d 2h 4min

Simulation clock updated: 2d 2h 4min
MRH-90 #2 delivered 38 packages to Wainikeli
- Cumulative known need fulfilled: 27 %
- Now returning to Suva, scheduled to arrive at 2d 3h 40min

Simulation clock updated: 2d 2h 19min
MRH-90 #1 delivered 32 packages to Lomaloma
- Cumulative known need fulfilled: 100 %
- Now heading to Rabi, scheduled to arrive at 2d 3h 30min

Simulation clock updated: 2d 2h 23min
MRH-90 #3 delivered 4 packages to Cikobia
- Cumulative known need fulfilled: 100 %
- Now heading to Mualevu, scheduled to arrive at 2d 2h 58min

Simulation clock updated: 2d 2h 58min
MRH-90 #3 delivered 33 packages to Mualevu
- Cumulative known need fulfilled: 100 %

- Now heading to Cicia, scheduled to arrive at 2d 3h 49min

Simulation clock updated: 2d 3h 30min
MRH-90 #1 delivered 6 packages to Rabi
- Cumulative known need fulfilled: 33 %
- Now returning to Suva, scheduled to arrive at 2d 5h 9min

Simulation clock updated: 2d 3h 40min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 299.0 packages in stock
MRH-90 #2 will take off at 2d 4h 40min to deliver relief supplies to:
- Cakaudrove: 38 pcks, representing 10 % of the known packages needed (cumulative known need fulfilled: 10 %)

Simulation clock updated: 2d 3h 45min
Packages arrived (Quantity: 2166)
Package storage updated: 2465.0 packages in stock

Simulation clock updated: 2d 3h 49min
MRH-90 #3 delivered 1 packages to Cicia
- Cumulative known need fulfilled: 25 %
- Now returning to Suva, scheduled to arrive at 2d 5h 28min

Simulation clock updated: 2d 4h 40min
MRH-90 #2 departed from Suva to deliver supplies to Cakaudrove
- Scheduled to arrive at 2d 5h 39min

Simulation clock updated: 2d 5h 0min
AP-3C departed from Suva to assess Nadi
- Scheduled to arrive at 2d 5h 17min

Simulation clock updated: 2d 5h 9min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 2427.0 packages in stock
MRH-90 #1 will take off at 2d 6h 9min to deliver relief supplies to:
- Cakaudrove: 38 pcks, representing 10 % of the known packages needed (cumulative known need fulfilled: 19 %)

Simulation clock updated: 2d 5h 10min
Packages arrived (Quantity: 2166)
Package storage updated: 4593.0 packages in stock

Simulation clock updated: 2d 5h 17min
AP-3C arrived at Nadi and started assessment

- Scheduled to finish at 2d 5h 57min

Simulation clock updated: 2d 5h 28min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4555.0 packages in stock
MRH-90 #3 will take off at 2d 6h 28min to deliver relief supplies to:
- Naviti: 38 pcks, representing 36 % of the known packages needed
(cumulative known need fulfilled: 36 %)

Simulation clock updated: 2d 5h 39min
MRH-90 #2 delivered 38 packages to Cakaudrove
- Cumulative known need fulfilled: 10 %
- Now returning to Suva, scheduled to arrive at 2d 7h 8min

Simulation clock updated: 2d 5h 57min
AP-3C finished assessing Nadi
- Assessment results will be processed after landing
- Now heading to Nawaka, scheduled to arrive at 2d 5h 57min

Simulation clock updated: 2d 5h 57min
AP-3C arrived at Nawaka and started assessment
- Scheduled to finish at 2d 7h 6min

Simulation clock updated: 2d 6h 9min
MRH-90 #1 departed from Suva to deliver supplies to Cakaudrove
- Scheduled to arrive at 2d 7h 8min

Simulation clock updated: 2d 6h 28min
MRH-90 #3 departed from Suva to deliver supplies to Naviti
- Scheduled to arrive at 2d 7h 20min

Simulation clock updated: 2d 7h 6min
AP-3C finished assessing Nawaka
- Assessment results will be processed after landing
- Now heading to Vuda, scheduled to arrive at 2d 7h 9min

Simulation clock updated: 2d 7h 8min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4517.0 packages in stock
MRH-90 #2 will take off at 2d 8h 8min to deliver relief supplies to:
- Nasavusavu: 38 pcks, representing 11 % of the known packages needed
(cumulative known need fulfilled: 11 %)

Simulation clock updated: 2d 7h 8min
MRH-90 #1 delivered 38 packages to Cakaudrove
- Cumulative known need fulfilled: 19 %
- Now returning to Suva, scheduled to arrive at 2d 8h 37min

Simulation clock updated: 2d 7h 9min
AP-3C arrived at Vuda and started assessment
- Scheduled to finish at 2d 8h 10min

Simulation clock updated: 2d 7h 20min
MRH-90 #3 delivered 38 packages to Naviti
- Cumulative known need fulfilled: 36 %
- Now returning to Suva, scheduled to arrive at 2d 8h 42min

Simulation clock updated: 2d 8h 8min
MRH-90 #2 departed from Suva to deliver supplies to Nasavusavu
- Scheduled to arrive at 2d 8h 59min

Simulation clock updated: 2d 8h 10min
AP-3C finished assessing Vuda
- Assessment results will be processed after landing
- Now heading to Ba, scheduled to arrive at 2d 8h 13min

Simulation clock updated: 2d 8h 13min
AP-3C arrived at Ba and started assessment
- Scheduled to finish at 2d 9h 8min

Simulation clock updated: 2d 8h 37min
MRH-90 #1 arrived at Suva
- MRH-90 #1 will undergo scheduled maintenance and will finish at 2d 12h 37min

Simulation clock updated: 2d 8h 42min
MRH-90 #3 arrived at Suva
- MRH-90 #3 will undergo scheduled maintenance and will finish at 2d 12h 42min

Simulation clock updated: 2d 8h 59min
MRH-90 #2 delivered 38 packages to Nasavusavu
- Cumulative known need fulfilled: 11 %
- Now returning to Suva, scheduled to arrive at 2d 10h 21min

Simulation clock updated: 2d 9h 8min
AP-3C finished assessing Ba
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 2d 9h 24min

Simulation clock updated: 2d 9h 24min
  AP-3C arrived at Suva
  - Assessment results for the following location(s) will be available at 2d 12h 24min:
      Nadi
      Nawaka
      Vuda
      Ba
    - AP-3C will undergo scheduled maintenance and will finish at 2d 11h 24min

Simulation clock updated: 2d 10h 21min
  MRH-90 #2 arrived at Suva
    - MRH-90 #2 will undergo scheduled maintenance and will finish at 2d 14h 21min

Simulation clock updated: 2d 11h 24min
  AP-3C returned from maintenance and is available for new flights
  AP-3C is being setup for take off at 2d 12h 24min to assess:
    - Sasa
    - Tavua
    - Magodro
    - Navosa

Simulation clock updated: 2d 12h 24min
  Population in need at Nadi was updated to 51%
  Population in need at Nawaka was updated to 12%
  Population in need at Vuda was updated to 65%
  Population in need at Ba was updated to 26%
  AP-3C departed from Suva to assess Sasa
    - Scheduled to arrive at 2d 12h 39min

Simulation clock updated: 2d 12h 37min
  MRH-90 #1 returned from maintenance and is available for new flights
  Packages loaded onto cargo flight (total quantity: 38.0)
  Package storage updated: 4479.0 packages in stock
  MRH-90 #1 will take off at 2d 13h 37min to deliver relief supplies to:
    - Malolo: 38 pcks, representing 26 % of the known packages needed
        (cumulative known need fulfilled: 26 %)

Simulation clock updated: 2d 12h 39min
  AP-3C arrived at Sasa and started assessment
    - Scheduled to finish at 2d 13h 36min

Simulation clock updated: 2d 12h 42min
  MRH-90 #3 returned from maintenance and is available for new flights
  Packages loaded onto cargo flight (total quantity: 38.0)
  Package storage updated: 4441.0 packages in stock
  MRH-90 #3 will take off at 2d 13h 42min to deliver relief supplies to:

- Wainunu: 38 pcks, representing 17 % of the known packages needed
      (cumulative known need fulfilled: 17 %)

Simulation clock updated: 2d 13h 36min
AP-3C finished assessing Sasa
- Assessment results will be processed after landing
- Now heading to Tavua, scheduled to arrive at 2d 13h 38min

Simulation clock updated: 2d 13h 37min
MRH-90 #1 departed from Suva to deliver supplies to Malolo
- Scheduled to arrive at 2d 14h 22min

Simulation clock updated: 2d 13h 38min
AP-3C arrived at Tavua and started assessment
- Scheduled to finish at 2d 14h 59min

Simulation clock updated: 2d 13h 42min
MRH-90 #3 departed from Suva to deliver supplies to Wainunu
- Scheduled to arrive at 2d 14h 23min

Simulation clock updated: 2d 14h 21min
MRH-90 #2 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4403.0 packages in stock
MRH-90 #2 will take off at 2d 15h 21min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed
      (cumulative known need fulfilled: 5 %)

Simulation clock updated: 2d 14h 22min
MRH-90 #1 delivered 38 packages to Malolo
- Cumulative known need fulfilled: 26 %
- Now returning to Suva, scheduled to arrive at 2d 15h 38min

Simulation clock updated: 2d 14h 23min
MRH-90 #3 delivered 38 packages to Wainunu
- Cumulative known need fulfilled: 17 %
- Now returning to Suva, scheduled to arrive at 2d 15h 34min

Simulation clock updated: 2d 14h 59min
AP-3C finished assessing Tavua
- Assessment results will be processed after landing
- Now heading to Magodro, scheduled to arrive at 2d 15h 4min

Simulation clock updated: 2d 15h 4min
AP-3C arrived at Magodro and started assessment
- Scheduled to finish at 2d 16h 10min

Simulation clock updated: 2d 15h 21min
MRH-90 #2 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 2d 15h 58min

Simulation clock updated: 2d 15h 34min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4365.0 packages in stock
MRH-90 #3 will take off at 2d 16h 34min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed
(cumulative known need fulfilled: 8 %)

Simulation clock updated: 2d 15h 38min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4327.0 packages in stock
MRH-90 #1 will take off at 2d 16h 38min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed
(cumulative known need fulfilled: 10 %)

Simulation clock updated: 2d 15h 58min
MRH-90 #2 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 5 %
- Now returning to Suva, scheduled to arrive at 2d 17h 5min

Simulation clock updated: 2d 16h 10min
AP-3C finished assessing Magodro
- Assessment results will be processed after landing
- Now heading to Navosa, scheduled to arrive at 2d 16h 13min

Simulation clock updated: 2d 16h 13min
AP-3C arrived at Navosa and started assessment
- Scheduled to finish at 2d 17h 40min

Simulation clock updated: 2d 16h 34min
MRH-90 #3 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 2d 17h 11min

Simulation clock updated: 2d 16h 38min
MRH-90 #1 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 2d 17h 15min

Simulation clock updated: 2d 17h 5min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4289.0 packages in stock

MRH-90 #2 will take off at 2d 18h 5min to deliver relief supplies to:
- Koro: 38 pcks, representing 31 % of the known packages needed
  (cumulative known need fulfilled: 31 %)

Simulation clock updated: 2d 17h 11min
MRH-90 #3 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 8 %
- Now returning to Suva, scheduled to arrive at 2d 18h 18min

Simulation clock updated: 2d 17h 15min
MRH-90 #1 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 10 %
- Now returning to Suva, scheduled to arrive at 2d 18h 21min

Simulation clock updated: 2d 17h 40min
AP-3C finished assessing Navosa
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 2d 17h 50min

Simulation clock updated: 2d 17h 50min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 2d 20h 50min:
  Sasa
  Tavua
  Magodro
  Navosa

Simulation clock updated: 2d 18h 5min
MRH-90 #2 departed from Suva to deliver supplies to Koro
- Scheduled to arrive at 2d 18h 41min
AP-3C is being setup for take off at 3d 5h 0min to assess:
- Saivou
- Nalawa
- Wainimala
- Ruwailevu

Simulation clock updated: 2d 18h 18min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4251.0 packages in stock
MRH-90 #3 will take off at 2d 19h 18min to deliver relief supplies to:
- Vuya: 38 pcks, representing 25 % of the known packages needed
  (cumulative known need fulfilled: 25 %)

Simulation clock updated: 2d 18h 21min
MRH-90 #1 arrived at Suva

Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4213.0 packages in stock
MRH-90 #1 will take off at 2d 19h 21min to deliver relief supplies to:
- Vuda: 38 pcks, representing 1 % of the known packages needed (cumulative known need fulfilled: 1 %)

Simulation clock updated: 2d 18h 41min
MRH-90 #2 delivered 38 packages to Koro
- Cumulative known need fulfilled: 31 %
- Now returning to Suva, scheduled to arrive at 2d 19h 48min

Simulation clock updated: 2d 19h 18min
MRH-90 #3 departed from Suva to deliver supplies to Vuya
- Scheduled to arrive at 2d 19h 54min

Simulation clock updated: 2d 19h 21min
MRH-90 #1 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 2d 19h 57min

Simulation clock updated: 2d 19h 48min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4175.0 packages in stock
MRH-90 #2 will take off at 2d 20h 48min to deliver relief supplies to:
- Vuda: 38 pcks, representing 1 % of the known packages needed (cumulative known need fulfilled: 2 %)

Simulation clock updated: 2d 19h 54min
MRH-90 #3 delivered 38 packages to Vuya
- Cumulative known need fulfilled: 25 %
- Now returning to Suva, scheduled to arrive at 2d 21h 1min

Simulation clock updated: 2d 19h 57min
MRH-90 #1 delivered 38 packages to Vuda
- Cumulative known need fulfilled: 1 %
- Now returning to Suva, scheduled to arrive at 2d 21h 3min

Simulation clock updated: 2d 20h 48min
MRH-90 #2 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 2d 21h 23min

Simulation clock updated: 2d 20h 50min
Population in need at Sasa was updated to 94%
Population in need at Tavua was updated to 27%
Population in need at Magodro was updated to 22%
Population in need at Navosa was updated to 14%

Simulation clock updated: 2d 21h 1min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4137.0 packages in stock
MRH-90 #3 will take off at 2d 22h 1min to deliver relief supplies to:
- Vuda: 38 pcks, representing 1 % of the known packages needed
(cumulative known need fulfilled: 4 %)

Simulation clock updated: 2d 21h 3min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 4099.0 packages in stock
MRH-90 #1 will take off at 2d 22h 3min to deliver relief supplies to:
- Vuda: 38 pcks, representing 1 % of the known packages needed
(cumulative known need fulfilled: 5 %)

Simulation clock updated: 2d 21h 23min
MRH-90 #2 delivered 38 packages to Vuda
- Cumulative known need fulfilled: 2 %
- Now returning to Suva, scheduled to arrive at 2d 22h 29min

Simulation clock updated: 2d 22h 1min
MRH-90 #3 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 2d 22h 36min

Simulation clock updated: 2d 22h 3min
MRH-90 #1 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 2d 22h 38min

Simulation clock updated: 2d 22h 29min
MRH-90 #2 arrived at Suva

Simulation clock updated: 2d 22h 36min
MRH-90 #3 delivered 38 packages to Vuda
- Cumulative known need fulfilled: 4 %
- Now returning to Suva, scheduled to arrive at 2d 23h 42min

Simulation clock updated: 2d 22h 38min
MRH-90 #1 delivered 38 packages to Vuda
- Cumulative known need fulfilled: 5 %
- Now returning to Suva, scheduled to arrive at 2d 23h 44min

Simulation clock updated: 2d 23h 10min
Packages arrived (Quantity: 549)
Package storage updated: 4648.0 packages in stock
Packages loaded onto cargo flight (total quantity: 38.0)

  Package storage updated: 4610.0 packages in stock
  MRH-90 #2 will take off at 3d 0h 10min to deliver relief supplies to:
    - Vuda: 38 pcks, representing 1 % of the known packages needed
          (cumulative known need fulfilled: 6 %)

Simulation clock updated: 2d 23h 42min
  MRH-90 #3 arrived at Suva
  Packages loaded onto cargo flight (total quantity: 38.0)
  Package storage updated: 4572.0 packages in stock
  MRH-90 #3 will take off at 3d 0h 42min to deliver relief supplies to:
    - Vuda: 38 pcks, representing 1 % of the known packages needed
          (cumulative known need fulfilled: 7 %)

Simulation clock updated: 2d 23h 44min
  MRH-90 #1 arrived at Suva
    - MRH-90 #1 will undergo scheduled maintenance and will finish at 3d 3h 44min

Simulation clock updated: 3d 0h 10min
  MRH-90 #2 departed from Suva to deliver supplies to Vuda
    - Scheduled to arrive at 3d 0h 45min

Simulation clock updated: 3d 0h 42min
  MRH-90 #3 departed from Suva to deliver supplies to Vuda
    - Scheduled to arrive at 3d 1h 17min

Simulation clock updated: 3d 0h 45min
  MRH-90 #2 delivered 38 packages to Vuda
    - Cumulative known need fulfilled: 6 %
    - Now returning to Suva, scheduled to arrive at 3d 1h 51min

Simulation clock updated: 3d 1h 5min
  Packages arrived (Quantity: 2166)
  Package storage updated: 6738.0 packages in stock

Simulation clock updated: 3d 1h 17min
  MRH-90 #3 delivered 38 packages to Vuda
    - Cumulative known need fulfilled: 7 %
    - Now returning to Suva, scheduled to arrive at 3d 2h 23min

Simulation clock updated: 3d 1h 51min
  MRH-90 #2 arrived at Suva
  Packages loaded onto cargo flight (total quantity: 38.0)
  Package storage updated: 6700.0 packages in stock
  MRH-90 #2 will take off at 3d 2h 51min to deliver relief supplies to:
    - Vuda: 38 pcks, representing 1 % of the known packages needed
          (cumulative known need fulfilled: 8 %)

Simulation clock updated: 3d 2h 23min
MRH-90 #3 arrived at Suva
- MRH-90 #3 will undergo scheduled maintenance and will finish at 3d 6h 23min

Simulation clock updated: 3d 2h 51min
MRH-90 #2 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 3d 3h 26min

Simulation clock updated: 3d 3h 26min
MRH-90 #2 delivered 38 packages to Vuda
- Cumulative known need fulfilled: 8 %
- Now returning to Suva, scheduled to arrive at 3d 4h 32min

Simulation clock updated: 3d 3h 44min
MRH-90 #1 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6662.0 packages in stock
MRH-90 #1 will take off at 3d 4h 44min to deliver relief supplies to:
- Vuda: 38 pcks, representing 1 % of the known packages needed (cumulative known need fulfilled: 9 %)

Simulation clock updated: 3d 4h 32min
MRH-90 #2 arrived at Suva
- MRH-90 #2 will undergo scheduled and unscheduled maintenance and will finish at 3d 13h 32min

Simulation clock updated: 3d 4h 44min
MRH-90 #1 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 3d 5h 19min

Simulation clock updated: 3d 5h 0min
AP-3C departed from Suva to assess Saivou
- Scheduled to arrive at 3d 5h 10min

Simulation clock updated: 3d 5h 10min
AP-3C arrived at Saivou and started assessment
- Scheduled to finish at 3d 6h 9min

Simulation clock updated: 3d 5h 19min
MRH-90 #1 delivered 38 packages to Vuda
- Cumulative known need fulfilled: 9 %
- Now returning to Suva, scheduled to arrive at 3d 6h 25min

Simulation clock updated: 3d 6h 9min
AP-3C finished assessing Saivou
- Assessment results will be processed after landing

- Now heading to Nalawa, scheduled to arrive at 3d 6h 11min

Simulation clock updated: 3d 6h 11min
AP-3C arrived at Nalawa and started assessment
- Scheduled to finish at 3d 6h 58min

Simulation clock updated: 3d 6h 23min
MRH-90 #3 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6624.0 packages in stock
MRH-90 #3 will take off at 3d 7h 23min to deliver relief supplies to:
- Vuda: 38 pcks, representing 1 % of the known packages needed (cumulative known need fulfilled: 11 %)

Simulation clock updated: 3d 6h 25min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6586.0 packages in stock
MRH-90 #1 will take off at 3d 7h 25min to deliver relief supplies to:
- Sasa: 38 pcks, representing 16 % of the known packages needed (cumulative known need fulfilled: 16 %)

Simulation clock updated: 3d 6h 58min
AP-3C finished assessing Nalawa
- Assessment results will be processed after landing
- Now heading to Wainimala, scheduled to arrive at 3d 7h 1min

Simulation clock updated: 3d 7h 1min
AP-3C arrived at Wainimala and started assessment
- Scheduled to finish at 3d 8h 5min

Simulation clock updated: 3d 7h 23min
MRH-90 #3 departed from Suva to deliver supplies to Vuda
- Scheduled to arrive at 3d 7h 58min

Simulation clock updated: 3d 7h 25min
MRH-90 #1 departed from Suva to deliver supplies to Sasa
- Scheduled to arrive at 3d 7h 57min

Simulation clock updated: 3d 7h 57min
MRH-90 #1 delivered 38 packages to Sasa
- Cumulative known need fulfilled: 16 %
- Now returning to Suva, scheduled to arrive at 3d 9h 0min

Simulation clock updated: 3d 7h 58min
MRH-90 #3 delivered 38 packages to Vuda

- Cumulative known need fulfilled: 11 %
- Now returning to Suva, scheduled to arrive at 3d 9h 4min

Simulation clock updated: 3d 8h 5min
AP-3C finished assessing Wainimala
- Assessment results will be processed after landing
- Now heading to Ruwailevu, scheduled to arrive at 3d 8h 11min

Simulation clock updated: 3d 8h 11min
AP-3C arrived at Ruwailevu and started assessment
- Scheduled to finish at 3d 9h 13min

Simulation clock updated: 3d 9h 0min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6548.0 packages in stock
MRH-90 #1 will take off at 3d 10h 0min to deliver relief supplies to:
- Ba: 38 pcks, representing 8 % of the known packages needed
(cumulative known need fulfilled: 8 %)

Simulation clock updated: 3d 9h 4min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6510.0 packages in stock
MRH-90 #3 will take off at 3d 10h 4min to deliver relief supplies to:
- Ba: 38 pcks, representing 8 % of the known packages needed
(cumulative known need fulfilled: 15 %)

Simulation clock updated: 3d 9h 13min
AP-3C finished assessing Ruwailevu
- Assessment results will be processed after landing
- Now returning to Suva, scheduled to arrive at 3d 9h 25min

Simulation clock updated: 3d 9h 25min
AP-3C arrived at Suva
- Assessment results for the following location(s) will be available at 3d 12h 25min:
Saivou
Nalawa
Wainimala
Ruwailevu

Simulation clock updated: 3d 10h 0min
MRH-90 #1 departed from Suva to deliver supplies to Ba
- Scheduled to arrive at 3d 10h 33min

Simulation clock updated: 3d 10h 4min
MRH-90 #3 departed from Suva to deliver supplies to Ba
- Scheduled to arrive at 3d 10h 37min

Simulation clock updated: 3d 10h 33min
MRH-90 #1 delivered 38 packages to Ba
- Cumulative known need fulfilled: 8 %
- Now returning to Suva, scheduled to arrive at 3d 11h 36min

Simulation clock updated: 3d 10h 37min
MRH-90 #3 delivered 38 packages to Ba
- Cumulative known need fulfilled: 15 %
- Now returning to Suva, scheduled to arrive at 3d 11h 39min

Simulation clock updated: 3d 11h 36min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6472.0 packages in stock
MRH-90 #1 will take off at 3d 12h 36min to deliver relief supplies to:
- Tavua: 38 pcks, representing 12 % of the known packages needed
(cumulative known need fulfilled: 12 %)

Simulation clock updated: 3d 11h 39min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6434.0 packages in stock
MRH-90 #3 will take off at 3d 12h 39min to deliver relief supplies to:
- Magodro: 38 pcks, representing 73 % of the known packages needed
(cumulative known need fulfilled: 73 %)

Simulation clock updated: 3d 12h 25min
Population in need at Saivou was updated to 82%
Population in need at Nalawa was updated to 98%
Population in need at Wainimala was updated to 90%
Population in need at Ruwailevu was updated to 5%

Simulation clock updated: 3d 12h 36min
MRH-90 #1 departed from Suva to deliver supplies to Tavua
- Scheduled to arrive at 3d 13h 5min

Simulation clock updated: 3d 12h 39min
MRH-90 #3 departed from Suva to deliver supplies to Magodro
- Scheduled to arrive at 3d 13h 5min

Simulation clock updated: 3d 13h 5min
MRH-90 #3 delivered 38 packages to Magodro

- Cumulative known need fulfilled: 73 %
- Now returning to Suva, scheduled to arrive at 3d 14h 2min

Simulation clock updated: 3d 13h 5min
MRH-90 #1 delivered 38 packages to Tavua
- Cumulative known need fulfilled: 12 %
- Now returning to Suva, scheduled to arrive at 3d 14h 5min

Simulation clock updated: 3d 13h 32min
MRH-90 #2 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6396.0 packages in stock
MRH-90 #2 will take off at 3d 14h 32min to deliver relief supplies to:
- Rakiraki: 38 pcks, representing 6 % of the known packages needed (cumulative known need fulfilled: 6 %)

Simulation clock updated: 3d 14h 2min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6358.0 packages in stock
MRH-90 #3 will take off at 3d 15h 2min to deliver relief supplies to:
- Rakiraki: 38 pcks, representing 6 % of the known packages needed (cumulative known need fulfilled: 13 %)

Simulation clock updated: 3d 14h 5min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6320.0 packages in stock
MRH-90 #1 will take off at 3d 15h 5min to deliver relief supplies to:
- Saivou: 38 pcks, representing 13 % of the known packages needed (cumulative known need fulfilled: 13 %)

Simulation clock updated: 3d 14h 32min
MRH-90 #2 departed from Suva to deliver supplies to Rakiraki
- Scheduled to arrive at 3d 14h 57min

Simulation clock updated: 3d 14h 57min
MRH-90 #2 delivered 38 packages to Rakiraki
- Cumulative known need fulfilled: 6 %
- Now returning to Suva, scheduled to arrive at 3d 15h 53min

Simulation clock updated: 3d 15h 2min
MRH-90 #3 departed from Suva to deliver supplies to Rakiraki
- Scheduled to arrive at 3d 15h 27min

Simulation clock updated: 3d 15h 5min
MRH-90 #1 departed from Suva to deliver supplies to Saivou
- Scheduled to arrive at 3d 15h 26min

Simulation clock updated: 3d 15h 26min
MRH-90 #1 delivered 38 packages to Saivou
- Cumulative known need fulfilled: 13 %
- Now returning to Suva, scheduled to arrive at 3d 16h 17min

Simulation clock updated: 3d 15h 27min
MRH-90 #3 delivered 38 packages to Rakiraki
- Cumulative known need fulfilled: 13 %
- Now returning to Suva, scheduled to arrive at 3d 16h 23min

Simulation clock updated: 3d 15h 53min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6282.0 packages in stock
MRH-90 #2 will take off at 3d 16h 53min to deliver relief supplies to:
- Wainimala: 38 pcks, representing 20 % of the known packages needed
(cumulative known need fulfilled: 20 %)

Simulation clock updated: 3d 16h 17min
MRH-90 #1 arrived at Suva
- MRH-90 #1 will undergo scheduled maintenance and will finish at 3d 20h 17min

Simulation clock updated: 3d 16h 23min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6244.0 packages in stock
MRH-90 #3 will take off at 3d 17h 23min to deliver relief supplies to:
- Nalawa: 38 pcks, representing 16 % of the known packages needed
(cumulative known need fulfilled: 16 %)

Simulation clock updated: 3d 16h 40min
Packages arrived (Quantity: 549)
Package storage updated: 6793.0 packages in stock

Simulation clock updated: 3d 16h 53min
MRH-90 #2 departed from Suva to deliver supplies to Wainimala
- Scheduled to arrive at 3d 17h 14min

Simulation clock updated: 3d 17h 14min
MRH-90 #2 delivered 38 packages to Wainimala
- Cumulative known need fulfilled: 20 %
- Now returning to Suva, scheduled to arrive at 3d 18h 5min

Simulation clock updated: 3d 17h 23min
MRH-90 #3 departed from Suva to deliver supplies to Nalawa
- Scheduled to arrive at 3d 17h 43min

Simulation clock updated: 3d 17h 43min
MRH-90 #3 delivered 38 packages to Nalawa
- Cumulative known need fulfilled: 16 %
- Now returning to Suva, scheduled to arrive at 3d 18h 32min

Simulation clock updated: 3d 18h 5min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6755.0 packages in stock
MRH-90 #2 will take off at 3d 19h 5min to deliver relief supplies to:
- Nakorotubu: 38 pcks, representing 21 % of the known packages needed
(cumulative known need fulfilled: 21 %)

Simulation clock updated: 3d 18h 32min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 6717.0 packages in stock
MRH-90 #3 will take off at 3d 19h 32min to deliver relief supplies to:
- Ovalau: 38 pcks, representing 10 % of the known packages needed
(cumulative known need fulfilled: 10 %)

Simulation clock updated: 3d 19h 0min
Packages arrived (Quantity: 2166)
Package storage updated: 8883.0 packages in stock

Simulation clock updated: 3d 19h 5min
MRH-90 #2 departed from Suva to deliver supplies to Nakorotubu
- Scheduled to arrive at 3d 19h 22min

Simulation clock updated: 3d 19h 22min
MRH-90 #2 delivered 38 packages to Nakorotubu
- Cumulative known need fulfilled: 21 %
- Now returning to Suva, scheduled to arrive at 3d 20h 10min

Simulation clock updated: 3d 19h 32min
MRH-90 #3 departed from Suva to deliver supplies to Ovalau
- Scheduled to arrive at 3d 19h 46min

Simulation clock updated: 3d 19h 46min
MRH-90 #3 delivered 38 packages to Ovalau
- Cumulative known need fulfilled: 10 %
- Now returning to Suva, scheduled to arrive at 3d 20h 30min

Simulation clock updated: 3d 20h 10min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8845.0 packages in stock
MRH-90 #2 will take off at 3d 21h 10min to deliver relief supplies to:
- Ovalau: 38 pcks, representing 10 % of the known packages needed (cumulative known need fulfilled: 19 %)

Simulation clock updated: 3d 20h 17min
MRH-90 #1 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8807.0 packages in stock
MRH-90 #1 will take off at 3d 21h 17min to deliver relief supplies to:
- Wainibuka: 38 pcks, representing 68 % of the known packages needed (cumulative known need fulfilled: 68 %)

Simulation clock updated: 3d 20h 30min
MRH-90 #3 arrived at Suva
- MRH-90 #3 will undergo scheduled maintenance and will finish at 4d 0h 30min

Simulation clock updated: 3d 21h 10min
MRH-90 #2 departed from Suva to deliver supplies to Ovalau
- Scheduled to arrive at 3d 21h 24min

Simulation clock updated: 3d 21h 17min
MRH-90 #1 departed from Suva to deliver supplies to Wainibuka
- Scheduled to arrive at 3d 21h 31min

Simulation clock updated: 3d 21h 24min
MRH-90 #2 delivered 38 packages to Ovalau
- Cumulative known need fulfilled: 19 %
- Now returning to Suva, scheduled to arrive at 3d 22h 8min

Simulation clock updated: 3d 21h 31min
MRH-90 #1 delivered 38 packages to Wainibuka
- Cumulative known need fulfilled: 68 %
- Now returning to Suva, scheduled to arrive at 3d 22h 15min

Simulation clock updated: 3d 22h 8min
MRH-90 #2 arrived at Suva

Simulation clock updated: 3d 22h 15min
MRH-90 #1 arrived at Suva

Simulation clock updated: 4d 0h 30min
MRH-90 #3 returned from maintenance and is available for new flights

Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8769.0 packages in stock
MRH-90 #1 will take off at 4d 1h 30min to deliver relief supplies to:
- Tunuloa: 37 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Saqani: 1 pcks, representing 7 % of the known packages needed (cumulative known need fulfilled: 7 %)

Simulation clock updated: 4d 1h 30min
MRH-90 #1 departed from Suva to deliver supplies to Tunuloa
- Scheduled to arrive at 4d 2h 35min
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8731.0 packages in stock
MRH-90 #2 will take off at 4d 2h 30min to deliver relief supplies to:
- Saqani: 13 pcks, representing 93 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Vaturova: 24 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Nairai: 1 pcks, representing 25 % of the known packages needed (cumulative known need fulfilled: 25 %)

Simulation clock updated: 4d 2h 30min
MRH-90 #2 departed from Suva to deliver supplies to Saqani
- Scheduled to arrive at 4d 3h 34min
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8693.0 packages in stock
MRH-90 #3 will take off at 4d 3h 30min to deliver relief supplies to:
- Yasawa: 10 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Nawaka: 28 pcks, representing 29 % of the known packages needed (cumulative known need fulfilled: 29 %)

Simulation clock updated: 4d 2h 35min
MRH-90 #1 delivered 37 packages to Tunuloa
- Cumulative known need fulfilled: 100 %
- Now heading to Saqani, scheduled to arrive at 4d 3h 10min

Simulation clock updated: 4d 3h 10min
MRH-90 #1 delivered 1 packages to Saqani
- Cumulative known need fulfilled: 7 %
- Now returning to Suva, scheduled to arrive at 4d 4h 44min

Simulation clock updated: 4d 3h 30min
MRH-90 #3 departed from Suva to deliver supplies to Yasawa
- Scheduled to arrive at 4d 4h 24min

Simulation clock updated: 4d 3h 34min
MRH-90 #2 delivered 13 packages to Saqani
- Cumulative known need fulfilled: 100 %
- Now heading to Vaturova, scheduled to arrive at 4d 4h 12min

Simulation clock updated: 4d 4h 12min
MRH-90 #2 delivered 24 packages to Vaturova
- Cumulative known need fulfilled: 100 %
- Now heading to Nairai, scheduled to arrive at 4d 5h 23min

Simulation clock updated: 4d 4h 24min
MRH-90 #3 delivered 10 packages to Yasawa
- Cumulative known need fulfilled: 100 %
- Now heading to Nawaka, scheduled to arrive at 4d 5h 28min

Simulation clock updated: 4d 4h 44min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8655.0 packages in stock
MRH-90 #1 will take off at 4d 5h 44min to deliver relief supplies to:
- Bua: 38 pcks, representing 73 % of the known packages needed
(cumulative known need fulfilled: 73 %)

Simulation clock updated: 4d 5h 23min
MRH-90 #2 delivered 1 packages to Nairai
- Cumulative known need fulfilled: 25 %
- Now returning to Suva, scheduled to arrive at 4d 6h 22min

Simulation clock updated: 4d 5h 28min
MRH-90 #3 delivered 28 packages to Nawaka
- Cumulative known need fulfilled: 29 %
- Now returning to Suva, scheduled to arrive at 4d 6h 35min

Simulation clock updated: 4d 5h 44min
MRH-90 #1 departed from Suva to deliver supplies to Bua
- Scheduled to arrive at 4d 6h 27min

Simulation clock updated: 4d 6h 22min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8617.0 packages in stock
MRH-90 #2 will take off at 4d 7h 22min to deliver relief supplies to:
- Ruwailevu: 12 pcks, representing 100 % of the known packages needed
(cumulative known need fulfilled: 100 %)
- Navosa: 26 pcks, representing 70 % of the known packages needed
(cumulative known need fulfilled: 70 %)

Simulation clock updated: 4d 6h 27min
MRH-90 #1 delivered 38 packages to Bua
- Cumulative known need fulfilled: 73 %
- Now returning to Suva, scheduled to arrive at 4d 7h 41min

Simulation clock updated: 4d 6h 35min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 8579.0 packages in stock
MRH-90 #3 will take off at 4d 7h 35min to deliver relief supplies to:
- Batiki: 2 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)
- Matailobau: 36 pcks, representing 92 % of the known packages needed (cumulative known need fulfilled: 92 %)

Simulation clock updated: 4d 7h 22min
MRH-90 #2 departed from Suva to deliver supplies to Ruwailevu
- Scheduled to arrive at 4d 7h 48min

Simulation clock updated: 4d 7h 35min
MRH-90 #3 departed from Suva to deliver supplies to Batiki
- Scheduled to arrive at 4d 7h 55min

Simulation clock updated: 4d 7h 41min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 30)
Package storage updated: 8549.0 packages in stock
MRH-90 #1 will take off at 4d 8h 41min to deliver relief supplies to:
- Waimaro: 30 pcks, representing 100 % of the known packages needed (cumulative known need fulfilled: 100 %)

Simulation clock updated: 4d 7h 48min
MRH-90 #2 delivered 12 packages to Ruwailevu
- Cumulative known need fulfilled: 100 %
- Now heading to Navosa, scheduled to arrive at 4d 8h 23min

Simulation clock updated: 4d 7h 55min
MRH-90 #3 delivered 2 packages to Batiki
- Cumulative known need fulfilled: 100 %
- Now heading to Matailobau, scheduled to arrive at 4d 8h 54min

Simulation clock updated: 4d 8h 23min
MRH-90 #2 delivered 26 packages to Navosa
- Cumulative known need fulfilled: 70 %
- Now returning to Suva, scheduled to arrive at 4d 9h 16min

Simulation clock updated: 4d 8h 41min
MRH-90 #1 departed from Suva to deliver supplies to Waimaro
- Scheduled to arrive at 4d 8h 57min

Simulation clock updated: 4d 8h 50min
Packages arrived (Quantity: 2166)
Package storage updated: 10715.0 packages in stock

Simulation clock updated: 4d 8h 54min
MRH-90 #3 delivered 36 packages to Matailobau
- Cumulative known need fulfilled: 92 %
- Now returning to Suva, scheduled to arrive at 4d 9h 36min

Simulation clock updated: 4d 8h 57min
MRH-90 #1 delivered 30 packages to Waimaro
- Cumulative known need fulfilled: 100 %
- Now returning to Suva, scheduled to arrive at 4d 9h 42min

Simulation clock updated: 4d 9h 16min
MRH-90 #2 arrived at Suva
- MRH-90 #2 will undergo scheduled and unscheduled maintenance and will finish at 4d 18h 16min

Simulation clock updated: 4d 9h 36min
MRH-90 #3 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 10677.0 packages in stock
MRH-90 #3 will take off at 4d 10h 36min to deliver relief supplies to:
- Rakiraki: 38 pcks, representing 6 % of the known packages needed (cumulative known need fulfilled: 19 %)

Simulation clock updated: 4d 9h 42min
MRH-90 #1 arrived at Suva
- MRH-90 #1 will undergo unscheduled maintenance and will finish at 4d 14h 42min

Simulation clock updated: 4d 10h 36min
MRH-90 #3 departed from Suva to deliver supplies to Rakiraki
- Scheduled to arrive at 4d 11h 1min

Simulation clock updated: 4d 11h 1min
MRH-90 #3 delivered 38 packages to Rakiraki
- Cumulative known need fulfilled: 19 %
- Now returning to Suva, scheduled to arrive at 4d 11h 57min

Simulation clock updated: 4d 11h 57min
MRH-90 #3 arrived at Suva

Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 10639.0 packages in stock
MRH-90 #3 will take off at 4d 12h 57min to deliver relief supplies to:
- Cakaudrove: 38 pcks, representing 10 % of the known packages needed (cumulative known need fulfilled: 29 %)

Simulation clock updated: 4d 12h 55min
Packages arrived (Quantity: 549)
Package storage updated: 11188.0 packages in stock

Simulation clock updated: 4d 12h 57min
MRH-90 #3 departed from Suva to deliver supplies to Cakaudrove
- Scheduled to arrive at 4d 13h 56min

Simulation clock updated: 4d 13h 56min
MRH-90 #3 delivered 38 packages to Cakaudrove
- Cumulative known need fulfilled: 29 %
- Now returning to Suva, scheduled to arrive at 4d 15h 25min

Simulation clock updated: 4d 14h 42min
MRH-90 #1 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 11150.0 packages in stock
MRH-90 #1 will take off at 4d 15h 42min to deliver relief supplies to:
- Nasavusavu: 38 pcks, representing 11 % of the known packages needed (cumulative known need fulfilled: 22 %)

Simulation clock updated: 4d 15h 25min
MRH-90 #3 arrived at Suva
- MRH-90 #3 will undergo scheduled maintenance and will finish at 4d 19h 25min

Simulation clock updated: 4d 15h 42min
MRH-90 #1 departed from Suva to deliver supplies to Nasavusavu
- Scheduled to arrive at 4d 16h 34min

Simulation clock updated: 4d 16h 34min
MRH-90 #1 delivered 38 packages to Nasavusavu
- Cumulative known need fulfilled: 22 %
- Now returning to Suva, scheduled to arrive at 4d 17h 56min

Simulation clock updated: 4d 17h 56min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 11112.0 packages in stock
MRH-90 #1 will take off at 4d 18h 56min to deliver relief supplies to:
- Wainunu: 38 pcks, representing 17 % of the known packages needed

(cumulative known need fulfilled: 35 %)

Simulation clock updated: 4d 18h 16min
MRH-90 #2 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 11074.0 packages in stock
MRH-90 #2 will take off at 4d 19h 16min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed
(cumulative known need fulfilled: 13 %)

Simulation clock updated: 4d 18h 56min
MRH-90 #1 departed from Suva to deliver supplies to Wainunu
- Scheduled to arrive at 4d 19h 37min

Simulation clock updated: 4d 19h 16min
MRH-90 #2 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 4d 19h 52min

Simulation clock updated: 4d 19h 25min
MRH-90 #3 returned from maintenance and is available for new flights
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 11036.0 packages in stock
MRH-90 #3 will take off at 4d 20h 25min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed
(cumulative known need fulfilled: 15 %)

Simulation clock updated: 4d 19h 37min
MRH-90 #1 delivered 38 packages to Wainunu
- Cumulative known need fulfilled: 35 %
- Now returning to Suva, scheduled to arrive at 4d 20h 48min

Simulation clock updated: 4d 19h 52min
MRH-90 #2 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 13 %
- Now returning to Suva, scheduled to arrive at 4d 20h 59min

Simulation clock updated: 4d 20h 25min
MRH-90 #3 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 4d 21h 2min

Simulation clock updated: 4d 20h 48min
MRH-90 #1 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 10998.0 packages in stock
MRH-90 #1 will take off at 4d 21h 48min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed

(cumulative known need fulfilled: 18 %)

Simulation clock updated: 4d 20h 59min
MRH-90 #2 arrived at Suva
Packages loaded onto cargo flight (total quantity: 38.0)
Package storage updated: 10960.0 packages in stock
MRH-90 #2 will take off at 4d 21h 59min to deliver relief supplies to:
- Nadi: 38 pcks, representing 3 % of the known packages needed
(cumulative known need fulfilled: 20 %)

Simulation clock updated: 4d 21h 2min
MRH-90 #3 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 15 %
- Now returning to Suva, scheduled to arrive at 4d 22h 9min

Simulation clock updated: 4d 21h 48min
MRH-90 #1 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 4d 22h 25min

Simulation clock updated: 4d 21h 59min
MRH-90 #2 departed from Suva to deliver supplies to Nadi
- Scheduled to arrive at 4d 22h 36min

Simulation clock updated: 4d 22h 9min
MRH-90 #3 arrived at Suva

Simulation clock updated: 4d 22h 25min
MRH-90 #1 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 18 %
- Now returning to Suva, scheduled to arrive at 4d 23h 31min

Simulation clock updated: 4d 22h 36min
MRH-90 #2 delivered 38 packages to Nadi
- Cumulative known need fulfilled: 20 %
- Now returning to Suva, scheduled to arrive at 4d 23h 43min

Simulation clock updated: 4d 23h 31min
MRH-90 #1 arrived at Suva

Simulation clock updated: 4d 23h 43min
MRH-90 #2 arrived at Suva

Simulation completed

APPENDIX E. FULL RESULTS

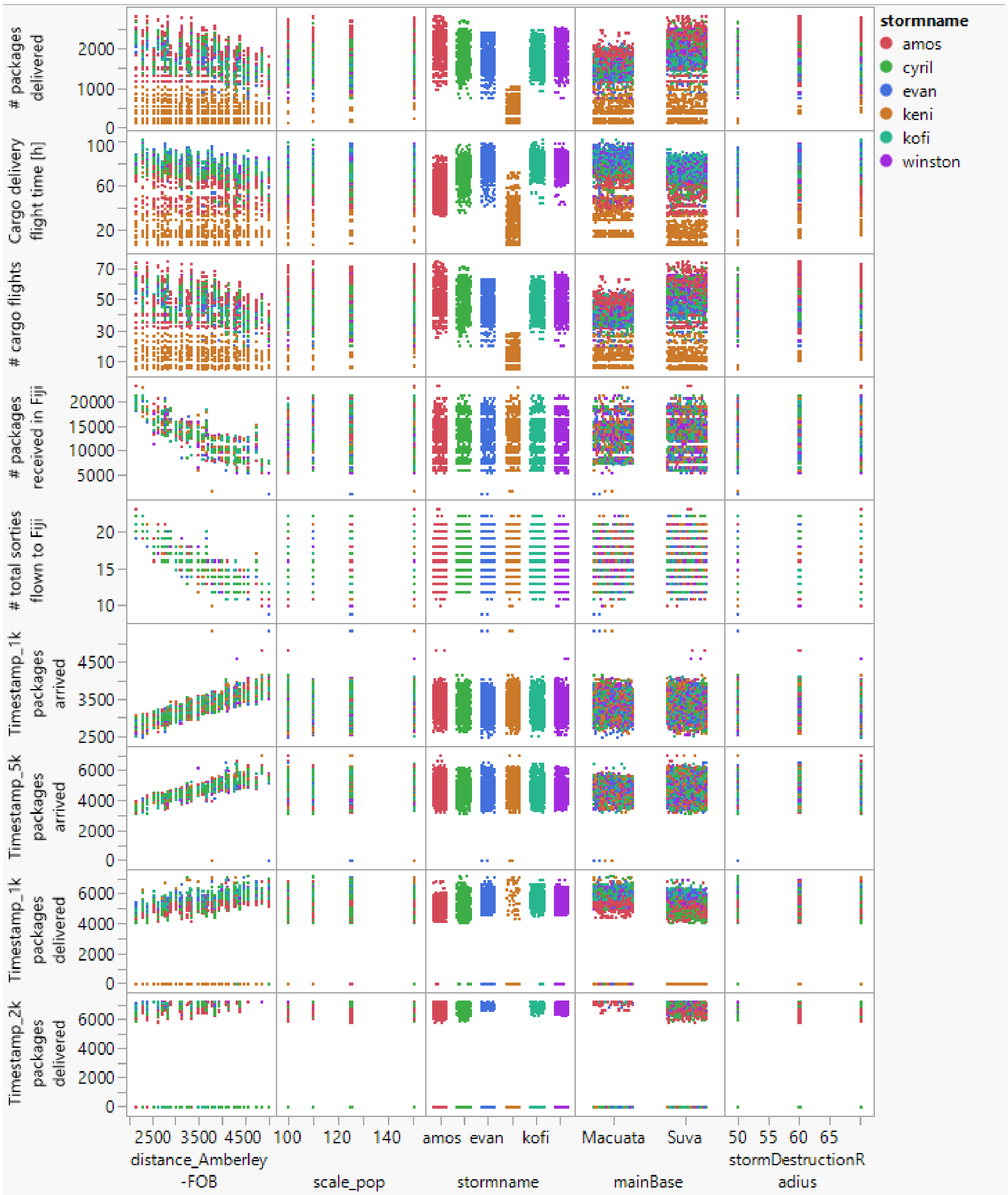


Figure 66: Scatterplot visualization of the results of the Scenario Modularization Validation for the Fiji theater

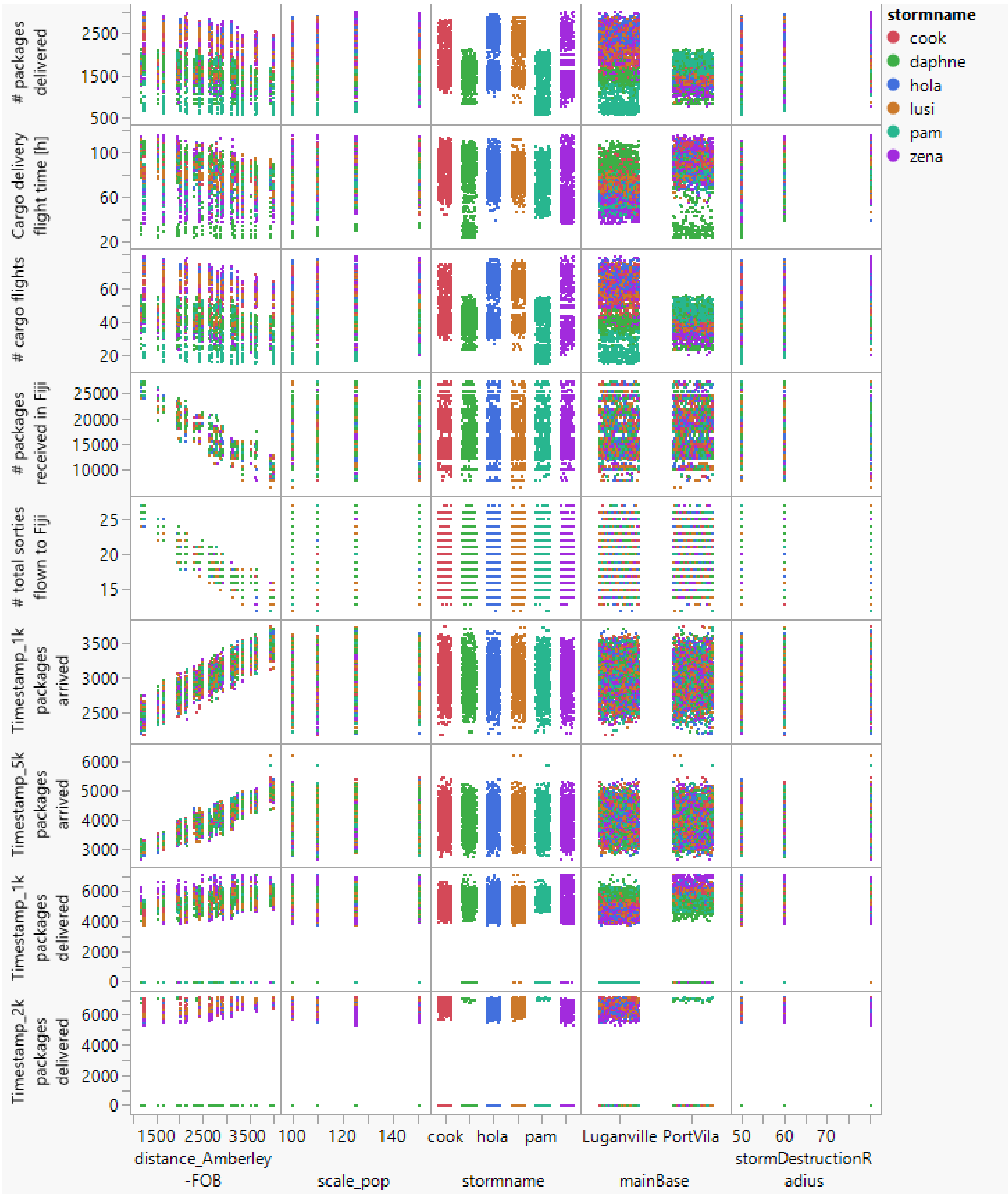


Figure 67: Scatterplot visualization of the results of the Scenario Modularization Validation for the Vanuatu theater

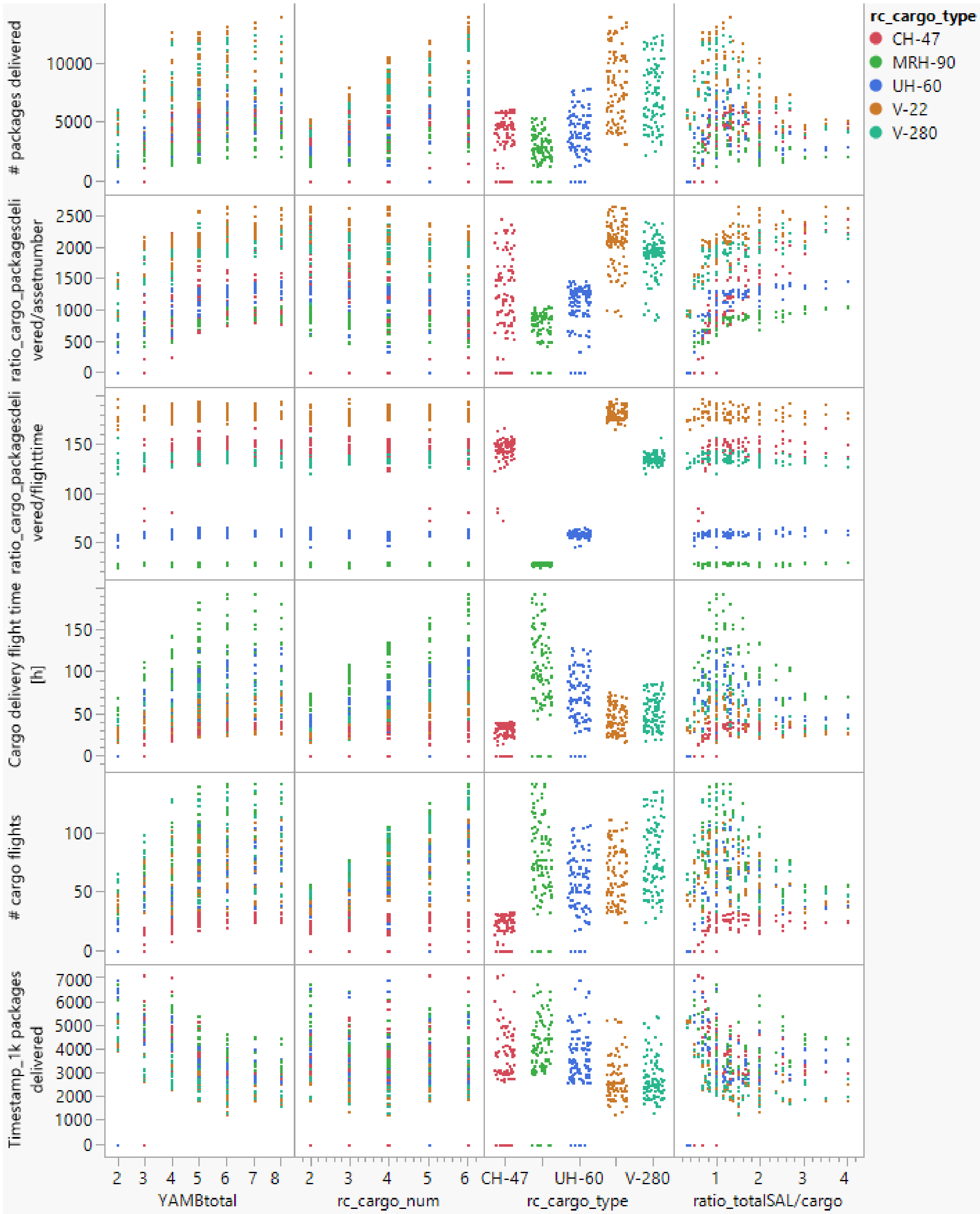


Figure 68: Scatterplot visualization of the results of the Design and Options Space Validation for materiel aspects with vertical airlift

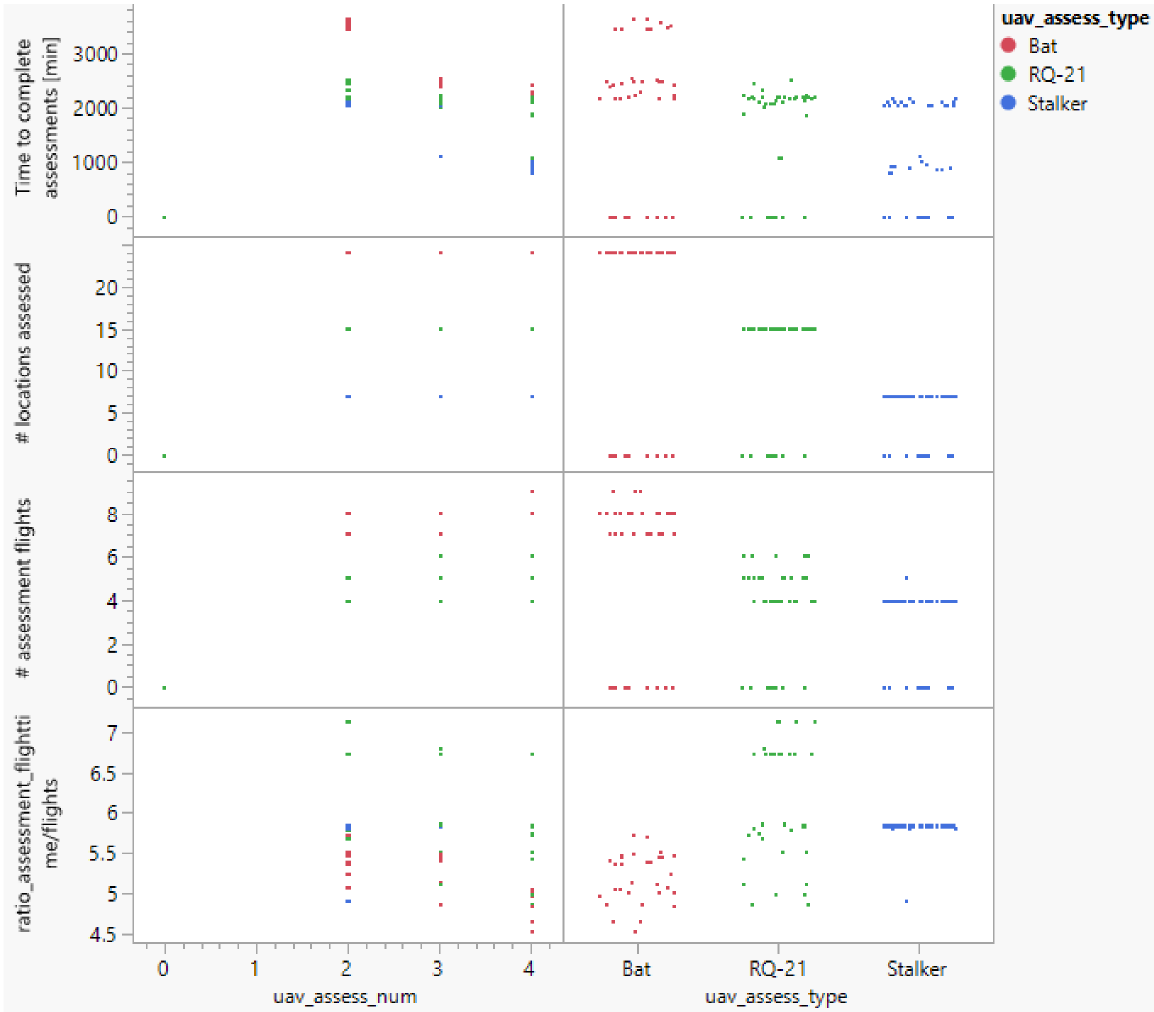


Figure 69: Scatterplot visualization of the results of the Design and Options Space Validation for materiel aspects with assessment vehicles

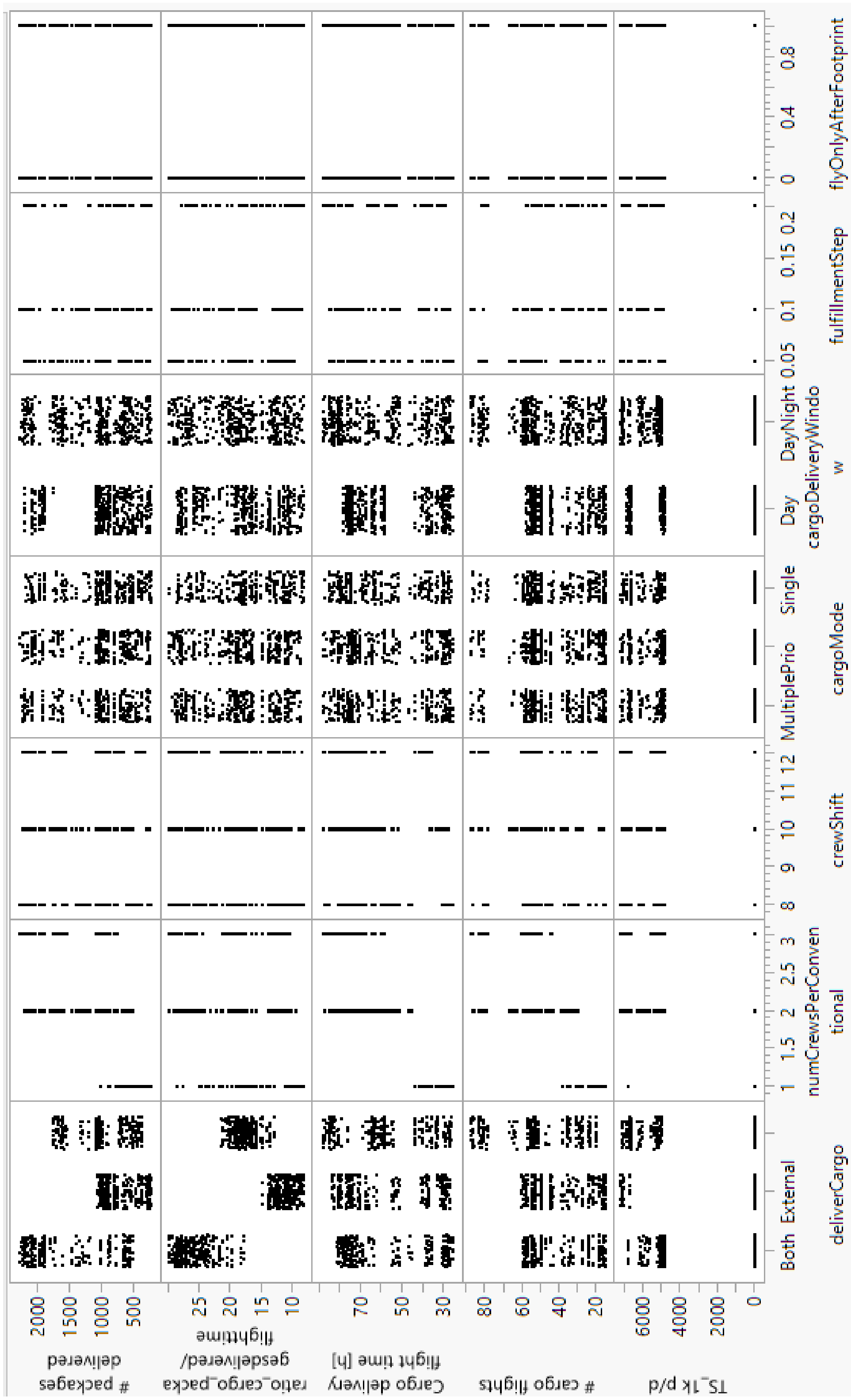


Figure 70: Scatterplot visualization of the results of the Design and Options Space Validation for doctrinal aspects concerning aid delivery

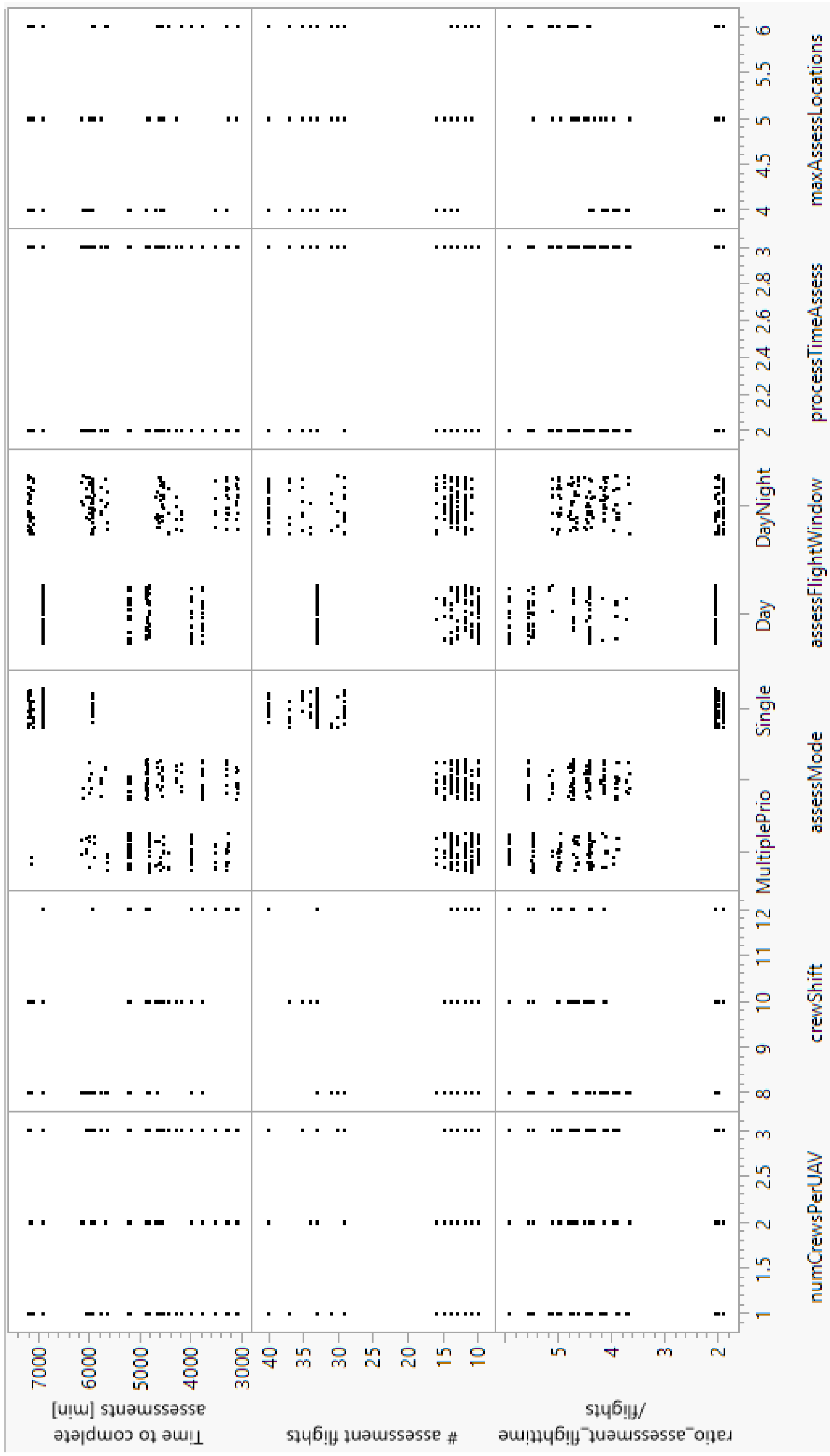


Figure 71: Scatterplot visualization of the results of the Design and Options Space Validation for doctrinal aspects concerning theater assessment

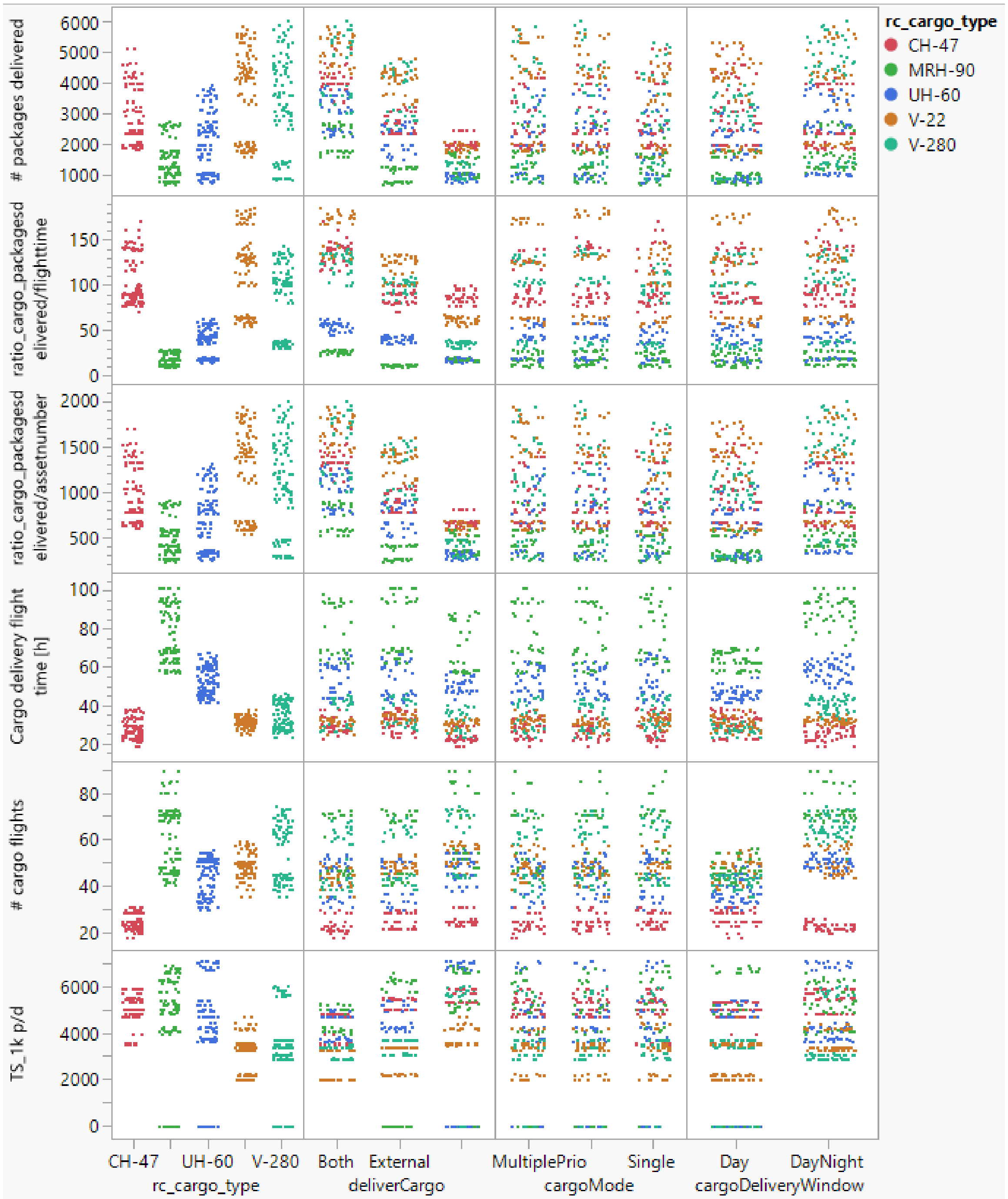


Figure 72: Scatterplot visualization of the results of the Demonstration Case Study for the Fiji theater

Figure 73: Scatterplot visualization of the results of the Demonstration Case for the Vanuatu theater

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