



CONCEPT OF OPERATIONS IN AN AGENT-BASED SIMULATION: A SYSTEM-OF-SYSTEMS APPROACH

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Abstract

This paper introduces a novel method for developing Concepts of Operations (ConOps) through Agent-Based Simulations (ABS) within a System-of-Systems (SoS) framework, employing the Unified Architecture Framework (UAF) to enhance operational adaptability in forest firefighting scenarios. ConOps serve as strategic frameworks that define system operations to meet specific user needs and are crucial in environments where independent systems interact complexly as in SoS. ABS is a technique that can be used to model these interactions and provide insights into emergent behaviours which are critical for understanding system dynamics. The UAF organizes these interactions and align diverse stakeholder needs with operational requirements. By integrating diverse stakeholder needs and operational requirements, the proposed method facilitates the iterative development and validation of ConOps, ensuring that the simulations effectively reflect complex real-world interactions and behaviours. The method also prioritizes the identification and analysis of emergent behaviours within SoSs which are key aspects for adapting to the unpredictable dynamics of forest firefighting. This paper outlines the process from stakeholder analysis to the operational implementation of ConOps, providing a comprehensive framework that aims to enhance the effectiveness of ABS in strategic decision-making processes.

Keywords: System-of-Systems (SoS), Agent-Based Simulation (ABS), Concept of Operations (ConOps), Forest Firefighting, Unified Architecture Framework (UAF)

1. Introduction

In the contemporary landscape of systems engineering, the concept of a System-of-Systems (SoS) represents an advanced framework where multiple independent systems are integrated to perform functions that surpass their individual capabilities towards a goal that cannot be achieved by a single system alone [1]. This integration presents both unique challenges and opportunities for modelling and simulation, particularly through Agent-Based Simulations (ABS), which may provide insights into emergent behaviours, highly regarded aspects for understanding the dynamics within SoSs. Employing the Unified Architecture Framework (UAF) [2], the work presented in this paper seeks to systematically map and manage the interactions among disparate systems, aligning complex operational needs with overarching strategic objectives.

ABS are intended to be utilized to simulate the interactions of autonomous agents within the SoS, revealing the complex behaviours and dependencies that emerge from these interactions. This approach can be aimed towards domains such as forest firefighting, where dynamic responses to evolving situations are vital. The paper leverages UAF's operational viewpoints to explore how different configurations of systems can be orchestrated to improve collective operational effectiveness and adaptability. The Department of Defence's (DoD) Mission Engineering Guide [3] provides methods to extract the necessary inputs to describe the tasks for each system, and outputs for measuring the success criteria for each individual system and the SoS in general. Through detailed case studies, the

method demonstrates how integrating ABS with UAF can facilitate the development of comprehensive Concepts of Operations (ConOps). This ConOps method guides the deployment and operation of SoS in an ABS environment, enhancing decision-making processes by mapping the critical information regarding the agents' behaviour and environmental conditions to increase operational fidelity. The exploration of the ConOps method in this paper contributes to the body of knowledge on SoS by demonstrating a possible application of ABS and UAF in a critical real-world scenario, such as the wildfire fighting presented in this work as a use case. The findings suggest that the strategic integration of system simulations with architectural frameworks not only enhances understanding but also improves the performance and responsiveness of SoSs to meet both current and future challenges. The primary objective of this work is to define and analyse a range of alternative ConOps within an ABS framework, guided by the principles and structures of the UAF. The method aims to align the simulated operations with the diverse expectations and requirements of various stakeholders, ensuring that each ConOps addresses and fulfils their unique needs.

1.1 V-Model Perspective

The V-model [4] represents the system life cycle using an illustrative "V" that contains the decomposition and project definition on its left side, implementation or manufacturing on the bottom and system integration and testing on the right hand side. The V-model can have slightly different descriptions of the phases according to its usage, for example in avionics system development or software development among others [5, 6]. Figure 1 shows an illustration of a V-model.

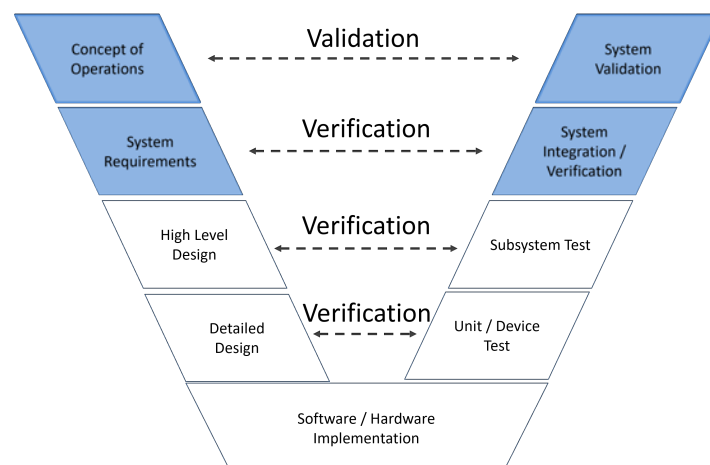


Figure 1 – V-model with emphasis on the initial stages (ConOps, System Requirements and their subsequent verification and validation stages).

The ConOps typically forms the initial phase of the V-model in systems engineering, serving as a link between high-level strategic objectives and detailed technical requirements, setting definitive benchmarks for functionality and performance.

The validation of ConOps through simulations ensures that the generated operational strategies are not only theoretically sound but also practically viable and effectively addressing real-world complexities and stakeholder needs.

The validation process at the ConOps stage aims to test and refine the system's operational strategies against predefined criteria, ensuring alignment with user requirements and operational feasibility. This not only confirms the efficacy of the ConOps but also facilitates a smoother transition to the system requirements phase, where detailed technical specifications are developed. By establishing a robust ConOps, the foundation is laid for the critical system integration and verification stages, ensuring that the transition from theoretical models to operational systems is seamless and effective. Focusing on the ConOps within the V-model allows for a structured progression from conceptual planning to practical implementation, ensuring that all system developments are traceable back to validated operational needs and stakeholder objectives. This structured approach assures to maintain coherence across the system's lifecycle, enhancing the system's adaptability and effectiveness in dynamic operational environments.

1.2 Related Research

This research is part of the broader initiatives under the Collaborative System of Systems Exploration of Aviation Products, Services & Business Models (COLOSSUS) project, funded by the European Union's Horizon 2020 research and innovation program. COLOSSUS aims to enhance the integration and management of complex SoS across critical sectors such as environmental management, emergency response, and aviation [7]. It seeks to develop innovative methods and tools that allow for the effective coordination and operational optimization of interconnected systems that are typically autonomous but must work collaboratively to address large-scale challenges. The project aspires to push the boundaries of current SoS applications, improving adaptability, scalability, and efficiency in response to dynamic operational demands.

Within the frame of the COLOSSUS project, a forest firefighting case study exemplifies the application of SoS methods in managing the complexities of wildfire control and mitigation. The forest firefighting case study demonstrates how SoS methods can be practically applied to the critical and increasingly prevalent issue of wildfire management. This case study is of relevant importance due to the rising frequency and intensity of forest fires [8], which present significant risks to life, ecosystems, and properties. It focuses on strategic resource deployment and the seamless coordination between aerial and ground-based firefighting units, employing state-of-the-art simulation tools to forecast fire progression, optimize firefighting tactics, and ultimately reduce environmental and economic impacts.

2. Problem Description

The presence of various stakeholders necessitates simulations that can accommodate a wide range of requirements and expectations. This diversity may lead to emergent behaviours in ABS, where the interaction of multiple agents yields outcomes that are not predictable from the individual agent's behaviour alone. The emergent behaviours add another layer of complexity to the outcomes of the operation, as they can significantly alter the course of firefighting efforts.

Agents in a forest firefighting scenario could include different types of aircraft, ground crews, and even autonomous systems, each with its own set of capabilities and limitations. Simulating all possible actions and interactions of these agents is a colossal task, requiring sophisticated algorithms to ensure that the simulated behaviours are realistic and effective.

The creation of a ConOps in an ABS within an SoS context is challenging due to the need to encompass a wide range of elements and considerations. One of the primary difficulties in capturing everything in a ConOps is the diversity of stakeholders and their differing needs and perspectives. For instance, in forest firefighting, stakeholders could range from local firefighting units to environmental agencies, each with unique priorities and objectives. It must communicate a vision that is comprehensive enough to encompass these varied viewpoints.

Another challenge is the need to define the roles and responsibilities of different stakeholders throughout the process. The ConOps should provide clear directives to realize the system's goals and objectives, detailing strategies, tactics, policies, and constraints affecting the system. It should also encompass the entire life cycle of the system, including processes for initiating, developing, maintaining, and retiring the system. Given the vast array of factors involved in forest firefighting and the need to coordinate multiple agents and systems, creating a ConOps that effectively captures all these elements is a complex task.

To guide the creation of a ConOps, the Object Management Group's UAF will be used to describe how the system interacts with its operational environment. The UAF Grid, as seen in Figure 2, provides a clear view of operational aspects that are aligned with the previously mentioned characteristics of a ConOps. Operational processes detail the execution of tasks, paralleling the ConOps' focus on procedural flow. Operational States reflecting the system's readiness and conditions are fundamental to ConOps' portrayal of the operational context. Interaction Scenarios outlines potential events and responses, echoing ConOps' situational narratives and lastly Operational Constraints frame the system's functional perimeters which are critical to ConOps' practical applicability within real-world limits.

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	Taxonomy Tx	Structure Sr	Connectivity Cn	Processes Pr	States St	Interaction Scenarios Is	Information If	Parameters Pm	Constraints Ct	Roadmap Rm	Traceability Tr
Metadata Md	Metadata Taxonomy Md-Tx	Metadata Structure Md-Sr	Metadata Connectivity Md-Cn	Metadata Processes Md-Pr	Metadata States Md-St	-	Conceptual Data Model, Logical Data Model, Physical schema, real world results	Environment Pm-En Measurements Pm-Me	Metadata Constraints Md-Ct	Metadata Roadmap Md-Rm	Metadata Traceability Md-Tr
Strategic St	Strategic Taxonomy St-Tx	Strategic Structure St-Sr	Strategic Connectivity St-Cn	-	Strategic States St-St	-			Strategic Constraints St-Ct	Strategic Deployment, St-Rm Strategic Phasing St-Rm	Strategic Traceability St-Tr
Operational Op	Operational Taxonomy Op-Tx	Operational Structure Op-Sr	Operational Connectivity Op-Cn	Operational Processes Op-Pr	Operational States Op-St	Operational Interaction Scenarios Op-Is			Operational Constraints Op-Ct	-	Operational Traceability Op-Tr
Services Sv	Service Taxonomy Sv-Tx	Service Structure Sv-Sr	Service Connectivity Sv-Cn	Service Processes Sv-Pr	Service States Sv-St	Service Interaction Scenarios Sv-Is			Service Constraints Sv-Ct	Service Roadmap Sv-Rm	Service Traceability Sv-Tr
Personnel Pr	Personnel Taxonomy Pr-Tx	Personnel Structure Pr-Sr	Personnel Connectivity Pr-Cn	Personnel Processes Pr-Pr	Personnel States Pr-St	Personnel Interaction Scenarios Pr-Is			Competence, Drivers, Performance Pr-Ct	Personnel Availability, Personnel Evolution, Personnel Forecast Pr-Rm	Personnel Traceability Pr-Tr
Resources Rs	Resource Taxonomy Rs-Tx	Resource Structure Rs-Sr	Resource Connectivity Rs-Cn	Resource Processes Rs-Pr	Resource States Rs-St	Resource Interaction Scenarios Rs-Is			Resource Constraints Rs-Ct	Resource evolution, Resource forecast Rs-Rm	Resource Traceability Rs-Tr
Security Sc	Security Taxonomy Sc-Tx	Security Structure Sc-Sr	Security Connectivity Sc-Cn	Security Processes Sc-Pr	-	-			Security Constraints Sc-Ct	-	Security Traceability Sc-Tr
Projects Pj	Project Taxonomy Pj-Tx	Project Structure Pj-Sr	Project Connectivity Pj-Cn	Project Processes PJ-Pr	-	-			-	Project Roadmap Pj-Rm	Project Traceability Pj-Tr
Standards Sd	Standard Taxonomy Sd-Tx	Standards Structure Sd-Sr	-	-	-	-			-	Standards Roadmap Sr-Rm	Standards Traceability Sr-Tr
Actuals Resources Ar		Actual Resources Structure Ar-Sr	Actual Resources Connectivity Ar-Cn	Simulation				Parametric Execution/ Evaluation	-	-	
Dictionary Dc											
Summary & Overview Sm-Ov											
Requirements Req											

Figure 2 – UAF grid matrix with emphasis on the operational viewpoints (highlighted in yellow).
Adapted from [2]

3. Frame of Reference

A Concept of Operations (ConOps) is a critical document in the development of systems, especially in complex scenarios. In an ABS for SoSs, the creation of a ConOps is an important input to describe in detail the needs of the stakeholders into behavioural characteristics of each agent. This section presents the literature focused on ConOps standards, best practices and use cases.

3.1 Standards and Definitions

According to the Department of Defense (DoD), a ConOps is a *"verbal or graphic statement that clearly and concisely expresses what the joint force commander intends to accomplish and how it will be done using available resources"* [9]. The IEEE describes ConOps as *"a user-oriented document that describes system characteristics for a proposed system from the user's viewpoint"* [10]. It is essentially a verbal or graphic statement that outlines a commander's assumptions or intent regarding an operation or series of operations.

The standard IEEE 1362-1998 [11] defines the System Definition-Concept of Operations document content and provides best practices of the approaches to represent the needed content such as diagrams or visual representations. It was later merged into the standard ISO/IEC/IEEE 29148:2018 [12] which provides the engineering requirements and serves as a guide for implementing the concepts described in the standard ISO/IEC/IEEE 15288 [13].

It is worth pointing out that the definition of ConOps differs between INCOSE [14] and NASA's Systems Engineering Handbook [15]. INCOSE views ConOps as a document that describes how an organization intends to operate a system to achieve its goals, focusing on the leadership's vision for operation and the assumptions about using the system under development. Meanwhile, NASA's definition of ConOps, as per the NASA Systems Engineering Handbook, aligns more closely with what

INCOSE terms an Operational Concept (OpsCon). NASA's approach to ConOps outlines the high-level concept of how the system will be used to meet stakeholder expectations. It includes describing the system from an operational perspective, capturing stakeholder needs, system goals, objectives, and key assumptions.

The NASA Systems Engineering Handbook differentiates between the Concept of Operations (ConOps) and the Operations Concept as follows:

- **Concept of Operations (ConOps):** Developed early in the system life cycle, the ConOps outlines the overall high-level concept of how the system will be used to meet stakeholder expectations, usually in a time-sequenced manner. The inputs for this initial stage are stakeholder needs, goals and objectives, constraints and success criteria. It offers an operational perspective of the system and aids in facilitating an understanding of the system's goals. It also serves as the foundation for subsequent definition documents and long-term operational planning activities.
- **Operations Concept:** This is a detailed description of how systems are used together to ensure the operational feasibility of the system. It includes how mission data, such as engineering or scientific data, are captured, returned, processed, made available to users, and archived for future reference. The Operations Concept focuses on the practical aspects of system operations, ensuring the operational plan is reasonable and achievable.

3.2 Frameworks and Engineering Guidelines

The DoD's Mission Engineering Guidelines [3] is a comprehensive guide on mission engineering, emphasizing a systematic approach to identifying, analysing, and addressing gaps in capabilities, technologies, and systems for mission success. It details methodologies for mission engineering, including digital engineering principles, robustness, transparency, and stakeholder engagement. The guide advocates for an iterative, data-driven process to improve decision-making and outcomes through detailed analysis, simulation, and evaluation of mission architectures, and engineering threads. It highlights the importance of adapting mission engineering methodologies to specific mission contexts, objectives, and operational environments, aiming to enhance the DoD's mission planning and execution capabilities. One of the most important features of the document is the approach for mapping if the outcomes of the operation have been correctly addressing the needs of the stakeholders. This is done by establishing multiple measures of performance (MoP), measures of effectiveness (MoE) and measures of success (MoS) criteria between the tasks of the operation. This is an important step towards validating the system to the stakeholders' needs since it explicitly exemplifies the necessary outcomes that must be measured to assure that the system is capturing all the necessary outcomes.

The Object Management Group's (OMG) Unified Architecture Framework (UAF) [2] is a comprehensive guide for creating Enterprise Architecture (EA) views. UAF facilitates understanding complex relationships between organizations, operations, systems, and services, ensuring they meet user community expectations. Operational viewpoints are the most important viewpoints for generating ConOps, providing a structured approach to identify and analyse operational needs and capabilities. This framework supports the development of a clear operational concept, by defining operational roles, activities, performers, and the integration of services and resources, thus enhancing decision-making and operational planning.

3.3 Research Initiatives

According to Fairley et al. [16], ConOps documents describe the characteristics and intended usage of proposed and existing systems. They serve to bridge operational requirements to technical specifications, offering a detailed view of how a system operates within its environment and how it should meet the operational needs of the stakeholders.

Martin et al. [17] explores how the UAF supports Mission Engineering, focusing on its use for defining mission architectures. It details the compatibility of UAF with the Mission Engineering process outlined in the DoD's Mission Engineering Guide, emphasizing the standardization and efficiency UAF brings to modelling various aspects of architecture. The paper highlights UAF's role in facilitating Mission Engineering activities, such as defining operational concepts, roles, and scenarios for generating a comprehensive ConOps. It outlines how the UAF can model operational sketches providing a high-level overview of the mission for stakeholders using the Operational Taxonomy (Op-Tx), diagram, similar to the Department of Defence Architecture Framework's (DoDAF) Operational Viewpoint 1 (OV-1). Mission architecture and operational performers can be described by the Operational Structure (Op-Sr) diagram, similar to the DoDAF's Operational Viewpoint 2 (OV-2).

The work performed by Cloutier et al. [18] provides valuable insights into the nature of ConOps documents. In summary, the findings are as follows:

- Less than 75% of the ConOps researched actually list or identify specific mission needs.
- Nearly a third of the investigated ConOps documents had no description of the background or context of the current system or situation.
- There was a shortage of information relating to the current system/situation in terms of technical capabilities.
- Little attention was paid to stakeholders who do not directly interact with the system, including acquisitions staff, and government and regulatory agencies.
- Less than 20% of the ConOps examples identified associated risks of the system and its development.

A paper by Cohen et al. [19] outlines NASA's Human Research Program's Exploration Medical Capability Element's transition from a document-centric to a model-centric Systems Engineering approach for developing medical systems ConOps. It details the benefits of this transition, such as improved stakeholder communication and more robust system development, by incorporating all ConOps content within a Model-Based Systems Engineering (MBSE) framework. Key lessons learned, the process journey, and the revised MBSE process for future project implementations are discussed, emphasizing the importance of agile workflows, stakeholder involvement, and continuous model updates to enhance medical system design and decision-making for space exploration.

The work from Solli et al. [20] examines the use of illustrative ConOps and the Pugh Matrix in concept selection within the sub-sea oil and gas domain, focusing on their effectiveness in early validation of concepts, influencing holistic engineering mindsets, and potential for reducing late design changes. It highlights the application to a case study by detailing the creation of graphical ConOps to depict operational procedures and the utilization of a Pugh Matrix for concept evaluation. This approach is shown to facilitate communication among project members and stakeholders, providing a clearer understanding of operational needs and concept qualities, thereby aiding in the identification of opportunities early in the system development process. Among the identified gaps, the author cites the following:

- Late Design Changes: A major issue identified is the occurrence of late design changes due to insufficient early identification of operational needs. This leads to increased costs and schedule delays.
- Operational Needs Awareness: The industry's prevalent approach tends to neglect the detailed operational needs early in the design phase, which are critical for preventing late-stage modifications.
- Communication Breakdown: There is an implicit gap in effective communication of conceptual solutions' qualities between project members and stakeholders, hindering a unified understanding of operational requirements and concept evaluations.

The proposed approach by Solli et al. involves an early validation to address the gaps to improve the awareness of operation needs among engineers and assist in reducing late design changes. The approach emphasizes a holistic engineering mindset and mainly an illustrative ConOps to depict the operational procedures. It can enhance communication among project members and stakeholders since the ConOps documentation should be a user-oriented document and therefore easily understandable by all the stakeholders and designers involved.

The methods and frameworks reviewed in this section highlight the critical role of a well-defined ConOps in ensuring effective system development and operational success. The insights provided by the literature emphasize the importance of early stakeholder assessment, clear communication of operational needs, and iterative validation processes. These elements are essential for aligning the system's design with stakeholder expectations and operational realities, thereby minimizing risks and enhancing decision-making efficiency.

4. Method

Building upon the work from section 3, this section presents a detailed method that integrates the best practices into a comprehensive framework. This approach not only addresses the identified gaps but also leverages advanced simulation techniques to optimize resource allocation and operational planning.

As pointed out by Clotier et al. [18], stakeholder involvement in the early phases of the system definition is necessary and rarely addressed in ConOps documentation. Overall, the method to derive the stakeholder's needs into a detailed and comprehensive ConOps, tailored for an ABS in an SoS environment can be described by the first two steps of the System Engineering Life Cycle [13], as highlighted in Figure 3.

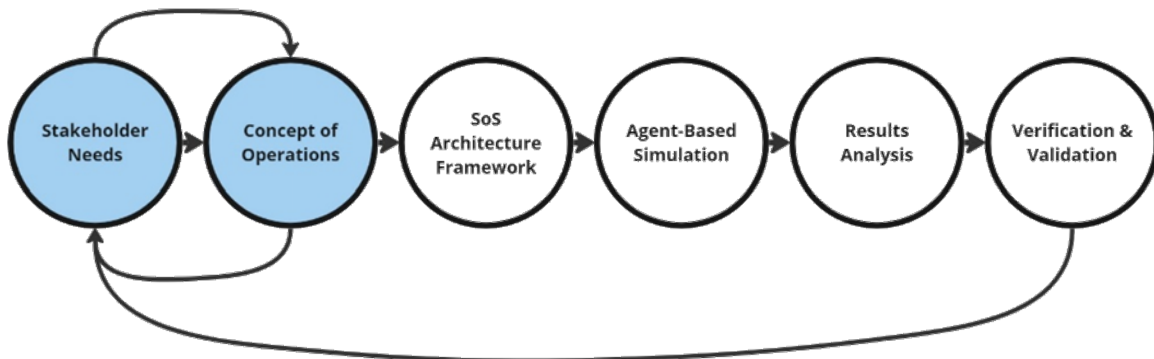


Figure 3 – System Engineering Life Cycle with Stakeholder involvement and ConOps highlighted in blue.

For the following parts of the method, Figure 4 exemplifies the process for each phase:
Where:

- [1] Indicates the flow of stakeholder needs and requirements to develop the value function and further strategy & tactics for the operational viewpoint.
- [2] Indicates the iterative process of checking if the Key Performance Indicators (KPI) and MoPs are consistent and representative of necessary needs derived from the stakeholder engagement phase.
- [3] Indicates the information flow from the operational viewpoint towards the implementation of the ABS.
- [4] Indicates the collection of results towards the evaluation and subsequent validation of results, according to the V-model.
- [5] Indicates the iterative process of providing the MoPs to feed the value function as well as the validation towards the intended operational viewpoint

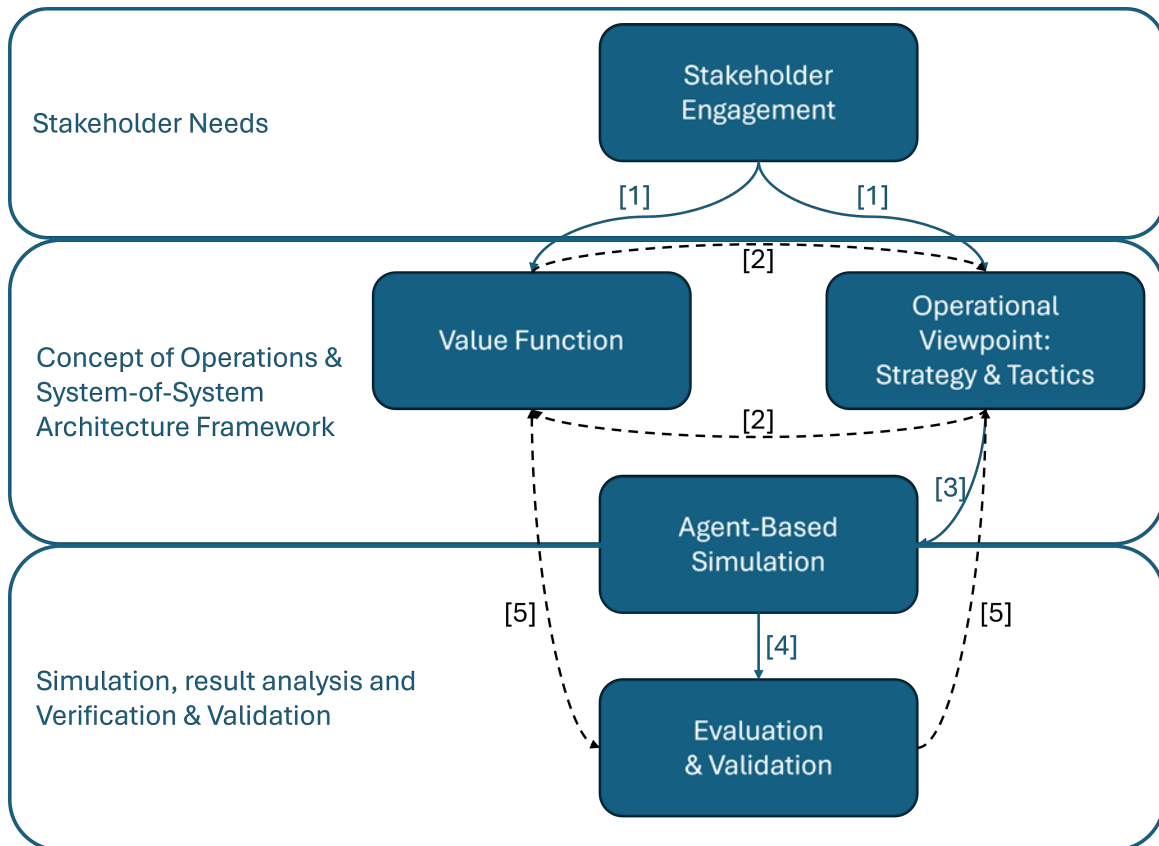


Figure 4 – Proposed framework for tailoring the ConOps for an ABS environment.

4.1 Stakeholder Engagement

The creation of a ConOps starts with the definition of the stakeholders and their needs. Since all operations are performed to reach a common goal in an SoS environment, the objectives and interest of each stakeholder are not necessarily the same. Therefore, mapping the interest of each stakeholder and weighting how they can influence the outcomes of the operation is a good first step towards having a clear view of their needs and how important they are for each stakeholder. Each stakeholder must be divided by a ranking among different types of categorizations. The higher the ranking of each stakeholder, the higher their influence should be on the final outcomes of the ConOps documentation. Next, once the stakeholders are clearly defined, various KPI, a measurable value that demonstrates how effectively an organization is achieving its key business objectives, are defined to represent the needs of the stakeholders. KPIs can be quantifiable indicators or qualitative/descriptive indicators. Translating stakeholders needs into KPIs can be divided into the following steps:

- Define Clear Objectives: Understand requirements and needs to achieve the established objectives.
- Identify Critical Success Factors: Determine what activities or processes are critical to achieving these objectives.
- Choose Relevant KPIs: Select KPIs that provide clear insights into the performance of these critical success factors.
- Set Objectives: Establish realistic targets for each KPI.

It is possible that one KPI is bounded to multiple interested stakeholders. Once all KPIs are defined, they are then provided to the value function and operational viewpoint for strategy and tactics, that will be described further in this work in sections 4.2 and 4.3.

4.2 Value Functions

Value functions are employed as a systematic method to assess how well the results of the ABS align with and fulfil the defined needs of stakeholders. These functions quantify the effectiveness of different operational scenarios in meeting specified KPIs, MoP, MoE and MoS.

After a simulation, value functions will translate the various outputs, such as agent behaviours and system responses, into quantifiable metrics. These metrics are then used to evaluate the success of the simulation in achieving the desired outcomes, thereby ensuring that the system's operations align with stakeholder expectations. The integration of value functions allows for the iterative refinement of ConOps by providing feedback on the efficacy of the system under different operational conditions. This enables designers to make informed decisions about potential adjustments and enhancements to the system design and operational strategies, ultimately leading to optimized system performance and stakeholder satisfaction. As seen in Figure 4, "[2]" represents the iteration between the operational viewpoint and the value function to check if the KPIs, MoP, MoE and MoS are the same, maintaining not only the consistency of the model but also allowing for the traceability of the parameters, a fundamental requirement when dealing with systems engineering for complex systems.

4.3 Operational Viewpoint: Strategy & Tactics

In the process of ConOps development, strategies define what actions will be undertaken, by which elements (agents or resources), and where these activities will occur within the operational environment. Tactics, on the other hand, detail how these actions will be executed and the quantity of resources that will be engaged.

The strategy and tactics are formulated using the approach of defining **what** is going to be performed, by **which** agents, **where** those agents should operate (either geographically or focusing on a unit/module), **how** the agents should operate, and **how many** agents should be used, which simplifies the decision-making process by focusing on essential questions that direct the operational planning.

- **What:** Defining 'what' needs to be achieved sets the objective of the operation, guiding all subsequent planning and actions. It establishes the goal or outcome that the operational strategy aims to accomplish, serving as the foundation upon which all tactical decisions are based.
- **Which:** Identifying 'which' resources or agents will be involved specifies the assets at the disposal of the operation. This not only involves choosing the right type of resources but also ensuring that they are best suited to achieve the 'what' efficiently. This selection is critical because it directly affects the operation's effectiveness and feasibility.
- **Where:** Stating 'where' the operations will take place helps in preparing the environment and understanding the geographic and contextual limitations or advantages. It involves logistical considerations that can significantly influence tactical choices, such as positioning and movement of resources within the defined area.
- **How:** Describing 'how' the objectives will be achieved involves outlining the methods and processes that will be utilized in the operation. This includes the techniques and manoeuvres that will be employed to utilize the 'which' effectively in the 'where' to achieve the 'what'. It is about translating strategy into actionable steps and sequences.
- **How Many:** Determining 'how many' refers to quantifying the resources needed, which is crucial for effective resource allocation. This ensures that the operation is neither resource-starved nor wastefully over-resourced, optimizing efficiency and responsiveness to operational demands.

By integrating the aforementioned definitions into the simulation environment, the method enables the extraction of outputs such as MoP, MoE, and MoS. These metrics serve as quantitative benchmarks to evaluate the success of the simulation in meeting predefined objectives, thus providing a direct link to the value function. The definition of MoP, MoE and MoS according to [3] are defined as follows:

- **Measure of Performance (MoP) - Evaluating Specific Actions:** MoP assesses the performance of specific actions or processes within the system. It is more about the efficiency and effectiveness of the operational aspects of the system.
- **Measure of Effectiveness (MoE) - Assessing Constituent System's Success:** MoE evaluates how well the system achieves its intended objectives or outcomes. It is focused on the effectiveness of the overall system in meeting its strategic goals.
- **Measure of Success (MoS) - Assessing Overall Achievement:** MoS is a holistic assessment metric that evaluates the cumulative success of a system or SoS in achieving its overarching mission or vision. Unlike MoP, which focuses on operational efficiency, or MoE, which assesses effectiveness towards specific objectives, MoS encompasses a broader view, integrating multiple dimensions of performance and effectiveness to ascertain overall mission fulfilment.

The proposed method forms the foundation for the case study presented in the next section where the method is used to implement a forest firefighting scenario. The case study thereby illustrates the practical application of the aforementioned steps, demonstrating the utility of the method in a real-world context and highlighting the benefits of an integrated approach for managing complex operational environments in ABS.

5. Case Study

Wildfires have been increasing in frequency and intensity globally, driven by factors such as climate change, urban expansion into wildland areas, and land management practices [21]. These fires pose significant threats to life, property, and ecosystems.

The dynamic nature of wildfires requires simulations that can adapt to rapidly changing conditions, such as shifting wind patterns, available resources, water sources, topology, and vegetation types. The need for numerous simulations to represent a vast array of possible scenarios, each with unique variables and outcomes, increases with the level of fidelity that the model requires. This complexity is further amplified by the involvement of multiple stakeholders, each with differing priorities and objectives, such as minimizing property damage or prioritizing habitat preservation.

The forest firefighting use case within the COLOSSUS project serves as a testbed for demonstrating the practical application of advanced SoS methods and was chosen due to its inherent dynamism and complexity, which align well with the objectives of developing a ConOps method for ABS. The intricate interactions between various firefighting resources, including ground crews, Electric Vertical Take-off and Landing vehicles (EVTOLs), and seaplanes—both of which are being specifically developed under the COLOSSUS project—can be effectively modelled within this framework to enhance coordination and operational efficiency.

Also, studies have shown that the incidence of wildfires has been increasing over the years. For instance, the European Commission's Joint Research Centre reported a significant rise in wildfire activity in Europe, noting that 2022 was one of the most devastating years for forest fires on record [8]. This escalation underscores the urgent need for advanced firefighting operations strategies, making this use case relevant for the development of a ConOps that addresses the gaps from unforeseen environmental and situational conditions.

5.1 Stakeholders Engagement

The application of a ConOps starts with the definition of the stakeholders' needs and requirements. Since all operations are performed to reach a common goal in an SoS environment, the objectives and interest of each stakeholder are different, as seen in Figure 5.

Each stakeholder has unique goals and priorities. These could range from financial performance for investors, operational efficiency for managers, to customer satisfaction for clients. Understanding these objectives is the first step in creating a comprehensive ConOps.

Once the stakeholders' objectives are identified, the next step is to define KPIs that can measure progress towards these objectives. KPIs should be specific, measurable, achievable and relevant. From the example provided in Figure 5, disaster relief agencies, which operate at both European and national levels, show a strong interest in multiple KPIs, focusing on minimizing wildfire damage,

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KPIs	Stakeholders interested	Stakeholders	Objectives				
			Minimize the wildfire damage (€/operation)	Minimize the greenhouse gas emissions from the fire (kg CO ₂ /operation)	Minimize the environmental impact from the firefighting operation (kg CO ₂ /operation)	Minimize cost of operation (cost/operation)	Maximize effectiveness of aerial firefighting vehicle (suppression rate or minimize spread rate (area/time))
Burnt area	5	disaster relief - European level, disaster relief - national/supra-regional, rural communities, suburban communities	X	X	X	0	X
Number of assets	5	disaster relief - European level, disaster relief - national/supra-regional, rural communities, suburban communities	X	0	0	0	X
Location of fire	4	fire departments - regional/local, flight operator - regional/local, investors, OEM - eVTOL	0	0	0	0	0
Value of properties lost	4	residents - rural areas, rural communities, suburban communities	X	0	0	0	X
Costs of fire fighting missions	3	disaster relief - European level, disaster relief - national/supra-regional, fire departments - regional/local	X	X	X	X	X

Figure 5 – An example of a mapping between Stakeholders, KPIs and objectives for a wildfire fighting scenario.

greenhouse gas emissions, environmental impact, cost of operation, and maximizing firefighting effectiveness. Residents and communities, particularly those in rural and suburban areas, are primarily concerned with the value of properties lost and the burnt area. Fire departments and flight operators focus on the location of fires, resource allocation, and the costs associated with firefighting missions, while investors and Original Equipment Manufacturers (OEMs) are interested in the location of fires for operational and investment purposes.

Each objective in Figure 5 is linked to specific KPIs that measure its achievement. The objective of minimizing wildfire damage, measured in Euros per operation, is connected to KPIs such as the burnt area, danger to life, value of properties lost, and costs of firefighting missions. This objective is of particular interest to disaster relief agencies and rural and suburban communities. The objective of minimizing greenhouse gas emissions from the fire, measured in kilograms of CO₂ per operation, is connected to the KPIs of burnt area and costs of firefighting missions, appealing mainly to disaster relief agencies and environmental organizations. Minimizing the environmental impact from firefighting operations, also measured in kilograms of CO₂ per operation, is linked to the same KPIs and stakeholders. The objective of minimizing the cost of operation, expressed as cost per operation, directly ties to the KPI of firefighting mission costs and is relevant to disaster relief agencies and fire departments. Lastly, the objective of maximizing the effectiveness of aerial firefighting vehicles, measured by suppression rate or minimizing fire spread rate (area/time), is connected to KPIs such as burnt area, danger to life, value of properties lost, and costs of firefighting missions. This objective is particularly important to disaster relief agencies and rural and suburban communities.

The connections marked with "X" in Figure 5 indicate where each KPI aligns with an objective. These connections were determined based on the guidelines from Section 4, which outline a systematic approach to identifying and prioritizing stakeholder needs and translating them into measurable performance indicators. This ensures that each KPI is directly relevant to the stakeholders' objectives and provides a clear framework for tracking progress and strategic planning.

The results from an SoS ABS for such use cases can provide a substantial amount of data which are difficult to interpret. Dealing with such extensive datasets often leads to data overload, making it hard to identify critical insights and trends. To address these challenges and ensure effective decision-making, a systematic approach to data evaluation and interpretation should be considered. A possible approach is to use a value function, which will be discussed in the next section.

5.2 Value Functions

In this section, the value function is introduced, which is a weighted sum of various KPIs and MoPs, designed to evaluate and prioritize the performance of the system based on stakeholder preferences. This approach is a valuable resource to evaluate the effectiveness of an SoS due to the simplicity to combine various outputs and large amounts of data into single functions that can be used as a means for decision making.

Value functions serve as integral tools in assessing the performance of systems within an SoS. They synthesize KPIs and MoPs into a unified assessment metric, allowing for comprehensive evaluations across diverse operational domains. The value function incorporates various parameters like burned area, operational costs, and resource utilization, translating them into weighted scores based on

stakeholder-defined priorities. This approach ensures that the evaluation reflects a balanced consideration of efficiency, cost-effectiveness, and strategic outcomes.

The formulation of value functions involves defining each parameter's contribution to the overall system's effectiveness. For instance, reducing the burned area in wildfire management is a significant indicator of success, thus it is inversely related to the value function score—smaller areas mean higher performance scores. Similarly, operational costs and resource utilization are minimized to enhance the function's score, promoting economic and environmental sustainability.

An example of a value function for the proposed use case is described as follows in Equation 1:

$$\begin{aligned}
 VF = & w_1 \left(\frac{1}{KPI_{\text{Burned Area}}} \right) + w_2 \left(\frac{1}{KPI_{\text{Burned Buildings}}} \right) + w_3 \left(\frac{1}{MoP_{\text{Used Fuel}}} \right) \\
 & + w_4 \left(\frac{1}{MoP_{\text{Distance Traveled}}} \right) + w_5 \cdot KPI_{\text{Number of Assets}} - w_6 \cdot (CostOperation_{\text{per Time}}) \\
 & - w_7 \cdot OperatingTime + w_8 \cdot Area_{\text{Value}} + w_9 \cdot BuildingArea_{\text{Value}}
 \end{aligned} \tag{1}$$

Where:

- $w_1, w_2, \dots, w_9$ are the weights assigned by stakeholders to each parameter, reflecting the relative importance or impact of these metrics on the stakeholder's evaluation of system performance. These weights are values between 0 and 1, representing the degree of importance of the parameter it is associated to. The weights are variables assigned by the user or stakeholders to adapt the level of importance of a parameter according to their objectives in order to facilitate the decision-making process for the optimal SoS configuration and architecture to be used.
- $KPI_{\text{Burned Area}}$ and $KPI_{\text{Burned Buildings}}$ are measured such as the amount of land area burnt, and the number of buildings affected respectively. Thus, they are inverted in the value function to increase the score with smaller impacted areas.
- $MoP_{\text{Used Fuel}}$ and $MoP_{\text{Distance Traveled}}$ are also inverted, promoting efficiency by favouring lower values. They can be traced back to the KPI "Cost of firefighting missions".
- $CostOperation_{\text{per Time}}$ and $OperatingTime$ represent operational costs and are thus subtracted, as lower costs are preferable, increasing the overall value function score when minimized.
- $Area_{\text{Value}}$ and $BuildingArea_{\text{Value}}$ contribute positively to the value function, indicating higher values are better and increase the overall score.

Given that the KPIs and MoPs are in different units and types of values, it is essential to normalize them to fit into the value function uniformly (as illustrated in Equation 2). Normalization transforms different scales into a common scale, typically between 0 and 1. This ensures that no single KPI or MoP disproportionately influences the value function due to its scale.

$$\text{Normalized Value} = \frac{\text{Actual Value} - \text{Min Value}}{\text{Max Value} - \text{Min Value}} \tag{2}$$

The adaptability of value functions is crucial for maintaining their effectiveness over time. As operational priorities shift or as new data becomes available, the weights assigned to different parameters can be adjusted to ensure that the value function remains aligned with current objectives and conditions. Since operational aspects can influence the value functions, the next part of the method involves defining in detail the operational viewpoint by exploring the strategy and tactics of the constituent systems.

5.3 Operational Viewpoint: Strategy & Tactics

Following the establishment of stakeholder requirements and the formulation of the value function, the next step involves defining the strategy and tactics necessary for an effective operation. The value function serves as a bridge, translating diverse stakeholder needs into quantifiable metrics that guide

decision-making processes. However, to operationalize these insights, a comprehensive strategy and tactical plan must be developed.

The operational viewpoint focuses on delineating the strategy and tactics not only for individual agents but also for the entire SoS. This is particularly important in this presented method given the complexity and extensive potential interactions between constituent systems in an ABS environment. The number of possible interactions can be vast and challenging to map, necessitating a strategic focus on essential interactions that facilitate satisfactory operational performance.

Given the limitations of fidelity in any simulation [22], the best approach is to focus on the necessary interactions between the agents to perform the operation in a satisfactory manner and mapping the expected actions so that the outcomes of the simulation are not being influenced by strict constraints. The UAF and DoDAF operational viewpoints are aimed towards describing the responsibilities of the assets as well as their relation to the stakeholders and other organizations. For this, the UAF can model operational sketches providing a high-level overview of the mission for stakeholders using the Operational Taxonomy (Op-Tx) diagram, similar to the DoDAF's Operational Viewpoint 1 (OV-1), as illustrated in Figure 6.

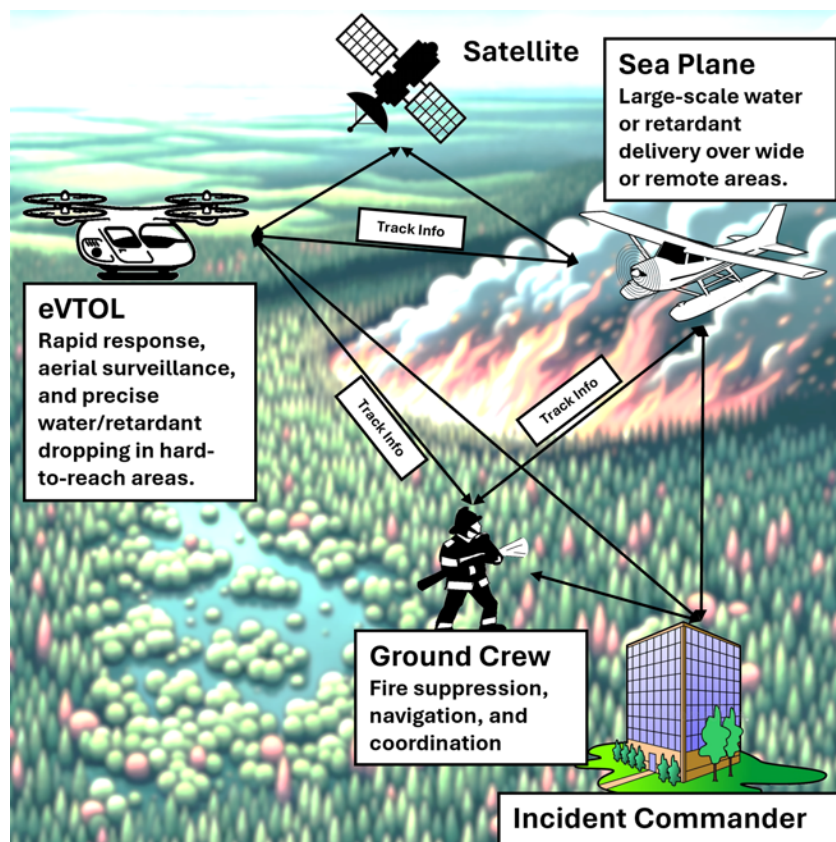


Figure 6 – Operation Taxonomy (Op-Tx) based on UAF [2] or Operational View OV-1 based on DoDAF [23] for a forest firefighting scenario.

Mission architecture and operational performers are detailed in the Operational Structure (Op-Sr) diagram [2], which parallels the DoDAF's Operational Viewpoint 2 (OV-2) [23]. The diagram serves as a strategic framework, evaluating weather conditions, available resources, and fire conditions to determine the optimal approach for water dropping, asset distribution, and identifying focal points for firefighting efforts. Similar to all constituent systems, it comprehensively accounts for all environmental conditions that could impact the operation of various assets. A Systems Modelling Language (SysML) action diagram is utilized to provide the necessary diagram blocks for effectively depicting these outcomes, ensuring a thorough and precise operational plan, as exemplified in Figure 7. This methodological approach enables a clear visualization of the operational architecture and the strategic interactions among different systems within the firefighting effort.

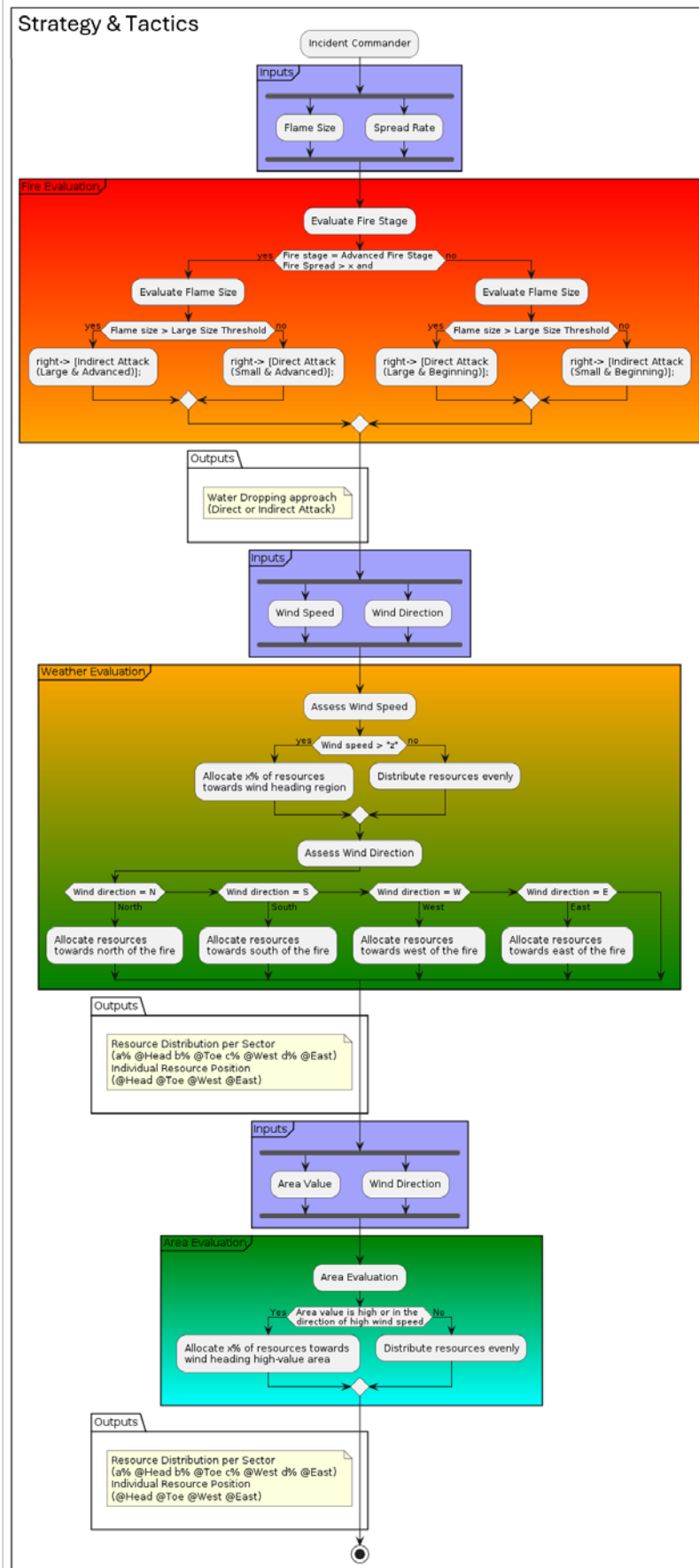


Figure 7 – Comprehensive Strategy and Tactics Flowchart for Wildfire Response: Inputs, Decision-Making Processes, and Resource Allocation.

In an ABS environment, employing a detailed and structured method that includes specifying 'who', 'what', 'where', 'how', and 'how many' enhances the realism and effectiveness of the simulation. This approach is particularly useful because it mirrors real-world decision-making processes, allowing for more accurate modelling and analysis of complex dynamic systems such as wildfire management. Defining each aspect of the response strategy ensures that simulations are both comprehensive and detailed. For instance, specifying which agents to deploy based on the fire characteristics ensures that the simulation considers the capabilities and limitations of different resources. In the context of the COLOSSUS forest firefighting use case, these agents include seaplanes, EVTOLs, and ground crews. Seaplanes are utilized for their ability to quickly collect and drop large volumes of water on fires, EVTOLs offer rapid response times and flexibility in accessing hard-to-reach areas, and ground crews provide essential on-the-ground support for firefighting efforts, including direct fire suppression and containment. This leads to more realistic scenarios where the effectiveness of various strategies can be tested and compared.

As for the use-case, the definition of the approach can be described as follows:

1. Fire Evaluation

- Which Agent: Assign specific aerial assets, like seaplanes, EVTOLs or ground assets to the firefighting efforts.
- What: The goal here is to assess the fire to determine the appropriate response for containment and extinguishing.
- Where (Location of Agents): Agents will be located at strategic vantage points around the fire zone to accurately assess and respond.
- Water Dropping & Fuel Removal Approach (How): Determine the method of attack, be it direct or indirect, and choose between high-intensity, mixed-intensity, or low-intensity water drops for vehicles. Fixed for ground crew (fuel removal).
- How Many Agents: Decide on the number and type of agents based on the size and intensity of the fire for the initial and sustained response.

2. Water Dropping Approach

- Which Agent: Assign specific aerial assets, like seaplanes or EVTOLs, to execute the water dropping strategy.
- What: The action is the delivery of water or fire retardant to the fire zone using the chosen approach.
- Where (Location of Agents): The agents will be positioned according to the operational plan that targets the most intense parts of the fire and protects high-value areas.
- How Many Agents: Determine the fleet size for each type of aerial asset required to implement the water dropping approach effectively.

3. Area Evaluation

- Which Agent: Assign specific aerial assets according to the risk and value of different areas.
- What: While this block does not directly deal with firefighting, the action here is prioritizing the areas to ensure the agents focus their fire suppression efforts effectively.
- Where (Location of Agents): Placement of these agents will be in areas where they can best assess the risk to high-value regions or protected zones.
- How Many Agents: Determine the number of assessment agents needed to cover the at-risk areas and provide accurate, timely data to inform resource allocation.

As a reference to the forest firefighting use-case, the diagram in Figure 8 provides the possible outputs (MoPs and KPIs) that will be used in the value function as well as the inputs for the agent individual behaviours (positioning, water dropping approach etc.).

Additional parameters, besides the MoPs and KPIs described for the value function in section 5.2, can be detailed as follows:

- $Cost_{Operation\ per\ Time}$: Represents the financial expenditures related to the operation, where minimizing costs is crucial for enhancing operational efficiency and overall budget management.
- $Operating_{Time}$: Indicates the total duration of the firefighting operation, where shorter operational times are preferred to reduce costs and risks.
- $Area_{Value}$ and $Building_{Area\ Value}$: These parameters contribute to the value function, where higher values represent increased importance or significance of the area or buildings being protected.

6. Discussion

The proposed method for developing ConOps in an ABS within an SoS context highlights several critical considerations. These considerations revolve around stakeholder engagement, value function formulation, and operational strategy and tactics, ensuring that the complex interactions within SoS are effectively modelled and analysed. Having the ConOps in a V-model, where verification and validation (V&V) are important aspects of the project lifecycle, it is important to point out that any changes in the previously established KPIs for each stakeholder can be reflect in the designing process. The V&V stages should capture if the needs of stakeholders are being effectively and properly addressed. The V-model suggests a validation of the ConOps to the operation itself. However, the operation should be evaluated not only in terms of whether behaviours are being performed as expected and without disruptions, but also in terms of whether the needs of the stakeholders are being fulfilled. In an ABS case, all the necessary outputs should be sufficient for a value function to be executed and evaluated with different weights afterwards.

Though V&V are not usually easily performed from an SoS perspective, having a default design of experiments where strategies and tactics are fixed according to the real application of the assets is beneficial, as it provides a reference frame for evaluating results.

The introduction of value functions, as discussed in section 5.2, is an important aspect when evaluating the system's performance. These functions aggregate multiple KPIs and Measures of Performance (MoP) into a single, weighted score, facilitating straightforward comparisons and decision-making. The normalization of KPIs, essential due to the differing units and scales, ensures a balanced evaluation. Equation 2 provides the formula for normalization, transforming values to a common scale between 0 and 1, thus preventing any single KPI from disproportionately influencing the overall score. Transitioning to the operational viewpoint, the method emphasizes defining clear strategies and tactics for the constituent systems. This step ensures that the simulation accurately reflects the real-world dynamics of wildfire management.

The paradox within the generation of the ConOps for ABS, derived from a real use case of the same document, is the level of detail that should be considered by the modeller of the ABS. It can directly impact the quality and outcomes of the simulation since more constraints can be added or not. Therefore, one of the main questions is *"What is the limitation of details that should be implemented to the extent that emergent behaviours are still allowed to occur?"*. When it comes to simulations with direct directives based on environmental and situational conditions to the agents, a clear path of commands should be described to the agents for them to perform their work. What can be easily understood in a real use case of a ConOps directive in the behaviour model for an agent to make a decision or perform a task can be challenging for a modeller to implement, considering the many different possibilities that were not predicted but could occur. One of the possibilities to tackle this challenge is to directly code functions for the agent to proceed to a certain path, guiding the agent to do a certain task in a direct and clear way. Another way is to implement only the constraints for each agent and implement reward functions for each agent. The latter one might be more interesting from the SoS perspective since it provides a level of freedom that is expected and can allow emergent behaviours. However, some of the emergent behaviours can be disruptive towards the simulations,

for example, if there is a penalty for an agent each time it cannot perform a task, it might be that it is more "rewarding" standing still and not performing the task.

The use case of forest firefighting within the COLOSSUS project exemplifies the practical application of the proposed method. This case study is particularly relevant given the increasing frequency and intensity of wildfires, necessitating advanced strategies for effective management. The integration of various firefighting resources, such as seaplanes, EVTOLs, and ground crews, is modelled to enhance coordination and operational efficiency. Figure 8 further elaborates on the strategy and tactics flowchart, detailing inputs, decision-making processes, and resource allocation.

The main goal for a ConOps is to provide an easy-to-read user-oriented document that can detail all the information about the requirements and operational aspects for the involved constituent systems. The usage of diagrams to describe the behaviour of the agents and define the strategies and tactics is a user friendly and easy to visualize tool. However, providing the correct block diagrams within SysML for each task might not effectively illustrate the needed scenarios, inputs, outputs and actions. The sequence diagram can describe complex interactions and feedback loops. Also, even though proven a solid tool for describing a timeline of actions in the system, SysML might not be a user-friendly language. Therefore, a mix of different SysML block diagrams was chosen as a better approach where the formalities of the modelling language are kept within the intended usage without jeopardizing the understanding of the users by requiring a deeper knowledge of SysML diagrams.

According to the literature, ConOps content is standardized through IEEE 1362 [11], ISO/IEC/IEEE 29148 [12] and later merged to ISO/IEC/IEEE 15288 [13], but the format of the documentation is left open. Since there is a vast variety of applications of ConOps, from enterprise usage for an early view of the operational aspects to the original intent of military operations, a standardized format of the documentation cannot be defined. Instead, the approach to generate a different ConOps can vary with the application intended. For an ABS scenario, defining the roles, requirements and capabilities of the constituent systems is no different than how it would be performed for a real case scenario. However, providing the details of the agent's behaviour can be a challenging task. Out of the definitions of an SoS from Maier [1], emergent behaviour, managerial independence, and geographic distribution are among the most important ones when considering an ABS.

6.1 Future Work

The presented method for developing a ConOps through ABS has shown promising potential in enhancing the coordination and operational efficiency of forest firefighting efforts. However, several areas for future research and development have been identified to further refine and expand upon this work:

- **Incorporating Advanced Machine Learning Techniques:** Integrating machine learning algorithms into the ABS framework can further enhance the simulation's capability to predict and adapt to dynamic operational conditions. Future research on the application of reinforcement learning to enable agents to learn and optimize their behaviours over time can improve the overall system's adaptability and performance.
- **Integration with Real-Time Data:** Future exploration of the integration of real-time data feeds into the ABS framework will enable the simulation to adapt to real-world conditions dynamically, providing more accurate and timely insights for decision-making rather than a set of predefined strategy and tactics rules. Such integration can be particularly valuable in scenarios where conditions change rapidly, such as during active wildfire incidents.
- **Integration of Value Functions as Reward Functions:** While the value functions provide a structured way to evaluate system performance, there is potential for further refinement by integrating them as reward functions to guide agent behaviour. Future work includes developing more sophisticated decision-making techniques while using value functions as reward mechanisms can help agents learn optimal strategies that align closely with stakeholder-defined objectives.

7. Conclusion

The proposed method in this paper integrates stakeholder engagement, value function formulation, and operational strategies and tactics to ensure simulations can be robust, adaptable, and aligned with real-world dynamics. By employing value functions, this method provides a structured way to evaluate and prioritize system performance based on multiple Key Performance Indicators (KPIs) and Measures of Performance (MoP). The normalization of these metrics guarantees a balanced evaluation, facilitating clear decision-making and resource allocation. This is crucial for managing the extensive data produced by Agent-Based Simulations (ABS) and ensuring that critical insights are not lost in the complexity. The operational viewpoint further refines this approach by detailing strategies and tactics for constituent systems. Utilizing structured frameworks such as the Unified Architecture Framework's (UAF) Operational Taxonomy (Op-Tx) and Operational Structure (Op-Sr) diagrams, the method offers clear visual representations of roles, responsibilities, and interactions, aiding in strategic planning and resource allocation.

A case study on forest firefighting within the COLOSSUS project exemplifies the practical application of the proposed method. This study underscores the increasing relevance of advanced strategies for effective wildfire management, driven by the rising frequency and intensity of wildfires. The integration of various firefighting resources into the simulation model enhances coordination and operational efficiency, demonstrating the method's applicability and utility.

Overall, the method provides a comprehensive framework for developing Concept of Operations in ABS within a System-of-Systems context. It ensures that stakeholder needs are effectively captured and addressed, system performance is rigorously evaluated, and operational strategies are clearly defined. This approach not only aims to enhance decision-making processes but also to improve system performance and responsiveness, enabling the system to meet both current and future challenges in complex operational environments.

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