



LARGE LANGUAGE MODEL-DRIVEN SIMULATIONS FOR SYSTEM OF SYSTEMS ANALYSIS IN FIREFIGHTING AIRCRAFT CONCEPTUAL DESIGN

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Abstract

Conceptual design of aircraft tailored for a specific role requires a holistic view to account for requirements at different levels, from systems to sub-systems and their components. This is the case with aircraft designed for firefighting, where they collaborate and communicate with other systems towards a common goal. This collaborative and holistic perspective is what a *System of System* (SoS) analysis tries to achieve. To conduct a SoS analysis, the use of *Agent-Based Modelling and Simulations* (ABMSs) is widely adopted. A crucial aspect of this approach is the ability to capture emergent behaviours that arise from collaborative systems, which are represented in the *Agent-Based Simulation* (ABS) by agents whose actions are traditionally governed by decision trees. The present study introduces a novel methodology using ABMS where a *Large Language Model* (LLM) plays the role of a human in the loop. The purpose is to represent the decision-making of an *Incident Commander* (IC) by allowing a LLM to play this role within a wildfire situation. The IC will follow operational guidelines and guide the agents' behaviour in order to provide them with more degrees of freedom and remove the constraints associated with traditional behaviour trees. This approach not only aids in simulating realistic operational scenarios but also generates valuable insights for *Aircraft Conceptual Design* (ACD), enabling the derivation of specific design requirements based on simulation outcomes.

Keywords: Aircraft Conceptual Design, System of Systems Analysis, Wildfire Management, Agent-Based Modelling, Large Language Models

1. Introduction

During the last decade, wildfires have increased in number and size, earning the designation of **megafires**. For this reason, more resources are being allocated to the prevention and combat of wildfires [1]. These resources may include increased funding for firefighting efforts and improved technology for early detection and monitoring. Additionally, collaboration among government agencies, environmental organizations, and local communities has become increasingly vital to address the growing threat of wildfires and minimize their devastating impact on both the environment and human lives [2]. To achieve this, developing a SoS framework for conducting comprehensive, holistic analyses is a logical approach. By considering all constituent systems involved in a mission and assessing the resulting operational outcomes, it becomes possible to identify emergent behaviours that arise from collaboration, unmet needs, and desired capabilities. These insights will provide a data-driven foundation for ACD.

However, despite multiple technological advancements, there is still a gap in the conceptualisation phase of aircraft design, particularly in modelling realistic operational scenarios and collaborative dynamics to fully understand the outcome of different sets of capabilities [3]. For such scenarios and dynamics, the use of ABMS is generally recognised as adequate and capable of capturing emergent behaviours from collaborative agents, which are very difficult to predict [4]. Agents represent constituent systems and are defined by sets of behaviours. These behaviours traditionally rely on decision trees such as the one shown in Figure 1, which, whilst structured, constrain the fluidity and

collaborative essence of real-life situations, such as those encountered in wildfire suppression operations. This limitation not only distorts the design process, but also potentially impacts the operational efficacy of the designed system.

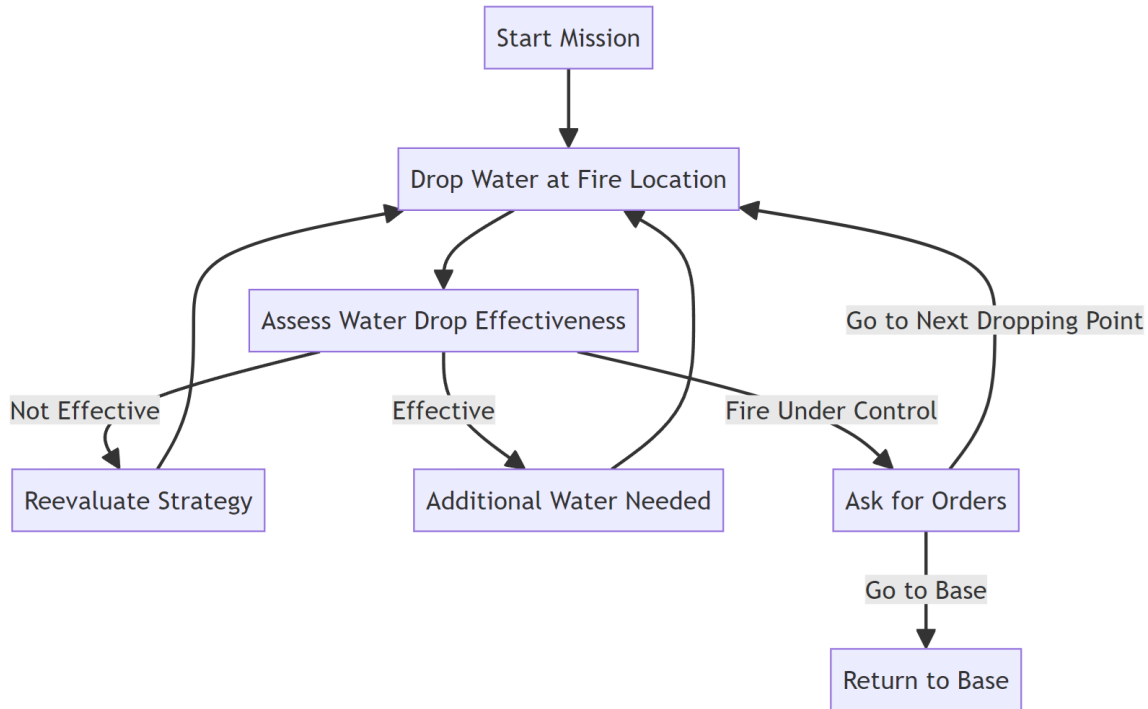


Figure 1 – Example of decision tree for a firefighting agent.

1.1 Objectives of the Paper

The present study aims to conduct an ABS whose agents' behaviour will be driven by a LLM. The goal is to evaluate the combination of both for future SoSs analyses with decision trees removed to the extent possible, offering a more dynamic and realistic representation of decision-making. The feasibility and potential benefits of utilizing LLMs to model human decision-making within an ABS will be evaluated. The unique challenges of ACD specifically for wildfire fighting – such as the need for rapid response, operational versatility, and coordination with other systems – make the application of ABS and LLMs to the study of SoSs particularly relevant if a more accurate, holistic, and operationally relevant analysis is achieved.

2. Theoretical Background

This section introduces the theoretical basics to understand the different concepts needed to perform the present work.

2.1 Agent-Based Modelling and Simulation

Field-testing data is sometimes scarce or even impossible to obtain. Such is the case with wildfires, where creating a real wildfire situation is not feasible due to the obvious costs and disastrous side effects. Therefore, a model is necessary, but modelling complex systems in a dynamic and interactive environment is a challenging task [5]. ABMS become particularly convenient in this context, thanks to their approach of representing singular entities, or '*agents*', each with unique behaviours and decision-making capabilities. This is a very valuable aspect in systems engineering [6]. However, it is particularly relevant for wildfire management scenarios, where diverse agents interact dynamically with the environment. ABMS enhances the exploration of emergent behaviours that arise from these interactions with the environment and the agents with one another, providing additional insights into the systems' performance both individually and collectively [7].

2.2 System of Systems

A SoS can be seen as a set of independent constituent systems, each useful in its own right, working together to achieve a common goal. The following characteristics [8] are generally accepted for a SoS and the constituent systems that form it:

1. Operational independence, with each constituent system able to perform a mission by itself.
2. Managerial independence, with each constituent system having an independent evolution through enhancements or maintenance.
3. The overall SoS evolves and develops over time.
4. Emergent behaviours present in the SoS are not found when operating any of the constituent systems alone.
5. The constituent systems are geographically distributed but still capable of performing information exchange.

During the life cycle of a SoS, different levels of centralization can be seen. For instance, several fire departments or governmental agencies might be involved in containing and extinguishing a wildfire, thus working towards a common goal. The level of centralization can be used to categorize the type of SoS [9]:

- Systems with high centralisation are categorised as directed SoS.
- Systems with medium-high centralisation are categorised as acknowledged SoS.
- Systems with medium-low centralisation are categorised as collaborative SoS.
- Decentralised are categorised as virtual SoS.

2.3 Large Language Models

LLMs are based on advanced forms of *Statistical Language Models* that model the likelihood of a word appearing in a given sequence of words [10]. Over the years, different methods of combining Statistical Language Models with machine learning have been applied, such as recurrent neural networks or reinforcement learning [11]. The result is the LLMs, which will undergo training in an iterative process, with some form of feedback, learning to provide an outcome expected by humans. This capability opens new possibilities in many fields, including SoS, where human behaviours can and should be included to obtain evolving models that better reflect real-world decision-making [12].

2.3.1 Structure of Neural Networks

A neural network is defined as “a group of interconnected units called neurons that send signals to one another” [13]. The neural networks used in some sort of machine learning or artificial intelligence typically consist of:

- **Input Layer:** Receives the inputs.
- **Hidden Layers:** Intermediate layers where the computations take place.
- **Output Layer:** Produces the final outputs.

2.3.2 Universal Approximation Theorem

The *Universal Approximation Theorem* states that a feedforward neural network with enough hidden layers can approximate the linear output layer to a non-zero amount of error for any *Borel measurable* function from a finite-dimensional space to another one. A continuous function is *Borel measurable* if it is continuous on a closed and bounded subset of $\mathbb{R}^n$ [14][15]. Feedforward networks with hidden layers require *activation functions* to introduce non-linearity into the model for the hidden layers [16], some common examples being:

- **Sigmoid:** $\sigma(x) = \frac{1}{1+e^{-x}}$
- **Hyperbolic tangent:** $\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$

The theorem is relevant for LLMs because it guarantees that if the neural network used is sufficiently complex, it can *approximate* any continuous function. In other words, LLMs with enough training can model and generate a wide range of natural language patterns effectively.

2.3.3 Information Theory

Information theory was developed by Claude Shannon for sending signals with noise [10]. The theory helps to compute the expected length of a message sampled from probability distributions. The original theory uses base-2 logarithms and *bits* or *shannons* as a unit system. However, when the theory is applied to the study of neural networks, base-e natural logarithms are used, thus the unit system used is *nats*. To quantify the uncertainty in a probability distribution, the concept of Shannon entropy is used and defined as:

$$H(x) = H(P) = -\mathbb{E}_{x \sim P}[\log P(x)] \quad (1)$$

where $P(x)$ is a probability distribution and x is a variable. This is the basis for comparing the training data and the predictions of a neural network model [16].

2.4 Operational Concepts

Planning for emergency situations involves making assumptions about the conditions that might exist when such crises occur. This type of planning includes developing strategies for deploying, employing, sustaining, and redeploying assets in response. When a crisis emerges, an existing plan with a similar scenario might be used as a starting point for further planning. The *Concept of Operations* (ConOps) is defined as a statement that clearly and concisely expresses what the joint force commander intends to accomplish and how it will be done using available resources [17].

The ConOps outline assumptions, phases of the operation, prioritized missions, and requirements for deployment of the assets. Through detailed and simulated planning, the requirements are determined for likely operational needs, which allows for rapid adaptation by comparing hypothetical conditions with real-time needs [18].

2.5 Basics of Rotary-Wing Aerodynamics

Helicopter aerodynamics studies the numerous complex interactions during the different flight regimes, such as the main rotor wake structure and its effect on the tail rotor, transonic flows over the blades, stalled regions, etc. There are, however, several results based on *Momentum Theory* that are simple enough for quick estimations [19], [20]. The thrust coefficient is one of the most relevant values and is defined as:

$$C_T = \frac{T}{\rho A \Omega^2 R^2} \quad (2)$$

Where T is the thrust, A is the rotor disk area, Ω is the rotor rotational velocity, R is the rotor radius and ρ is the flow density.

2.6 Basics of Fixed-Wing Aerodynamics

For the case of fixed-wing aircraft there are some very useful closed-form solutions under the assumption of inviscid and incompressible flow, especially for finite wings [21]. An important value is the lift coefficient:

$$C_L = \frac{2L}{\rho_\infty V_\infty^2 S} \quad (3)$$

Where L is the lift force, ρ is the flow density, V is the flight velocity, and S is the wing area. From Equation 3, using the maximum lift coefficient achievable, the stalling velocity can be obtained, which is particularly relevant when designing air tankers that will drop water or retardant:

$$V_{stall} = \sqrt{\frac{2W}{\rho_\infty S C_{L,max}}} \quad (4)$$

2.7 System Capabilities

Stakeholders will define the desired capabilities for the systems that are yet to be designed. These capabilities will constrain the requirements for the new system concepts, whether they are aircraft or any other kind. Several of the capabilities that will define the system requirements are shared between concepts. The capabilities derived from the operational needs are defined and listed here, alongside the proposed requirement when common to all systems:

1. **Adaptability:** Ability to respond to dynamic and unforeseen changes in the environment. *Common requirements for all systems:* Modular design for new technologies' integration and easier manufacturing [22]; capable of handling various weather conditions and terrains.
2. **Communication:** Effective use of communication protocols for coordination between different units. *Common requirements for all systems:* Advanced communication systems for interoperability with ground units and other aircraft; encrypted communication.
3. **Environmental Assessment:** Ability to assess and respond to environmental factors like fire magnitude and weather conditions. *Common requirements for all systems:* Onboard sensors and cameras for real-time fire and weather monitoring; assessment of terrain features, vegetation types, and weather patterns.
4. **Operational Efficiency:** Ability to perform its intended functions by minimizing resources needed and maximizing output.
5. **Safety and Emergency Response:** Ability to respond to medical emergencies and ensure safety protocols. *Common requirements for all systems:* Fire-resistant features to avoid degradation [23].
6. **Autonomy:** Ability for autonomous operation with minimal human intervention.

3. Method

The main points extracted from ConOps found in the reviewed literature are presented in this section [24] [25]. They will be used as prompts for the selected state-of-the-art LLM [26] and constrain its responses to the required operational concepts. Figure 2 shows a sequence diagram for a *directed SoS* driven by the LLM-commander. The prompts given follow a *Latex*-based structure, which the authors have found to be easier to interpret by LLM due to its clear structure. If the concept of LLM-driven simulations is considered satisfactory, the results with fixed capabilities will be analysed in a traditional way, without any artificial intelligence interaction. The analysis of the outcomes will be needed to understand the decisions taken, identify successful strategies or find hidden bias before moving on to more statistically oriented analyses.

3.1 Responsibilities and Actions of an Incident Commander

The IC guidelines in terms of responsibilities and communication are listed in this section. All the following points listed here are used as a prompt for the LLM.

- **Provide Complete Briefings:**
 - Clearly communicate the task, purpose, and end state of the assignment to subordinates.
 - Ensure subordinates have a clear understanding of the assignment.
- **Evacuation Procedures:**
 - Plan how to get injured personnel to a road or helispot.
 - Identify the required personnel and equipment for evacuation.
 - Calculate the time needed to get the injured to a hospital and determine the closest hospital.
 - Decide on air or ground transportation and consider factors that could affect the timeline.

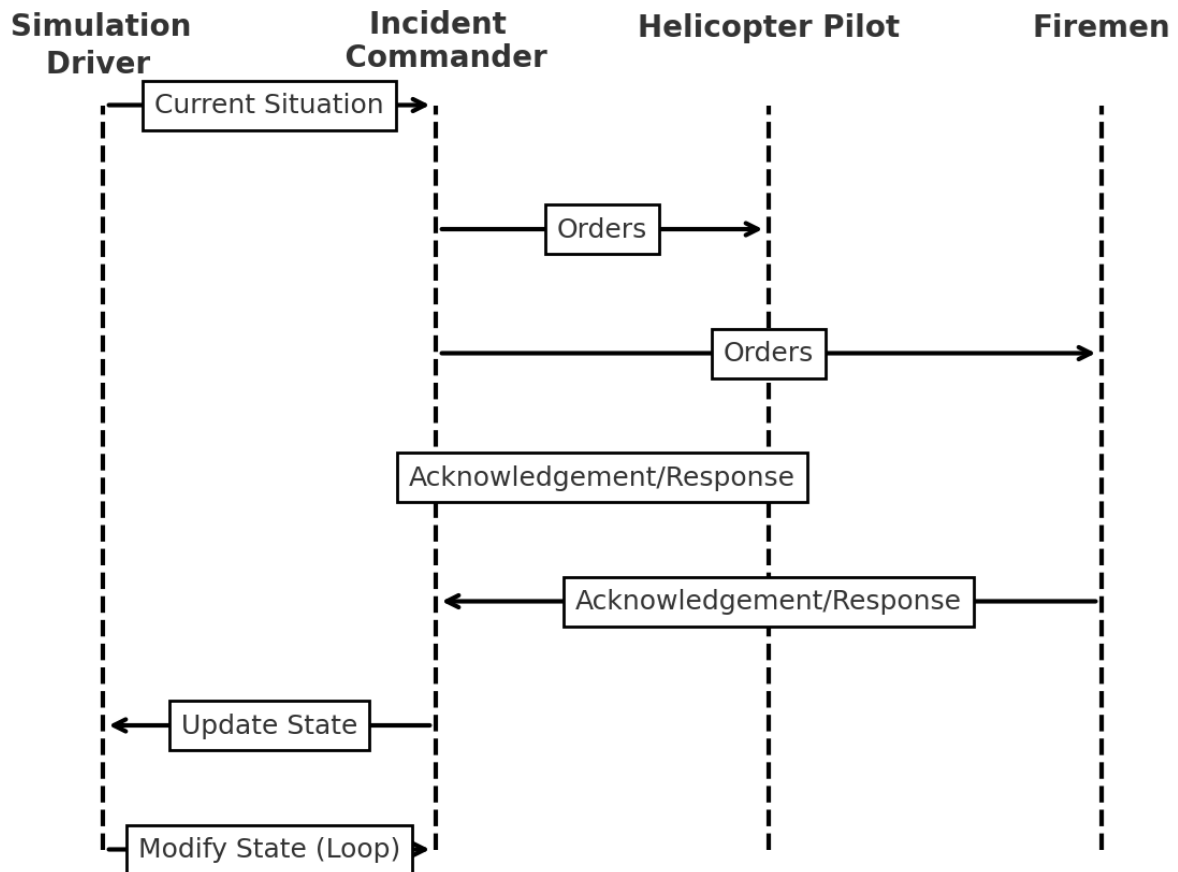


Figure 2 – UML Sequence Diagram for Wildfire Incident Management

- **Recognize Common Denominators of Fire Behaviour in Tragedy Fires:**

- Be aware of the conditions under which fatal or near-fatal fires often occur, such as:
 - * Small or quiet areas of large fires.
 - * Light fuels like grass and light brush.
 - * Unexpected shifts in wind direction or speed.
 - * Critical burn periods between 1400 and 1700 hours.

- **Radio Traffic and Discipline:**

- Maintain disciplined and concise radio communication.
- Use clear text for all operations.
- Follow established procedures for radio calls, identifying the resource being called, and the frequency used.

- **Issuing Air Traffic Information and Advisories:**

- Provide clear air traffic information and ensure pilots acknowledge it.
- Pass on new information and ensure no missions are launched in conflict areas.
- Follow standard scripts for communication to ensure clarity and consistency.

- **Risk Management Principles:**

- Accept no unnecessary risk and make risk decisions at the appropriate level.
- Balance risk against the benefits and integrate risk management into planning and execution at all levels.

3.2 Responsibilities and Duties of Helicopter Personnel

The helicopter personnel guidelines in terms of responsibilities and communication are listed in this section adapted from [27]. It is assumed that the pilot is responsible for ensuring that all of them are followed, hence only the pilot is considered for the communication. All the points listed here are used as a prompt for the LLM.

- **General Responsibilities:**

- Adhere to Federal Aviation Regulations (FARs) and agency-specific regulations.
- Coordinate with dispatchers, helicopter managers, and/or Helibase Managers.
- Ensure aircraft and communication equipment are in good condition and operable.

- **Flight Operations:**

- Do not deviate from the flight plan without notifying the appropriate dispatch office.
- Do not descend below 500 feet Above Ground Level (AGL) without prior authorization or a high-level reconnaissance.

- **Risk Management:**

- Accept no unnecessary risk.
- Make risk decisions at the appropriate level.
- Accept risk only when benefits outweigh costs.
- Integrate risk management into planning and execution phases.

3.2.1 Helicopter-Specific Procedures

- **Landing Area Selection:**

- Choose a flat area free of obstructions (trees, poles, wires, etc.).
- Ensure the area is clear of stumps, brush, rocks, and any objects over 18 inches high.
- Consider wind direction for landing and takeoff.

- **Aerial Delivered Retardant/Water Drop Considerations:**

- Maintain communication with aerial resources.
- Identify and communicate flight hazards to aerial supervisors.
- Provide specific target information using clear descriptions and signal markers.
- Clear the area to avoid direct flights over ground personnel and equipment.

- **Aircraft Mishap Response Actions:**

- Prioritize life preservation and secure the area.
- Exercise caution due to potential hazards at the wreckage site.

3.2.2 Communication Protocols

- **Radio Discipline and Clear Text Usage:**

- Ensure all aircraft and ground personnel have compatible radios and frequencies.
- Maintain disciplined and concise radio traffic.
- Use clear text on all operations, keeping messages brief and to the point.

- **Standard Scripts for Communication:**

- **Flight Following Departure Script:**

- * Identify tail number or designated identifier.
- * State the frequency being used.
- * Provide departure location, number onboard, fuel onboard, Estimated Time En route (ETE), and destination.
- * Confirm Automated Flight Following (AFF).
- **Flight Traffic Advisory (FTA) Calls in the Blind:**
 - * Identify the receiving unit.
 - * State the tail number or designated identifier.
 - * Provide distance and direction from the incident, altitude, intent, and frequency.
- **Landing and Departure Communications:**
 - **When Helicopter Contacts Helibase:**
 - * Provide helicopter number and helibase identification.
 - * Report wind speed and direction.
 - * Notify about traffic status (inbound/outbound aircraft).
 - **Before Helicopter Departs Helibase:**
 - * Provide helicopter number and helibase identification.
 - * Report wind speed and direction.
 - * Notify about traffic status (inbound/outbound aircraft).

3.3 Responsibilities and Actions of Firemen in Firefighting Operations

The guidelines for the firemen in terms of responsibilities and communication are listed in this section. It is assumed that the team leader is responsible for ensuring that all of them are followed and performing communication when needed. All the following points listed here are used as a prompt for the LLM.

3.3.1 Fireline Construction and Safety

- **Establishing Firelines:**
 - Use direct attack whenever possible, constructing a fireline as close to the fire edge as conditions safely permit.
 - If an indirect attack is required, locate the fireline at an adequate distance from the main fire to allow for completion, firing, and holding, considering the predicted rate of fire spread.
 - Make the fireline as short and straight as practical, using topography to your advantage.
 - Use existing natural and human-made barriers.
- **Communication Requirements and Procedures:**
 - Assign experienced and competent lookouts at good vantage points with knowledge of crew locations, escape and safety locations, and trigger points.
 - Confirm radio frequencies and establish backup procedures and check-in times.
 - Provide updates on any changes in the situation and sound alarms early.
- **Radio Traffic and Discipline:**
 - Use clear and concise radio communication.
 - Identify yourself and the resource you are calling first, followed by the message.
 - Follow established procedures for radio calls and ensure disciplined radio traffic.
 - Confirm receipt of critical information and acknowledge messages.

3.3.2 Reporting Issues

- **Reporting Injuries:**

- Immediately report any injuries to the supervisor or IC.
- Provide details about the injury, including the nature and severity of the injury, and the number of injured personnel.
- Communicate the need for medical support and transportation.

- **Reporting Stress:**

- Report signs of fatigue or stress among crew members to the supervisor.
- Monitor crew members for symptoms of overexposure to smoke, such as headaches, visual impairment, and impaired decision-making.

3.3.3 Specific Communication Scripts

- **Initial Contact Script:**

- Identify the resource being called and your identification.
- Provide a brief message regarding the situation.

- **Requesting Medical Support Script:**

- Identify the resource being called and your identification.
- State the nature of the injury and the need for medical support.
- Provide your location and any relevant details.

3.4 Agent-Based Simulation Setup

The simulation is performed using NetLogo [28], a software designed for modelling and simulation of complex systems using agents. Advanced models for simulating wildfires can be built to include features such as compatibility with Geographic Information System (GIS) data, dynamic changes in weather conditions, and smoke [4]. For the present work, however, a simplified version is used and shown in Figure 3. The model includes a variety of agents, each assigned with a specific role in wildfire suppression scenarios: *Helicopters*, *Unmanned Aerial Vehicles (UAVs)* and *Firemen*. Among these, the agents representing aircraft are of particular significance for this study, more so than those performing ground operations. The reason for this is the specific interest of the authors in generating requirements for performing ACD and *Systems Engineering*. The firemen will remove material around the fire to stop the spread. The helicopters will assist with water drops, but they can also drop or rescue firemen at designated points. The UAVs can fly around the map and report areas on fire or loiter over the firemen. Both firemen and helicopters can report random emergency calls during the simulation, such as engine problems for the helicopters or health issues for the firemen. The map limits are (-50,-50) to (50,50). Water areas (shown in blue) and wildfire starting points are generated randomly during the initialization. It is possible to start additional fires during the simulation. The wildfire spreads every 500 steps in all directions where trees are present. Time steps are taken dimensionless to simplify, and all agents move 1 position in the grid per time step when they decide to do so. In the simulation, everything coloured in yellow is the information the commander can request: UAV's vision and the locations of firemen and helicopters. Only what the agents can see or report is provided if and only if an event is triggered or the LLM-commander requests it.

3.5 Incorporation of Large Language Models

Figure 1 has shown the decision trees that the present work aims to replace for a LLM representing the IC. For the present proof of concept, a web-based chat interface is used for the communication between LLM and the simulation. The roles of the commander and the different agents involved are taken by several versions of the LLM, whereas the information regarding the simulation situation is provided as prompts by the user.

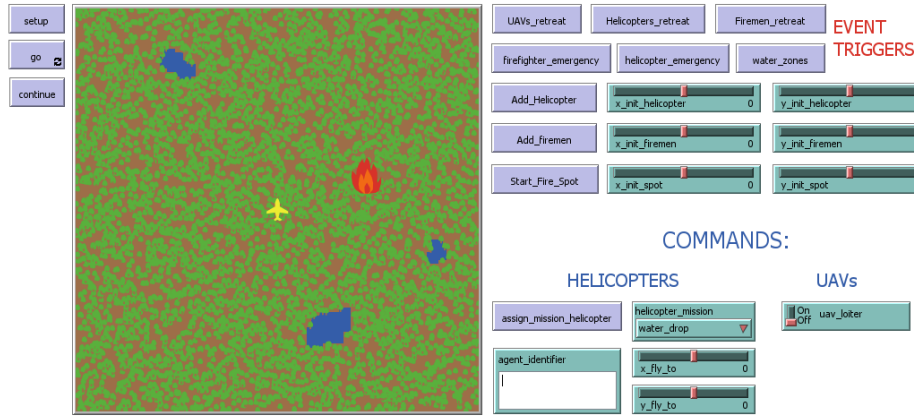


Figure 3 – Agent-Based Model User Interface.

4. Results

This section presents the results from the interaction with the LLM and its interactions with the wildfire simulation. Due to the length of the LLM outputs, the most relevant part of the conversation has been extracted and presented here. The ConOps from Section 3.1 are given as initial prompt for the commander-LLM, whereas Section 3.2 and Section 3.3 are given respectively to the helicopter pilot-LLM and the firemen-LLM. The simulation driver is the human in the loop, providing the prompts to the different LLMs that respectively play the role of IC, helicopter pilot, and firemen teams and using the output to reconfigure the simulation.

LLM-Incident Commander

“Initial Briefing and Intent

Task: Our primary task is to contain and control the wildfire while ensuring the safety of all personnel involved.

Purpose: The purpose of this mission is to prevent wildfire from spreading to populated areas, protect natural resources, and minimize damage to property and infrastructure.

End State: The end state of this operation is to have the wildfire fully contained with no injuries to personnel, minimal damage to property, and a thorough plan for monitoring and managing hotspots.

Summary of Communication Requirements:

- Clear and complete briefings.
- Pre-operational medical emergency planning.
- Tactical pauses and reassessments.
- Establish and communicate LCES (Lookouts, Communications, Escape Routes, Safety Zones).
- Safe transitions between shifts.
- Disciplined radio communication.
- Standardized air traffic advisories and acknowledgments.
- Integration of risk management into all phases of operation.”

Simulation Driver

“The map of remote area is divided in coordinates from -50 to 50 in the X axis and -50 to 50 in the Y axis. An UAV is patrolling over the area and a wildfire is reported. It is unknown for how long it has been burning and its actual size. One helicopter and two firefighter teams are available in the local agency. Please state your decision and keep consistency with the IC CONOPS.”

LLM-Incident Commander

"[...] Summary of Actions

- *UAV: Conduct initial fire location and assessment.*
- *Brief Teams: Ensure all personnel are aware of their roles, LCES, and medical plans.*
- *Medical Preparedness: Confirm medical personnel, equipment, and evacuation routes.*
- *Deploy Helicopter: For reconnaissance or water drops as needed.*
- *Deploy Firefighter Teams: From strategic directions to create containment lines.*
- *Tactical Pause: Reassess the situation around 1400 hours.*
- *Continuous Communication: Maintain disciplined and clear radio communication."*

Simulation Driver

"The wildfire coordinates are reported to be: (-17.88, 36.07). When checking the map of the area, the following coordinates are lakes with water available for water drops: 1) Lake A: (7, -11); 2) Lake B: (-31, 47). Entrance point to the map from the helicopter is (-31,-50). Please, state your decisions and how you would communicate them."

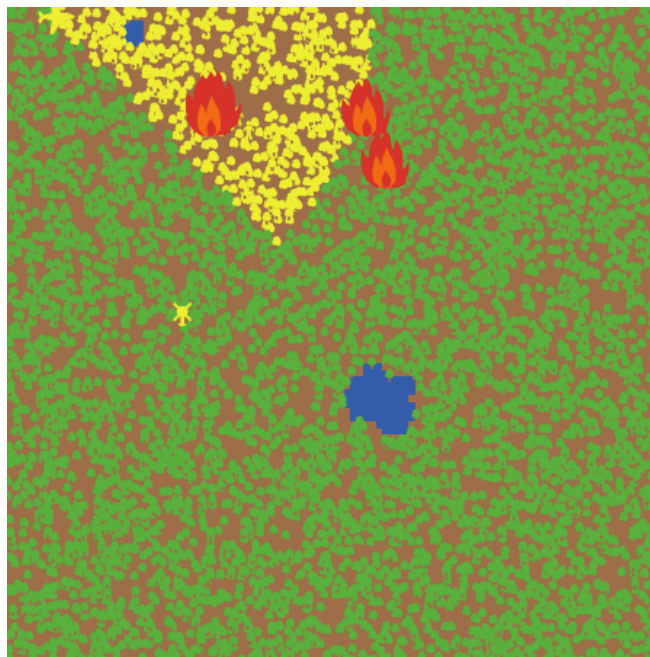


Figure 4 – UAV detecting fires.

LLM-Incident Commander

"[...] Communication Plan:

- *To Helicopter Crew: "Helicopter Team, this is Incident Command. Enter the map at (-31, -50) and proceed directly to Lake B at (-31, 47) to fill water tanks. After filling, head to the wildfire at coordinates (-17.88, 36.07) for water drops and aerial reconnaissance. Maintain communication on primary frequency Alpha and report any significant changes. Over."*
- *To Firefighter Team A: "Team A, this is Incident Command. Proceed to coordinates (-17.88, 50) and establish a line approaching the wildfire from the north. Ensure LCES is established and be ready for tactical pause at 1400 hours. Maintain communication on primary frequency Bravo and update status every 30 minutes. Over."*

- To Firefighter Team B: "Team B, this is Incident Command. Proceed to coordinates (-17.88, -50) and establish a line approaching the wildfire from the south. Ensure LCES is established and ready for tactical pause at 1400 hours. Maintain communication on primary frequency Bravo and update status every 30 minutes. Over."
- To UAV Operator: "UAV Operator, continue monitoring the wildfire and provide real-time updates on fire behaviour, spread, and intensity. Report any critical changes immediately on primary frequency, Charlie. Over."

[...]Summary

- Helicopter: Fill water at Lake B, perform water drops, and conduct aerial reconnaissance.
- Firefighter Teams A and B: Approach wildfire from the north and south, respectively, ensuring safety protocols (LCES) are in place.
- UAV: Provide continuous monitoring and updates.
- Communication: Maintain disciplined, clear, and regular communication with all teams, ensuring updates and adjustments are communicated promptly."

Figure 4 shows the situation after following the commander's orders. Notice the helicopter flying towards the required destination with water.

Simulation Driver

The simulation continues. The helicopter pilot reports this upon reaching the wildfire: "Alpha frequency, Helicopter six eight x-ray (68X) arrived at coordinates (-17.88, 36.07) for water drops and aerial reconnaissance. Beginning operations now. Over." At the same time, another fire spot has been reported by the UAV: (-19, 36)

LLM-Incident Commander

"Acknowledgement and Instructions to Helicopter Pilot:

- To Helicopter Pilot (68X): "Alpha frequency, this is Incident Command. Acknowledged, Helicopter 68X. Begin water drops at coordinates (-17.88, 36.07) and continue aerial reconnaissance. Be advised, that a new fire spot has been reported by UAV at coordinates (-19, 36). After initial water drops, proceed to assess and report on the new fire spot. Maintain visuals on both spots and update on progress. Over."
- To Firefighter Team A: "Bravo frequency, this is Incident Command. Be advised, that a new fire spot has been reported at coordinates (-19, 36) in close proximity to your current target. Adjust your approach to include containment of both fire spots. Maintain LCES protocols and ensure regular status updates. Over."
- To Firefighter Team B: "Bravo frequency, this is Incident Command. Be advised, that a new fire spot has been reported at coordinates (-19, 36) near the initial fire location. Adjust your approach accordingly to assist Team A in containing both fire spots. Maintain LCES protocols and ensure regular status updates. Over."

[...]Summary of Actions

- Helicopter 68X: Perform initial water drops, then assess and report on both fire spots.
- Firefighter Teams A and B: Coordinate to contain both fire spots with adjusted strategies.
- UAV: Provide detailed real-time updates and monitoring of fire behaviour for both spots.
- Tactical Pause: Reassess the situation at 1400 hours to ensure effectiveness and safety."

Simulation Driver

Team B reports the following: "Command, Team B, reporting a medical emergency. Firefighter experiencing heat stroke symptoms. We need immediate medical assistance at our current location. Over."

LLM-Incident Commander

"Acknowledgment and Instructions to Helicopter Pilot:

- To Helicopter Pilot (68X): "Alpha frequency, this is Incident Command. We have a medical emergency at Team B's current location, a firefighter experiencing a heat stroke. Requesting immediate medevac (medical evacuation). Proceed to Team B's coordinates. Secure a safe landing zone and prepare for transport. Over."
- To Firefighter Team A: "Bravo frequency, this is Incident Command. Be advised, that Team B is experiencing a medical emergency. A firefighter with heat stroke symptoms. Continue current operations, but prepare to assist with medical evacuation if required. Over."
- To Firefighter Team B: "Bravo frequency, this is Incident Command. Acknowledged, Team B. Medical emergency confirmed. Immediate medical assistance will be dispatched to your current location. Ensure the firefighter is moved to a shaded area and start cooling measures immediately. Maintain hydration and monitor vital signs. Stand by for further instructions. Over."

[...]Summary of Immediate Actions

- Team B: Administer first aid for heat stroke, move firefighter to a shaded area, and prepare for medevac.
- Helicopter 68X: Divert to Team B's location for medevac, ensure safe landing and transport.
- UAV: Provide aerial monitoring and support for medevac operations.
- Team A: Continue firefighting operations, and remain on standby to assist with evacuation if needed.
- All Units: Maintain clear communication and follow updated instructions from Incident Command."

Simulation Driver

Before this prompt during the conversation, the LLM is informed that it can request help from other agencies. After doing so, it is informed of the following: You receive the following over the radio: "Command, Team A, reporting signs of severe exhaustion among crew members. Requesting immediate relief and rotation of resources. Over." "Command, Team C, entering the area from point (-1,50). Over." "Command, Team D, we are entering from point (-1,50). Over." "Command, Team E, now entering from point (-1,50). Over." "Incident Command, this is Helicopter Five Four Zulu (54Z). Entering from point (50, 8). Ready for further instructions. Over." "Incident Command, this is Helicopter Two one tango (21T). Entering from point (50, 8). Ready for further instructions. Over."

LLM-Incident Commander

"[...]To All Units: "All units, this is Incident Command. Be advised, that Team A is experiencing severe exhaustion. Teams C, D, and E are now entering the area for relief and rotation. Helicopters 54Z and 21T are refilling at lakes A and B respectively and will provide aerial support and water drops. Maintain LCES protocols and update status regularly. Over."

Monitor and Adjust Operations as Necessary

- Team A: Provide immediate relief and ensure safe rotation with incoming teams.
- Teams C, D, and E: Establish LCES, focus on their assigned fire spots, and ensure a smooth transition.

- *Helicopters 54Z and 21T: Conduct water drops and provide aerial reconnaissance.*
- *UAV: Monitor the situation and provide real-time updates.*

Summary of Updated Plan of Action

- *Team A: Immediate relief by Teams C, D, and E. Ensure safe rotation and rest.*
- *Teams C, D, and E: Take over firefighting operations with clear focus areas and support.*
- *Helicopter 54Z: Refill at Lake A, conduct water drops, and provide reconnaissance.*
- *Helicopter 21T: Refill at Lake B, conduct water drops, and provide reconnaissance.*
- *UAV Support: Monitor relief operations and fire behaviour, providing real-time updates.*
- *Continuous Communication: Maintain clear and regular communication with all units, updating on the status and any changes."*

Figures 5 show the final stages of the operation. The wildfire is being reduced with the different agents around it, continuing until the end of the simulation when the wildfire is completely extinguished. Notice the area where the vegetation has been removed by either the fire or the work of the agents.

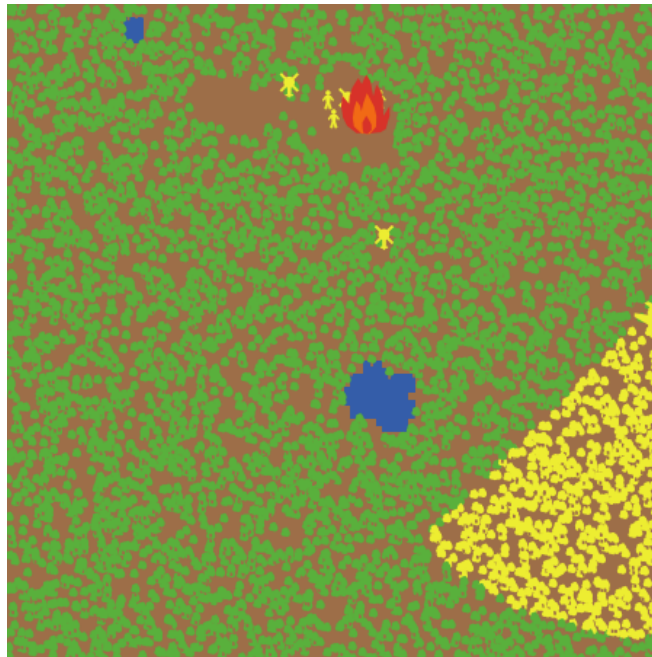


Figure 5 – Wildfire under control.

5. Discussion

In this section the results are discussed in terms of the performance of the LLM as IC, and in terms of operational capabilities for generation of system requirements.

5.1 Performance of the LLM-IC

The simulation results highlight several key aspects of the LLM's behaviour and decision-making in wildfire scenarios. The LLM effectively tracked the agents' actions and whereabouts. It also demonstrated adaptability, for example, by transitioning an UAV from surveillance to loitering over Team A for support. The LLM's tendency to utilize all resources indicates a focus on maximizing effectiveness, possibly due to lack of cost information, although it is acceptable since literature suggests that undermanned fire operations are more costly than overmanned ones [29]. On the other hand, LLM did not enquire about the fire's magnitude, indicating an oversight in evaluating environmental factors.

Although it adhered to scheduled weather checks, it did not inquire about current conditions of wind and temperature, revealing a discrepancy between planned and adaptive decision-making. An unexpected feature was the LLM's use of the NATO phonetic alphabet ("T Tango", etc.), demonstrating the value of diverse neural network training for enhancing interoperability and communication across contexts. However, a challenge is to predict when LLM might deviate from ConOps and make biased decisions. Having the ability to maintain the coherence and relevance of the dialogue whilst ensuring periodic updates of mission status without the overload of information is crucial. Another consideration is to adjust the randomness of the LLM, which affects creativity and determinism. This choice is important for decision-making dynamics and operational performance optimization, especially in simulation environments, where reproducing human errors helps to evaluate the resilience, adaptability, and response time of a SoS or to identify architectural flaws.

5.2 Operational Capabilities

The simulations results must be considered also in terms of ACD. From the operational capabilities used to fulfil the mission, the top-level requirements are to be extracted for generating new system concepts and add them to those that could have been given by stakeholders. Four different concepts of aircraft could be proposed, as shown in Table 1 to Table 4, using the results of the simulation.

Table 1 – Helicopter 1: Firefighting Helicopter

Capability	Requirement
Adaptability	Modular design for new technologies' integration and easier manufacturing. Capable of handling various weather conditions and terrains.
Communication	Advanced communication systems for interoperability with ground units and other aircraft. Encrypted communication.
Environmental Assessment	Onboard sensors and cameras for real-time fire and weather monitoring. Assessment of terrain features, vegetation types, and weather patterns. Integration of data for strategic planning.
Operational Efficiency	Extended operational periods. High hover stability and precision in water drop targeting. Advanced targeting and navigation systems. Large water carrying capacity (min. 2000 liters) with quick refill capability.
Safety and Emergency Response	Fire-resistant features to avoid degradation. Automatic fire suppression systems. Real-time status monitoring of critical systems.
Autonomy	Semi-autonomous hovering capabilities with autopilot systems for precision operations. Real-time obstacle detection and avoidance systems. Flight path optimization for quicker turnarounds.

The vehicles need to be able to handle different weather conditions and terrains, since the location of a wildfire is going to be unknown *a priori*. In terms of collaboration, the various constituent systems must include communication subsystems, which is crucial from a SoS point of view. The communication capabilities must ensure interoperability in a safe way, whether for requesting evacuation or informing about new issues, as observed in the simulation when one team was in distress or the new fire spot started. Another requirement identified is the inclusion of different types of sensors and cameras to provide enhanced situational awareness throughout the mission, which was the main task of the UAV when patrolling the perimeter of the map and supporting the firemen.

Specific requirements extracted for helicopters, shown in Table 1 and Table 2. The amount of water to be carried will depend on the system being specific for water drops or for a multi-role one. The requirements for a multi-role will reduce the size of the water bucket in exchange for being able to

Table 2 – Helicopter 2: Multi-Role Support Helicopter

Capability	Requirement
Adaptability	Modular design for new technologies' integration and easier manufacturing. Easy firefighting and search and rescue re-configuration. Capable of handling various weather conditions and terrains.
Communication	Advanced communication systems for interoperability with ground units and other aircraft. Encrypted communication.
Environmental Assessment	Onboard sensors and cameras for real-time fire and weather monitoring. Assessment of terrain features, vegetation types, and weather patterns. Integration of data for strategic planning.
Operational Efficiency	Extended operational periods. Quick deployment and retrieval of rescue teams and equipment. Advanced navigation and targeting systems. Moderate water carrying capacity (max. 1000 litres) and additional cargo space for equipment.
Safety and Emergency Response	Advanced medical support systems and easy access for emergency evacuations with a stretcher. Fire-resistant features to avoid degradation. Automatic fire suppression systems. Real-time status monitoring of critical systems.
Autonomy	Enhanced navigation systems (obstacle detection and avoidance). Automated flight paths and water drops for firefighting. Real-time assisted decision-making based on data from sensors and cameras. Capability to switch between manual and autonomous modes as needed.

Table 3 – UAV 1: Fixed-Wing configuration

Capability	Requirement
Adaptability	Modular design for new technologies' integration and easier manufacturing. Easy firefighting and search and rescue re-configuration. Capable of operating in various weather conditions and in diverse terrains.
Communication	Advanced communication systems for interoperability with ground units and other aircraft. Encrypted communication
Environmental Assessment	Onboard sensors and cameras for real-time fire and weather monitoring. Assessment of terrain features, vegetation types, and weather patterns.
Operational Efficiency	Extended operational periods (minimum 10 hours) for both firefighting and rescue missions. Rapid deployment. Minimization of maintenance downtime. Advanced navigation and targeting systems for precise operations. Flight path optimization.
Safety and Emergency Response	Fire-resistant features to avoid degradation. Emergency protocols for automated return or safe landing. Real-time status monitoring of critical systems.
Autonomy	Fully autonomous operation with advanced mission planning and execution capabilities. Autonomous navigation and obstacle detection for search and rescue missions. Ability to switch between autonomous and manual control as needed.

Table 4 – UAV 2: Tilt-Rotor configuration

Capability	Requirement
Adaptability	Modular design for new technologies' integration and easier manufacturing. Easy firefighting and search and rescue reconfiguration. Capable of operating in various weather conditions and in diverse terrains. Capable of vertical take-off and landing (VTOL) and transitioning to fixed-wing flight.
Communication	Advanced communication systems for interoperability with ground units and other aircraft. Encrypted communication
Environmental Assessment	Onboard sensors and cameras for real-time fire and weather monitoring. Assessment of terrain features, vegetation types, and weather patterns.
Operational Efficiency	High manoeuvrability with the ability to hover and perform precise drops. Rapid deployment. Minimization of maintenance downtime. Advanced navigation and targeting systems for precise operations. Flight path optimization.
Safety and Emergency Response	Fire-resistant features to avoid degradation. Emergency protocols for automated return or safe landing. Real-time health monitoring of critical systems.
Autonomy	Fully autonomous operation with advanced mission planning and execution capabilities. Autonomous navigation and obstacle detection for search and rescue missions. Ability to switch between autonomous and manual control as needed.

land on forestry areas to transport or evacuate people, as happened during the simulation. Equation 2 can be used for initial predictions related to the helicopter rotor thrust needed for these different operational situations. For example, a smaller rotor radius will be convenient to be able to land in forestry areas and avoid collisions, but the performance will differ to a helicopter with bigger radius and specific for water drops.

For the case of UAVs, Equations 3 and 4 can be used together with common weight estimation methods during the phase of generating the concept of an aircraft [30]. These predictions are relevant because, if the UAVs is requested to change its mode from surveillance to support, it will fly at a slower velocity and, depending on the needs, being able to either loiter or hover could make a difference. Hence, considering fixed-wing or tilt-rotor configurations is relevant for proposing new concepts, as well as the prediction from Equation 4. The reason is that the fixed-wing concept can be designed with endurance as the main goal, but when in loitering mode, its capabilities to support firemen could be insufficient. Whereas a tilt-rotor concept will trade an enhanced loitering or hovering capability for reduced endurance.

6. Conclusion

This work has shown that allowing an LLM to drive an ABS helps to reduce the need to include long decision trees for modelling behaviours. This provides more degrees of freedom for the simulation and extends the analysis of SoS. The ABS was used to evaluate the LLM's decision-making and its capability to follow operational guidelines as an IC, with a satisfactory outcome. Moreover, from the decisions taken, it was possible to evaluate what kind of capabilities would be required from the constituent systems that are part of the SoS. The operational capabilities found have been related to requirements that can be used for ACD and generate different aircraft concepts, such as helicopters or UAVs. Future work will be oriented to evaluate the effect of the randomness level in the answers of the LLM and emerging bias resulting from longer conversations. It will also be interesting to study the effect of adding costs to the available resources. Another interesting topic for future research would be to study the possibility to give the LLM the capability to re-write parts of the model code and expand

the boundaries of the simulation. In terms of ACD, future work will be oriented to perform analyses using design of experiments, where multiple simulations will be run with varying capabilities to let the LLM determine which features lead to optimal outcomes, generate requirements and propose aircraft concepts by itself.

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