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Sensitivity Analysis of Aerial Wildfire Fighting Tactics with Heterogeneous Fleets Using an Agent Based Simulation Framework

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SENSITIVITY ANALYSIS OF AERIAL WILDFIRE FIGHTING TACTICS WITH HETEROGENEOUS FLEETS USING AN AGENT BASED SIMULATION FRAMEWORK

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ABSTRACT

SENSITIVITY ANALYSIS OF AERIAL WILDFIRE FIGHTING TACTICS WITH HETEROGENEOUS FLEETS USING AN AGENT BASED SIMULATION FRAMEWORK

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The increase in the average temperature of the global surface temperature caused longer wildfire seasons, which have caused more severe and frequent incidents, resulting in higher expenses, unrecoverable losses and civilian casualties. Moreover, the increased number of wildfires has contributed to higher levels of carbon in the atmosphere, further exacerbating global warming. Fighting wildfires is a complex phenomenon that requires various resources, and the System of Systems (SoS) approach can be leveraged to analyze the problem. This study utilizes an SoS simulation framework to model wildfire suppression missions, focusing on a mixed fleet composition of suppression drones with different characteristics such as airframe configurations, payload capacity, flight velocity, and powertrain architectures. The study evaluates multiple suppression tactics, considering factors such as fleet composition, available agents, and resources. The results of the analysis show the impact of various environmental parameters on fire growth and provide a rigorous sensitivity analysis for wildfire containment use cases. The use of the SoS framework helps to reveal nuanced patterns at the SoS level, which can aid in the development of new solutions for wildfire fighting. This study highlights the importance of considering the complexities of the problem and the need for innovative approaches to combat wildfires effectively.

Keywords: Aerial Firefighting, Agent-Based Simulation, Wildfire Suppression Tactics, System of Systems

ÖZ

AJAN TABANLI SİMÜLASYON ÇERÇEVESİ KULLANILARAK HETEROJEN FİLOLARLA HAVADAN ORMAN YANGINLARIYLA MÜCADELE TAKTIKLERININ DUYARLILIK ANALIZI

Çığal, Nazlıcan
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Ortalama küresel yüzey sıcaklığındaki artış, orman yangını mevsimlerinin genişlemesine neden olmakta ve daha şiddetli ve yoğunluklu olaylara sebep olarak baskı giderlerinde, kayıplarda ve can kayıplarında önemli bir artışa neden olmaktadır. Ayrıca, artan orman yangını olayları, atmosferde kalan daha yüksek karbon salınımına neden olmaktadır, bu da küresel ısınmayı daha da şiddetlendirmektedir. Orman yangınlarını kontrol altına almak, farklı kaynaklara ihtiyaç duyan karmaşık bir görev olduğundan dolayı Sistemlerin Sistemi (SoS) yaklaşımı, bu sorunu analiz etmek için kullanılabilir. Bu çalışma, farklı özelliklere sahip bir dizi farklı baskı dronlarından oluşan heterojen bir filoya odaklanarak, SoS simülasyon çerçevesini kullanarak orman yangını söndürme görevlerini modellemektedir. Baskı dronları farklı hava aracı konfigürasyonları, yük kapasitesi, uçuş hızı ve güç aktarma mimarisi gibi özelliklere sahiptir. Bu çalışma, filo kompozisyonu, mevcut ajanlar ve kaynaklar gibi faktörleri göz önünde bulundurarak çoklu bastırma taktiklerini değerlendirmektedir. Ayrıca, yangın yayılması üzerindeki farklı orman yangını ortam parametrelerinin etkisini araştıran kapsamlı bir analiz sunulmaktadır. Bu çalışma, farklı taktikleri içeren orman yangını sınırlama kullanım durumu için kapsamlı bir hassasiyet analizi sunmakta ve SoS çerçevesini kullanarak sistem düzeyinde ince nüanslı eğilimleri ortaya koymaktadır. Ayrıca, yangınların karmaşıklıklarını dikkate almanın önemini ve yangınlarla etkili bir şekilde mücadele etmek için yenilikçi yaklaşımların gerekliliğini vurgulamaktadır.

Anahtar Kelimeler: Orman Yangını Söndürme Taktikleri, Havadan Yangınla Mücadele, Ajan Tabanlı Simülasyon, Sistemler Sistemi

This thesis is dedicated to my loving family, who have supported and encouraged me throughout my academic journey. Their unwavering love and encouragement have been the driving force behind my achievements, and I am forever grateful for their sacrifices and constant motivation. I also dedicate this thesis to my dear friends, who have been a source of inspiration and strength. Their support and guidance have been instrumental in shaping my thoughts and ideas.

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LIST OF ABBREVIATIONS

AAM	Advanced Air Mobility
ABM	Agent-Based Modeling
ABS	Agent-Based Simulation
ANOVA	Analysis of Variance
CA	Cellular Automata
DLR	The German Aerospace Center
EBM	Event-Based Modeling
eVTOL	Electric Vertical Takeoff and Landing
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LSD	Least Significant Difference
MTOM	Maximum Takeoff Mass
MoE	Measure of Effectiveness
NASA	The National Aeronautics and Space Administration
OOP	Object Oriented Programming
SoS	System of Systems
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicles
UML	Unified Modeling Language

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

Forest fires have become a major concern globally due to their increasing frequency, intensity, and duration, resulting in environmental and socio-economic damage. Climate change, specifically the rising global temperature, has contributed significantly to the increase in wildfires, resulting in more greenhouse gas (GHG) emissions that exacerbate the impacts of climate change. In 2022, the global temperature was the sixth warmest since records began in 1880, with a temperature of 0.86°C above the 20th-century average [1]. This is slightly lower than the record set in 2016 and only slightly higher than the temperature in 2021, which was the seventh highest. The past 10 years have seen the 10 warmest years on record, with the last nine years being the warmest [1]. This warming cycle is likely to continue due to the combination of deteriorating air quality, droughty vegetation and slow regeneration of forests.

In response to these challenges, aerial firefighting has become an increasingly popular approach to combating forest fires. Aircraft equipped with specialized firefighting tanks can reach remote and hazardous areas that are difficult for ground personnel to access. Aerial firefighting can also help contain fires by creating firebreaks and providing a better understanding of the fire's location and behavior. By utilizing aerial firefighting, fire agencies can respond more quickly and effectively to the threat posed by forest fires, thereby reducing the environmental and socio-economic damage they can cause.

Despite the advantages of using aerial vehicles in firefighting, their deployment is not always viable due to operational costs. Even when deployed, how they are used is critical to the effective suppression of forest fires. Forest fires are a significant problem around the world, and different countries face varying levels of risk depending on their climate and geography. Portugal is one such country that has a long history of forest fires, with a number of major incidents occurring in recent years. The devastating forest fire in Portugal in 2017 burned more than 500,000 hectares of land, destroyed homes and property, and tragically led to the loss of many lives [2]. This disaster highlighted the importance of effective forest fire preparedness and response strategies to minimize damage and loss of life. Sweden, on the other hand, is not typically considered a fire-prone country. However, a major forest fire in 2018 resulted in the burning of over 23,000 hectares of land, the largest civil protection operation in Europe, and again led to the loss of lives and property [2]. This incident demonstrated that even in areas with low fire proneness, there is a risk of severe and intractable damage from forest fires, which underscores the need for better understanding and prevention of wildfires.

There are many factors that can contribute to the occurrence and severity of forest fires, including climate change, human activity, and natural conditions such as drought and lightning strikes. With climate change, increasing temperatures and more frequent droughts are leading to more extreme fire conditions in many areas, making it more challenging to prevent and control fires. According to a report by the United Nations Intergovernmental Panel on Climate Change (IPCC), the frequency and severity of wildfires are expected to increase in many regions of the world as temperatures continue to rise [3].

To combat the rising threat of forest fires, countries around the world are investing in various strategies and technologies to better prevent, detect, and respond to fires. One such technology is drones, which can be used for early detection and monitoring of fires, providing real-time data to firefighters and enabling them to respond more quickly and effectively [4]. Other innovations, such as fire-resistant materials and better land management practices, can also help reduce the risk and impact of wildfires.

To mitigate the impact of forest fires on the environment and society, it is essential to develop and implement effective strategies that prioritize forest fire preparedness and mitigation. Such strategies should include a combination of preventative measures, such as vegetation management and prescribed burning, and proactive suppression efforts, such as early detection and rapid response. Additionally, continued research and investment in new technologies and methods, such as the use of drones for aerial firefighting, can also help improve firefighting effectiveness and reduce costs. With continued research and investment in prevention and response strategies, it is possible to mitigate the risks and prevent future tragedies.

1.2 Proposed Methods and Models

The system of systems (SoS) approach is an engineering method that deals with the interactions between various independent systems, each with its own purposes and capabilities, to form a larger, more complex system. It is used to create a single, unified system from multiple heterogeneous systems, each with a specific purpose or function. It is mainly used to address the challenges of managing large-scale, complex systems and to develop solutions that are more efficient and effective than those used for smaller, simpler systems. Since aerial wildfire suppression is a very complex phenomenon and involves a high level of nonlinear dynamics, the authors utilize a SoS approach to provide an optimal solution to this complex problem. The authors adopt the term SoS as defined in [5], with a limited taxonomy and a basic set of architectural principles.

Previous research has shown how to simulate wildfires and ways to put them out, but they only looked at the effects of using different types of vehicles and methods to fight fires. This new study focuses on how using a mix of vehicles and different firefighting methods can affect the outcome of aerial firefighting missions in forests. Earlier studies [6] have presented how to simulate wildfires and a way to put them out, but they only considered the effects of using same types of vehicles and a single method to combat wildfires. This study focuses on how using a mix of vehicles and different firefighting methods can affect the outcome of aerial firefighting missions in wildfire incidents. Furthermore, the study presents a sensitivity analysis of wildfire environment, investigating the effects of environmental parameters. This thesis extends the above-mentioned research and presented in [7] by first introducing a background for

SoS and its applications, simulation approaches and the available aerial wildfire fighting assets and suppression techniques used in wildfire suppression missions. Next, the SoS framework is explained as an agent-based simulation, including aircraft design, fire model, suppression mission, as well as the cost model. Thereafter, a case study for the overall evaluation of the wildfire and its suppression is demonstrated. Lastly, the outcomes of the sensitivity analysis for each case are presented and the thesis is finalized with the overall conclusions and the direction of future work.

1.3 Contributions and Novelties

The author uses an agent based simulation framework driven by SoS approach[8] for general wildfire suppression mission modeling. It expands on previous research conducted at DLR [6] by:

- Introducing a comprehensive analysis of the impact of wildfire environmental parameters on fire spread.
- Implementing various suppression strategies that can bring new solutions for combating wildfires, as well as revealing subtle patterns at the SoS level using agent based simulation.
- Utilizing a mixed fleet composition of different eVTOL configurations with varying airframe configurations, payload capacity, flight velocity, and powertrain architecture.

1.4 The Outline of the Thesis

The present study commences with a concise literature review on the SoS approach, followed by an exploration of simulation techniques applicable for modeling SoS frameworks. It also provides an overview of the current suppression techniques for combating wildfires, the use of advanced air mobility, and fire model simulations. Subsequently, it presents the use of agent-based modeling, with a focus on SoS, and defines standard system and component definitions. The characteristics of the heterogeneous fleet for aerial firefighting utilizing advanced air mobility are also discussed. The research then delves into forest fire modeling, cost modeling, and the deployment of multiple suppression methods. Finally, the study concludes with an assessment of the results, findings, and possible future directions for research.

The study highlights the need to adopt an SoS approach for combating wildfires, given their complex nature and the diverse range of interconnected systems involved. This involves using simulation techniques, such as agent-based modeling, to accurately represent the SoS framework. Furthermore, the research emphasizes the significance of employing multiple suppression techniques, including advanced air mobility, to combat wildfires efficiently. The study's findings also highlight the importance of cost modeling in determining the most cost-effective suppression strategies.

CHAPTER 2

BACKGROUND

2.1 System of Systems Literature Review

An examination of System of Systems (SoS) as an additional research field relevant to this thesis due to the SoS-driven agent-based simulation framework is provided in the following. It includes a review of the context, definitions, uses, and strategies of SoS.

2.1.1 Definition

System of Systems is a term used to describe the integration of multiple systems and subsystems working together to form a larger, more complex system. SoS can be used to describe a variety of domains and applications, including but not limited to military, finance, healthcare, and transportation. This literature review will examine various aspects of SoS, including the challenges associated with its implementation. The term "SoS" is frequently used, but there is no universally accepted definition for its meaning. The use of this term suggests that systems can be categorized into different groups, which may be useful for engineering purposes only if they have specific design, development, or operational requirements. However, the term "SoS" is not a descriptive term in a formal sense. [5] suggests two main distinguishing features from system definition for the application of the term SoS or alternatively collaborative system. The first criterion, operational independence of components, requires that each component system must be able to function independently and fulfill customer-operator objectives on its own, without relying on other components of the system. This is necessary to ensure that the SoS can still operate if one or more components fail.The second criterion, managerial independence of components, requires that each component system can operate independently from the SoS, even if they are acquired and integrated separately. This allows for flexibility in the development and management of the component systems, as well as the ability to upgrade or replace individual components without affecting the rest of the system. Overall, these two criteria are important to ensure the success of a SoS approach, by promoting operational and managerial autonomy of individual components within the larger system. According to [9], SoS refer to extensive assemblages that are geographically dispersed, and are created through coordinated and directed development efforts. The constituent systems and their integration are intentionally and centrally planned to serve a specific purpose. [10] defines SoS as a group of distinct systems that are interconnected or linked in a way that enables them to achieve outcomes that cannot be accomplished by any of the individual systems in isolation. Compiling various previous descriptions of SoS, [11] identifies five distinguishing characteristics to define SoS as operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development. The characteristics of a SoS are multifaceted and complex. Firstly, it is imperative that the individual systems comprising the larger system are capable of independent operation and able to perform valuable functions in their own right. Secondly, the component systems must operate independently in a managerial capacity, with the ability to achieve their own objectives. Thirdly, the constituent systems are often widely dispersed geographically, which can limit the exchange of physical materials and energy. Fourthly, emergent behavior can manifest from the interactions of the constituent systems, allowing the SoS to achieve its overarching objectives. Finally, a SoS is not static, but rather dynamic and subject to constant evolution and adaptation as the community gains experience with the individual systems and the composite system as a whole.

A common fallacy in the academic literature is the conflation of the terms "system" and "SoS". To clarify the distinction between the two concepts, a brief summary of their defining characteristics can be presented as following,

Scope: A "system" typically refers to a limited set of components or subsystems that work together to achieve a specific purpose or goal. A "SoS" refers to a collection of interconnected systems that have their own goals, but also work together to achieve a higher-level goal [11].

Complexity: Systems can be complex, but they are generally less complex than systems of systems. Systems of systems are characterized by multiple levels of hierarchy, many different types of interdependencies, and a high degree of autonomy among the constituent systems [11].

Interconnections: A "system" may consist of a small number of components that are connected to each other, but not necessarily to external systems. In contrast, a "SoS" consists of multiple systems that are connected to each other and may interact with external systems [11].

Purpose: A "system" has a specific purpose or function that it is designed to achieve. A "SoS" has a broader purpose that requires the integration of multiple systems to achieve a common goal. [12]

2.1.2 Applications

The SoS approach has been used in various application areas where complex and interdependent systems need to be managed and integrated. Some examples are provided in the following:

- **Disaster response**: The disaster response sector uses the SoS approach to manage and integrate various types of systems, such as emergency services, communication systems, and transportation systems, to ensure a rapid and effective response to natural and anthropogenic disasters. Disaster management involves the coordination of resources and information to address changing conditions in a given geographical area. In the aftermath of a disaster, relief, and recovery efforts are organized in a decentralized manner involving a variety of participants and resources. It is crucial that disaster management takes into account the requirements, processes, and interdependencies of the system to ensure an effective response. Therefore, accurate models are needed that can anticipate and address logistical, technical, operational, and financial challenges. A broad understanding of the system and its needs, along with the evolving situation, makes such models essential for effective disaster management. [13] uses methodology to create a situation model that illustrates how resources, functional assets, and various phases of infrastructure renewal are causally linked.

- **Transportation**: The transport sector uses the SoS approach to manage and integrate various modes of transport such as road, rail, air, and sea to provide efficient and effective transport services [11]. A great demonstration of the use of SoS in air transportation is discussed by [14]. The study expresses how transportation, especially air transportation, can be understood as a SoS problems. Such a perspective is necessary as a basis for developing effective analysis and design approaches that take into account the considerable complexity in this field and enable a transition to a superior future state. A preliminary investigation into the characteristics of the SoS and their mapping to transportation shows that there is indeed an urgent need for new methods. To this end, a framework for analysis in systems engineering is presented, including a discussion of its three main phases: Identification, Abstraction, and Implementation. Each instance involves taking measures to ensure that the most difficult behaviors observed in SoS are appropriately addressed: 'evolutionary' and 'emergent' behavior. This large network exhibits new properties that are not observed in the ensemble of systems when viewed in isolation. In this context, it is these difficult-to-observe features that are the main target of the design. This emergent behavior and the already existing complexity of evolutionary behavior that proceeds on various time scales (some even over generations) summarizes perhaps the greatest challenge posed by the SoS problem class. Although it will take considerable time before the full benefits of studying SoS are realized, simply considering a wider perspective can offer additional understanding into our apparently complicated pursuit of improved aviation vehicles and air transportation systems. Within this broader framework, the inadvisable practice of a single system such as aircraft or infrastructure optimization may become clearer as the role and impacts of other systems become clearer. By acknowledging the existence of multiple levels of the organization, it is possible to solve some of the vexing challenges faced in developing tomorrow's transportation solutions.

- **Defense and military**: The defense and military sector has been a major user of the SoS approach, especially for integrating various types of systems such as land, air, and sea-based systems to achieve common goals[11]. The use of a SoS approach in military applications is highly beneficial for several reasons. Firstly, military systems are inherently complex, with numerous subsystems and components that must work in tandem to achieve a mission. Implementing a SoS approach provides a comprehensive framework for managing this complexity and ensuring that the system functions optimally and efficiently. Secondly, military operations frequently take place in dynamic and unpredictable environments, with constantly changing threats and operational requirements. A SoS approach permits the system to adapt and evolve over time, ensuring that it can continue to operate effectively in response to changing conditions. Finally, military systems often involve multiple stakeholders and users with diverse needs and requirements. A SoS approach facilitates the integration of these varied perspectives, ensuring that the system as a whole is aligned with the needs and goals of all stakeholders. Therefore, a SoS approach is a highly effective means of ensuring that military systems are agile, efficient, and adaptable to meet changing conditions and requirements. [15] suggests that the the Department of Defense's focus is on developing joint and coalition warfighting capabilities, and that these needs will be addressed through a combination of legacy systems (existing technology and infrastructure), new programs (likely referring to new investments in research and development), and technology insertion (incorporating new technology into existing systems). This approach is as previously referred to as SoS, which emphasizes the need to integrate and coordinate diverse systems to achieve a common goal. Furthermore, [15] points out that the DoD possesses a substantial collection of legacy systems that are expected to remain in use for the foreseeable future and thus must be taken into consideration when developing an SoS strategy. Given that defense budgets are either stagnant or decreasing, and the time and cost required for new developments are substantial, it is essential to maximize the value of existing investments. Consequently, there is a strong impetus to explore new ways of employing current systems in innovative combinations to satisfy new requirements, all while confronting an operational environment that demands greater adaptability and ingenuity in response to evolving threat scenarios.

- **Energy and power systems**: The energy and power sector uses the SoS approach to manage and integrate various energy and power systems, such as renewable and traditional energy sources, to ensure reliable and sustainable energy supplies [11]. The SoS approach promotes collaboration and coordination among energy systems to achieve optimal efficiency, reliability, and sustainability. It involves identifying key stakeholders, developing a governance structure, and integrating and optimizing energy systems to create an interconnected network. The SoS approach to sustainable energy emphasizes the importance of incorporating social, economic, and environmental factors into decision-making to ensure that energy solutions are equitable and effective. This concept has gained significant attention and support in recent years as society continues to grapple with the urgent need to transition to more sustainable energy systems to combat climate change.

- **Healthcare**: The healthcare industry uses the SoS approach to manage and integrate various healthcare systems such as hospitals, clinics, and emergency departments to provide coordinated and efficient healthcare services [16]. [16] provides an extensive overview of the concept of SoS and its application to the healthcare sector by presenting condition of the healthcare system and highlights the necessity for a more unified and collaborative approach to healthcare delivery. The study argues that adopting an SoS approach in healthcare can lead to better patient outcomes, cost reduction, and improved quality of care. The paper also introduces a theoretical framework for establishing a healthcare SoS, which includes identifying key stakeholders and developing a governance structure. In addition, the paper delves into the challenges that arise from implementing an SoS in healthcare, such as concerns regarding data privacy and security, and provides possible solutions. The study concludes by proposing that an SoS approach in healthcare is a promising strategy that can address the complicated and interconnected challenges faced by the healthcare industry.

- **Smart cities**: The concept of smart cities uses the SoS approach to manage and integrate various types of systems such as transportation, energy, and communication systems to create sustainable and livable urban environments [11]. Smart cities are characterized by the presence of numerous distributed systems that establish intricate connections and work in tandem to provide novel functionalities. As a result of these interrelationships, a diverse array of independent and heterogeneous complex systems known as SoS emerges [17].

Figure 2.1: A smart city SoS incorporating heterogeneous, independent systems, both public and private, in different domains [17].

- **Aerospace Industry**: SoS approach has been increasingly used in the aerospace industry to address the complexity and interconnectedness of modern aircraft systems. NASA has adopted an SoS approach to address the challenges associated with designing and operating complex space systems. This approach emphasizes the need to consider the interactions and interdependencies between different systems to achieve optimal performance and mission success [18]. Another approach is considering aircraft in the context of SoS. [19] explains how aircraft development involves integrating many different systems into a single design, making it a system of many systems. The article emphasizes the complexity of designing such a system, with decisions and constraints affecting multiple areas of the design process. The analysis emphasizes the need for federating the systems of different organizations, which were built and run independently of each other.

  The increasing complexity of aerospace systems has led to a shift in focus from a singular system perspective to a SoS perspective. [20] proposes an approach to using architecture frameworks and ontologies with description logic reasoning to break down SoS needs into required capabilities and functions. The approach is tested in a search and rescue case study, and the results indicate that it is possible to break down SoS needs consistently and use ontologies to process the captured knowledge.

2.2 Simulation Approaches for SoS

As extensively discussed in Section 2.1, SoS is a group of autonomous systems that collaborate to achieve a common objective. SoS have a set of distinct characteristics that distinguish them from conventional systems. These characteristics include **emergent behavior**, where the behavior of the SoS as a whole is not directly predictable from the behavior of its individual systems. **Heterogeneity** is another attribute, which refers to the diverse structure, function, and operational characteristics of the systems that make up a SoS, leading to interoperability challenges. **Interoperability** is a critical attribute, ensuring that different systems work together to achieve the overall objective. **Scalability** is also a characteristic of SoS, where the system's architecture can accommodate the addition or removal of systems without disrupting its overall operation. SoS are evolutionary and dynamic, with the ability to change over time due to system upgrades or replacements, leading to changes in overall behavior and performance. **Resilience** is also crucial for SoS, enabling them to adapt to changing circumstances and recover quickly from system failures or disruptions. Lastly, SoS are typically managed by a set of stakeholders who share the same goal, requiring effective **governance** structures to ensure the SoS operates efficiently and achieves its objectives. Understanding these attributes is vital for designing, developing, and managing SoS effectively, influencing the architecture, design, and operation of SoS, and addressing interoperability, resilience, and scalability challenges.

When choosing a simulation approach for systems of systems, it is essential to consider the unique attributes that define such systems, including emergent behavior, heterogeneity, interoperability, scalability, evolutionary nature, resilience, and governance. These attributes must be satisfied for an accurate representation of the

SoS under consideration. The simulation approaches for systems of systems can be broadly categorized into three distinct categories, namely **event-based modeling (EBM)**, **agent-based modeling (ABM)**, and **mathematical equation modeling** [21]. Each of these approaches has its unique set of advantages and disadvantages, and the selection of an approach depends on various factors such as the specific attributes of the SoS being modeled, and the research questions being addressed. Thus, careful consideration must be given to the suitability of each approach to ensure that the most appropriate method is chosen for the intended purposes.

Modeling and simulation serve as an effective means of verifying and identifying novel features attributed to the behavioral characteristics of SoS. A model is essentially a simplified representation of a complex system, and simulation involves executing the model to analyze its behavior. The primary objective of a model is to accurately replicate the essential features of a system to observe its specific behaviors, thereby enhancing our understanding of SoS. [21] suggests that the majority of model types can be simplified to either a top-down(EBM) or bottom-up(ABM) perspective and that some mathematical modeling can be considered a form of EBM [22] or used as a part of ABM [23].

ABM is a computational modeling technique used to simulate the behavior of complex systems composed of interacting autonomous agents. In ABM, the agents are modeled as individuals with their own behaviors, decisions, and interactions. The agents can be programmed with different sets of rules or decision-making algorithms, which may be influenced by the environment or by the actions of other agents [24]. On the other hand, EBM is a technique used to represent the behavior of a system in terms of discrete events that occur over time. In EBM, the system is represented as a set of interacting components, where each component has a set of states and transitions. The occurrence of an event triggers a transition from one state to another, which results in a change in the system's behavior [25]. [21] conducts a thorough analysis of both ABM and EBM, outlining the distinctions between the two and tabulating the findings in Table 2.1.The EBM provides a top-down view by revealing microstructures through macro-specifications. It is based on externally observable events and programmed responses to discrete events. Events are required to adhere to system-level observable information and lead to changes in the state of the system of interest. Events impact the entire entity, and the internal behavior of the system is not known. It is relatively easy to test, but difficult to validate. In contrast, ABM provides a bottom-up view by generating macro-structures through micro-specifications. It involves autonomous decision-making entities or agents, which have programmed functionality and adhere to behavioral rules that are boundedly rational. Agents function independently and flexibly and interact as distinct parts of the simulation. The modeling rules are simple, and events emerge. However, it is difficult to validate this approach.

Table 2.1: Comparison of EBM and ABM [21]

Event-Based Modeling	**Agent-Based Modeling**
Top-down view	Bottom-up view
Externally observable phenomenon (events)	Autonomous decision making entities (agents)
Programmed response to discrete events	Programmed functionality of agents
Events adhere to system-level observable information	Agents adhere to behavioral rules (boundedly rational)
System of interest changes state in response to events	Agents function independently and flexibly
Event impacts the entire entity	Agents interact as distinct parts of simulation
Simplicity in modeling inputs, state, and outputs	Simplicity in modeling rules
Unknown internal behavior	Events emerge
Easier to validate	Challenging for validation

Determining which modeling approach to use between Agent-Based Modeling (ABM) and Event-Based Modeling (EBM) for modeling SoS depends on the specific requirements of the model and the nature of the system under consideration.

EBM can be a better option when the SoS is composed of well-defined and easily identifiable discrete events, and the interactions between the events are relatively straightforward. This approach can be beneficial in analyzing the interrelationships between events and how they affect the overall system. EBM can also help in identifying and addressing potential issues within the SoS.

On the other hand, ABM may be a more appropriate choice when the SoS is comprised of numerous entities that exhibit complex behavior that cannot be easily reduced to discrete events. This modeling approach allows for the simulation of the behavior of individual entities and the interactions between them, making it a useful tool for modeling intricate systems. ABM may also be more applicable when the behavior of individual entities can be simulated using decision-making rules.

In conclusion, the selection between ABM and EBM for modeling a SoS will ultimately depend on the specific requirements of the model, the complexity of the system, and the level of detail necessary to accurately represent the system. Therefore, careful consideration of the specific requirements of the SoS is crucial in selecting the most appropriate modeling approach.

This research advocates the use of the ABM approach for modeling SoS because it can capture the complex interactions among multiple entities, which cannot be easily represented using discrete events. The ABM approach involves representing each entity as a separate agent, which can interact with other agents and the environment.

By defining decision-making rules for each agent, the ABM approach can simulate the behavior of each entity in response to events or other agents in the system. The emergent behavior of agents can also be observed, which can reveal patterns and dynamics in the overall system that may not be evident in a top-down view.

ABM can be a powerful tool for analyzing and predicting the behavior of an SoS under different scenarios, as it enables the investigation of the effects of changes in the behavior of individual agents on the overall system. It can also be used to evaluate different policies and strategies for managing the system, and to identify potential issues or areas for improvement.

However, it is crucial to acknowledge that implementing ABM can be complex and challenging. Defining the behavior of each agent and modeling their interactions in a realistic way requires careful consideration. The model must also be validated to ensure that it accurately represents the behavior of the real-world system, which can be a demanding process.

CHAPTER 3

WILDFIRE SUPPRESSION

3.1 Currently used Suppression Tactics

It is possible to broadly categorize wildfire suppression tactics into 2 different types: direct attack and indirect attack [26]. These tactics are used in combination to control and extinguish wildfires, depending on the specific fire and its location.

Direct Attack: Direct attack is a tactic where firefighters go directly to the fire, and attack it with water, retardants, or other firefighting agents. This tactic involves putting out the fire by depriving it of fuel and oxygen.

- **Water Drops:** Firefighters use water to suppress a fire. This can be done using hoses, sprinklers, or fire engines that carry water to the fire. Helicopters and air tankers can also be used to drop water on the fire from the air.
- **Retardants:** Fire retardants are chemical substances that can be dropped on the fire to slow down its progress. These substances are typically a mixture of water, fertilizer, and other chemicals that can reduce the intensity of the fire.
- **Hand Crews:** Hand crews are groups of firefighters who work on the ground to cut down trees and other vegetation and create fire breaks. This tactic is effective in preventing the fire from spreading further.

Indirect Attack: Indirect attack is a tactic where firefighters create a buffer zone around the fire, by removing fuel or vegetation. This tactic is used when a direct attack is not possible, or when the fire is too dangerous to approach.

- **Backburning:** Backburning is a tactic where firefighters intentionally start a smaller fire to burn the fuel ahead of the main fire and create a buffer zone. This tactic can be very effective in preventing the fire from spreading further.
- **Fireline:** Fireline is a tactic where firefighters create a barrier around the fire, by removing fuel or vegetation. This barrier can be created by digging a trench or using heavy equipment to remove trees and other vegetation.
- **Air Attack:** Air attack is a tactic where helicopters or air tankers drop water or fire retardants on the fire to slow down its progress. This tactic is used to support ground crews and create a buffer zone around the fire.

According to [27], direct attack methods are based on expected fire behavior, and it is advantageous to extinguish the tail of a fire as soon as possible. A flank attack involves attacking the fire from the flanks, where fire behavior is usually less intense, and can be extended to a pinching attack, see Figure 3.1 (left). A head attack should be employed once the flanks have been extinguished, and it is not recommended to attack a head fire from the front, particularly in unburnt vegetation, see Figure 3.1 (right).

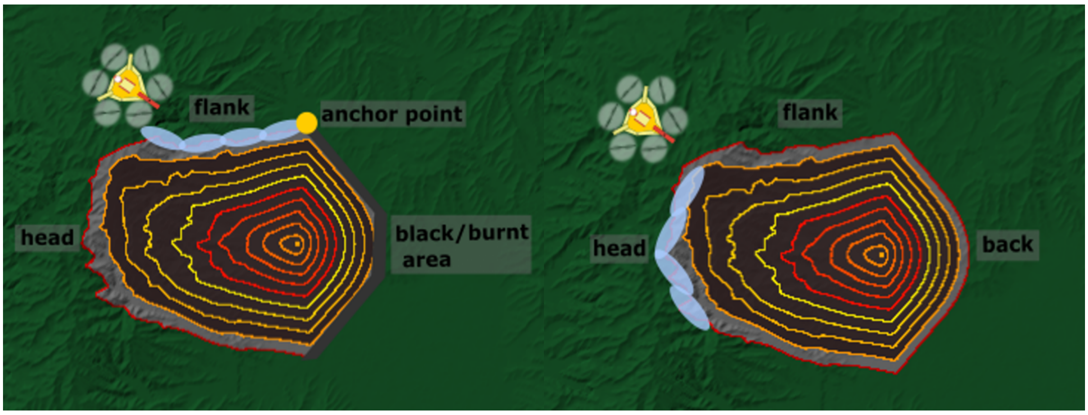


Figure 3.1: A representation of direct attack from flank (left) and head (right)

Indirect attack methods are used for higher-intensity fires and can be safer, as firefighting techniques are applied away from the fire's edge, see Figure 3.2. The three principal methods of indirect attack include the use of control lines, parallel attack, and the use of fire as a tool. Control lines can be manually, mechanically, or chemically constructed and are used to form a barrier to prevent fire spread. The parallel attack involves constructing control lines from a strong anchor point to the rear of the fire and moving around the flanks. The use of fire as a tool can be a higher-risk strategy, but it can be used with confidence if carried out by well-trained personnel with relevant experience [27].

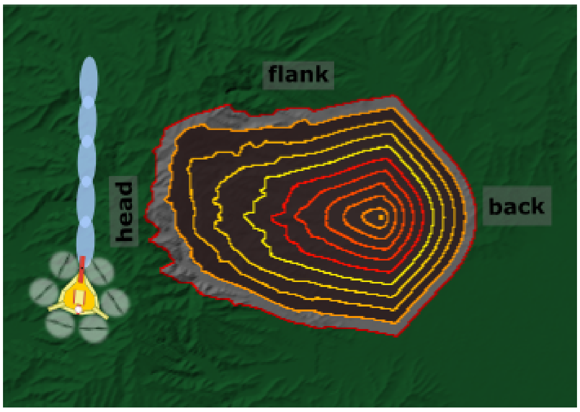


Figure 3.2: Indirect attack initiated from the head

3.2 Use of Aerial Assets in Wildfire Combat

Wildfires can pose a significant threat to both human life and natural resources. As such, it is crucial to have effective tools for wildfire suppression, and the use of aerial assets can be an important component of a comprehensive wildfire-fighting strategy. Aerial assets include helicopters, fixed-wing aircraft, and unmanned aerial vehicles (UAVs), which can be equipped with a range of tools, such as water tanks, foam systems, and infrared cameras. By using aerial assets, firefighters can quickly access remote or hard-to-reach areas, deliver rapid and targeted water or retardant drops, and gain real-time situational awareness through thermal imaging and other advanced technologies. However, it is important to note that the use of aerial assets is not a one-size-fits-all solution, and the effectiveness of such tools will depend on factors such as weather conditions, terrain, and the type of wildfire being fought. Additionally, the use of aerial assets can be costly, and it is important to consider the balance between the costs and benefits of such an approach in each specific context. Nevertheless, when used appropriately and in conjunction with other firefighting tactics, aerial assets can be a valuable and effective tool in the fight against wildfires [28].

3.3 Overview of Fire Model Simulation Techiques

Fire model simulation is an important field of research that has gained increasing attention in recent years. This literature review provides an overview of the existing literature on fire model simulation, including the different approaches that have been used to model and simulate fire spread in natural environments. There are several ways to categorize the spread of fire, such as through deterministic and stochastic modeling approaches, vector-based methods using adaptations of Huygens' wave principle, and grid-based approaches using cell automata or bond percolation [29]. Although it is not easy to define a clear boundary between various fire modeling systems, hybrid fire modeling systems encompass multiple fire models to address various scenarios. For instance, the widely-used wildfire software, [30], employs diverse mathematical models for fuel moisture modeling, spotting fires, and surface fire spread, while using a vector-based method to depict the fire front. Likewise, the deterministic fire simulator, [31], is a vector-based simulator that utilizes physics-based differential equations incorporating Huygens' wave principle.

One of the earliest approaches to fire model simulation was based on empirical and semi-empirical models, which rely on experimental statistics to model fire behavior [29]. These models are relatively easy to implement and require lower computational power compared to physics-based models. However, they are limited by the amount and quality of available experimental data and include substantial approximations.

Physics-based models, on the other hand, use physics and/or chemical-based differential equations with numerical solutions to express fire spread [32]. These models consider limited areas with laboratory scales and are computationally expensive due to their complex nature. Although they have been proven to give more accurate results than empirical models for some studies, their prediction accuracy becomes questionable when the complexity of the fire spread increases due to the non-linear nature of the fire spread [33], [34].

Simulation and mathematical analogous models rely on mathematical concepts that express fire spread based on coincidental similarities [35]. These models have been widely used to simulate fire spread in natural environments. There are two common approaches used for modeling fire spread in simulation models: grid-based and vector-based. Grid-based approaches use square or hexagonal cell interactions to represent fire spread, while vector-based approaches use continuous moving with polygonal expanding in time and space to approximate the fire front.

Recent studies have focused on improving the accuracy of fire model simulations by coupling different models, including Cellular Automata (CA) models, which is a common use of the raster-based approach in recent years [36], [37], [38], [39]. CA models have a relatively straightforward structure and low computational complexity, and they are flexible in connecting to other existing models. They have been improved to detect fire spotting by implementing a relation considering wind and fire interaction to allow a fire to spread to nonadjacent cells. Furthermore, the propagation rate can be estimated stochastically by allocating a fire propagation probability factor to each cell.

Machine learning methods have also been used in fire model simulation to predict how the fire would grow based on topography and weather conditions data [40]. Deep reinforcement learning algorithms have been used to improve the accuracy of fire model simulations, outperforming physics-based models when enough data is fed to the algorithm [41]. Other approaches, such as real-time simulation using the information received from satellite and sensors, have been developed to predict fire spread, although the complexity of the model and computational cost remain challenges to overcome [42].

In conclusion, fire model simulation is an important field of research that has gained increasing attention in recent years. The different approaches used in fire model simulation, including empirical, semi-empirical, physics-based, and simulation and mathematical analogous models, have their advantages and limitations. Ongoing research continues to improve the accuracy and efficiency of fire model simulations, including the use of machine learning methods and real-time simulation driven by satellite and sensor data.

3.4 Advanced Air Mobility for Wildfire Suppression

Advanced Air Mobility (AAM) represents the next stage of air transportation, featuring electric vertical takeoff and landing (eVTOL) aircraft and unmanned aerial systems (UAS). These cutting-edge technologies offer the potential to fundamentally change the way wildfire suppression is conducted by providing faster and more efficient methods for delivering firefighting personnel, equipment, and fire retardants to remote areas.

AAM can help overcome some of the limitations faced by traditional aerial firefighting approaches, such as restricted payload capacity and the need for large operating zones. Specifically, eVTOL aircraft can take off and land in tight spaces, reducing the necessity for extensive staging areas and improving response times [43]. They can also fly at lower altitudes than conventional aircraft, enabling better visibility and more precise targeting of firefighting resources.

UAS can also provide vital assistance in wildfire suppression efforts by conducting aerial surveys to gather real-time information about fire behavior, terrain, and weather conditions [44], [45]. This information can be utilized to develop more effective firefighting strategies and allocate resources where they are most needed. Furthermore, UAS can transport fire retardants and water to areas that are inaccessible, lowering the risk to ground personnel.

Apart from enhancing firefighting capabilities, AAM technologies can minimize the environmental impact of wildfire suppression efforts. eVTOL aircraft and UAS produce fewer emissions than traditional aircraft and can operate more quietly, reducing disturbance to wildlife and local communities [46].

As AAM technologies advance and become more widespread, they possess the potential to revolutionize the manner in which wildfires are fought and managed. However, substantial investment and regulatory modifications are required to unlock the full potential of these technologies in wildfire suppression.

CHAPTER 4

SOS-DRIVEN AGENT-BASED SIMULATION FRAMEWORK

4.1 Overview of the Agent-Based Simulation Framework

The process of aerial wildfire suppression is a complex and challenging task that requires careful planning and precise execution. To achieve success in this endeavor, it is necessary to have a comprehensive understanding of the different components and systems involved in the process.

In order to capture the full complexity of aerial wildfire suppression, it is crucial to define subsystems, systems, and system of systems. By doing so, we can ensure that all the different components are accounted for and that their interactions are accurately modeled. This allows us to analyze the system as a whole and to understand how each subsystem contributes to the overall mission.

The subsystem definitions, such as aircraft powertrain architecture, are received by the simulation as input parameters. These parameters are used to define the different components of the system and their properties. The system definitions, such as aircraft and fire, are created using object-oriented programming (OOP) principles. In object-oriented programming paradigm, an object has its own unique identity, state, and behavior. Objects can conserve data and the set of rules to follow. They can also interact with other objects. This allows users to establish system properties and behaviors and to enable interaction between the different components. By using an agent-based simulation model, the synergies can be captured between the different systems and ensure that the simulation is as accurate as possible. As discussed in Section 2.2, in ABS, agents are defined as individuals which have their own behaviour and interactions following a set of rules. Therefore, it is very convenient to represent the systems as agents while modeling the simulation and the SoS driven framework establishes an equivalence between system-object-agent.

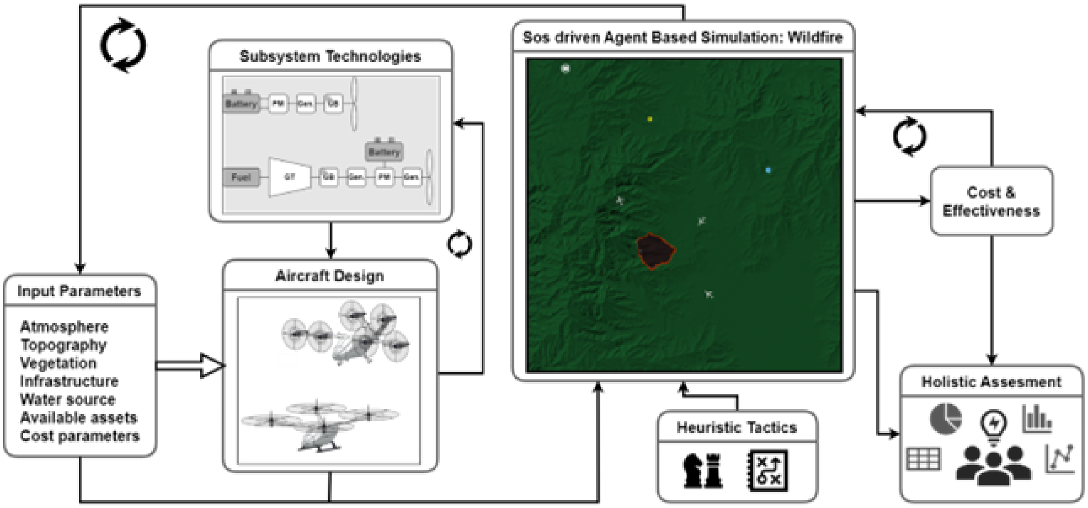


Figure 4.1: Overall representation of SoS driven ABS framework adopted from [6]

Once the simulation is set up, the user can begin to feed in the environmental conditions, fleet composition, and cost parameters (see Figure 4.1). These parameters are used to drive the fire, aircraft, and cost model, respectively. Depending on which logical task sequence is chosen to follow, the desired suppression mission is simulated in the framework, and the response of the mission is saved for post-processing. This allows users to analyze and evaluate the mission based on SoS level evaluation metrics, including the operational cost of the mission and the total burnt area.

The technical details of the framework is represented with a Unified Modeling Language(UML) diagram shown in Figure 4.2. As it is seen, the simulation uses ABCMeta metaclass as an abstract base class which is provided by a Python module so that a set of methods that must be implemented by any concrete subclass of the ABC can be defined easily. Then, the simulation architecture pattern is defined as Model-Viewer-Controller where each classes are abstracted from ABCMeta class. The model captures the logic of the agents and their data, it also provides an interface for controller to update the data. The viewer provides a user interface for the simulation and the controller acts as an interface between the model and the viewer. It receives input from the user and updates the model. It also updates the view to reflect changes made to the model. As seen in the Figure 4.2, the model consists of the agent and cellular automata models which are used to represent the aircraft and fire models. The agent model extends Mesa which offers the capability to rapidly create agent-based models using built-in core components or customized implementations, visualize them with a browser-based interface, and analyze the results using Python's data analysis tools [47]. The simulation framework used for this study is fully developed by DLR and the details of the framework is demonstrated in [8]. While the simulation framework is used to demonstrate a mission analysis for aerial wildfire suppression in various researches [48], [7], [6] along with this study; it is worth noting that the simulation framework is also capable of providing mission analyses for different use cases such as urban air mobility [49], [50], [51], [52].

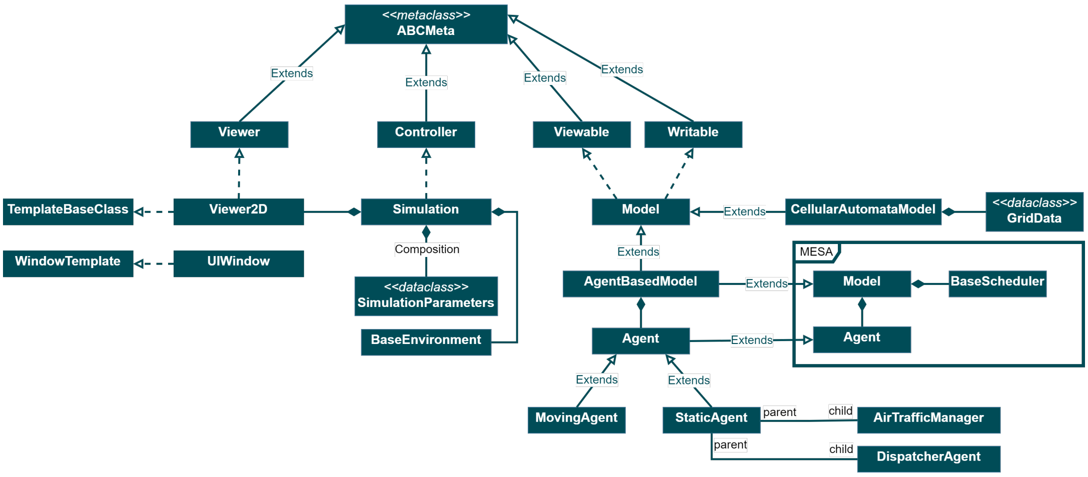


Figure 4.2: UML diagram for SoS driven ABS

Overall, the framework for aerial wildfire suppression is a highly sophisticated and complex system that requires careful planning and execution. By defining the different components and their interactions, a more accurate model can be created of the process and better understand how to optimize the system for maximum effectiveness.

4.2 Overview of the Aircraft Design Tool

This section describes a common sizing loop used to size different eVTOL aircraft configurations. The process is initiated by defining input parameters related to mission, rotor, wing, and fuselage or cabin sizing. The first iteration starts with rotor and wing sizing as well as performance, where the aircraft's geometry, aerodynamics, and mission performance are computed. In the second step, the component weights or masses are estimated concerning two major groups, namely airframe and onboard systems, which also include propulsion and powertrain modeling. The loop continues until the desired MTOM is achieved [53]. The details of the aircraft sizing is demonstrated in 4.3

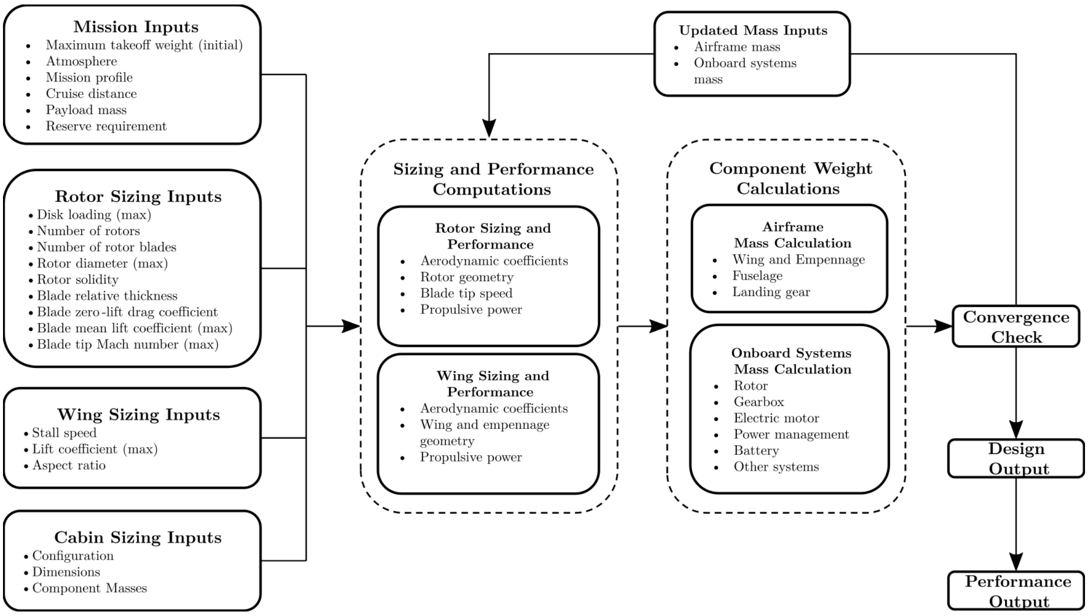


Figure 4.3: VTOL sizing loop implemented in the design tool [53]

Two major aircraft configurations are considered for the geometry sizing, namely winged and wingless. [53] adopted different methodologies for winged and wingless configurations from [54], [55], and [56] for estimating the fusulage geometry. For aerodynamics calculations, [53] considered hover and vertical flight as well as the forward flight for both winged and wingless configurations. The details of the design tool is extensively explained in [53]. The aircraft information such as flow rate and payload capacity are received for calculating the suppression patch area for the suppressant drop model. The power specifications of the aircraft is implemented in the mission profile. Lastly, aircraft related cost parameters such as empty mass fraction and battery specifications are fed to the cost model.

The aircraft design tool used for this work was developed entirely by the Institute of System Architectures in Aeronautics at DLR. It is worth noting that the design tool in this thesis is used as a black box where only the mission inputs and TLARs are provided by the author.

4.3 Heterogeneous Fleet Composition

The aerial fleet used for wildfire suppression has been carefully selected and consists of six different types of aircraft. This selection includes 2 different eVTOL configurations, namely multirotor and tiltrotor, as well as two distinct powertrain architectures, which are all-electric and serial hybrid-electric with different payload capacities. The payload capacity is used as a constraint for sizing the different aircraft types. It is worth nothing that flight velocity is not a sizing constraint but a result of sizing process. A detailed description of the setup can be found in Table 4.1. The reason for using these specific aircraft types is to enable a comparison of the payload capacity, flight velocity, and powertrain architecture between the different aircraft compositions. This provides insights into the optimal fleet composition for aerial wildfire suppression missions.

In order to optimize the performance of each aircraft, the energy limitations for each powertrain architecture have been taken into consideration. This ensures that each aircraft has a certain amount of energy available for the suppression mission. This available energy is a crucial parameter for the need of re-energizing during the suppression operation, and it helps to ensure that the aircraft are capable of carrying out their assigned tasks effectively.

The selection of different eVTOL configurations and powertrain architectures reflects the latest advancements in technology and provides a variety of options for use in aerial wildfire suppression. The use of all-electric and hybrid-electric powertrain architectures is particularly noteworthy, as it enables more efficient and environmentally friendly operations. The aircraft configurations for full electric multirotor and tiltrotor are represented in figures 4.4 and 4.5.

As the most influential aircraft parameters are indicated in the Table 4.1 for mission evaluation, the details of the each aircraft used during the mission are provided in the Appendix A.

Table 4.1: Aircraft configurations and their specifications for aerial wildfire suppression mission

	Aircraft 1	**Aircraft 2**	**Aircraft 3**	**Aircraft 4**	**Aircraft 5**	**Aircraft 6**
Aircraft Configuration	Multirotor	Multirotor	Multirotor	Tiltrotor	Tiltrotor	Tiltrotor
Powertrain Architecture	Electric	Hybrid	Hybrid	Electric	Hybrid	Hybrid
Payload Capacity [kg]	360	360	720	540	540	720
Flight Velocity [m/s]	∼40	∼40	∼40	∼65	∼65	∼65
Usable energy [MJ]	0.71	0.86	1.1	0.78	0.84	0.97
MTOM [kg]	∼2400	∼1500	∼3000	∼3400	∼2200	∼2600
Cruise Power [kW]	196	212	289	225	283	317
Hover Power [kW]	317	325	472	622	711	846

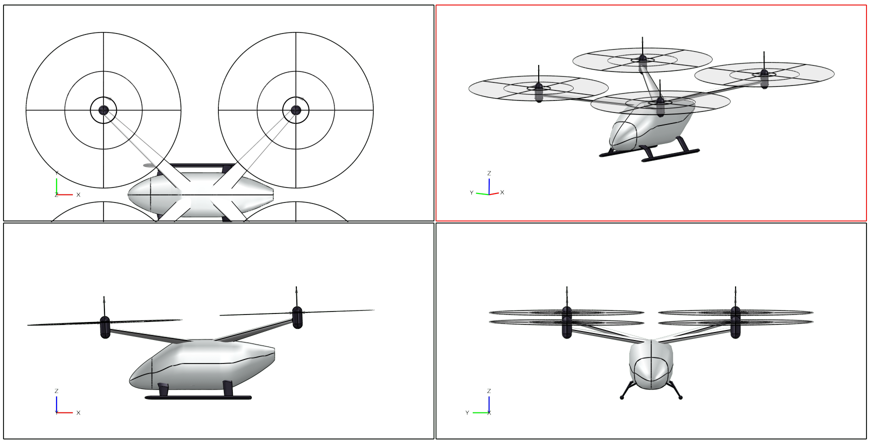


Figure 4.4: Multirotor configuration [53]

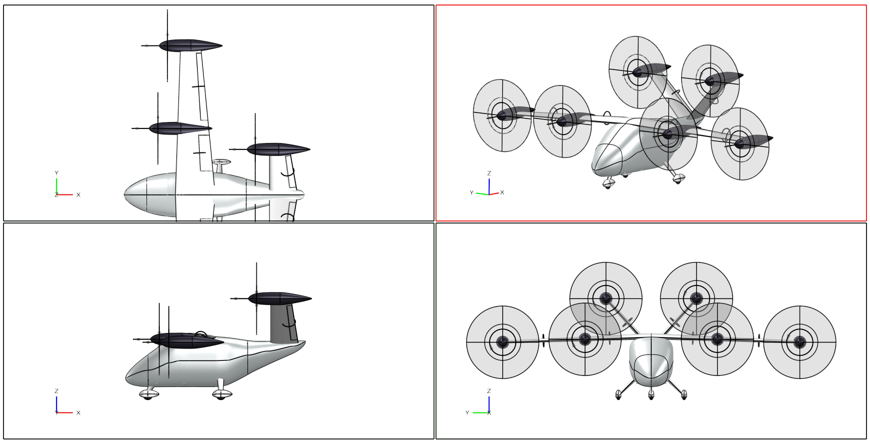


Figure 4.5: Tiltrotor configuration [53]

Overall, the selection of a fleet consisting of multiple aircraft types, each with unique features and capabilities, is essential for successful aerial wildfire suppression missions. By taking into account the various powertrain architectures and the available energy for each aircraft, a setup which is capable of carrying out the suppression mission effectively while minimizing environmental impact is created. The results of this research have important implications for the future development of aerial wildfire suppression technology and will help ensuring the safety and protection of our natural resources and communities.

4.3.1 Top Level Aircraft Requirements

To achieve the expected performance in wildfire suppression missions, it is essential to consider the operational constraints that aircraft may encounter. The constraints shall be taken into considerations when sizing the aircraft to ensure that they can operate safely and effectively. The mission requirements and operational constraints have been outlined below to guide the process:

- Wind speed should not exceed 12.8 m/s [25 knots] to ensure safe and stable flight conditions.
- The aircraft must cross ridges at a minimum altitude of 304.8 m [1,000 ft] above the ridge altitude to avoid potential obstacles and ensure safe passage.
- The payload capacities for each configuration must be fixed at 360, 540, and 720 kg to meet the demands of the mission.
- The powertrain must be either all-electric or serial hybrid-electric to reduce emissions and noise.
- A reserve time of 20 minutes must be included to allow for unexpected delays or emergencies.
- The range requirement for each aircraft is set at 100 km, which should provide adequate coverage for the wildfire suppression mission.

Considering these constraints and requirements will help ensure that the aircraft are appropriately sized and configured for the mission. Moreover, it will help to achieve the expected level of performance while also minimizing risks and maximizing efficiency. It is essential to carefully analyze and evaluate each constraint to achieve the best results.

4.3.2 Mission Profile

In this section, a brief description of the mission profile of the suppression fleet and its logical execution in the simulation framework is presented.

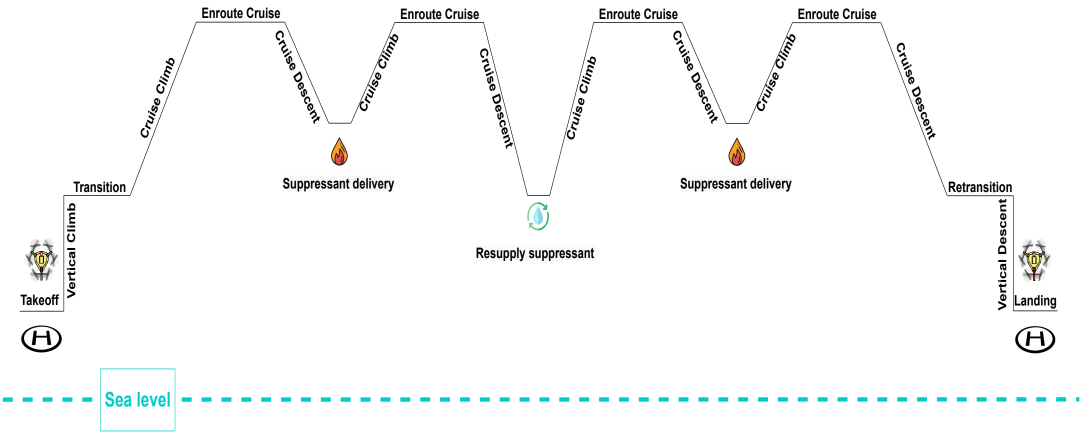


Figure 4.6: Mission profile depicting suppressant delivery and resupply

The ABS framework incorporates the wildfire suppression logic to ensure that the aerial suppression mission is accurately represented. This is achieved by integrating the mission profile into the simulation, which comprises two distinct legs that correspond to the drop and resupplying tasks. The mission profile used in the simulation is shown in Figure 4.6, which demonstrates how the aircraft is expected to behave during the mission.

In each section, agents use the power based on their specifications provided in Appendix A. The agents resupply water either from a base or water source based on their location, however reenergization is only possible through bases.

In Figure 4.7, the logical segmentation of the mission profile into agent task sequences is presented, providing an illustration of how each task is expected to be carried out by the aircraft. By implementing the mission profile into the ABS framework, the behavior of the aircraft during the suppression mission can be more accurately predicted, which is crucial for optimizing the performance and effectiveness of the mission.

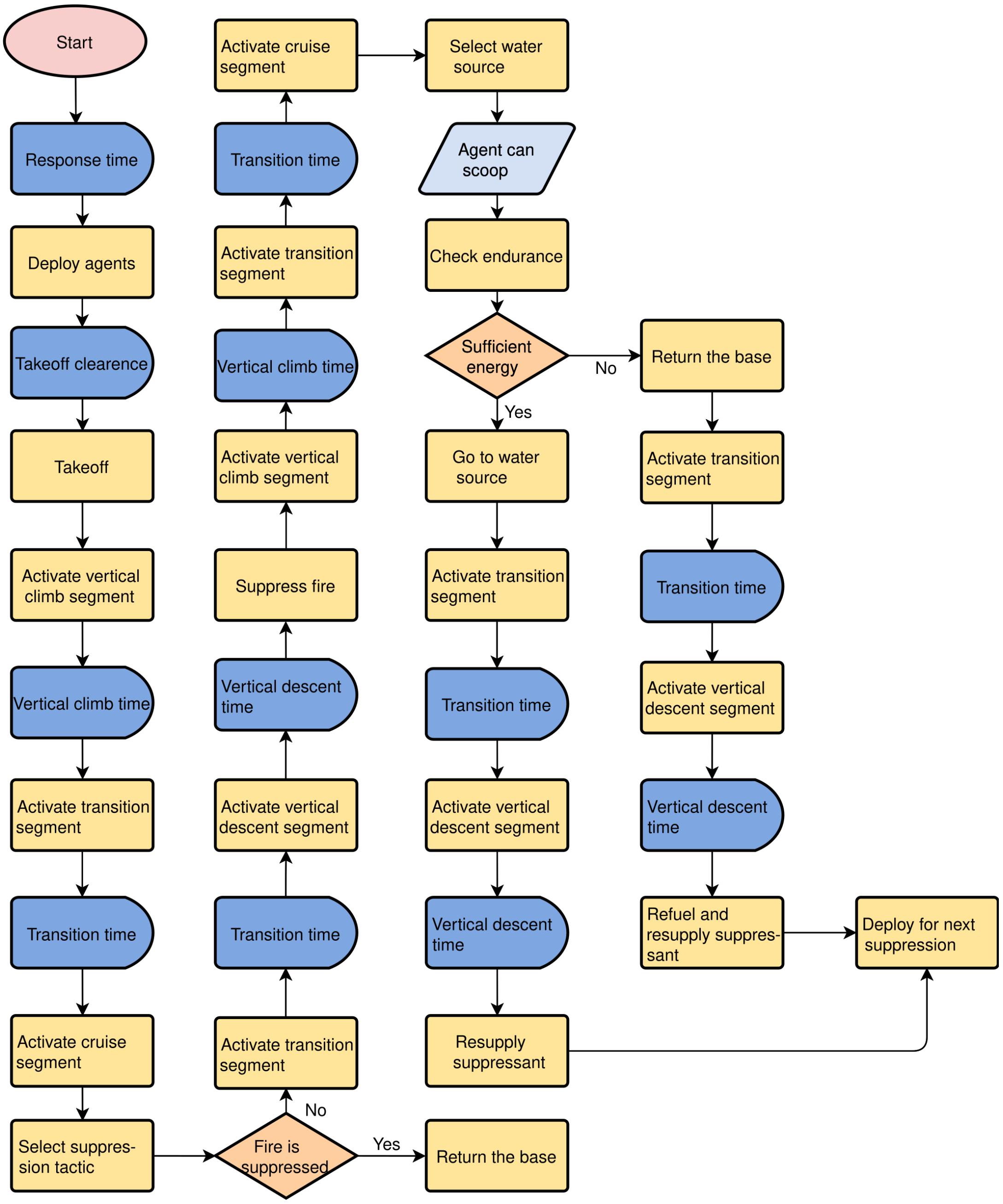


Figure 4.7: The logic followed by the fleet considering the mission profile

4.4 Aerial Wildfire Suppression Tactics

In the multi-agent simulation environment, a set of rules is imposed on all agents or the fleet composition to effectively contain the wildfire. The dynamics of the suppression task can be altered depending on the heuristic algorithm used by the agents. To explore the significance of different tactics in the overall suppression task, this study extends the tactics available to the agents by testing four different algorithms.

The first suppression tactic is a direct attack approach which involves **tracking firefront** with the highest fire growth rate. While choosing a firefront, the agents aim to decrease the distance between the agent and the fire while increasing the distance between the fire and established protection sites like urban areas. In the case that a fire position is already selected by an aircraft, the next aircraft picks a different fire position based on the same criteria. After the firefront is selected, the Moore neighborhood within a radius of the selected location is searched for identifying the neighbor with the highest rate of spreading to be picked for suppression. The fire growth rate is estimated using a mathematical model that takes into account factors such as vegetation combustibility, terrain elevation, wind speed and direction, relative humidity, and temperature, as discussed in [36]. It is worth nothing that the slope of the topography is an essential parameter influencing the fire growth rate in Section 5.3.3.

The next tactic used in the simulation to account for the influence of terrain slope uses a similar logic as the former tactic, however, while choosing the fire position, it also considers the slope of the fire position. By factoring in the slope, the agents can select the best location for suppression and prioritize their efforts based on the fire's characteristics. The selection of the firefront in **tracking with terrain slope** is based on the minimization of 3 cost parameters, which include the distance of the aircraft to the fire, the distance of the fire to the protected areas and the average slope of the Moore neighborhood with a radius of one of the fire position. This approach is illustrated in Figure 4.8 on the left side. In addition to the other suppression cost parameters, the terrain slope is also considered as an influential factor in the fire suppression task. By taking into account the terrain slope, the suppression strategy can be further optimized to ensure efficient and effective fire suppression.

Encircling a fire is a common and well-established method of controlling a fire, especially when the fire is particularly large. As explained in Section 3.1, there are various ways to encircle a fire using both direct and indirect attack methods. One way is creating a continuous fireline or by suppressing various locations using hot spotting. In the simulation, agents prioritize the distance of fire locations from the boundaries of

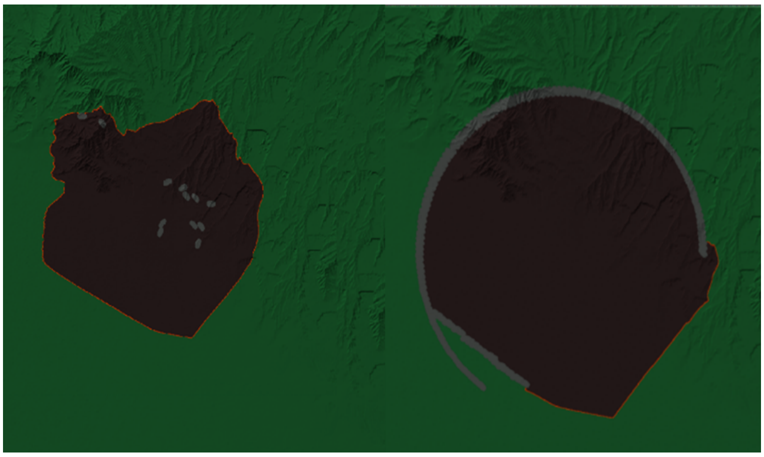


Figure 4.8: Direct attack by minimizing terrain slope cost (left), and elliptic fire line construction(right)

the area of interest to execute the **firefront encircling**.

To begin, the algorithm is informed by the ignition center and considers an area of interest around it by positioning a fictitious polygon. In the setup, the polygon is given four corners. Afterwards, agents search for the fire position closest to each center of the polygon edge. If the fire position is already taken by another agent, the agent selects the next closest position to suppress. The agent selects the closest fire position to suppress when all the corners of the polygon have been taken.

The dimension of the imaginary polygon is expanded when any fire position reaches a position on the boundary of the area of interest. This sequence is then repeated until the boundary of the area of interest reaches the boundary of the real map of the fire incident. The aim of this method is to encircle the fire by attacking from different positions on each of the 4 sides so that the fire does not propagate in a specific direction, which may cause increase in the fire growth rate. Furthermore, this tactic is capable of capturing spot fires which enables multiple fire incident locations to be implemented.

When dealing with large fires and a fire crew, building a fireline from a distance can be the safest method to contain the fire. This approach combines indirect and direct attacks sequentially, and the **elliptic fireline building** method is chosen for this purpose. According to previous studies [30], fire propagation can be modeled using a wave propagation model based on the assumption that the fire shape can be represented by an enclosed area, such as a combination of elliptical fire particles. As a result, it is beneficial to build the fireline in an elliptical shape to indirectly attack the fire.

To implement this indirect attack, a predefined ellipse is considered surrounding the fire ignition center. Then, the ellipse is rotated in the direction of the wind, since the propagation of the fire is likely to follow the direction of the wind, as shown in the environmental impact study in Section 5.3. During the simulation, the ellipse dimension is kept constant and its center is shifted towards the direction of possible fire growth to reduce the risk of propagation of the fire before the fireline is built. Once the fireline construction is completed, agents continue with a direct attack by tracking the firefront. In the case that the fire extends beyond the predefined ellipse area, the agents activate the direct attack, tracking firefront, as shown in Figure 4.8, right.

Figure 4.9 illustrates the rationale behind each tactic's implementation. When dealing with a challenging and difficult fire, a combination of direct and indirect attacks can be a powerful approach. To enhance the effectivity of indirect attack, a fireline can be built dynamically while monitoring the fire, as done in a parallel attack, by constructing a fireline from a distance based on the active fire positions. It is also worth questioning whether performing both types of attacks simultaneously by dividing the fleet into preassigned tasks or implementing both attacks sequentially, as in elliptic fireline construction. However, since each tactic has their own limitations, it is not possible to determine the most suitable tactic or whether there is an optimal tactic as wildfires are a non-linear phenomenon. In addition, it is important to note that the effectiveness of suppression tactics will not only depend on the fleet size involved in the mission but also on the various fleet combinations.

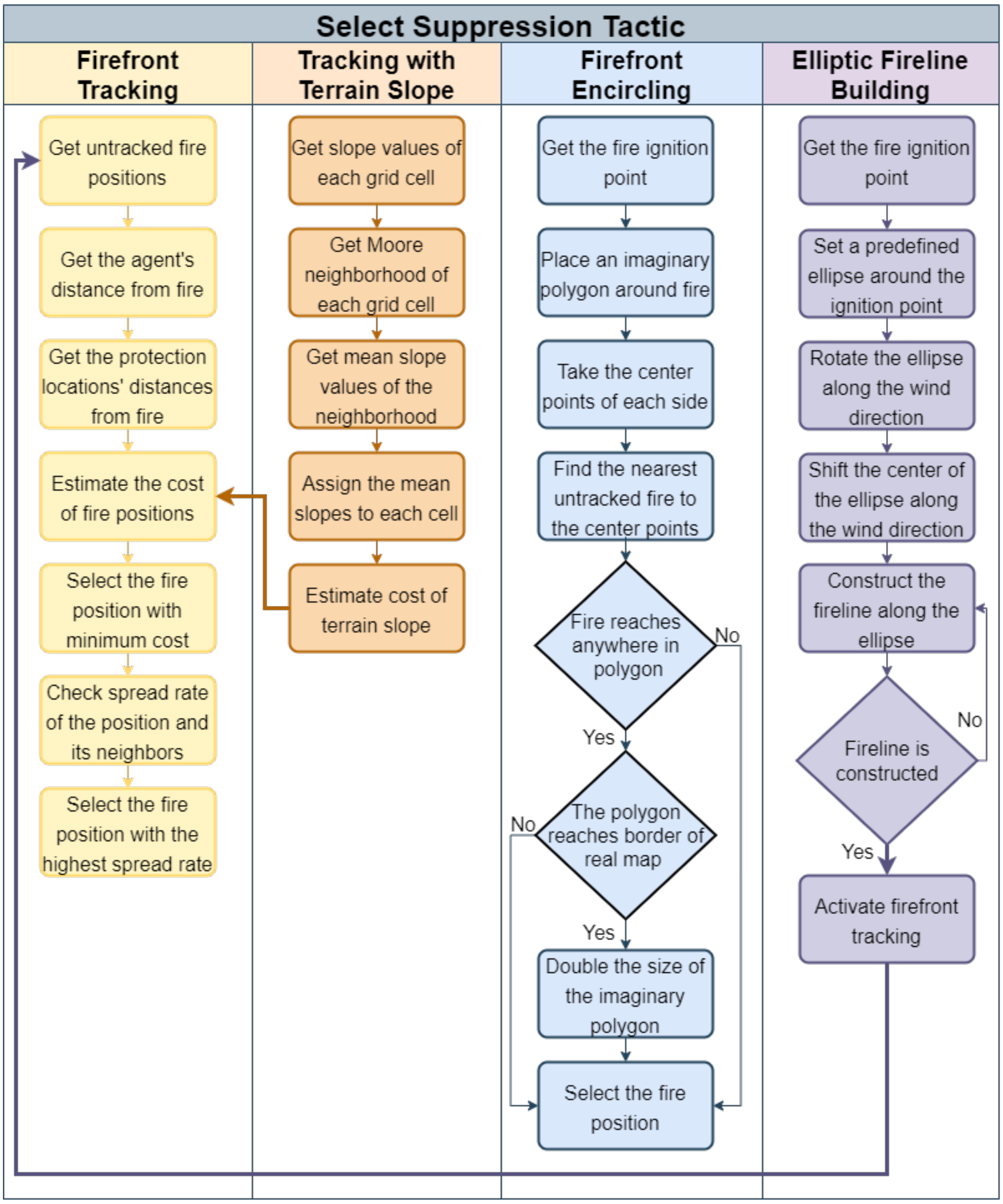


Figure 4.9: A flow chart representing the logical sequence of each tactic for suppression

4.5 Cost Model

The overall operational expenditure is determined by combining operating and capital costs on a per-mission basis. The operating costs encompass both direct and indirect expenses. The direct operating costs are further categorized into the costs of remote pilots, maintenance, and energy. On the other hand, the indirect operating costs are estimated as a fixed proportion of the direct operating costs. The capital costs solely focus on the depreciation cost of the aircraft for each mission. To calculate the depreciation cost, the aircraft's acquisition cost is included as an intermediate step in the cost model, encompassing expenses related to the airframe, avionics, and batteries. A general breakdown of the cost structure can be observed in Figure 4.10. The mathematical model utilized to estimate the costs can be found in the previous research done in [6].

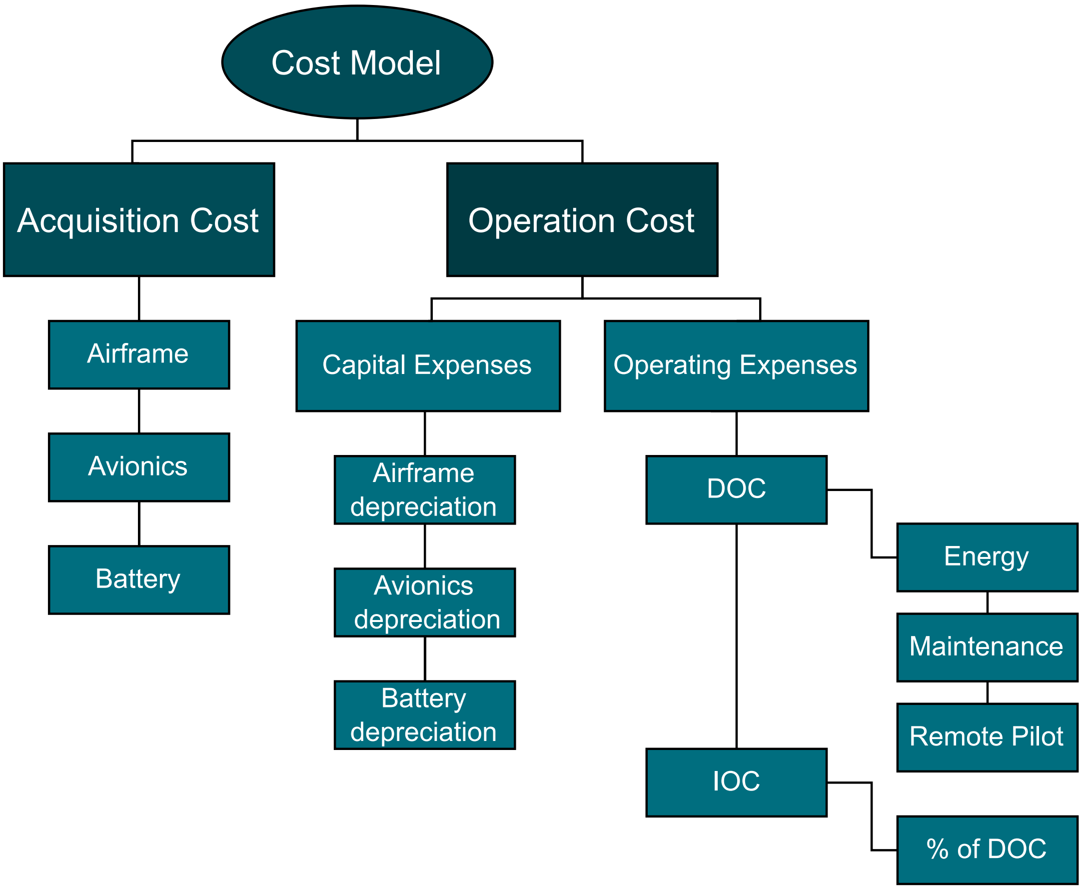


Figure 4.10: Structural breakdown of the cost model used in the framework

The estimation of the cost for each mission is specific to wildfire suppression, making it difficult to provide a general breakdown of operational cost. Previous research [6] has indicated that the capital cost of the aircraft drives the total cost of operation and dominates the all other cost elements, likely due to the limited number of times aircraft assets are being used.

Capital expenses are not inclusive of finance costs, as it is assumed that a loan will

Table 4.2: Assumptions for approximation of total operating cost [6]

Cost Components	Methodology	Assumptions		
		Cost Parameter	Value	Unit
Capital Expenses	Capital expenses are estimated as the sum of airframe, avionics and battery depreciation costs. Airframe and avionics depreciation is estimated as an exponential decay over time. Battery depreciation is estimated by allocating the unit price of the battery to on-mission consumption. Insurance cost and finance cost are not included in capital expenditures for the wildfire suppression mission.	Airframe price	1,102	USD/kg
		Avionics price	100,000	USD
		Depreciation rate	7.5	%
		Aircraft life time	15	years
		Number of missions	60	1/years
		Battery specific energy	250	Wh/kg
		Battery capacity specific cost	300	USD/kWh
		Battery life cycle	500	-
Energy Cost	Estimated as a summation of fuel cost and electricity cost per mission.	Electricity price	0.2	USD/kWh
		Fuel price	3.3	USD/kg
Maintenance Cost	Estimated by multiplying the mechanic wrap rate and ratio of maintenance man-hours to flight hours.	Mechanic wrap rate	75	USD/hour
		MMH/FH	0.6	-
Remote Pilot Cost	Estimated by multiplying pilot's hourly rate and mission time. The remote pilot is assumed to be responsible for all the fleet.	Pilot wrap rate	150	USD/hour
		Number of aircraft assigned to pilot	Fleet size	-
Indirect Operating Cost (IOC)	Assumed to be constant fraction of direct operating cost.	Fraction	20	%

not be required for this type of humanitarian project. Insurance cost is also ignored, assuming that private liabilities will not be necessary, and the residual value of the aircraft is neglected. To simplify the calculation of the direct operating cost, the ground crew cost, route cost, and infrastructure cost are not included. Instead, indirect operation cost is determined as a constant fraction of the direct operating cost.

Separating the capital expenses from the direct operating cost helps to avoid the domination of the former. The energy cost of the fleet is estimated by assuming semi-autonomous flight conditions for aerial firefighting, taking into account the energy consumption of various fleet combinations with different powertrain architectures. It is assumed that the remote pilot operates all fleets, and the maintenance cost is estimated similarly for any aircraft types regardless of their sizes. Therefore, any difference in maintenance cost arising from the aircraft size is ignored. Further information on the methodology and parameter assumptions for the cost estimation is shown in Table 4.2.

4.6 Fire Model

This section provides a brief explanation of CA model used for modeling the wildfire in the SoS-driven ABS framework. The model implemented in the simulation is adopted from [36]. In the study done in [36], the algorithm simulates the spread of fire by assigning states to cells in a grid representing a forest.

The algorithm takes into account various factors that influence fire spread such as wind direction and speed, fuel load, and slope of the terrain. The simulation starts with setting an ignition point and calculating the probability of fire spread to neighboring cells based on the aforementioned factors. As the simulation progresses, the algorithm updates the states of the cells based on the probability of fire spread and the state of the neighboring cells.

The forest fire spread model evaluates the impact of combustibles, wind, temperature, humidity, and slope on the spread of forest fires, using physical, statistical, or empirical perspectives. Drawing on the [57] and [58] models, a time correction coefficient was introduced to enhance the consistency between simulated and actual fires. Equa-

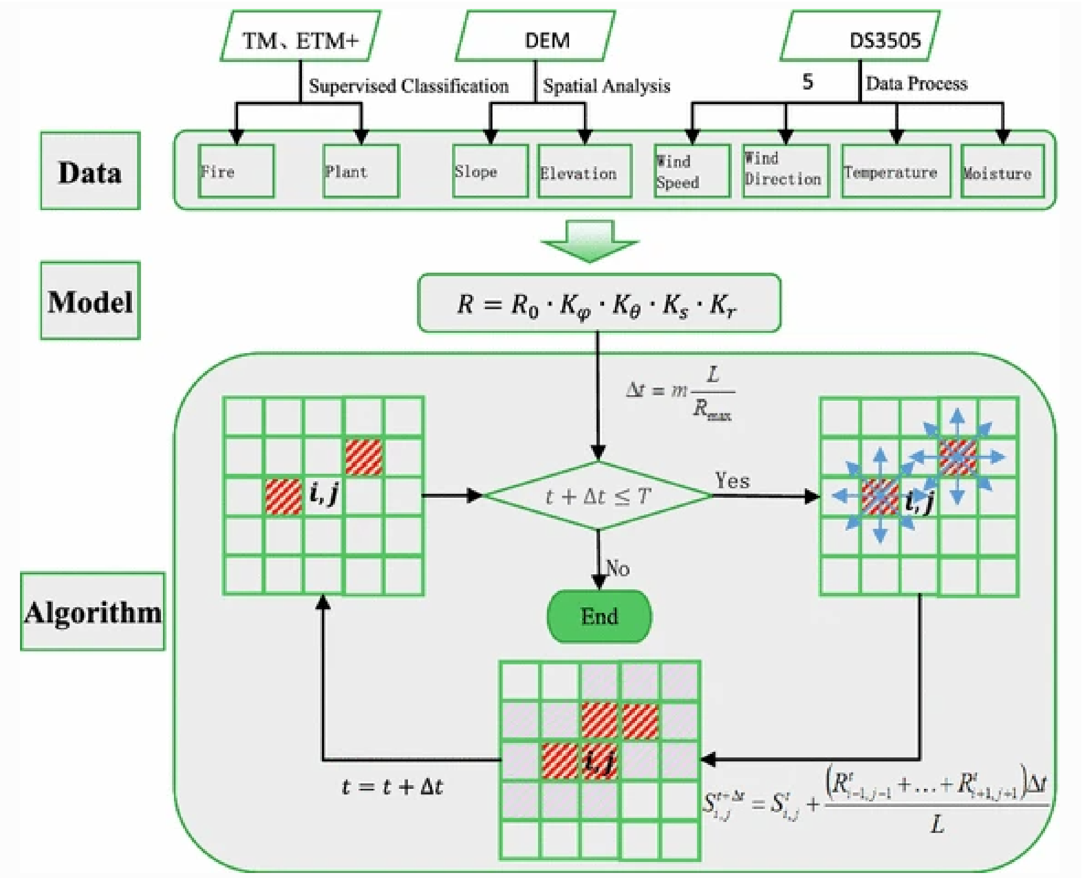


Figure 4.11: Geographical cellular automata based wildfire propagation algorithm design [36]

tion 4.1 expresses the relationship between the forest fire spread speed (R), the initial speed of forest fire spread (R_0), wind coefficient (K_θ), terrain factor (K_ϕ), combustible index (K_s), and time correction coefficient (K_r). The model considers combustibles, wind, temperature, humidity, and slope as factors affecting forest fire spread. The time correction coefficient is adjusted according to the spatial and temporal differences between simulated and actual fires. If the simulated fire occurs earlier than the actual fire, K_r should be reduced, whereas if the actual fire occurs earlier, K_r should be increased [36]. Therefore, it must be noted that the fire model is fine-tuned based on actual fires.

$$R = R_0 * K_\phi * K_\theta * K_s * K_r \tag{4.1}$$

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Mission Evaluation at SoS Level

This section presents an analysis at SoS level for investigating the research questions outlined below:

1. The effect of weather conditions and topography on fire growth.
2. The effect of various tactics employed in wildfire suppression missions.
3. The effect of a mixed fleet composition with varying payload capacity, flight velocity, and powertrain architecture on the efficiency of wildfire suppression missions.

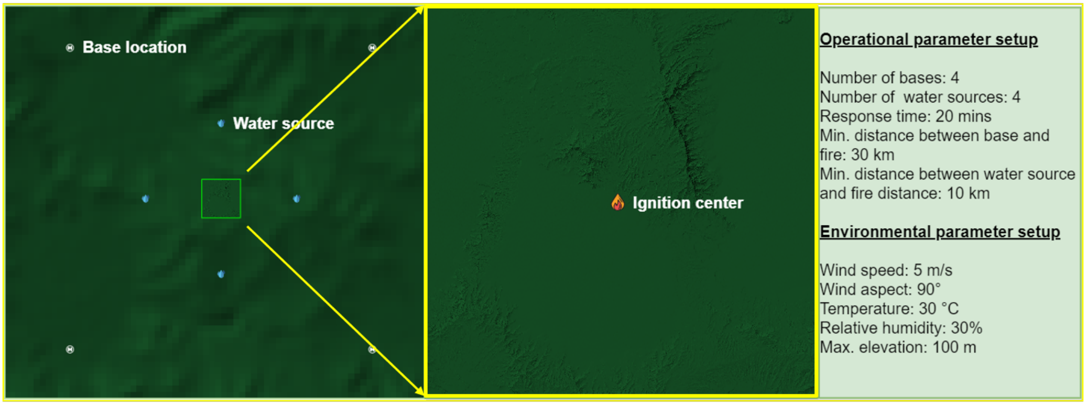
The success of the objectives is evaluated based on two criteria: total cost of operation and total area burned. To determine the effectiveness of every mission, measure of effectiveness is calculated by taking the average and normalized sum of these two functions. Higher values of this measure indicate a more efficient fleet.

In conclusion, this section provides a comprehensive evaluation of the SoS-level analysis and the effectiveness of different design points in the wildfire suppression mission. It also highlights the importance of considering the environmental impact of such missions in the decision-making process.

5.2 Background for Result Analysis

5.2.1 Mission Setup

For the fire model, a challenging mission was designed to conduct a sensitivity analysis covering the impact of fleet composition and suppression strategies. The fire was deliberately ignited in a mountainous region with hazardous weather conditions to capture the full spectrum of successful and failed missions. The success of the mission is determined by whether the fire is suppressed before it exceeds the boundary of the map. The size of the active area where fire incidents occur is 5km x 5km whereas the operational map size is 20km x 20km. A comprehensive view of the fire infrastructure and setup is shown in Figure 5.1.



Operational parameter setup

Number of bases: 4
Number of water sources: 4
Response time: 20 mins
Min. distance between base and fire: 30 km
Min. distance between water source and fire distance: 10 km

Environmental parameter setup

Wind speed: 5 m/s
Wind aspect: 90°
Temperature: 30 °C
Relative humidity: 30%
Max. elevation: 100 m

Figure 5.1: Fire and infrastructure set up for aerial firefighting mission

To evaluate tactics, the simulation was conducted on both a homogeneous and a heterogeneous fleet. A full factorial design was used, with each base assigned a single type of 0, 4, and 8 aircraft for creating the design of experiments. For the tactical evaluation, two different aircraft configurations were selected, multirotor and tiltrotor, which have a large payload capacity. The different composition of the fleet is described in detail in Section 4.3. Furthermore, the study treats environmental parameters independently from the suppression mission meaning that no operations were conducted during fire propagation. Originally, the study was designed with 3 different values for the environmental parameters: low, medium and high. However, the study parameters were then expanded according to their impact to better capture their effects. The environmental parameters that are taken into account for this study are wind speed, maximum relative elevation, wind direction, temperature, and relative humidity.

5.2.2 Assumptions and Limitations

The heterogeneous fleet employed in the simulation comprises different aircraft types with distinct powertrain architectures. It is anticipated that the battery recharge time may cause slight variations in the turnaround time for each aircraft. However, the current setup overlooks this difference in turnaround time. Furthermore, the composition of the fleet excludes large air tankers, and therefore, the leading airplane in the fleet configuration for building fireline is not taken into account.

The termination of the mission occurs when any fire position reaches the edge of the map. Therefore, the success of the mission heavily relies on the distance of the ignition center to the boundaries of the map. For this study, the ignition center is located towards the center of the fire map to prevent the simulation from ending prematurely and to give the fleet ample time to suppress and contain the fire. It is also assumed that all the information related to the incident location, fire shape, and incident time is acquired through Global Positioning System (GPS) services.

Moreover, the suppressant drop model in the simulation determines the suppression area probabilistically, resulting in changes in the suppressed area based on different resolutions. Therefore, this probabilistic approach raises a potential source of uncertainty in the response. To mitigate this uncertainty, the simulation is conducted with a resolution of 2 meters of cell size. Increasing the resolution enhances the efficiency of the fire model, but reducing the cell size exclusively can decrease the accuracy of the simulation as mentioned in [36]. Thus, the time step is also reduced to 0.05 in this study. It is crucial to maintain a balance between resolution and accuracy to achieve reliable results.

5.2.3 Overview of the ANOVA Statistical Test

A statistical test called ANOVA (Analysis of Variance) is used to analyze the results of the study mainly to understand the impact of the environmental factors on the total burnt area. This section aims to provide a brief explanation about the methodology and how it is used in this study.

The ANOVA test works by analyzing within-group and between-group variability. In particular, it calculates the ratio of the variance between groups to the variance within groups. If the ratio is sufficiently large, it indicates that the means of the groups are most likely different from each other and the null hypothesis (that there is no difference between the groups) is rejected. ANOVA determines the variation between groups by first computing the mean of each group and then determining the combined mean of all groups. It then calculates the difference between each group's mean and the overall mean, squares the differences, and multiplies them by the number of observations in each group. The sum of these squared differences represents the variation between groups. To determine the variation within groups, ANOVA calculates the variance of each group and multiplies it by the number of observations in each group, subtracting one. The total of these values across all groups gives the sum of squares within groups. The total variation is the sum of the variation between groups and the variation within groups [59], [60].

After conducting an ANOVA test and observing a significant difference between group means, a post-hoc test is used to determine which specific groups within a set of groups have significant differences in means. Connecting letters in ANOVA serve as a visual tool to represent the results of the post-hoc test. When groups have the same letter, they are not significantly different from each other, while groups with different letters are significantly different. For instance, if groups A and B have the same letter but group C has a different letter, it means that group C has a significantly different mean from groups A and B, but groups A and B do not differ significantly from each other. To aid in interpretation, connecting letters are often included in a table or figure alongside the ANOVA results to provide a clear understanding of which groups have significant differences in means [61].

5.3 Analysis of Environmental Impact

5.3.1 Overview of the study

The propagation of forest fires is considerably impacted by the natural surroundings. The purpose of this research is to expose how weather and geographical factors affect the pace of fire spread. The variables of interest include wind velocity, maximum relative elevation, wind direction, temperature, and relative humidity. The primary objective is to evaluate the influence of these environmental parameters on the spread of wildfires and to establish a comprehensive understanding of their effect. By analyzing the relationship between these factors and the fire spread rate, we can gain valuable insights into how forest fires behave under different environmental conditions. Ultimately, this can aid in the development of effective strategies for managing and mitigating the impact of wildfires.

5.3.2 Wind Speed

An investigation has been conducted to evaluate the impact of varying wind speeds on the spread of fires, with the study covering a range from calm conditions to wind speeds of 10 meters per second. The study has utilized a metric of total area burnt to evaluate the results, with each unit of measurement equivalent to the area of one football field, or approximately 5500 square meters. The data collected over a period of three and a half hours has been visually presented in Figure 5.2, which provides an overview of the burnt area across the range of wind speeds tested.

Figure 5.2 shows that the slope of the curve becomes steeper as the wind speed increases, which is expected. However, it is observed that the steepness of the curve changes differently in each section. To quantify the changes in the rate of fire spread, a one-way ANOVA analysis was conducted using the least significant difference (LSD) test and connecting letters. This statistical test is commonly used to examine the relationship between the means of more than two groups using a single independent variable. Hence, it can be applied to investigate the impact of environmental factors by comparing the means of each level with respect to a single response variable,

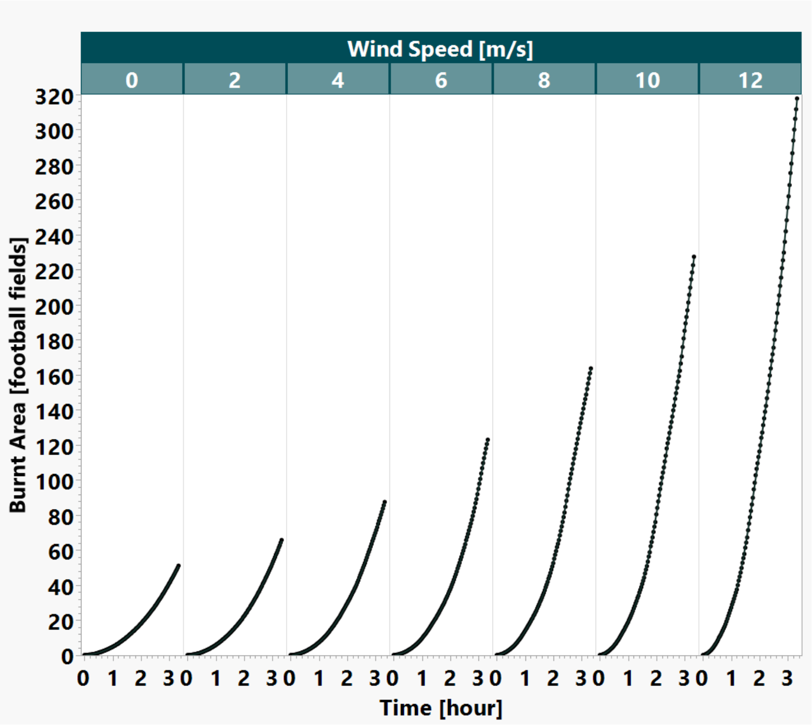
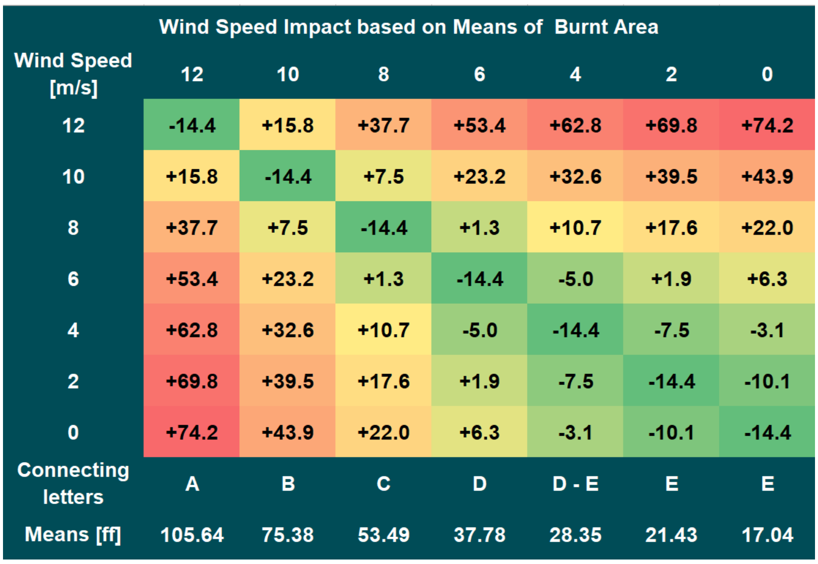


Figure 5.2: The total area burned in terms of football fields for varying wind speed conditions

which is the total burnt area in this study. In the LSD test, the positive values indicate that there is a significant difference between the levels, and to be able to visually classify each level, the analysis benefits from the use of connecting letters. The details of the ANOVA test is provided in Section 5.2

Table 5.1 presents a matrix where the lower triangular section displays the positive correlations between different wind speed levels that are significantly different from each other. This suggests that when the wind speed exceeds 6 m/s, it has a substantial impact on the burnt area. On the other hand, the upper triangular section of the matrix exhibits negative correlations, which indicates that each wind level has a similar effect on the total burnt area. Therefore, it can be concluded that the wind speed of 6 m/s acts as a threshold value in this context, above which any increase in wind speed leads to a significant rise in the burnt area. In other words, the analysis reveals that higher wind speeds have a substantial impact on the spread of the fire and, therefore, the wind speed level needs to be taken into account when designing firefighting strategies.

Table 5.1: Wind speed level correlation based on the means of total area burned



Wind Speed [m/s]	Wind Speed Impact based on Means of Burnt Area						
	12	10	8	6	4	2	0
12	-14.4	+15.8	+37.7	+53.4	+62.8	+69.8	+74.2
10	+15.8	-14.4	+7.5	+23.2	+32.6	+39.5	+43.9
8	+37.7	+7.5	-14.4	+1.3	+10.7	+17.6	+22.0
6	+53.4	+23.2	+1.3	-14.4	-5.0	+1.9	+6.3
4	+62.8	+32.6	+10.7	-5.0	-14.4	-7.5	-3.1
2	+69.8	+39.5	+17.6	+1.9	-7.5	-14.4	-10.1
0	+74.2	+43.9	+22.0	+6.3	-3.1	-10.1	-14.4
Connecting letters	A	B	C	D	D - E	E	E
Means [ff]	105.64	75.38	53.49	37.78	28.35	21.43	17.04

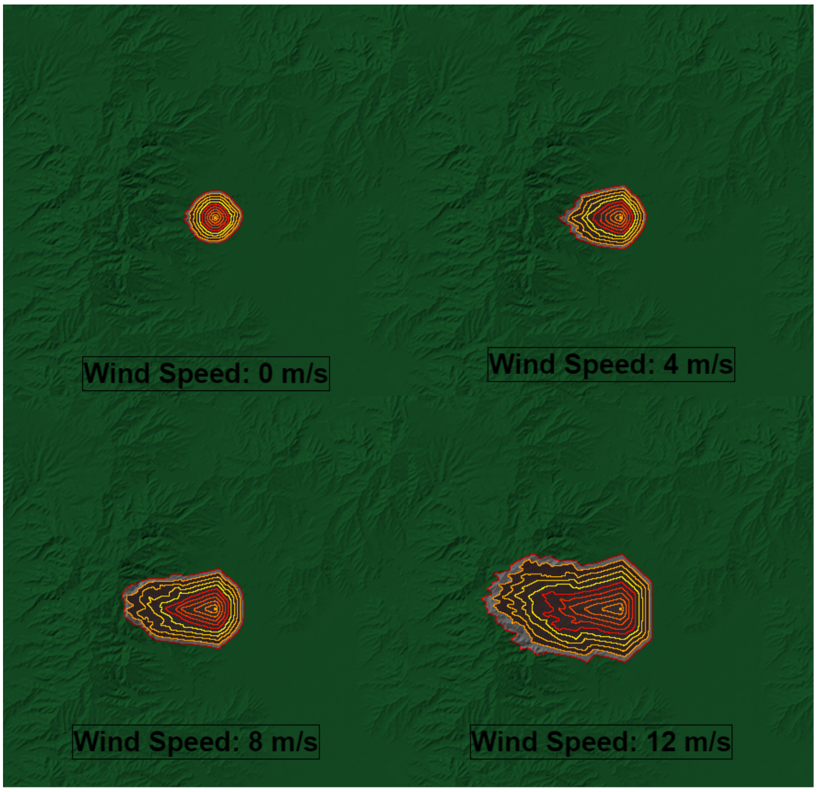


Figure 5.3: Wildfire behavior according to various wind speed values

Although wind speed has a significant impact on the total burnt area, there are other factors that also influence the spread of fire. As depicted in Figure 5.3, the direction of the wind affects the spread of fire towards mountainous regions. This indicates that the topography of the terrain also plays a crucial role in the spread of fire. Therefore, it is necessary to investigate the effect of elevation changes on the total burnt area as the next step. The results of this analysis will provide a more comprehensive understanding of the factors affecting the spread of forest fires. By incorporating the impact of both wind speed and elevation, a more accurate model for predicting and managing the spread of forest fires can be developed.

5.3.3 Maximum relative elevation

Fire growth rate varies according to the slope of the terrain. In this study, since the elevation of the terrain is highly correlated with the slope of the terrain, different elevation values were examined.

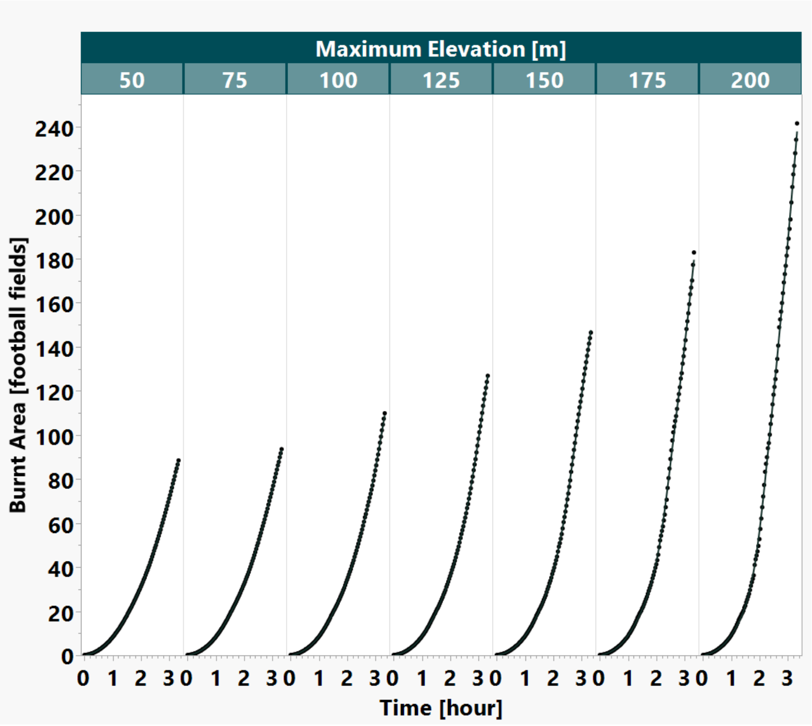
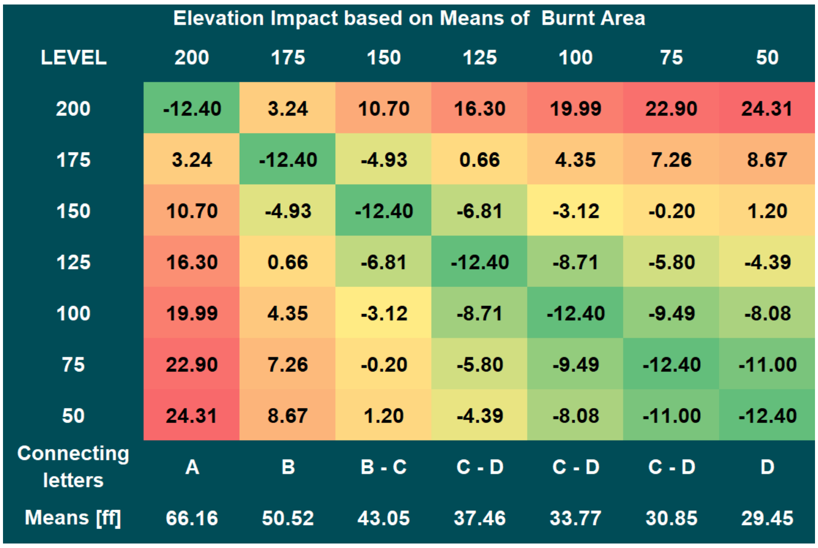


Figure 5.4: The total area burned in terms of football fields for varying maximum relative elevation values

The relationship between the fire growth rate and the maximum relative elevation is illustrated in Figure 5.4, which demonstrates that fire spreads more rapidly on steeper slopes than on gentler ones. The present study has considered maximum relative elevation values up to 200 m for feasibility, and it is evident that the steepness of the fitting curve does not increase as dramatically as in the case of wind speed. However, similar to the wind speed evaluation, the difference in total area burned becomes more pronounced as the elevation increases.

Table 5.2: Maximum relative elevation level correlation based on the means of total area burned



Elevation Impact based on Means of Burnt Area

LEVEL	200	175	150	125	100	75	50
200	-12.40	3.24	10.70	16.30	19.99	22.90	24.31
175	3.24	-12.40	-4.93	0.66	4.35	7.26	8.67
150	10.70	-4.93	-12.40	-6.81	-3.12	-0.20	1.20
125	16.30	0.66	-6.81	-12.40	-8.71	-5.80	-4.39
100	19.99	4.35	-3.12	-8.71	-12.40	-9.49	-8.08
75	22.90	7.26	-0.20	-5.80	-9.49	-12.40	-11.00
50	24.31	8.67	1.20	-4.39	-8.08	-11.00	-12.40
Connecting letters	A	B	B - C	C - D	C - D	C - D	D
Means [ff]	66.16	50.52	43.05	37.46	33.77	30.85	29.45

Table 5.2 shows the results of the LSD test for different elevation values up to 150 m. As can be observed from the connecting letters, the threshold value for elevation impact can be considered 150 m. The transition occurs between the elevation levels of 125 and 150 m and 150 and 175 m, after which the elevation value begins to significantly affect the spread rate. It is also seen that a 25 m elevation increment (1.5° in slope) is appropriate for capturing the transitions between elevation levels.

Figure 5.5 illustrates that as the elevation value increases, the fire reaches the mountainous area where the slope of the terrain is higher and much more irregular. Any changes in the terrain slope affects the response of maximum relative elevation due to direct correlation between elevation and slope. Thus, the following step would be to examine how the direction of fire propagation affects a particular scenario.

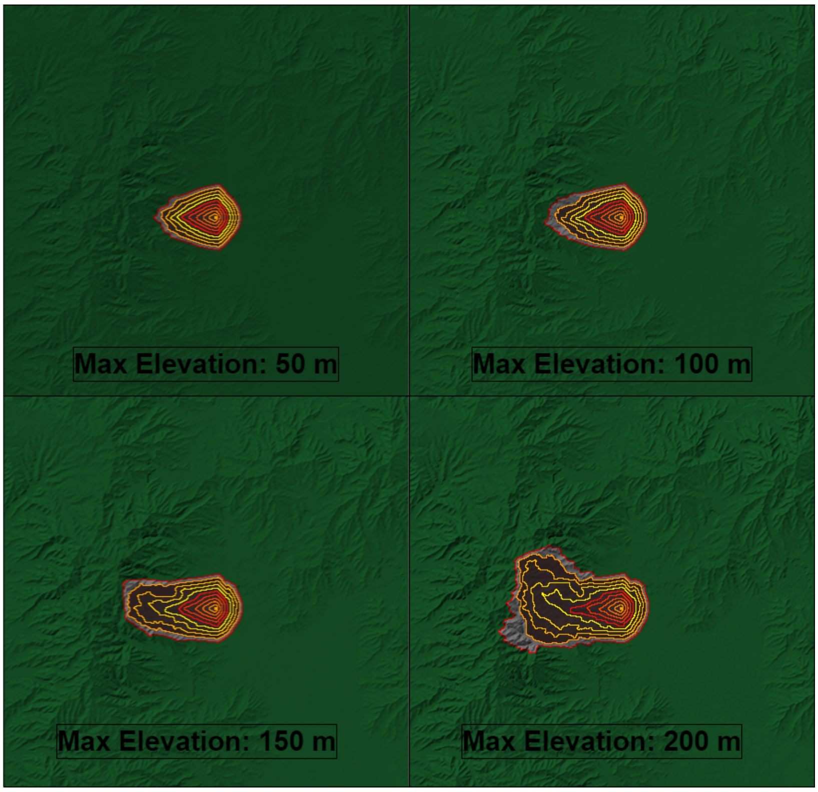


Figure 5.5: Wildfire behavior according to various maximum relative elevation values

5.3.4 Wind Aspect

The direction of the wind can have an indirect effect on the rate of fire spread, as it can differ based on location. If the wind is blowing towards an area with a steep terrain slope, the impact of wind speed on the fire spread can be magnified by the impact of the terrain slope.

As depicted in Figure 5.6, the extent of the burnt area differs significantly when the wind blows towards a terrain with high slope values. The contrast between the 90° (east) and 270° (west) wind directions implies that the effect of wind direction could be beneficial or harmful, depending on the region of interest. This indicates that the wind direction is an important factor to consider in the spread of forest fires, as it can have a significant impact on the burnt area.

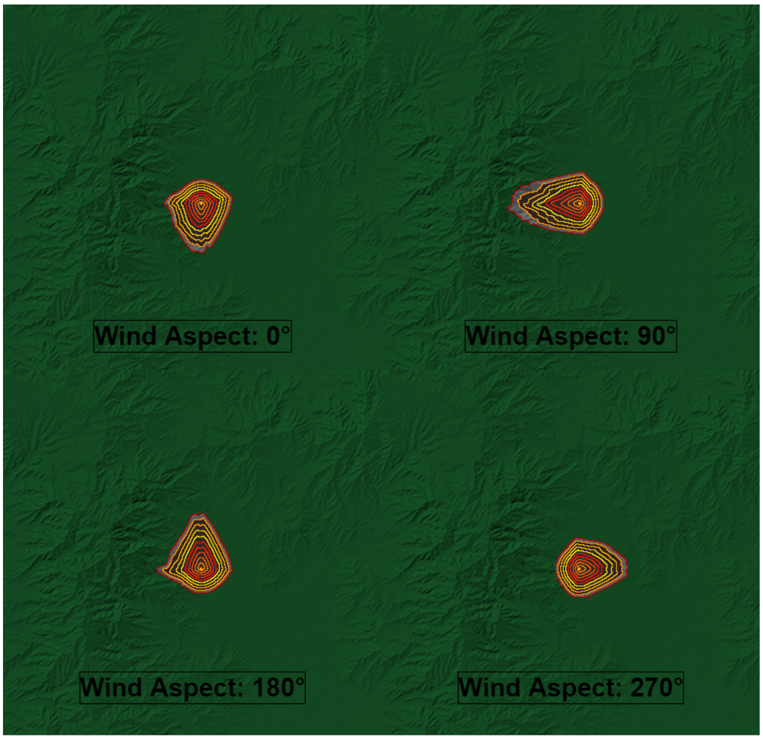


Figure 5.6: Wildfire behavior according to various wind aspect values

5.3.5 Temperature

The temperature of the weather has a significant impact on the rate at which fires spread. It is evident from Figure 5.7 that there is a strong correlation between temperature and total burnt area. As the temperature gradually increases from 10 °C to 40 °C, the steepness of the curve in Figure 5.7 increases substantially, indicating a corresponding rise in the fire spread rate. The effect is particularly significant beyond 30 °C, where the steepness of the curve is most prominent. The rise in temperature significantly affects the fuel's moisture content, which in turn affects the ease with which fires ignite and spread. Therefore, it is crucial to understand the relationship between temperature and the rate of fire spread to develop appropriate mitigation strategies.

Table 5.3 presents a quantitative analysis of the impact of temperature on the spread of fire. The results show that there are significant differences between most of the temperature levels. The table is divided into upper and lower triangular, which show the positive and negative relations between temperature levels and the total burnt area. It is clear that there is a significant distinction between the values before and after 25

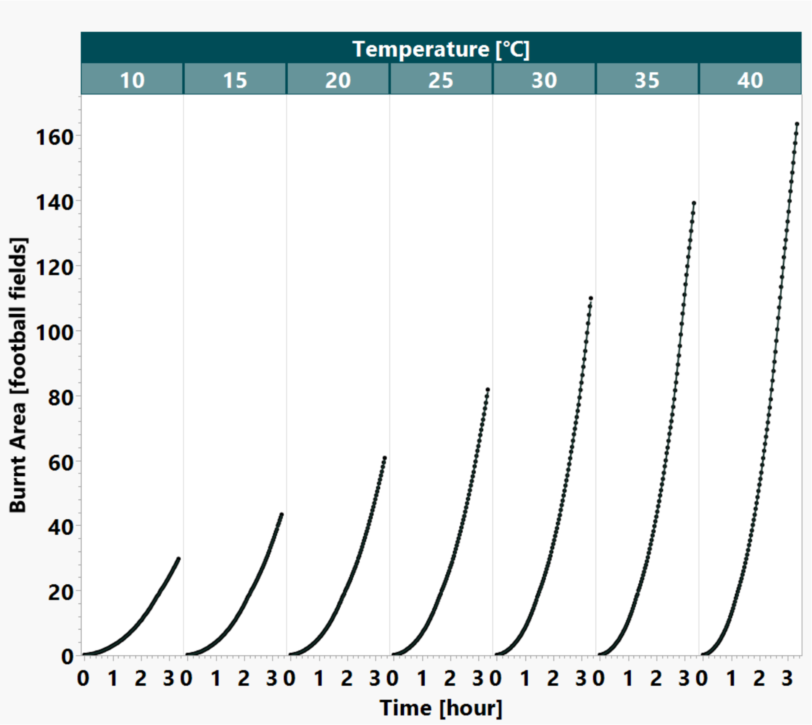
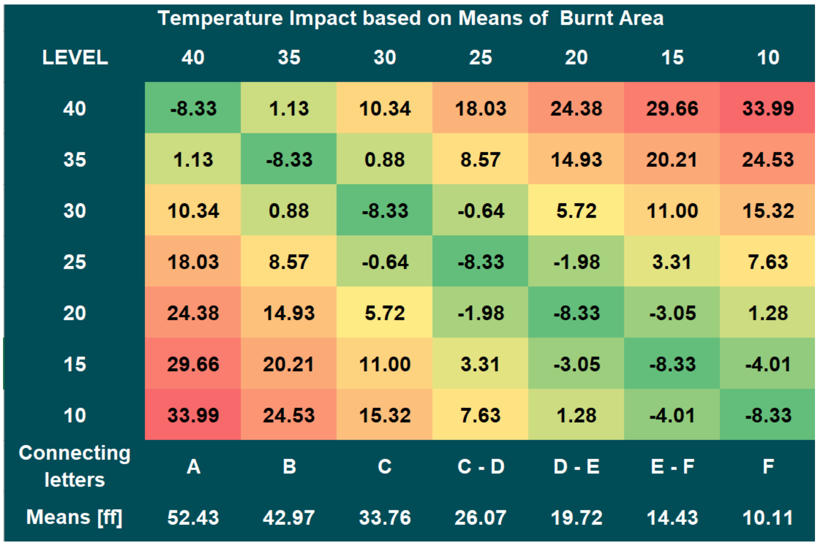


Figure 5.7: The total area burned in terms of football fields for varying temperature values

°C, and after 30 °C, any change in temperature significantly affects the spread rate, as indicated by the connecting letters.It should be noted that the 5 °C increments used to categorize the temperature values are not sufficient for high temperature values. In other words, the difference in temperature has a greater impact on the spread of fire as the temperature increases. As shown in Figure 5.7, the curve becomes steeper as the temperature rises, especially after 30 °C. This suggests that temperature is a crucial factor that should be considered in fire management strategies, and careful attention should be given to temperature values above 30 °C.

Additionally, it is noteworthy that the significant impact of temperature on fire spread can be seen independently of topography. The results shown in Figure 5.8 demonstrate that, even at the maximum temperature condition, the fire does not propagate only towards the mountainous areas, but instead expands in all directions. This is a clear indication that the temperature has a high impact on the rate of fire spread.

Table 5.3: Temperature level correlation based on the means of total area burned



Temperature Impact based on Means of Burnt Area

LEVEL	40	35	30	25	20	15	10
40	-8.33	1.13	10.34	18.03	24.38	29.66	33.99
35	1.13	-8.33	0.88	8.57	14.93	20.21	24.53
30	10.34	0.88	-8.33	-0.64	5.72	11.00	15.32
25	18.03	8.57	-0.64	-8.33	-1.98	3.31	7.63
20	24.38	14.93	5.72	-1.98	-8.33	-3.05	1.28
15	29.66	20.21	11.00	3.31	-3.05	-8.33	-4.01
10	33.99	24.53	15.32	7.63	1.28	-4.01	-8.33
Connecting letters	A	B	C	C - D	D - E	E - F	F
Means [ff]	52.43	42.97	33.76	26.07	19.72	14.43	10.11

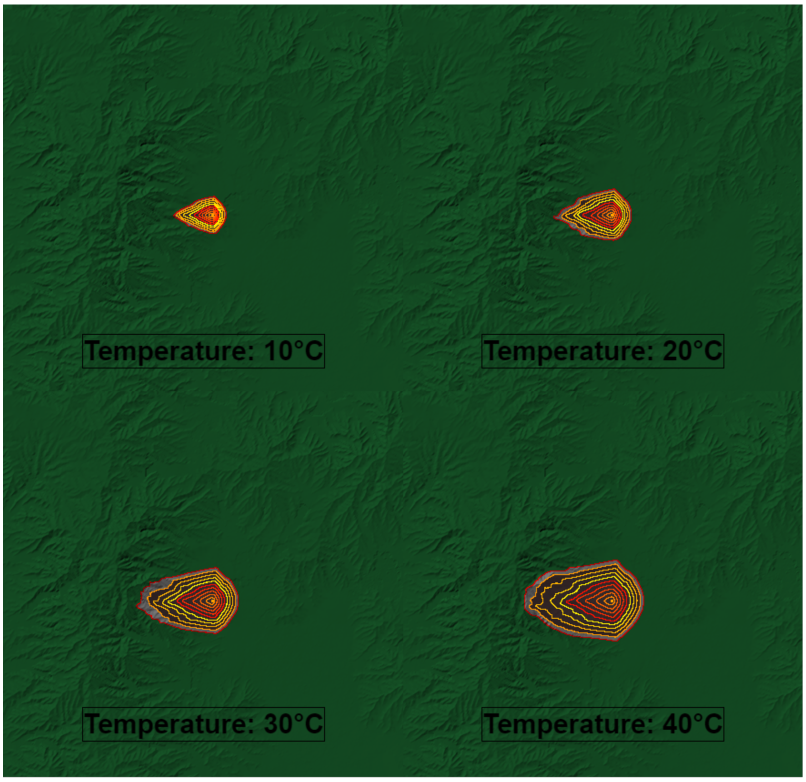


Figure 5.8: Wildfire behavior according to various temperature values

5.3.6 Relative Humidity

Fundamentally, the fuel moisture decreases as the humidity decreases and the temperature increases, leading to more vigorous fire growth. In comparison to the temperature effect, the transition in the fire growth rate for each segment is relatively more gradual, as depicted in Figure 5.9. The plot indicates that, while there is a noticeable difference between the fire growth rates in different segments, the overall pattern is relatively smooth.

The LSD test results in Table 5.4 indicate that the impact of humidity on the fire growth is comparable to that of low temperature when the humidity level is high. However, the overall pattern suggests that a 20% change in relative humidity is sufficient to detect the transitions between different labels.

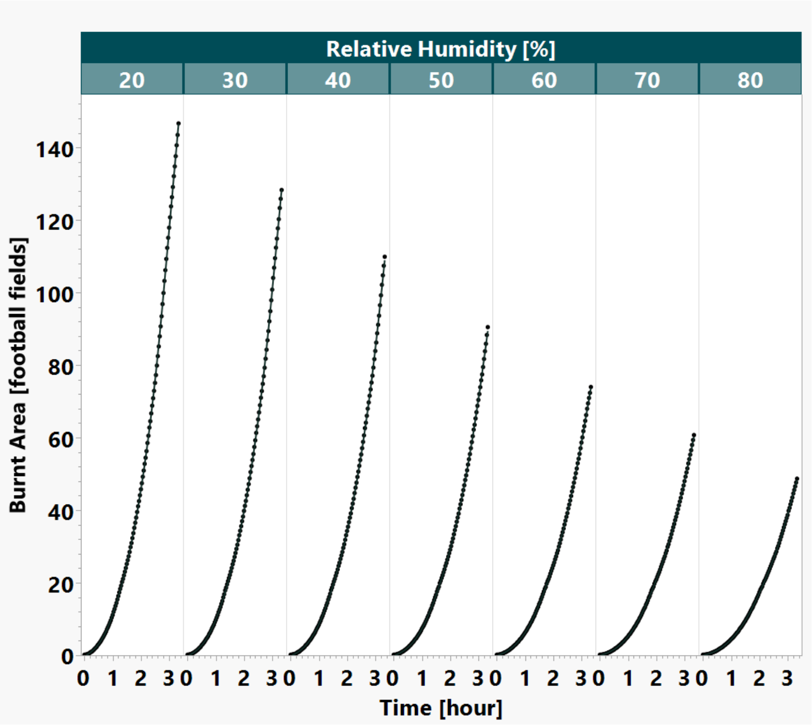
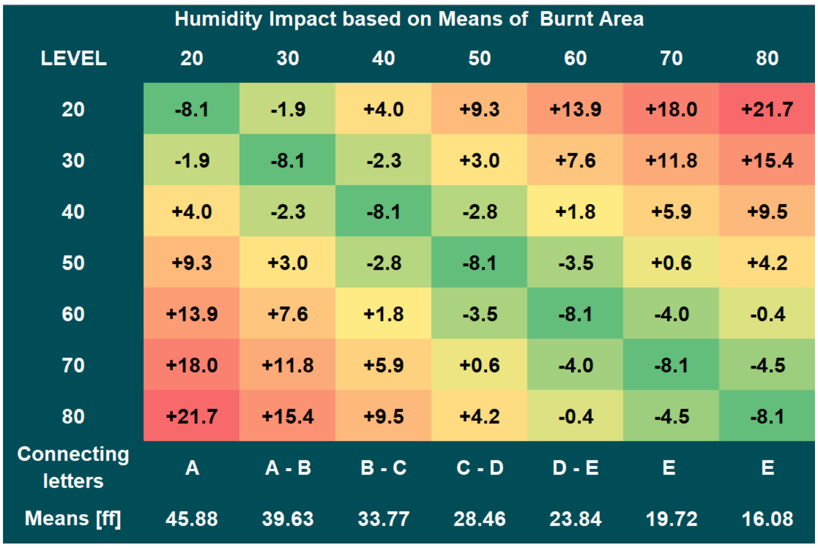


Figure 5.9: The total area burned in terms of football fields for varying relative humidity values

In other words, as shown in the table, there is a noticeable change in the burnt area for different humidity levels. The transition between different levels is more subtle compared to the effect of temperature, but still detectable by the LSD test. The hu-

Table 5.4: Relative humidity level correlation based on the means of total area burned



Humidity Impact based on Means of Burnt Area							
LEVEL	20	30	40	50	60	70	80
20	-8.1	-1.9	+4.0	+9.3	+13.9	+18.0	+21.7
30	-1.9	-8.1	-2.3	+3.0	+7.6	+11.8	+15.4
40	+4.0	-2.3	-8.1	-2.8	+1.8	+5.9	+9.5
50	+9.3	+3.0	-2.8	-8.1	-3.5	+0.6	+4.2
60	+13.9	+7.6	+1.8	-3.5	-8.1	-4.0	-0.4
70	+18.0	+11.8	+5.9	+0.6	-4.0	-8.1	-4.5
80	+21.7	+15.4	+9.5	+4.2	-0.4	-4.5	-8.1
Connecting letters	A	A - B	B - C	C - D	D - E	E	E
Means [ff]	45.88	39.63	33.77	28.46	23.84	19.72	16.08

midity levels are labeled as different categories, and the connecting letters in the table show that the 20% change in humidity level is sufficient to distinguish between these categories. The results indicate that higher relative humidity can suppress the spread of fire, whereas lower relative humidity can intensify it.

According to the statistical analysis of the burnt area, it can be inferred that the impact of relative humidity on the growth of fires is not as significant as that of other environmental factors. This observation is further supported by the data presented in Figure 5.10, which suggests that the relative humidity remained relatively stable despite the changes in topography caused by the fire. In fact, the fire did not spread to the mountainous region, as seen in previous incidents, indicating that the influence of relative humidity on fire growth is not as prominent as other factors such as wind speed and terrain elevation.

The findings of the environmental study demonstrate that the growth of fires is significantly impacted by two key factors, namely wind speed, and maximum relative elevation. As wind speed varies, there is a corresponding change in the rate of fire growth, and when combined with high terrain slopes, this can lead to a dramatic increase in the overall burnt area. The study also highlights the crucial role of wind direction, which can direct the spread of fire in challenging topographic conditions. While both temperature and relative humidity have a significant impact on fire growth, it is ob-

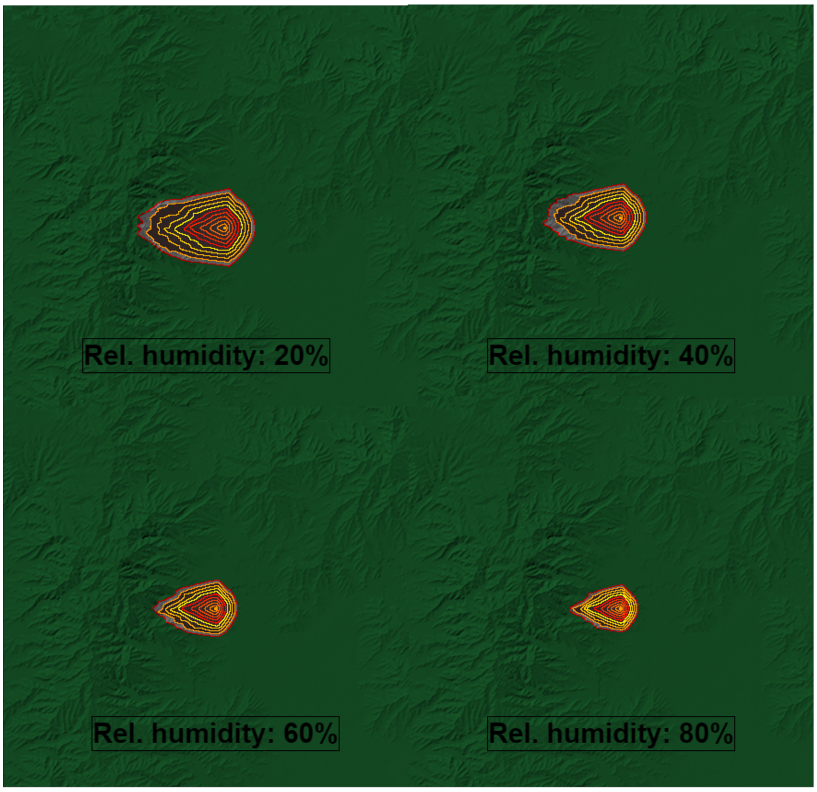


Figure 5.10: Wildfire behavior according to various relative humidity values

served that temperature is much more sensitive to changes in these environmental parameters. It is therefore essential to consider dynamic weather conditions during fire incidents, as demonstrated in [62], in order to effectively manage and control the spread of fires.

These findings underscore the complex and multi-faceted nature of wildfires, which require a comprehensive and integrated approach to management and prevention. It is essential to consider the interplay of various environmental factors, including wind speed, wind aspect, maximum relative elevation, temperature, and relative humidity, in order to develop effective strategies for wildfire management. This requires a nuanced understanding of the factors that contribute to the behavior of fires, as well as a commitment to ongoing monitoring and analysis of environmental conditions in order to quickly and effectively respond to fire incidents. Ultimately, the results of this study have important implications for policymakers, fire management professionals, and the broader public, highlighting the need for proactive and coordinated efforts to prevent and manage wildfires in a changing climate.

5.4 Suppression Tactic Sensitivities

Three measures of dispersion are used to assess the variation of the design space, namely: range, variance, and standard deviation. The accompanying Figure 5.11 illustrates the relationship between fleet size and total burnt area for four different suppression tactics. On the right-hand side of the figure, the tactics are ranked in descending order based on their respective burnt area. An important key observation is that when the fleet size is relatively compact, as indicated by the orange box in the figure, the dynamism in the response increases. It is evident that when resources are limited, the success of the mission is heavily influenced by the suppression tactic. Additionally, it is worth noting that mission success does not have a direct correlation with the total area burnt.

A design point (indicated by an orange dot in the figure) was tracked to analyze the influence of the tactics on the burnt area. It is observed that shifting the suppression tactic from firefront tracking to tracking with terrain slope can improve the mission by reducing the total burnt area up to an 86%. These findings underscore the importance of carefully selecting suppression tactics, particularly when resources are limited, in order to maximize mission success and minimize damage. The data presented in Figure 5.11 provides valuable insights for decision-makers and fire management professionals alike, highlighting the complex relationship between the suppression tactics and the total burnt area.

The dispersion metrics, which are measures of variability, are shown in the top right corner of Figure 5.11. The figure illustrates that the elliptic fireline building and firefront encircling tactics result in more successful missions compared to the firefront tracking tactic, which is being used as a default selection in the ABS framework.

The indirect attack (elliptic fireline building) is effective because it surrounds the fire before directly attacking it, resulting in a higher number of successful missions. Nonetheless, as the fire is permitted to continue burning while building the fireline, carrying out both indirect and direct attacks successively results in a greater extent of land being burnt, even in cases where the missions are executed successfully. On the other hand, the firefront encircling tactic enhances the likelihood of success by

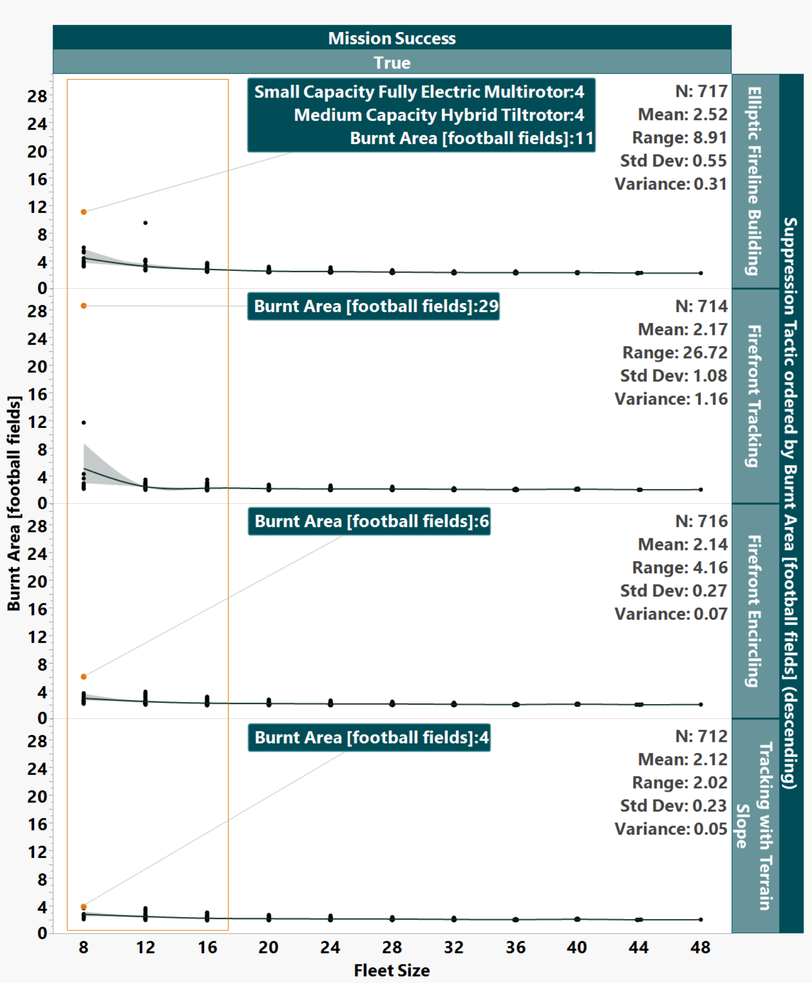


Figure 5.11: Total burnt area with various suppression tactics for the heterogeneous fleet with respect to fleet size

focusing on the four primary edges and inhibiting the fire from spreading in a specific direction. For this tactic, the agents do not receive information about the terrain slope or spread rate of the fire, but they are informed about the location of the leading edge. This approach allows the agents to observe the fire's behavior instead of attempting to control it directly, resulting in a reduction in the total burnt area. Therefore, the dispersion metrics for firefront encircling are relatively small compared to the other tactics.

The design point tracked in Figure 5.11 shows that following the firefront while considering the slope of the terrain can decrease the area being burned. However, it is observed that using tracking with terrain slope strategy also results in a decrease in the total number of successful missions. It is concluded that the dispersion metrics for this tactic are not reliable since crucial design points (the points where the mission success is at risk) correspond to mission failures.

These findings provide valuable insights into the effectiveness of different suppression tactics and their impact on mission success and total burnt area. Decision-makers and fire management professionals can use this information to select the most appropriate suppression tactic based on the available resources and the desired outcomes. The complexity of the relationship between suppression tactics and fire behavior underscores the need for ongoing research and development in this critical field.

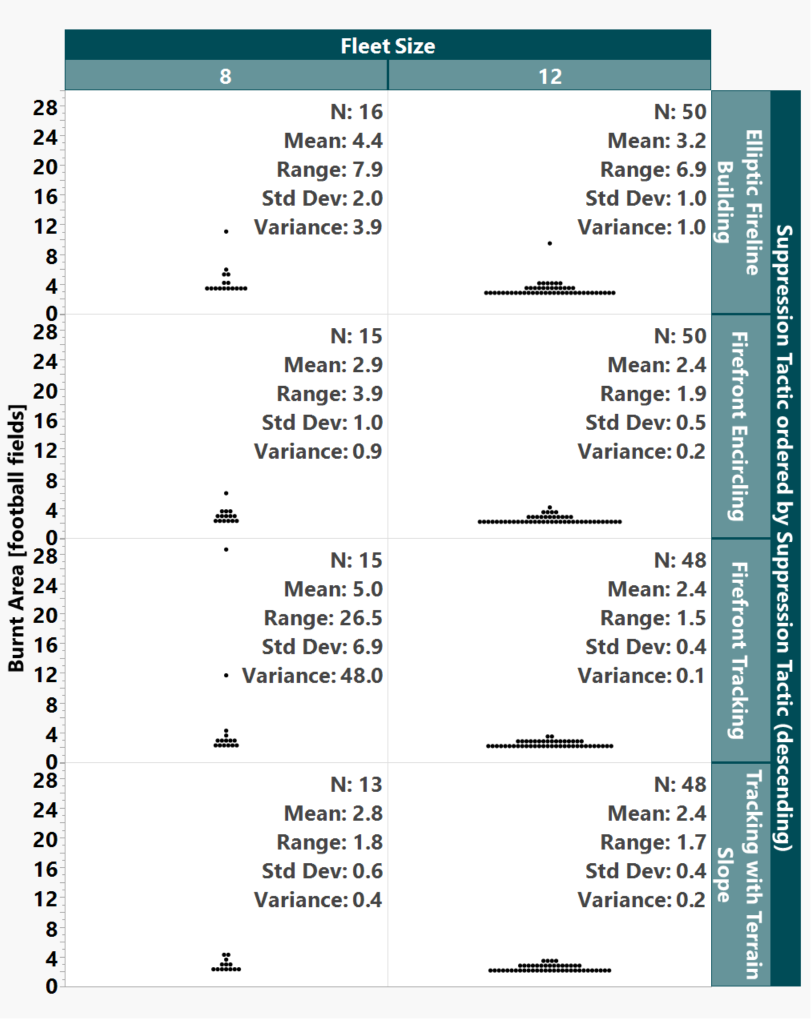


Figure 5.12: The overall burned area, taking into account the dispersion metrics, for various suppression methods in relation to compact fleet sizes of 8 and 12

Figure 5.12 emphasizes the importance of considering small fleet sizes when analyzing dynamicity in the design of suppression tactics. The results show that the elliptic fireline building and firefront encircling tactics are the most effective, with a higher number of successful missions compared to the other tactics. These tactics are designed to surround the fire using both direct and indirect attack methods. However, it's worth noting that a combination of indirect and direct attacks results in a higher success rate than solely relying on a direct attack.

Furthermore, the data indicate that tracking the firefront with terrain slope can lead to a decrease in the mean of the total burnt area for a fleet size of 8 aircraft. However, this also results in a decrease in the number of successful missions, making it less reliable to use dispersion metrics for this scenario. This decrease in successful missions can be attributed to the limitations of the tactic logic, which only considers surrounding locations with a Moore neighborhood radius of 1. Therefore, the irregularities of the terrain can mislead the actual value of the target location, leading to fewer successful missions.

These findings suggest that when designing suppression tactics for small fleet sizes, it is crucial to consider both direct and indirect attack methods, as well as the limitations of tactic implementation. By doing so, the success rate can be increased while minimizing the total burnt area. Further research and experimentation may be necessary to fully optimize suppression tactics for different fleet sizes and terrain conditions.

To gain a more detailed understanding of the impact of suppression tactics on the total burnt area, Figure 5.13 shows the results for two homogeneous fleets of different sizes. It is evident from the figure that the impact of suppression tactics decreases as the fleet size increases. The elliptic fireline building, which previously demonstrated higher success rates, loses its advantages when the missions are relatively easier, and the construction of a fireline is not necessary. Moreover, the use of indirect attacks followed by direct attacks does not improve mission effectiveness when the fleet size is large enough to handle direct attacks alone. In fact, it results in an increase in the total burnt area due to the time lost in constructing the fireline, leading to delayed mission completion. This delay is more pronounced in fleets with lower flight velocities, as seen in the fleet composition with multirotor. Although the burnt area may be higher for the indirect attack tactic, it can be considered to be more robust, as it

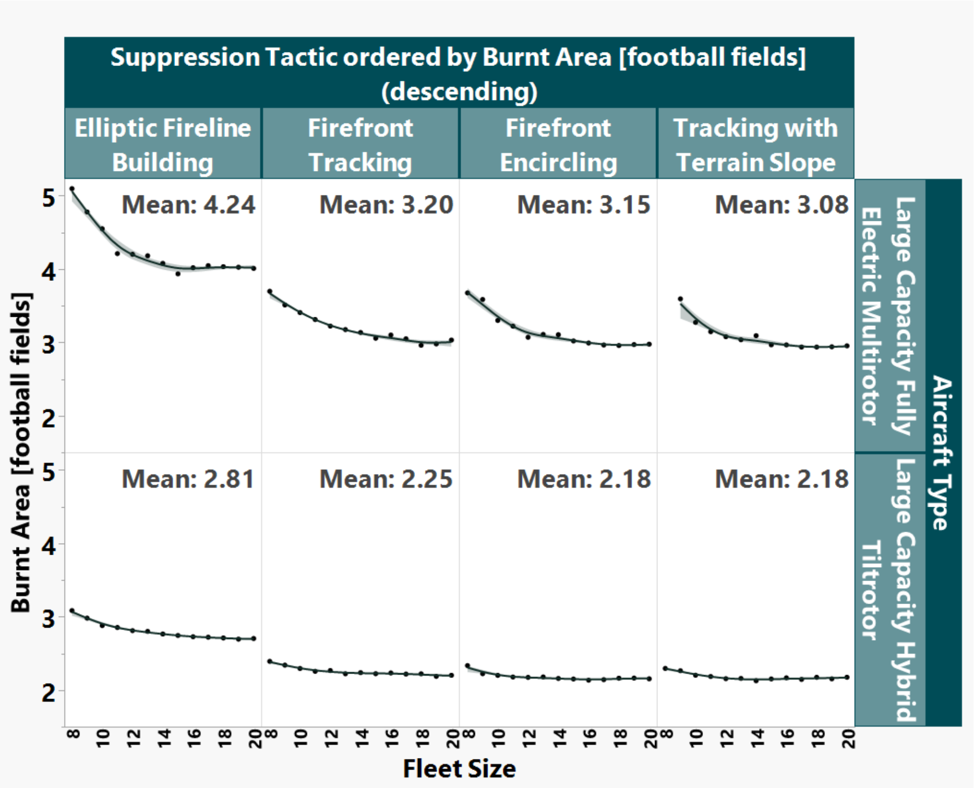


Figure 5.13: Response of various tactics when applied with two distinct groups of homogeneous fleets

results in slightly higher success rates for a fleet of 8 aircraft.

It is important to note that the use of indirect attacks followed by direct attacks may not always be effective, and may not be appropriate for all situations. The decision to use a particular suppression tactic should be made based on the specific conditions of the fire, including the size, location, and terrain, as well as the resources available. The findings from this study can provide valuable insights into the effectiveness of different suppression tactics and can inform decision-making in wildfire management.

The effectiveness of fire suppression tactics depends on various factors, including fleet size and composition. Figure 5.14 provides insight into how changing the fleet composition affects the selection of tactics to be used. When utilizing the firefront tracking tactic, employing a fleet of 8 fully electric tiltrotor aircraft with a medium capacity and a homogeneous configuration (design set 2, colored in red) yields superior results compared to using a mixed fleet with small capacity hybrid multirotor and medium capacity fully electric tiltrotor aircraft (design set 1, colored in orange). The firefront tracking tactic is not effective when used with the chosen mixed fleet in this scenerio. However, adjusting the fleet formation while maintaining the same fleet size could improve the performance of the firefront tracking tactic and make it one of the most successful approaches to combating the fire.

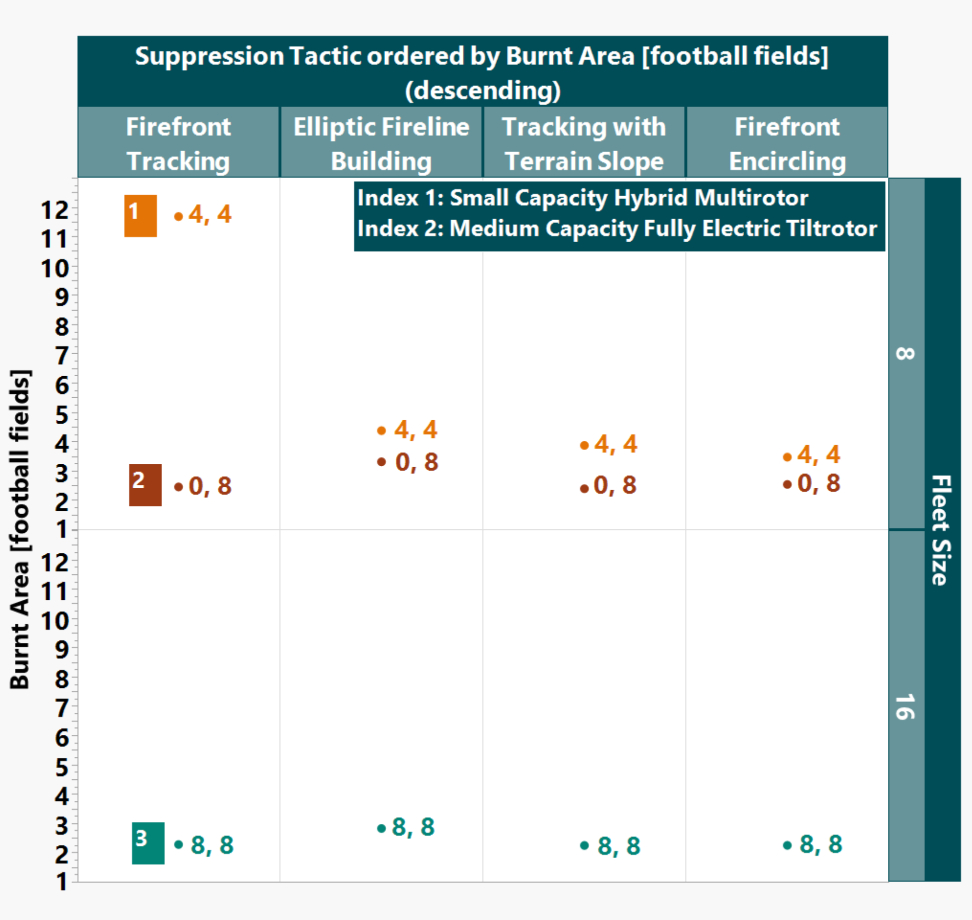
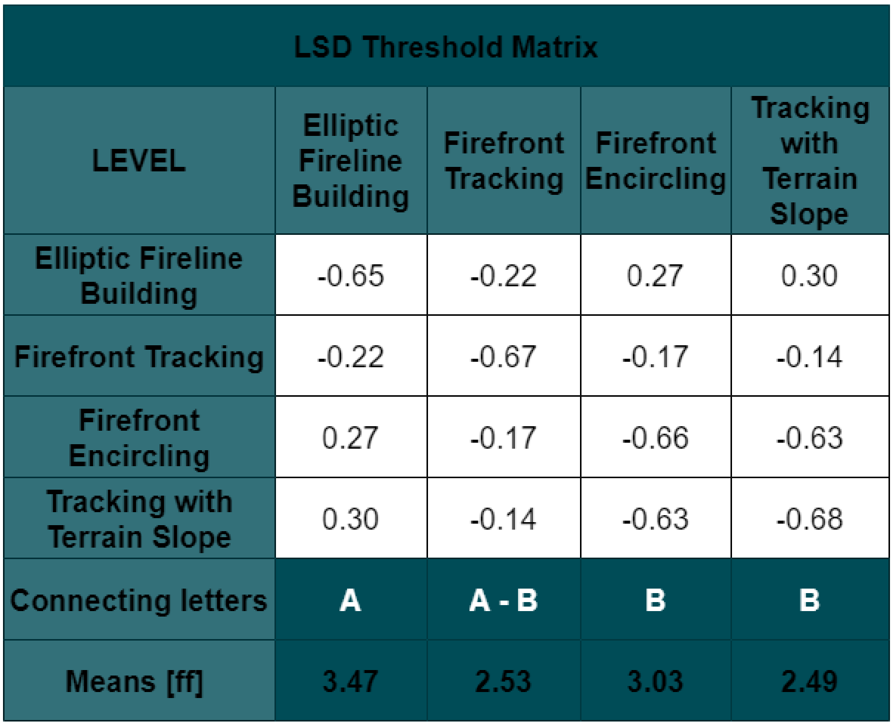


Figure 5.14: The impact of each tactic on the overall burned area, taking into account various fleet sizes and configurations

This finding suggests that enhancing the fleet composition by increasing the payload capacity and flight speed could alter the most effective suppression tactic for combating fires. Additionally, Figure 5.14 illustrates that the significance of selecting a particular tactic diminishes when the fleet size is doubled for a mixed composition fleet (design set 3, colored in green). Therefore, it can be concluded that the performance of fire suppression tactics is not only influenced by the tactics themselves but also by the fleet size and composition. Optimal fleet composition and tactics can be determined by considering all of these factors.

To better understand the effect of each suppression tactic on the total burnt area, a one-way ANOVA analysis was conducted and an LSD test was applied to connect letters and quantify the impact. The results are presented in Table 5.5, where positive values indicate a significant difference in the burnt area means. The connecting letters label the different levels of tactics based on the overall mean values of the total burnt area. The table only includes data from successful missions with fleet sizes of 8 and 12 aircraft. The connecting letters reveal that encircling the fire and suppressing it with slope consideration have similar effects on reducing the total burnt area. As expected, fireline construction differs from other tactics due to the time required to implement the direct suppression method. However, the LSD test values suggest that the impacts of all the tactics are not significantly different from one another. Further research may be needed to fully understand the relative strengths and weaknesses of each tactic and how they interact with different fleet characteristics.

Table 5.5: Suppression tactic correlation based on the means of total area burned



LSD Threshold Matrix				
LEVEL	**Elliptic Fireline Building**	**Firefront Tracking**	**Firefront Encircling**	**Tracking with Terrain Slope**
Elliptic Fireline Building	-0.65	-0.22	0.27	0.30
Firefront Tracking	-0.22	-0.67	-0.17	-0.14
Firefront Encircling	0.27	-0.17	-0.66	-0.63
Tracking with Terrain Slope	0.30	-0.14	-0.63	-0.68
Connecting letters	**A**	**A - B**	**B**	**B**
Means [ff]	**3.47**	**2.53**	**3.03**	**2.49**

5.5 Heterogeneous Fleet Sensitivities

The fleet composition of different aircraft types with varying payload capacities, flight velocities, and powertrain architectures can have a significant impact on the mission success or failure, the rate at which the fire grows, and the total area that burns. To assess the effectiveness of the system as a whole, a measure of effectiveness (MoE) is calculated by combining the total burnt area and the cost of operation. Both responses are normalized based on the maximum values achieved in successful missions, and the averaged summation is subtracted from one. Finding out how fleet composition can improve the MoE, is the main goal of this overall evaluation.

The Measure of Effectiveness is calculated as:

$$MoE = \frac{\text{Burnt Area}}{\text{Max Burnt Area}} + \frac{\text{Operational Cost}}{\text{Max Operational Cost}} \tag{5.1}$$

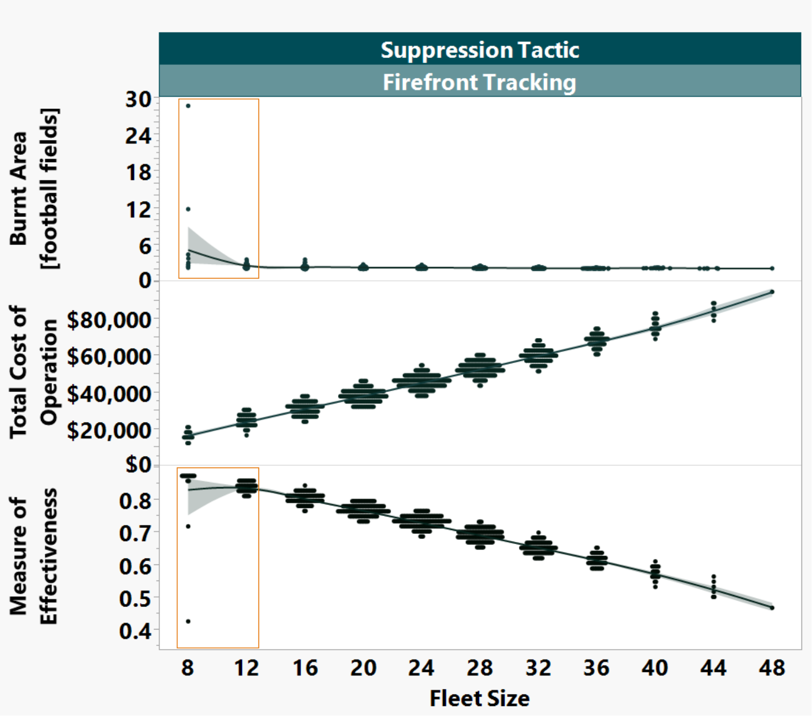


Figure 5.15: Holistic assessment of suppression missions varying both fleet size and composition using a single suppression tactic

Figure 5.15 indicates that MoE is significantly affected by total area burned when aircraft resources are constrained, as indicated by the orange box. However, when the size of the fleet is enlarged, MoE is controlled by the overall operating cost, due to the strong relationship between operating expenses and fleet size and the negligible variations in total burned area.

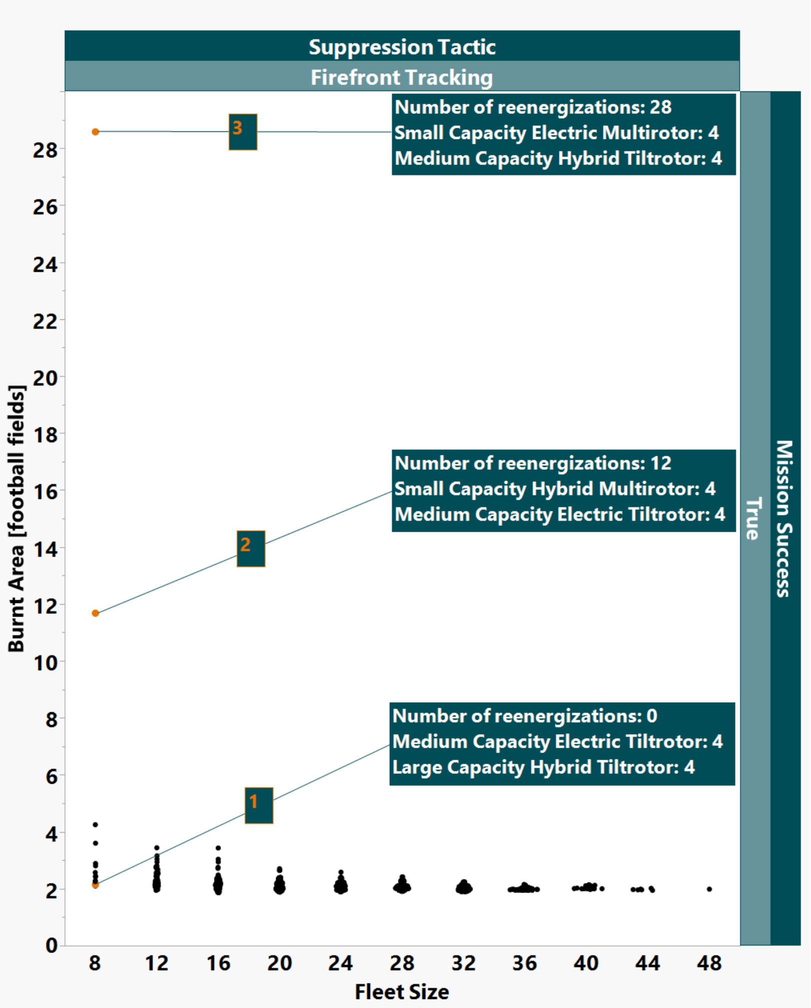


Figure 5.16: Variations in the overall burned area when utilizing various fleet compositions for successful fire suppression missions

The studies conducted on the heterogeneous fleet, using the firefront tracking tactic, have shown that the highest level of dynamicity occurs when there are 8 suppression aerial assets. Figure 5.16 reveals that increasing the payload capacity and flight velocity of half the fleet while keeping the other half constant, can result in an 83% improvement in the total burnt area (as demonstrated by design points 1 and 2). Design Point 3, on the other hand, stands out as an outlier in the dataset, indicating that it is one of the transitional design points that could lead to a shift from mission success to mission failure.

This highlights the significance of carefully selecting the fleet composition, payload capacity, and flight velocity to achieve mission success and minimize the total burnt area. It also emphasizes the importance of considering the impact of each Design Point on the overall performance of the system and identifying potential transition points to avoid mission failure.

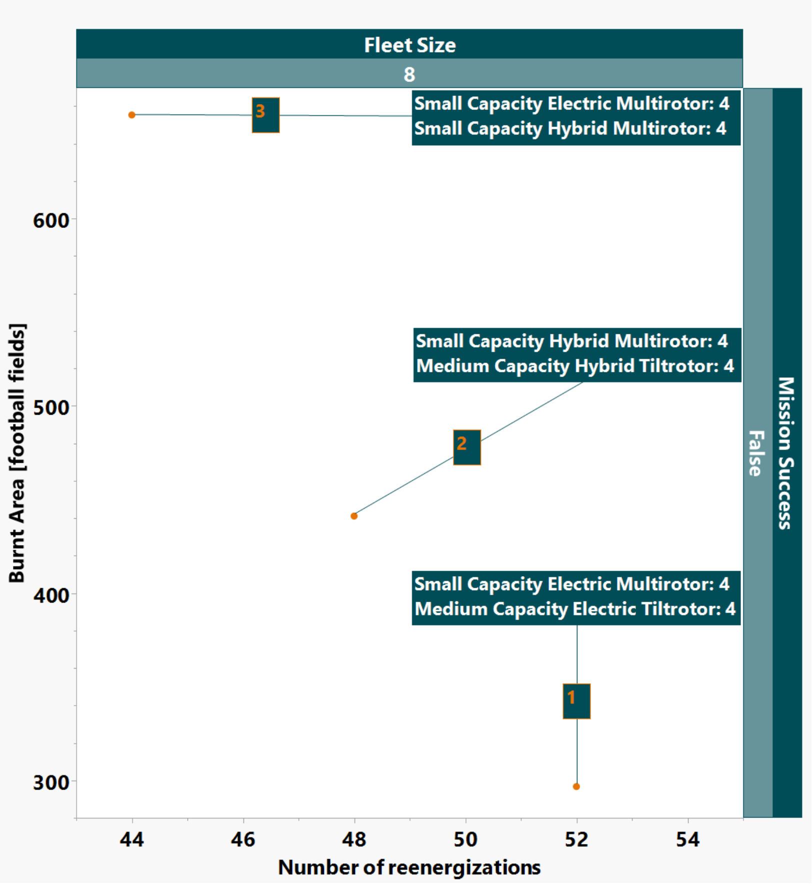


Figure 5.17: Total burned area with respect to different reenergization needs for unsuccessful fire suppression missions

The total burnt area variability observed at a fleet size of eight suggests that this compact fleet size carries a high potential to be the boundary between successful and unsuccessful missions. Hence, further investigations into unsuccessful missions are required to better understand the factors influencing mission outcomes. In Figure 5.16, the outlier Design Point 3 and in Figure 5.17, Design Point 1 illustrate that switching the fleet composition from hybrid to fully electric tiltrotor results in mission failure due to a change in the available energy of each configuration. As explained in Section 4.3, a higher available energy for hybrid tiltrotor results in active fire suppression without delays. Because the success of the mission is heavily reliant on early response time, a fleet that requires re-energization early on makes the fire more challenging to suppress since the fleet returns to suppression after re-energization. Additionally, Figure 5.17 demonstrates that the combination of high payload capacity, flight velocity, and usable energy significantly reduces the fire propagation rate, despite mission failure (see Design Point 2 and 3).

It is essential to understand the root causes of mission failure and identify how they can be addressed to enhance the effectiveness of firefighting strategies. The findings from these investigations provide valuable insights into the selection of fleet composition to maximize firefighting effectiveness. These insights may also be useful in informing the development of new firefighting technologies and methods.

An additional inquiry that needs to be addressed is whether diversifying the fleet enhances the effectiveness of the fire suppression mission. Figure 5.18 indicates that replacing the 8 small and slow fleet with a medium-sized and faster fleet configuration (design points 2 and 3) results not only in successful missions but also in cost-effective operations. In other words, optimizing the fleet composition by varying the fleet size, payload capacity, and flight velocity can lead to better mission outcomes and improved cost efficiency. This is a crucial consideration in the design and deployment of aerial firefighting systems, as it can have a significant impact on the effectiveness and sustainability of such operations.

In spite of the fact that the composition of multirotor and tiltrotor configurations in Design Point 1 results in a heavier fleet, leading to a rise in capital expenses, it is the operating expenses that become more significant when containment cannot be achieved within the given time constraints, as shown in Design Point 3. Figure 5.18 further indicates that modifying half of the fleet from medium to large capacity, as in Design Point 2 to 1, can lead to a 90% reduction in area burned, with only a 6% rise in total cost of operation. It is worth noting that, as expected, the impact of capital expenses has become more pronounced when the mission fails.

Capital expenses are a crucial factor in determining the most effective fleet composi-

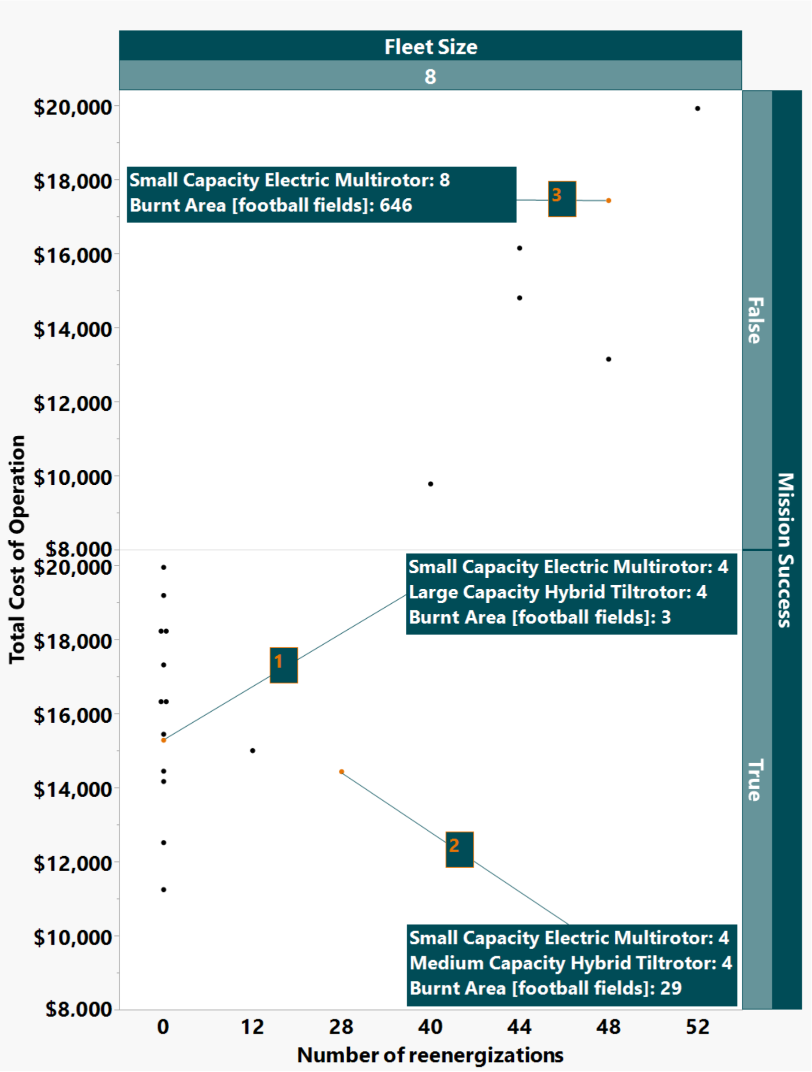


Figure 5.18: The total burned area response varying the fleet from homogeneous to heterogeneous fleet composition with a constant fleet size

tion. Figure 5.19 provides insights into the relationship between the number of aerial assets and the total burnt area, revealing that increasing the number of assets beyond a certain point does not significantly improve the suppression outcomes. Interestingly, the figure also highlights that two specific points, despite resulting in the same burnt area response, have a 40% difference in the total cost of operation. This underscores the importance of carefully assessing the costs associated with each asset and making informed decisions about which to deploy. Reducing the Maximum Takeoff Mass (MTOM) and selecting the proper power architecture can lead to significant improvements in the airframe and battery costs in the case the number of aerial assets is sufficient. This means that it's essential to consider the type of aerial asset and its specifications to determine the optimal composition of the fleet. Moreover, assessing the fire risk value of an aerial asset is crucial in selecting the most effective fleet composition. This assessment enables fire suppression teams to choose assets that are not only cost-effective but also meet the required fire suppression capabilities. By considering both the impact of capital expenses and carefully evaluating the aerial assets based on their fire risk value, it is possible to make informed decisions and optimize the fleet composition for efficient and effective fire suppression operations.

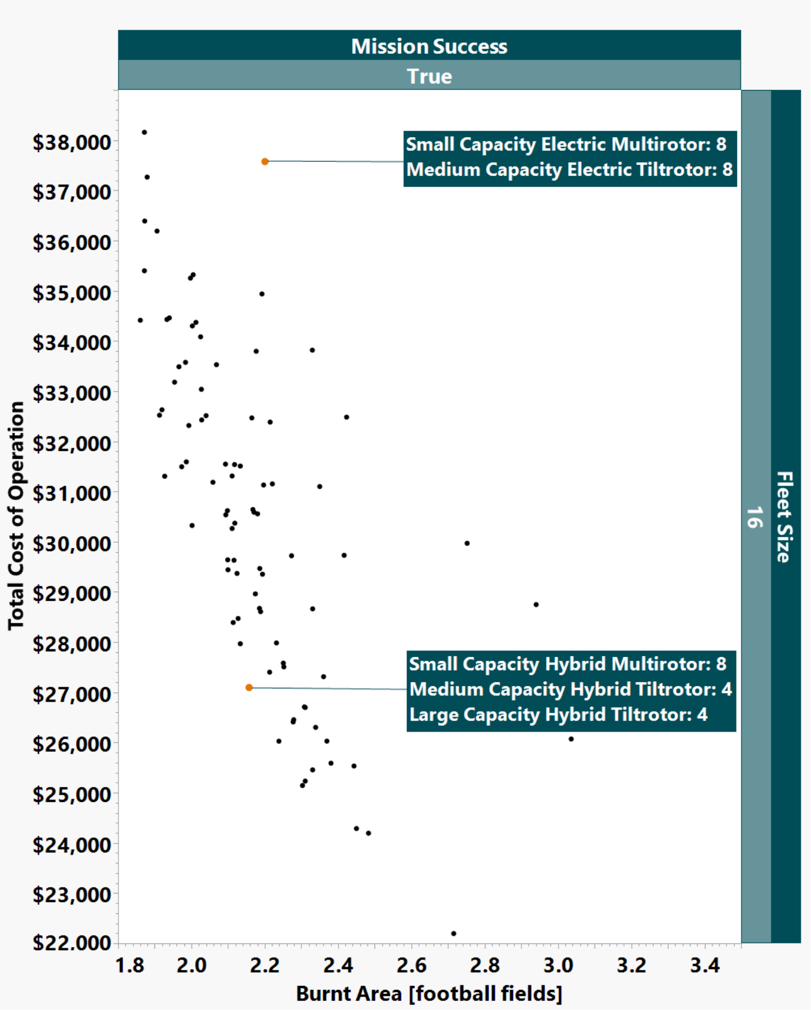


Figure 5.19: Change in the total operational cost according to the fleet composition for similar responses

In order to better understand the impact of heterogeneity on fleet composition, Figure 5.20 presents multiple design points, including both homogeneous and heterogeneous fleet compositions, with respect to the total burnt area and operational expenditures. The first Design Point demonstrated in Figure 5.20 consists of a homogeneous fleet with a large capacity hybrid multirotor configuration. Using this fleet results in the largest total burnt area compared to the other compositions. Despite its high payload capacity of 720 kg, the fact that it operates with low flight velocity (40 m/s) becomes more dominant for compact fleet sizes, leading to a rise in the total burnt area. However, due to its airframe configuration and powertrain architecture, this fleet composition has the lowest total cost of operation, with low airframe and battery costs. Hence, the MoE is still in a similar range (0.87) to that of other fleet compositions.

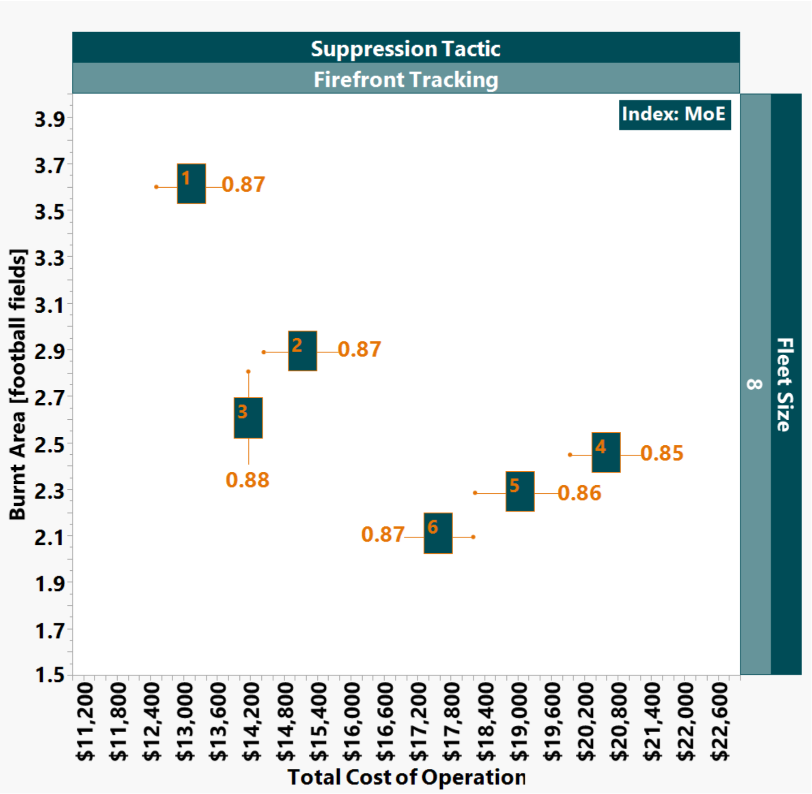


Figure 5.20: Comparing the total area burned and the overall operating cost across various design points for a fleet consisting of eight aircraft

Due to the fact that response of the use of homogeneous fleet with a multirotor configuration is highly influenced by low flight velocity (40 m/s), this fleet is not considered as a suitable candidate for a fair comparison between homogeneous and heterogeneous fleets. Hence, for a more reliable comparison, medium capacity fully electric tiltrotor (Design Point 4) and large capacity hybrid tiltrotor (Design Point 6) are selected.

In Design Point 4, there are 8 fully electric tiltrotor with a medium capacity of 540 kg each, whereas Design Point 5 has a composition of 4 fully electric tiltrotor and 4 medium capacity hybrid tiltrotor. Although there is only a small improvement in the total burnt area from Design Point 5 to 4, the significant impact is observed in the total cost of operation due to the use of a fleet with mixed types of aircraft. Table 4.1 illustrates that the homogeneous fleet has a greater weight compared to the heterogeneous fleet due to modifications in the powertrain architecture. In addition, the homogeneous fleet incurs higher battery costs. As a result, Design Point 4 has the highest operating cost and results in the lowest MoE (0.85) in the comparison. Hence, it appears to be the least effective mission in overall comparison.

Comparing Design Point 6 and Design Point 3, it was found that the former, which comprises of hybrid tiltrotor configurations with larger capacity, has a considerable effect in reducing the burnt area. Conversely, Design Point 3, which is made up of hybrid multirotor with small capacity and hybrid tiltrotor with large capacity configurations, results in a significant reduction in the total cost of operations due to the utilization of lighter aircraft. Moreover, the lower operational cost of the heterogeneous fleet in Design Point 3 also results in the best MoE in the overall comparison.

Finally, a comparison was made between two different heterogeneous fleet compositions, Design Point 2 and Design Point 3. Design Point 2 has a higher total payload capacity considering the overall fleet, but the flight velocity of the fleet becomes more dominant in this mission, resulting in a lower total burnt area compared to Design Point 3. Design Point 3, which uses large-capacity aircraft with faster flight velocity, improves the total burnt area more than Design Point 2. Therefore, using a large payload capacity on the faster composition instead of increasing the overall payload capacity of the whole fleet leads to a relatively more efficient mission.

CHAPTER 6

CONCLUSION AND FUTURE WORK

This study focused on evaluating the effectiveness of a SoS for aerial wildfire suppression by conducting a sensitivity analysis of fleet composition, suppression tactics, and environmental factors. The aim was to understand how different fleet compositions, suppression techniques, and environmental conditions affect the mission success and total burnt area.

The study found that the fleet composition is a critical factor in the success of a wildfire suppression mission. A heterogeneous fleet that considers payload capacity, flight velocity, and endurance can lead to significant reductions in the total burnt area and the cost of operations. The suppression tactic also plays a significant role in mission success and total burnt area. In this study both direct and indirect attack strategies were evaluated, and it was observed that the suppression tactic can have a significant impact on the number of successful missions and the total burnt area. Employing indirect attack tactics may result in a greater burnt area during less challenging missions, but it also increases the chances of containing the fire by partially encircling it.

The study also investigated the environmental factors that affect fire growth, such as wind speed, topology, and temperature. The findings showed that wind direction and topology affect fire growth, and changes in temperature have a significant impact on the total burnt area. It was observed that the fire growth rate increases significantly when high wind speed and high terrain slope are present, as captured by their non-linear impact. Thus, it is essential to consider environmental factors when planning a wildfire suppression strategy.

Lastly, the effect of environmental factors on fire growth was examined. The results showed that the wind speed and topology have a significant impact on fire growth. The direction of the wind plays a crucial role in fire spread, as it can indirectly affect fire growth through its influence on topographic properties. The research also found that the temperature of the environment is a critical factor in fire growth. Any changes in temperature have a considerable effect on the total burnt area. The study further revealed that the interaction between high wind speed and steep terrain slope has a nonlinear effect on fire growth. When these factors are combined, the fire growth rate increases dramatically. The findings highlight the importance of a simulation-based approach in forest fire containment strategies. By understanding the complex interplay of environmental factors affecting fire growth, effective and efficient containment measures can be implemented.

The study also emphasizes the requirement for a simulation-informed approach for wildfire containment and fleet assessment. The available assets, water resources, and base locations around the fire must be considered as well as the payload capacity and flight velocity of the available fleets. The power requirement of the fleet should also be estimated to assign the powertrain architecture precisely. Machine learning algorithms for decision-making can help find an optimal strategy for each fire incident. In addition, creating interconnected firelines and dynamically tracking the fire growth can enhance the containment of the fire.

In summary, the study highlights the importance of considering various factors such as fleet composition, suppression tactics, and environmental conditions for effective wildfire suppression. The findings suggest that a holistic approach that integrates simulation, decision-making algorithms, and environmental data is essential for successful wildfire containment.

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APPENDIX A

AIRCRAFT INFORMATION USED IN THE SIMULATION

A.1 Small Capacity Fully Electric Multirotor Configuration

```
{
"task": "",
"study": "wildfire",
"config": "multirotor",
"powertrain_architecture": "FullElectric1",
"icon": "aeroplane.svg",
"flow_rate": 1.2,
"can_scoop": true,
"mtom": 2394.68,
"payload": 360.0,
"persons_on_board": 1,
"flight_velocity": 40.34,
"battery": "NMC",
"battery_specific_energy": 250.0,
"fuel_cell_specific_power": 0.0,
"powertrain_efficiency": 0.912,
"total_energy": 884254.566,
"battery_energy": 707403.653,
"reserve_energy": 56421.357,
"battery_mass_fraction": 0.41,
"empty_mass_fraction": 0.439,
"taxi_power": [
```

```
26.508,
31.721
],
"hover_power": [
265.082,
317.209
],
"vertical_climb_power": [
283.676,
337.667
],
"transition_power": [
226.326,
258.938
],
"cruise_climb_power": [
285.014,
316.089
],
"cruise_power": [
182.481,
196.152
],
"cruise_descent_power": [
85.037,
80.73
],
"retransition_power": [
226.326,
258.938
],
"vertical_descent_power": [
283.676,
```

```
337.667
],
"reserve_power": [
187.57,
200.667
],
"actual_charger_power": 491.253,
"taxi_time": 30.0,
"transition_time": 20.568,
"retransition_time": 20.568,
"vertical_climb_altitude": 30.48,
"cruise_climb_altitude": 457.2,
"vertical_climb_rate": 1.016,
"vertical_descent_rate": 1.016,
"cruise_climb_rate": 4.572,
"cruise_descent_rate": -4.572
}
```

A.2 Small Capacity Hybrid Multirotor Configuration

```
{
"task": "",
"study": "wildfire",
"config": "multirotor",
"powertrain_architecture": "Serial",
"icon": "aeroplane.svg",
"flow_rate": 1.2,
"can_scoop": true,
"mtom": 1442.741,
"payload": 360.0,
"persons_on_board": 1,
"flight_velocity": 36.164,
```

```
"battery": "NMC",
"battery_specific_energy": 250.0,
"fuel_cell_specific_power": 600.0,
"powertrain_efficiency": 0.533,
"total_energy": 910249.2,
"battery_energy": 866174.4,
"reserve_energy": 68936.777,
"battery_mass_fraction": 0.17,
"empty_mass_fraction": 0.569,
"taxi_power": [
    23.944,
    32.585
],
"hover_power": [
    239.436,
    325.848
],
"vertical_climb_power": [
    257.421,
    346.953
],
"transition_power": [
    216.84,
    271.73
],
"cruise_climb_power": [
    282.485,
    336.651
],
"cruise_power": [
    188.531,
    212.919
],
```

```
"cruise_descent_power": [
    100.291,
    93.881
],
"retransition_power": [
    216.84,
    271.73
],
"vertical_descent_power": [
    257.421,
    346.953
],
"reserve_power": [
    194.245,
    217.613
],
"actual_charger_power": 505.694,
"taxi_time": 30.0,
"transition_time": 18.438,
"retransition_time": 18.438,
"vertical_climb_altitude": 30.48,
"cruise_climb_altitude": 457.2,
"vertical_climb_rate": 1.016,
"vertical_descent_rate": 1.016,
"cruise_climb_rate": 4.572,
"cruise_descent_rate": -4.572
}
```

A.3 Large Capacity Hybrid Multirotor Configuration

```
{
```

```
"task": "",
"study": "wildfire",
"config": "multirotor",
"powertrain_architecture": "Serial",
"icon": "aeroplane.svg",
"flow_rate": 1.2,
"can_scoop": true,
"mtom": 2095.315,
"payload": 720.0,
"persons_on_board": 1,
"flight_velocity": 38.0,
"battery": "NMC",
"battery_specific_energy": 250.0,
"fuel_cell_specific_power": 600.0,
"powertrain_efficiency": 0.533,
"total_energy": 1158498.0,
"battery_energy": 1103090.4,
"reserve_energy": 88007.397,
"battery_mass_fraction": 0.147,
"empty_mass_fraction": 0.5,
"taxi_power": [
    30.467,
    47.228
],
"hover_power": [
    304.666,
    472.283
],
"vertical_climb_power": [
    329.246,
    502.935
],
"transition_power": [
```

```
        279.221,
        384.081
    ],
    "cruise_climb_power": [
        365.427,
        469.029
    ],
    "cruise_power": [
        245.652,
        289.6
    ],
    "cruise_descent_power": [
        134.002,
        116.45
    ],
    "retransition_power": [
        279.221,
        384.081
    ],
    "vertical_descent_power": [
        329.246,
        502.935
    ],
    "reserve_power": [
        253.776,
        295.879
    ],
    "actual_charger_power": 643.61,
    "taxi_time": 30.0,
    "transition_time": 19.375,
    "retransition_time": 19.375,
    "vertical_climb_altitude": 30.48,
    "cruise_climb_altitude": 457.2,
```

```
"vertical_climb_rate": 1.016,
"vertical_descent_rate": 1.016,
"cruise_climb_rate": 4.572,
"cruise_descent_rate": -4.572
}
```

A.4 Medium Capacity Fully Electric Tiltrotor Configuration

```
{
"task": "",
"study": "wildfire_540",
"config": "tiltrotor",
"powertrain_architecture": "FullElectric1",
"icon": "aeroplane.svg",
"flow_rate": 1.2,
"can_scoop": true,
"mtom": 3398.136,
"payload": 540.0,
"persons_on_board": 1,
"flight_velocity": 62.708,
"battery": "NMC",
"battery_specific_energy": 250.0,
"fuel_cell_specific_power": 0.0,
"powertrain_efficiency": 0.912,
"total_energy": 980465.751,
"battery_energy": 784372.601,
"reserve_energy": 41498.092,
"battery_mass_fraction": 0.321,
"empty_mass_fraction": 0.52,
"taxi_power": [
    50.294,
```

```
    62.293
],
"hover_power": [
    502.941,
    622.926
],
"vertical_climb_power": [
    525.732,
    648.768
],
"transition_power": [
    329.085,
    401.696
],
"cruise_climb_power": [
    368.785,
    434.212
],
"cruise_power": [
    192.396,
    225.363
],
"cruise_descent_power": [
    17.648,
    16.733
],
"retransition_power": [
    329.085,
    401.696
],
"vertical_descent_power": [
    525.732,
    648.768
```

```
],
"reserve_power": [
    194.038,
    225.582
],
"actual_charger_power": 544.703,
"taxi_time": 30.0,
"transition_time": 31.972,
"retransition_time": 31.972,
"vertical_climb_altitude": 30.48,
"cruise_climb_altitude": 457.2,
"vertical_climb_rate": 1.016,
"vertical_descent_rate": 1.016,
"cruise_climb_rate": 4.572,
"cruise_descent_rate": -4.572
}
```

A.5 Medium Capacity Hybrid Tiltrotor Configuration

```
{
"task": "",
"study": "wildfire",
"config": "tiltrotor",
"powertrain_architecture": "Serial",
"icon": "aeroplane.svg",
"flow_rate": 1.2,
"can_scoop": true,
"mtom": 2219.44,
"payload": 540.0,
"persons_on_board": 1,
"flight_velocity": 65.088,
```

```
"battery": "NMC",
"battery_specific_energy": 250.0,
"fuel_cell_specific_power": 600.0,
"powertrain_efficiency": 0.533,
"total_energy": 883558.8,
"battery_energy": 840744.0,
"reserve_energy": 49818.163,
"battery_mass_fraction": 0.107,
"empty_mass_fraction": 0.642,
"taxi_power": [
    50.696,
    71.196
],
"hover_power": [
    506.964,
    711.957
],
"vertical_climb_power": [
    530.678,
    740.842
],
"transition_power": [
    347.976,
    470.33
],
"cruise_climb_power": [
    410.696,
    518.253
],
"cruise_power": [
    231.908,
    283.794
],
```

```
"cruise_descent_power": [
    57.446,
    51.421
],
"retransition_power": [
    347.976,
    470.33
],
"vertical_descent_power": [
    530.678,
    740.842
],
"reserve_power": [
    236.234,
    285.88
],
"actual_charger_power": 490.866,
"taxi_time": 30.0,
"transition_time": 33.186,
"retransition_time": 33.186,
"vertical_climb_altitude": 30.48,
"cruise_climb_altitude": 457.2,
"vertical_climb_rate": 1.016,
"vertical_descent_rate": 1.016,
"cruise_climb_rate": 4.572,
"cruise_descent_rate": -4.572
}
```

A.6 Large Capacity Hybrid Tiltrotor Configuration

```
{
"task": "",
"study": "wildfire_720",
"config": "tiltrotor",
"powertrain_architecture": "Serial",
"icon": "aeroplane.svg",
"flow_rate": 1.2,
"can_scoop": true,
"mtom": 2635.275,
"payload": 720.0,
"persons_on_board": 1,
"flight_velocity": 63.62,
"battery": "NMC",
"battery_specific_energy": 250.0,
"fuel_cell_specific_power": 600.0,
"powertrain_efficiency": 0.533,
"total_energy": 1025488.8,
"battery_energy": 976377.6,
"reserve_energy": 57483.041,
"battery_mass_fraction": 0.104,
"empty_mass_fraction": 0.616,
"taxi_power": [
    57.518,
    84.646
],
"hover_power": [
    575.182,
    846.456
],
"vertical_climb_power": [
    602.61,
```

```
    880.752
],
"transition_power": [
    388.492,
    550.757
],
"cruise_climb_power": [
    451.527,
    595.319
],
"cruise_power": [
    247.945,
    317.517
],
"cruise_descent_power": [
    48.672,
    41.021
],
"retransition_power": [
    388.492,
    550.757
],
"vertical_descent_power": [
    602.61,
    880.752
],
"reserve_power": [
    252.254,
    318.823
],
"actual_charger_power": 569.716,
"taxi_time": 30.0,
"transition_time": 32.437,
```

```
"retransition_time": 32.437,
"vertical_climb_altitude": 30.48,
"cruise_climb_altitude": 457.2,
"vertical_climb_rate": 1.016,
"vertical_descent_rate": 1.016,
"cruise_climb_rate": 4.572,
"cruise_descent_rate": -4.572
}
```