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DESIGN OF UNMANNED COMBAT AERIAL VEHICLES AND THEIR INTEGRATION INTO A STRIKE AIRCRAFT GROUP: A SYSTEM OF SYSTEMS APPROACH

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Abstract

Manned-Unmanned teaming with Unmanned Combat Aerial Vehicles (UCAVs) is part of every future fighter concept. However, while much effort is put into design and research, it remains to be seen whether the inclusion of UCAVs yields a better mission outcome. Additionally, there is much uncertainty about the ideal design and the concept of operations. This work aims to change that by addressing all three elements. Using knowledge-based engineering, a set of UCAVs is designed for the suppression and destruction of enemy air defenses. In the frame of a parameter study, physics-based combat simulations are conducted using agent-based modeling. The results are analyzed via the Mission Effectiveness, Survivability, Cost, and Lethality. The performance of formations including UCAVs is compared to formation without UCAVs, employing modern tactics. The results show significant improvements in mission outcomes when UCAVs are deployed as a part of a larger manned formation. Optimum results are achieved with UCAVs featuring low observability and balanced specific excess power. The concept of operations has an effect, too. Two UCAVs carrying four anti-radiation missiles each yield a higher overall survivability than four UCAVs carrying two missiles. The inverse holds for overall lethality. The results provide valuable insights into the optimal design and function of UCAVs and the Manned-Unmanned Teaming concept.

Keywords: Unmanned Combat Aerial Vehicle, Manned-Unmanned Teaming, Aircraft Design, System of Systems Engineering, Agent-Based Modeling

This paper is based on the Master's thesis titled "*Design of Loyal Wingmen and Their Integration into a Strike Aircraft Group - A System of Systems Approach*", by Felix Kuhnert. The thesis work was conducted at Delft University of Technology, in collaboration with the German Aerospace Center, under the supervision of Dr. ir. Roelof Vos (TU Delft), Tobias Dietl (DLR), and Prajwal Shiva Prakasha (DLR). It was successfully defended on August 26th 2024. [1]

1 Introduction

Since the early 1990s, Unmanned Combat Aerial Vehicles (UCAVs) have proven to be indispensable assets in modern warfare. While the first Unmanned Aerial Vehicles (UAVs) were fielded as early as WWI [2], UCAVs like *Predator*, *Reaper*, and *Global Hawk* revolutionized modern warfare. Engineers and military decision-makers had long envisioned UCAVs replacing manned fighter aircraft [3], and technological advancements were pointing in that direction.
However, companies like Lockheed Martin were simultaneously developing a different UCAV concept. They envisioned a system that would "complement, not compete with, existing manned and unmanned systems" and "operate as an element of the future system of systems" [4]. The *Unmanned Tactical Aircraft* concept they described back in 1995 is nowadays known as the *Loyal Wingman* or *Manned-Unmanned Teaming* (MUM-T) with *Remote Carriers* (RCs).

There are multiple advantages of using UCAVs as an element of a larger System of Systems:

- UCAVs can take over dangerous mission elements, such as suppressing enemy air defenses, while the manned command fighter stays at a safe distance, reducing risk to the pilot and airframe.
- UCAVs are not limited by human physical constraints, allowing for harder or more challenging maneuvers, potentially gaining an advantage.
- UCAVs hold the promise of being cheaper than manned aircraft, being potentially smaller, lighter, and designed for shorter service time, reducing costs.

Since the UCAV would be highly networked with the command fighter (CF), the concept also brings additional benefits [5, 6]:

- Using sensor fusion, the UCAV can increase the situational awareness of the command fighter pilot.
- The pilot's workload could be decreased, increasing their effectiveness. For example, the UCAV could address airborne threats so that the pilot of the manned fighter could focus on a different task, such as providing close air support.
- Unlike drones such as *Predator*, a networked UCAV like a Loyal Wingman would be primarily controlled in situ so that the commander would witness the situation directly. This eliminates many technical and logistical difficulties, as well as ethical concerns.

Recognizing these advantages, many countries have initiated the development of such networked UCAV concepts. Notable examples include the XQ-58 *Valkyrie* by Kratos Defense and the MQ-28 *Ghost Bat* from Boeing Australia. Airbus also has a vision for MUM-T as seen in Figure 1.

Figure 1 – Render of a networked UCAV developed by Airbus [1]

While significant efforts have been undertaken to develop these concepts, there are only a few flying prototypes. The few that exist are in the very early stages of testing. As such, there has yet to be a (publicly available) proof of concept. Often, publications focus on the "smaller" aspects of implementing MUM-T. Examples are the control algorithms [7], decision-making [8], or the design of the UCAV itself [9]. However, as others have shown [10, 11], comprehensive System of System (SoS) analyses are necessary to assess the effectiveness of any system interacting with a dynamic environment, as *Emergent Behaviors* play a significant role in the overall performance. In the context of MUM-T, examples of such SoS analyses exist [12–14] but are of low fidelity and have little connection to aircraft design aspects. A publication that stands out was published by Weiß, Haindl, and Gräßel. The group applied agent-based modeling to a combat scenario and concluded that including UCAVs offers a "force multiplication" [15]. However, for a proof of concept of MUM-T, and to gain a deeper understanding of the emergent behaviors, more quantitative data is needed. Whether the inclusion of UCAVs yields a better mission outcome remains to be seen. Also, it has yet to be shown if

[1] www.airbus.com

MUM-T with UCAVs brings the advantages it promises. Lastly, it remains unclear what such a UCAV should look like or how it should be used to yield the listed advantages. This paper aims to close this research gap. Furthermore, an attempt is undertaken to gain insight into the "optimal" design and requirements for a networked UCAV and its Concepts of Operations (CONOPS).
A primary research question is established based on the identified research gap, aiming to provide a proof of concept.

Question 1 *What impact does the inclusion of UCAVs have on a strike aircraft group's effectiveness?*

Secondary research questions connected to the design and use of UCAVs are derived, which are:

Question 2 *What is the optimal design of a networked UCAV for a given combat mission?*

Question 3 *What is the ideal tactic for using networked UCAVs, and what should the fleet composition be?*

To answer these questions, the following steps are conducted:

- A relevant conflict scenario is formulated.
- A combat mission and a range of top level aircraft requirements (TLARs) are derived from the scenario.
- Multiple UCAVs are designed based on the TLARs using the knowledge-based engineering (KBE) tool *VAMPzeroF* [16], developed by the *German Aerospace Center* (DLR).
- Using the mission profile, the scenario is implemented as an agent-based simulation utilizing Battlespace Simulations Inc.'s *Modern Air Combat Environment*[2] (MACE).
- A parameter study is conducted by deploying the varying UCAV designs within changing fleet compositions in combat simulations in MACE.
- Outcomes from the combat simulations are evaluated to determine the effectiveness of the overall System of Systems. Via Mission Effectiveness, Survivability, Cost, and Lethality, varying designs are compared to each other and to established reference cases to conclude on UCAV design, concept of operations (CONOPS), and the concept's validity.

None of the steps listed above is unheard of. However, a combination of the individual steps has not been found in the open literature. Furthermore, this method has not yet been applied to the analysis of the Wingmen concept, Remote Carriers, or Manned-Unmanned Teaming (MUM-T). Thus, this paper presents a novel approach for designing and evaluating novel aircraft configurations operating as an element of a larger and heterogeneous System of Systems.
The outlined steps form a framework, which can be applied to a wide variety of System of System analyses. This framework is shown in Figure 2. Similar frameworks have been proposed previously [17], especially for the use cases of urban air mobility [18–20], and aerial wildfire fighting [21, 22]. It also has been applied to military aircraft design [23, 24].
The steps outlined above also serve as the structure of Section 2, which covers the methodology. The results are presented in Section 3. Section 4 details the conclusions drawn from the discussion of the results and provides answers to the previously established research questions.

2 Methodology

This section shows and explains the methodology. Subsection 2.1 describes the scenario and how it is derived. Subsection 2.2 shows the steps of UCAV design, while Subsection 2.3 provides an insight into the agent-based model and the software used. Subsection 2.4 shows the Design of Experiment. Finally, Subsection 2.5 presents the definition and derivation of the Measures of Effectiveness.

[2] www.bssim.com

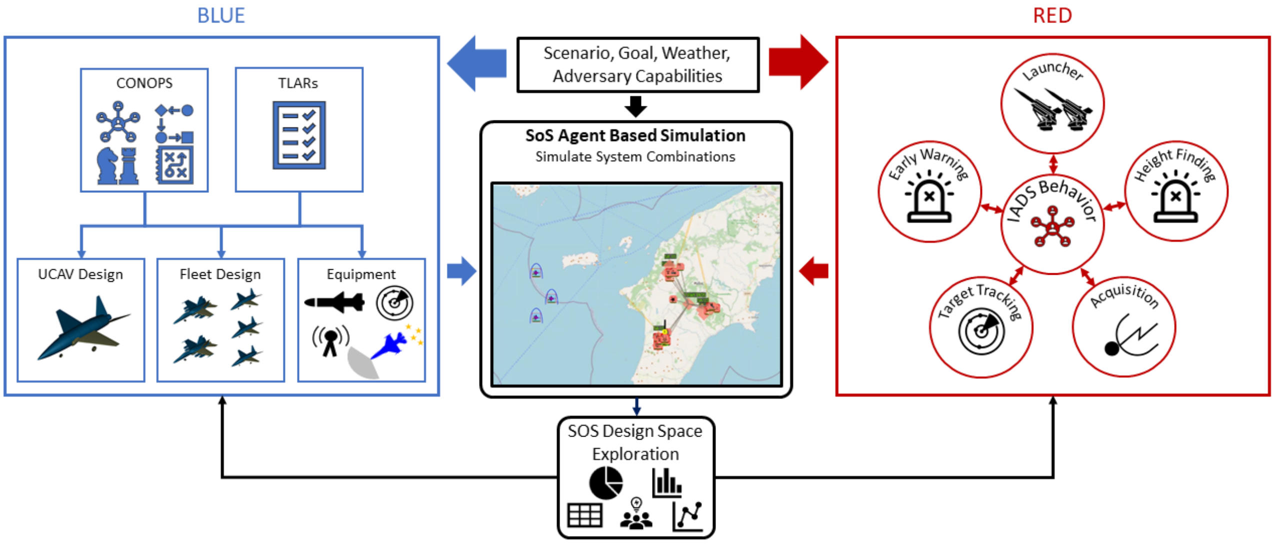


Figure 2 – Depiction of the framework, capturing the individual steps of the process

2.1 Scenario

To assess the potential benefits of UCAV integration, a scenario that challenges the individual aspects addressed by the concept is needed. For example, it needs to involve aspects that are either very dangerous or demanding for the pilot. Furthermore, the resulting mission must allow for a task distribution between the UCAV and the pilot.

When thinking about dangerous missions, the first type that comes to mind is the suppression or destruction of enemy air defenses (SEAD/DEAD). Modern surface-to-air missile systems (SAMs) are so advanced that they can engage very low-flying targets at ranges far over 100 km. The missiles used by a modern SAM system like the Russian S-300 or S-400 fly at hypersonic speeds and, guided by advanced radars, can hit targets the size of a cruise missile[3]. Considering the effectiveness, modern SAMs create exceptionally non-permissive environments, essentially denying air space. Considering this, SEAD and DEAD are vital capabilities of any air force that expose pilots to tremendous risks. As such, SEAD and DEAD could be ideal use cases for UCAVs. Thus, the scenario is constructed around enemy (Red) SAM systems.

Another potential benefit of UCAV integration that is brought up frequently is the task distribution between UCAV and command fighter. To test this, additional tasks have to be available. Air interdiction is a well-suited task where critical ground targets are located and destroyed. Depending on the environment, this is a difficult task for fighter pilots, as they have to discriminate between targets and non-combatants while also being on guard for possible threats. In this case, the UCAV could address potential threats, reducing the workload, while the pilot focuses on the air interdiction. Thus, the scenario also shall provide opportunities for air interdiction elements.

Merging both elements, the following scenario is defined:

Red forces have captured a Blue airfield. As the airfield is a vital strategic asset, Blue is attempting to liberate it. Meanwhile, Red reinforced their troops near the field with heavily armored vehicles and multiple air defense systems: one modern, long-range system consisting of multiple mobile launchers and radar systems, as well as one short-range system. The short-range system is deployed to defend the long-range system of incoming threats, e.g., cruise missiles or ballistic missiles. As a defensive measure, Red forces relocate in irregular intervals. Blue forces are tasked with the destruction of the armored targets, as well as SAMs. Due to the frequent relocating of Red forces, no long-range strikes can be conducted. Furthermore, due to the importance of the airfield, collateral damage must be avoided at all costs, so precision strikes are required.

[3] www.missilethreat.csis.org, retrieved 12-08-2024

2.2 UCAV Design

This subsection is further subdivided into smaller elements. Subsection 2.2.1 explains how the TLARs are derived, while Subsection 2.2.2 goes into the details of the airframe design and *VAMPzeroF*. Subsection 2.2.3 explains how the airframe cost is determined, and Subsection 2.2.4 shows the radar cross-section derivation.

2.2.1 Requirements

Before requirements are derived from the scenario, some independent top-level requirements can be established. They are:

- The UCAV should be interoperable with existing systems of European countries' air forces to facilitate integration and alignment of capabilities.
- The UCAV should have a limited attritability, i.e., it should be reusable. This is imposed to exclude cruise-missile-like aircraft and tactics. While those might be viable solutions in specific scenarios, they do not align with the idea of a heavy Remote Carrier. Thus, they are excluded to reduce the design space.
- The UCAV should be designed with stealth capabilities in mind to follow the design trend of 5^{th} and future 6^{th} generation fighter aircraft.

Unfortunately, the last point is rather difficult to address; to analyze radar cross-sections, higher fidelity tools are needed than currently implemented in *VAMPzeroF*. Also, stealth aircraft design is complex enough to fill multiple dissertations, so it is deemed out of scope for this work. However, an attempt can be made to avoid some pitfalls of stealth design. For example, the configuration is kept as clean as possible by storing the effectors in an internal payload bay, instead of utilizing external hardpoints. Furthermore, right angles are avoided and the air intakes are shaped to conceal the engines.
Additionally, the design space is further limited by requiring that the UCAV should operate like a "normal" fighter aircraft to reduce the need for additional support systems. Some existing concepts include catapult launches, deployments from larger carrier aircraft, or parachute recoveries. These CONOPS are purposefully excluded to limit the scope of this work.
Now, a set of functions and requirements can be derived from the scenario. First of all, to challenge the potential benefit of the networked UCAV of reducing the risk to the pilot, it shall perform the dangerous SEAD/DEAD elements of the mission. Based on this, the UCAV's mission profile can be determined. The military standard MIL-STD 3013B of the U.S. Department of Defense [25] provides a mission profile for a SEAD mission. It can be seen in Figure 3. The standard places the *Penetration/Withdrawal* segment at an altitude of 20,000 ft.

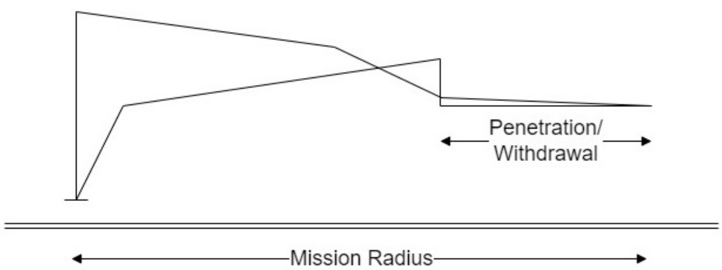


Figure 3 – Mission profile of a SEAD mission, adapted from MIL-STD 3013B[25]

However, trials in MACE show that higher flight altitudes during penetration of the contested airspace resulted in extremely low success rates when facing a modern SAM system. Thus, the profile is altered such that airspace penetration occurs at considerably lower altitudes, comparable to the *Interdiction HI-LO-LO-HI* profile of MIL-STD 3013B. An adapted version, as used for the remainder of this study, can be seen in Figure 4.

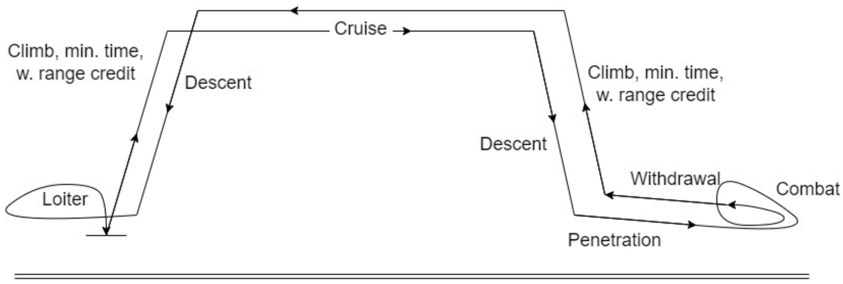


Figure 4 – Adapted *Interdiction HI-LO-LO-HI* profile from MIL-STD 3013B [25]

Having the mission profile, the individual segment lengths of the profile can be fixed. Since the UCAV is supposed to accompany existing aircraft, it shall have a combat radius equal to or larger than the command fighter's combat radius. An aircraft well suited for the air interdiction element of the scenario is the Panavia *Tornado*. For the given flight profile, it has a combat radius of 1390 km[4]. Accordingly, the UCAV shall also have a combat radius of 1390 km. Due to the lack of better values, cruise speed and altitude are fixed at Mach 0.80 and 10,000 m, respectively. Following MIL-STD 3013B, the radius of the *Penetration* and *Withdrawal* segments is fixed at 50 nmi ($\sim$ 90 km). The flight speed during those segments is Mach 0.80. However, based on the initial MACE trials, the flight altitude for airspace penetration provided by MIL-STD 3013B is deemed too high and reduced to 500 ft ($\sim$ 150 m). Climb profile and loiter times are constrained according to the MIL-STD as well.

Following the argument of the UCAV operating with and under the same conditions as the command fighter, requirements for takeoff and landing field length can also be defined. Some of the most constraining requirements can be found in SAAB's designs. Many of their designs (*Draken*, *Viggen*, *Gripen*) possess Short Takeoff and Landing (STOL) capabilities. This capability is rooted in the requirement to operate from improvised runways, which are repurposed public roads[5]. This distributed airfield concept, known as *Bas 90*, includes multiple tiers of runways. The shortest runway version, the *kortbanor*, has a length of 800 m[6]. This length is taken as takeoff and landing field length requirement for the UCAV.

Attempting to harness the lack of limitation due to the human physique, requirements for instantaneous and sustained load factors are imposed. To investigate the sensitivity of the Measures of Effectiveness (MoEs) to those parameters, they are not fixed as single values but as a range. For the instantaneous load factor, values of 6, 8, 10, 12, and 14 g are selected. The sustained load factor is varied simultaneously with values of 3, 4, 5, 6, and 7 g. Varying the sustained load factor also addresses the commonly used requirement for specific excess power (SEP). The specified load factors are to be achieved during the combat phase, i.e. at an altitude of 500 ft and a flight speed of Mach 0.80.

Another driving requirement is the UCAV's payload configuration. Given that the UCAV shall perform the SEAD role, its loadout shall consist of modern anti-radiation missiles (ARMs). One could imagine varying combinations of the number of UCAVs in formation and the number of missiles per UCAV. Hence, two payload configurations are considered (2 and 4 ARMs each). Additionally, the UCAV shall allow for a 100 kg electronic payload (e.g., jammers, sensor packages, cameras).

The quantifiable requirements are summarized in Table 1. Requirements connected to MIL-STD 3013B are converted to SI units and rounded for consistency. The implemented methods use exact values.

2.2.2 Airframe Design

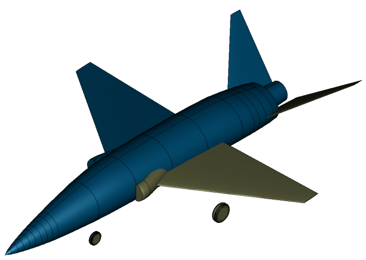
Following the establishment of requirements, one can continue with the aircraft design. The KBE tool *VAMPzeroF* [16] is used to design the UCAV. *VAMPzeroF* is a Python tool that allows for the rapid initiation of military aircraft designs. Its knowledge base is built upon methods from Roskam

[4]www.panavia.de, retrieved 25-07-2024
[5]www.saab.com, retrieved 25-07-2024
[6]www.forsvarsmakten.se, retrieved 25-07-2024

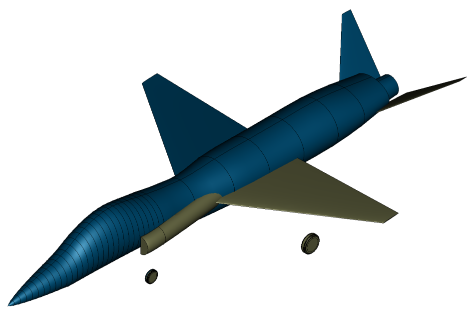
Table 1 – List of UCAV requirements

Requirement	Value
Combat Radius (HI-LO-LO-HI) [km]	1390
Cruise Altitude [m]	10,000
Cruise Mach Number [-]	0.80
Penetration Radius [km]	90
Penetration Flight Altitude [m]	150
Penetration Mach Number [-]	0.80
Reserve fuel (%)	5
Loiter time (min)	20
Payload	2/4 Anti-Radiation Missiles + 100 kg Electronic Payload
Sustained Load Factor [-]	[3, 4, 5, 6, 7]
Instantaneous Load Factor [-]	[6, 8, 10, 12, 14]

[26], Raymer [27], Torenbeek [28], and Airbus [29]. Methods for novel aircraft configurations can be added easily. The tool is "pre-calibrated" to start the design process using an existing aircraft. For a previous publication [23], the pre-calibration was done by generating a model of a well proliferated fighter/attack aircraft in air interdiction configuration, using reference data from Jane's [30] and declassified NATOPS manuals.
Knowing that *VAMPzeroF* can reliably create a conventional fighter aircraft, the knowledge base is adjusted for UCAV design. Following Gundlach, "the most obvious difference between an unmanned aircraft and a manned aircraft is the lack of a pilot or other flight crew" [5]. A logical conclusion is that all crew-related subsystems and pieces of inventory can be excluded from the design, but the rest of the design steps remain valid. Specifically, the weight groups for furnishing (e.g., ejection seats, armrests), oxygen supply, and the engine firewall are removed. Further following Gundlach's design methods, the weight knowledge base of all relevant systems is modified.
After implementing the new knowledge base, the UCAV designs can be generated. An exemplary UCAV (dubbed *Atreus*) can be seen in Figure 5a. The UCAV shown is designed for a sustained load factor of 7 g (14 g instantaneous) while carrying 2 ARMs in an internal payload bay. The afterburning turbofan is placed centrally inside the fuselage, with S-ducts concealing the fan blades. A V-tail design is chosen to avoid right angles of the tailplanes. It is also the lightest configuration compared to a conventional, twin-vertical, and canted-twin-vertical (*Hornet*-like) tail. Some key performance parameters and dimensions are listed in Table 2.



(a) *Atreus*, designed for a sustained load factor of 7 g, carrying 2 ARMs in an internal payload bay



(b) Single-Seater with otherwise identical requirements as the UCAV

Figure 5 – Comparison of UCAV and manned fighter

Unfortunately, it is not easy to validate the UCAV design. Little to nothing is known about existing networked UCAV concepts. According to Jane's [31], the Kronshtadt *Grom* (a comparable Russian Concept) has a Maximum Takeoff Mass of 7000 kg, with a slightly heavier payload (1300 kg). How-

Table 2 – Key metrics of the exemplary UCAV. V_{max} is the maximum flight speed at an altitude of 500 ft. Wing loading (W/S) and thrust-to-weight ratio (T/W) are given for MTOM.

Parameter	Symbol	Unit	Value
Maximum Takeoff Mass	MTOM	[kg]	9950
Operating Empty Mass	OEM	[kg]	5860
Wing Loading	W/S	[kg/m^2]	485
Thrust-to-Weight Ratio, dry	T/W_{dry}	[-]	0.43
Thrust-to-Weight Ratio, wet	T/W_{wet}	[-]	0.64
Maximum Speed at Sea Level	V_{max}	[m/s]	386
Service Ceiling	$h_{ceiling}$	[m]	22,000
Lenght	l	[m]	11.0
Wing Span	b	[m]	9.6
Payload Mass	$m_{payload}$	[kg]	1040

ever, according to Jane's, *Grom* 's mission radius is considerably smaller. Table 3 compares *Grom* to two different UCAV designs. One UCAV is designed for a sustained load factor of 7 g, while the other is designed for 3 g. As can be seen, the 3 g UCAV is almost 1100 kg heavier than *Grom* while carrying a smaller payload. However, the combat range is over 1000 km longer. The dimensions of the wing span and overall length are comparable. Thus, the implemented knowledge base provides a good early estimate for the design of a UCAV.

Table 3 – Comparison between *Grom* and two designed UCAVs. One UCAV is designed for a sustained load factor of 7 g, while the other one is designed for 3 g.

Parameter	Symbol	Unit	Atreus 7g	Atreus 3g	*Grom* [31]
Maximum Takeoff Mass	MTOM	[kg]	9950	8090	7000
Operating Empty Mass	OEM	[kg]	5860	4460	?
Range	R	[km]	2780	2780	1600
Internal Payload Mass	$m_{payload,int}$	[kg]	1040	1040	1300
Maximum Mach Number	M_{max}	[-]	1.15	1.0	0.8
Lenght	l	[m]	13.8	10.5	11.0
Wing Span	b	[m]	10.0	7.9	9.6

Using the previously existing knowledge base of *VAMPzeroF*, a comparison can be made to a manned aircraft (single seat) with otherwise identical requirements. The resulting design can be seen in Figure 5b. As can be seen, the resulting aircraft is significantly longer than the UCAV. This is due to the additional volume required by the cockpit. While the UCAV's front section of the fuselage can be utilized for the internal weapons bay, it had to be shifted behind the cockpit of the manned fighter.

Compared to a manned fighter, one can also look at the often-stated advantage: a UCAV would be lighter than a comparable manned aircraft. The manned fighter has an MTOM of 10950 kg, with an OEM of 6220 kg. So, indeed, assuming identical requirements, the manned fighter is about *10% heavier* than a comparable UCAV. It should be remembered that this result does not account for potential weight savings because of increased attritability/reduced service life. Thus, the differences could be even more significant as fatigue and wear become less problematic. Also, with increased attritability, one could argue that no redundancy is needed for the avionics and electrical subsystems, further reducing the weight.

2.2.3 Airframe Cost

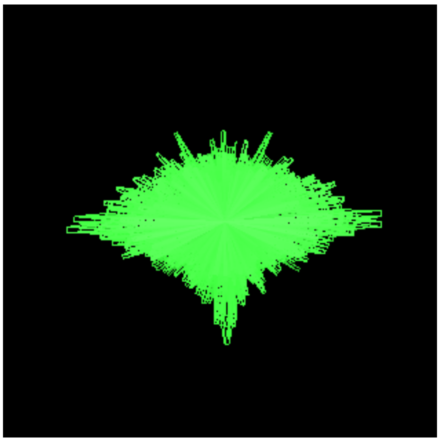
The airframe cost is determined by following a publication by the RAND corporation [32]. The authors conducted an exhaustive study of jet-powered fighter jets, ranging from F-4 *Phantom*, over F-111

Aardvark, to F-14 *Tomcat* and F-18 *Hornet*. The result was a collection of cost estimation relations (CERs) that account for many parameters, like complexity and production methods. This paper uses their CER for the program cost, as given in Equation 1, where $PROG_{100}$ is the program cost for 100 aircraft, given in 1986 USD. AUW is the Aircraft Unit Weight in lb, so the OEM. The OEM is converted into lb, and the program cost is inflation-adjusted to 2023 USD. Finally, the cost is broken down to the individual airframe. Using this relation, the exemplary UCAV has a unit cost of 32,110,000 USD.

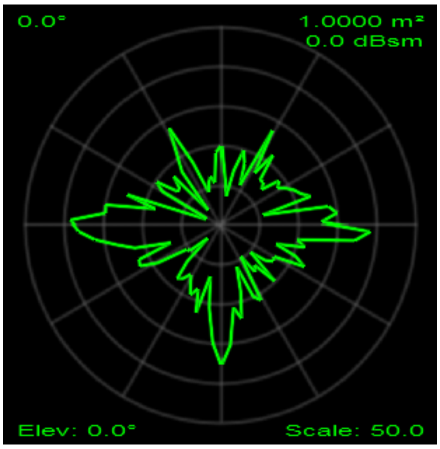
$$PROG_{100} = 550AUW^{0.812} \tag{1}$$

2.2.4 Radar Cross Section

As mentioned before, *VAMPzeroF* cannot generate radar cross-sections of aircraft models. However, MACE provides some pre-defined and three-dimensional cross-sections. The cross-sections consider the airframe geometry and depend on the radar band (four widely used frequencies are accounted for). For example, the MACE RCS of the F-18[7] is shown in Figure 6. Figure 6a shows a three-dimensional view of the RCS, while Figure 6b shows a two-dimensional "slice". While the F-18 looks considerably different than the designed UCAV, it is the available aircraft that comes closest. Thus, the UCAV RCS is modeled based on the MACE F-18 RCS. However, it is modified: to depict the impact of UCAV size and shape, the RCS is scaled based on the wing surface area. It must be noted that this is far from an accurate physical relation. An aircraft that is twice as large *does* have a larger mean RCS, but it will not be twice as large[8]. Unfortunately, this trend can only be adequately captured using detailed RCS analysis, which is deemed out of scope. Thus, the approximation via the aircraft scale is a stop-gap solution to implement a malus caused by UCAV size. While this method provides results that are far from accurate, previously, it was applied by other authors, too [11].



(a) Three-dimensional RCS of the F/A-18C in MACE. Visibly, the RCS is significantly higher when viewing the aircraft from below.



(b) Two-dimensional section of the MACE F-18 RCS. Vertical "slice" of three-dimensional RCS.

Figure 6 – RCS of the F/A-18C in MACE

In addition to the scaling, an attempt is made to capture the effects of radar-absorbing material (RAM) and stealth design. Additional UCAVs are generated featuring attenuated cross-sections by a factor of 10, 20, 30, and 40 dBm^2. An attenuation up to 15 dBm^2 can be achieved by applying RAM coatings [33]. Beyond that, shape modification would be necessary.
The MACE F-18 has an all-band average cross-section of 47 m^2. The exemplary UCAV RCS is reduced to 26 m^2 due to the scaling. Applying the RAM attenuation, the UCAV RCS reduces to 2.6, 0.26, 0.026, and 0.0026 m^2, respectively.

[7]The RCS is purely based on publicly available information

[8]While RCS is commonly measured in m^2, it is unrelated to the physical surface area of the object. An RCS of 1m^2 is equivalent to the RCS of a perfectly reflecting sphere with a cross-sectional area of 1m^2, hence the name.

2.3 Agent-Based Modeling

Again, this subsection is split into smaller elements. Subsection 2.3.1 explains the features and functions of MACE, while Subsection 2.3.2 explains how the scenario and DoE are implemented in MACE.

2.3.1 MACE

By now, the software *Modern Air Combat Environment* (MACE) has been mentioned multiple times throughout the paper. MACE is a real-time and physics-based simulation tool capable of simulating many-on-many combat scenarios. MACE is used by the Army, Navy, Air Force, and National Guard of the United States of America. An export (and thus limited) version is used by customers in Europe, Southeast Asia, and Australia. Initially intended as a mission rehearsal tool for Joint Terminal Attack Controllers (JTACs), it offers high-fidelity combat simulation capabilities. The tool takes aerodynamics, energy states, and propagation of electromagnetic waves of a large spectrum into account. The physics engine captures the entire wave spectrum between 30 MHz (VHF radio communication) and 3000 THz (highest end of UV-C). Effects like attenuation due to weather conditions, diffraction due to terrain features, and jamming are modeled.
The three-dimensional battle space is based on a Geographic Information System (GIS) core. Maps are implemented via external sources like OpenStreetMap or custom data. Topographic maps can be added via Digital Terrain Elevation Data (DTED) or data from the Shuttle Radar Topography Mission (SRTM). The combination allows the simulation of scenarios worldwide.
MACE has an extensive database of entities, ranging from heat-seeking missiles and stealth fighters to ships, submarines, intercontinental ballistic missiles (ICBMs), and satellites. All entities are modeled as individual agents that obey the same physics model and can interact with the world. For example, the infrared signature of a fighter engine plume can be detected by the seeker head of a heat-seeking missile, which itself is implemented via geometric, aerodynamic, and performance data. The seeker can guide the missile to the target using realistically implemented controllers. At the same time, the missile can be detected by SAM systems, which can attempt to intercept the missile with their weapon systems.[34]
MACE is especially interesting because the user can supply entity models via a set of .xml files. The files contain key geometric and performance data and tabulated values for aerodynamics, fuel consumption, and specific excess power (SEP). Also, radar cross-sections can be supplied via the files. A tool like *VAMPzeroF* can generate these files, which provides a unique synergy between the tools. Furthermore, MACE contains a script editor, enabling the implementation of custom agent behaviors. The combination of features allows for deterministic and physics-based modeling and evaluation of novel aircraft configurations in complex environments and scenarios.

2.3.2 Scenario in MACE

Now that the scenario is known and the UCAVs are designed, the scenario can be fully implemented into MACE. First, one has to decide on a location for the scenario. A neutral area is chosen to prevent associations with current or past conflicts. The location of the chosen region is ideally suited for the scenario, as there are two primary strategic interests in the direct neighborhood: a large in-land port with sea access and a large production plant with accompanying airfield. The surrounding area is urban, with green patches, small hills (50 m), and open waters.
Entities on the map are divided into three teams: Blue (friendly), Red (enemy), and Green (uninvolved). Green entities are commonly added to simulate clutter and add target identification elements. However, no Green entities are placed in the mission area in this case.

Red Team The Red team comprises three main groups: SAM 1, SAM 2, and armor elements. SAM 1 is the main target and opponent to the Blue fighters. It is a distributed Integrated Air Defense System (IADS). It is modeled after systems like the Russian SA-20A *Gargoyle*, based on publicly available data. It is chosen because it represents a modern, highly capable, and widely proliferated system. Countries with SA-20A systems in service include Ukraine, China, Greece, and Iran. The system is made up of multiple truck-based constituents, which are:

- Early warning radar. The rotating early warning radar periodically scans the entire sky. It is used for target acquisition, detecting and identifying any flying object.
- Additional early warning radar. It is specialized to detect low-flying targets with a more focused beam.
- Fire control radar (FCR). The FCR tracks and illuminates the target for missile guidance.
- Command vehicle (CP). The CP coordinates the action of the IADS. It handles target tracks, assigns targets, and gives the order to engage.
- Four transporter erector launcher (TEL). The TELs are mobile launcher platforms carrying four missiles each. The missiles reach hypersonic speeds and have a range of 150 km. The missile detects the FCR echo coming from the target. This information is sent back to the FCR, which calculates the missile's flight path. The flight path information is then returned to the missile to guide it to the target.

Modern radars, networking, and a distributed setup make SAM 1 a formidable foe. The behavior of SAM 1 is relatively simple. Target tracks coming from the radar systems are analyzed. If a target is identified as hostile, the track confidence is high, and the target is within range, the CP assigns the target to a launcher and gives the order to engage. Following that, the missile is guided to the target as described previously. Based on a given salvo interval, the CP can decide to launch additional missiles at a given target. The system can engage up to 100 targets simultaneously. Targets can be reassigned mid-flight. Because of this, later missiles can change their course if a previous missile hit the common target.

SAM 2 is a standalone system modeled after systems like the Russian SA-15 *Gauntlet*. SAM 2 combines target acquisition, tracking, and guidance radar into one tracked vehicle, including the launcher. The system's range is shorter than the range of SAM 1, and the radar systems are not as effective. The missiles are slower but highly maneuverable so the system can engage fast targets at significantly shorter ranges. Due to this, systems like SAM 2 are often used together with long-range systems. It is a short-range defense system that can intercept projectiles like cruise or anti-radiation missiles. The combination of the two types of systems increases the scenario difficulty exponentially. The behavior of SAM 2 is very similar to SAM 1. However, unlike SAM 1, SAM 2 *always* will launch multiple missiles at one target to increase the hit probability against projectiles.

Lastly, the armor elements are realized as three tanks spread throughout the area. Because tanks are hard to destroy, specialized effectors are needed. The tanks do not have a behavior and are static targets.

The distribution of the Red team is shown in Figure 7.

Figure 7 – Distribution of Red team in the mission area, as implemented in MACE

Blue Team To establish a baseline for comparison and to show the effects of differing UCAV CONOPS, multiple Blue teams are needed. The first Blue team consists of *two* fighter/attacker aircraft (*Blue-1* and *Blue-2*), based on a previously generated model [23]. This team serves as a reference, that all other teams will be compared to.

The Blue fighters of the reference case are equipped with two anti-radiation (ARM) and two air-to-ground missiles (AGM). The anti-radiation missiles' sole purpose is the destruction of ground-based radars. The ARMs detect and home onto radar emitters. If the radar emitter is switched off, the missile continues flying to the target's last known position, where it switches on its own radar. Using a library of known targets, it identifies SAM systems and uses the radar for terminal guidance. The anti-radiation missiles are fast and have a long range.

The used AGMs are made for roles like close air support (CAS). They are designed to destroy armored targets like tanks. Unlike ARMs, they are guided by an infrared sensor that identifies objects via their heat signature. Due to the sensor, the missile range is limited compared to the ARM. The missile is also significantly slower. While it is designed to be used against armored targets, it can also be used against SAM systems.

Additionally, the Blue fighters carry countermeasures. One type of countermeasure is the so-called chaff. Chaff consists of long strands of wire or metal-coated polymer. Aircraft can eject chaff to create large reflective clouds with a substantial radar echo. This is done as a defensive measure to break the radar lock and create clutter. Depending on the radar, chaff can be highly effective. Furthermore, the fighters are equipped with low-power jammer systems. The onboard systems detect hostile radars, which makes it possible to emit signals at the same frequency to jam the original emitter. Using chaff and jammer together can significantly increase the chances of survival against a SAM system. Hence, the use is standard practice.

With the given loadout, the Blue aircraft enter the mission area from the southwest. They form into line-abreast formation with a spacing of 2000 ft. With a flight speed of 530 kts ($\sim$ Mach 0.8), they fly along waypoints towards the scenario area while following the terrain contours at 500 ft above ground. When reaching the last waypoint, the fighters turn around and return to the starting point. Apart from that, the behavior is implemented using simple triggers and scripts. A simplified logic diagram of the described behavior can be seen in Figure 17.

When an aircraft detects a ground target within a radius of 6 nmi, it engages it, provided the target is not already designated to another aircraft. This trigger is simple yet effective in simulating visual identification and target designation in a formation. The distance of 6 nmi is significantly lower than the maximum viewing distance at an altitude of 500 ft. However, the pilot would not be able to positively identify a target. The distance of 6 nmi was chosen based on trials in MACE and in-person trials in a simulator. When a ground target is identified, the fighter climbs to an altitude of 5000 ft and engages the target with an AGM. The climb is implemented to give the missile more energy and to help the missile achieve a lock.

The second trigger is utilized to implement the SEAD/DEAD behavior. When the radar warning receiver (RWR) detects a radar of a hostile SAM site, all aircraft immediately turn toward the target and accelerate with military power. When in engagement range for the ARMs, the fighters again climb to an altitude of 5000 ft and launch an ARM. If no ARM is available because they have been launched already, the aircraft switches to AGMs, significantly reducing the standoff range.

The behavior of missile evasion is realized using simple triggers, too. If the aircraft is in a range of 7 nmi to a Red missile while being tracked by a Red radar, the aircraft accelerates using military power and drops down to the altitude of 500 ft, if not already. Then, chaff is deployed, and the aircraft breaks 120 degrees to either side. If the lock is not broken and the missile comes to within 3 nmi, the aircraft again deploys chaff and breaks 120 degrees in the opposite direction. This behavior is shown in Figure 8. As before, the trigger distances are based on initial trials. The distances are chosen so that the aircraft has a chance to evade the missile while also being feasible. Due to the burning motor and the plume, the missile is visible over large distances. However, if the aircraft flies the evasive maneuver too early, the missile only needs a minor angular course correction due to the larger distance. If the evasive maneuver is flown too late, the change of angular position of the aircraft relative to the missile again is too small to be effective.

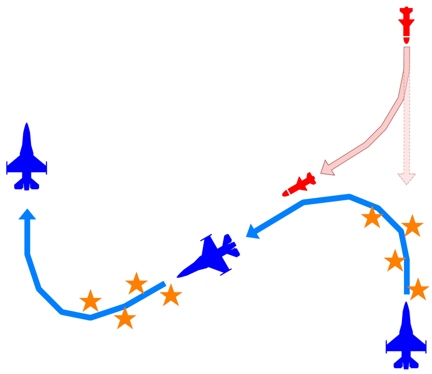


Figure 8 – Evasive maneuver of a Blue fighter. Countermeasures are depicted by stars. [23]

When the fighters have used up all their effectors, they again accelerate and leave the mission area to the west. The same behavior is triggered when the mission time elapsed reaches 15 minutes. This measure was implemented to enforce a definitive end to the mission consistently. When crossing a border far outside of the reach of SAM 1, the aircraft are forced into the "killed" state (the "death" is removed from the statistic). When all Blue *or* all Red units are destroyed, the mission restarts.
SEAD strategies have developed beyond this relatively simple *Wild Weasel* tactic. For example, aircraft began carrying *decoys* that could fly under their own power and mimic the radar signature and behavior of the actual fighter. Also, jammer technology was developed extensively, cumulating in aircraft for electronic warfare, like the EA-18G *Growler*. Modern jammers can emit high-power signals while also being able to point the emitter at the target using beam forming. This capability allows the creation of *jammer corridors* in which friendly aircraft are at a reduced risk. Both strategies are implemented as additional reference cases to evaluate how the use of networked UCAVs holds up against more modern tactics.
Reference case 2 implements the use of Tactical Air Launched Decoys (TALDs). TALDs essentially are small cruise missiles without a warhead and have a very limited range. However, they have engines and can maneuver to simulate additional targets. In this reference case, *Blue-1* carries one AGM less, but instead, it has six TALDs mounted to the hardpoint. The behavior is modified such that upon first missile evasion, the TALDs are deployed together with the chaff. The TALDs organize as a swarm and fly toward the hostile SAM site. The swarm is spatially distributed (also in altitude) to increase the chance of survival of the individual decoys. If the decoys reach the target, they start circling the SAM site to create further distraction. By implementing this tactic, one can simultaneously evaluate *wave tactics*, where SAMs are overwhelmed with targets.
Reference case 3 is based on the first case but includes an additional aircraft for Electronic Warfare (EW). The EW aircraft leads the strike group in echelon formation. Upon contact with hostile radars, it enables the jammer pods in designated radar bands to create a jammer corridor. Additionally, when evading missiles for the first time, the EW aircraft deploys a towed decoy. It functions similarly to a TALD but is attached to the aircraft by a long wire, so it is being towed. Apart from that, the EW aircraft's behavior is identical to *Blue-1* and *Blue-2*. The EW aircraft also carries two ARMs to engage the SAM sites.
Lastly, the UCAV can be implemented into the MACE scenario. To gain some initial results separate from the parameter study, two UCAV cases are implemented: one where each manned fighter receives one UCAV as a wingman and another case where each fighter receives two. The UCAV behavior is almost identical to the initially described behavior of the manned fighter. The only difference is that they do not move independently. At the beginning of the mission, they form up with their command fighter. When they detect a hostile radar, they break formation and engage. Meanwhile, the command fighters retreat to a loiter point at a safe distance. If the UCAVs successfully destroy the SAMs, the fighters return, and the UCAVs return to formation. If the UCAVs run out of effectors, they act as decoys while the fighters return and engage. If the UCAVs are destroyed, the fighters also return and engage. The exemplary UCAV from Subsection 2.2.2 is utilized (7 g sustained turns, 2 internal ARMs, 10 dB RCS attenuation).

2.4 Design of Experiment

As mentioned, this study aims to conduct a parameter study that varies TLARs and UCAV CONOPS to gain insights into the vast design space. It is now time to examine the Design of Experiment (DoE) for this parameter study. The previously established variables are once more summarized in Table 4. The experiment is conducted as a full factorial study, so *every* combination of parameters is tested. With the variables listed in Table 4, this results in 100 separate simulation cases. For the 100 cases, the exemplary UCAVs are manually replaced by the 50 distinct UCAV designs.

Table 4 – Summary of DoE variables

Variables	Values
Number of UCAVs [-]	[2, 4]
Number of ARMs per UCAV [-]	[2, 4]
UCAV Sustained Load Factor [g]	[3, 4, 5, 6, 7]
UCAV RCS Attenuation [dB]	[0, 10, 20, 30, 40]

2.5 Measures of Effectiveness

As a last step, before looking at the results, one has to determine how to evaluate and express them. In the case of a System of Systems, one commonly uses *Measures of Effectiveness* (MoEs). Many things can hold as MoE. For example, one could focus on the survival rate of the command fighter. However, only looking at a single aspect rarely shows the full result. Thus, the parameter *Mission Effectiveness* is established for this study to capture the overall picture. The mission effectiveness is determined using a so-called *Quality Integral*, as provided in Equation 2. J is the mission effectiveness. The value j presents a lower-level measure, like survival rate, while σ designates a + or -, based on whether j is a positive measure/a benefit or a cost. Finally, w gives the weight of each measure.

$$J = \sum_{k=1}^{N} \sigma_k w_k j_k \tag{2}$$

As with smaller tradeoffs, one can find many cases where weights are assigned arbitrarily. Fortunately, a team of researchers from the University of the Bundeswehr in Munich offered a robust method of determining w [35]. The approach, dubbed *Fuzzy AHP*[9], relies on a relative comparison of each parameter using *linguistic variables*. The linguistic variables are then turned into numeric weights using linear algebra.

Having found a method to determine weights, one can consider which criteria should be factored into the value of mission effectiveness. It is decided to utilize survivability, cost, and lethality. Survivability is chosen because the supposed strength of a networked UCAV is that it reduces the risk to the command fighter. Cost is also a recurring theme in the arguments for including UCAVs. While it was shown earlier that a UCAV is lighter (and thus probably cheaper) than a manned fighter, it is not said that the *entire strike group* is cheaper. Lastly, lethality is chosen as a criterion, as the best system has little value in a military conflict if it cannot achieve the mission goal.

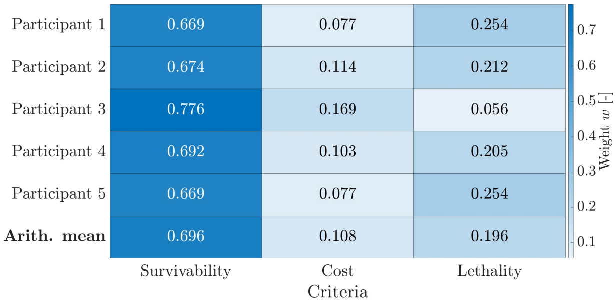
Regarding survivability, the survival rate of command fighters, UCAVs, and *effectors* expresses how well the "resources" are utilized. After all, in a war of attrition, it is important how well the limited amount of stock is used to solve a problem. Cost is considered as *replacement cost* of command fighter, UCAVs, effectors, and fuel. The cost of training a pilot is factored in as well[10]. This allows to express how cost-efficient the systems are when used. Lethality is measured via the total number of destroyed SAM 1, SAM 2, and tanks.

Seethaler, Strohal, and Stütz suggested that the weights be assigned *in a group* by providing a questionnaire to subject matter experts (SMEs) [35]. The SMEs received an explanation of the criteria,

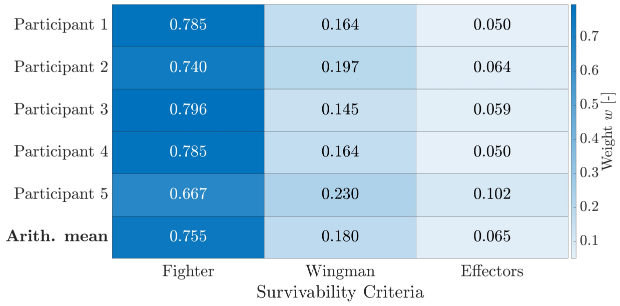
[9] AHP: Analytic Hierarchic Process

[10] This does not imply that a monetary value is affixed to the pilot's life. It stays the highest directive to protect human life. This is accounted for by the criterion of survivability, as discussed at a later point.

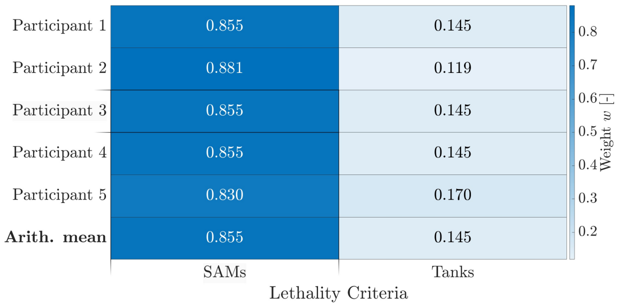
method, and matrices in which they could assign linguistic variables. The SMEs were not in contact with each other and devised weights separately.



(a) General criteria weights determined via Fuzzy AHP. Individual responses and arithmetic mean.



(b) Survivability sub-criteria weights determined via Fuzzy AHP. Individual responses and arithmetic mean.



(c) Lethality sub-criteria weights determined via Fuzzy AHP. Individual responses and arithmetic mean.

Figure 9 – Weights determined via Fuzzy AHP

Figure 9a shows the weights for the general criteria of survivability, cost, and lethality. As can be seen, all SMEs value survivability significantly higher than cost and lethality. Lethality is also valued higher than cost, with the exception of Participant 3, who values the cost higher than lethality. Apart from that, the responses generally agree with each other.
Figure 9b shows the weights for the individual constituents' survivability. The results show similar trends to the general criteria. Generally, the survival of command fighters and pilots is significantly more valued than that of UCAVs. Only Participant 5 is an outlier. Effectors only play a minor role.
Lastly, Figure 9c shows the weights for the lethality subcriteria. All Participants agree that the destruction of SAMs has absolute priority over the destruction of tanks.
Even though determining weights is a highly subjective subject, the individual SMEs' results are in good agreement. Smaller differences can be seen but the spread is still low. This can be taken as an indicator that Fuzzy AHP and the use of linguistic variables are very robust methods, providing meaningful results.

3 Results

The results of the established reference cases can be seen in Figure 10. As can be seen, the two-ship formation of command fighters has a low score for survivability. Since the cost score is related to the replacement cost, the cost score is relatively high (the cost score has a *negative* contribution). The lethality score is *extremely* low, indicating that the mission goal of destroying SAMs and tanks is rarely reached. In sum, this yields a low total score. The use of flying decoys yields significant improvements in all aspects. The survivability score jumps up drastically, which is an interesting result, considering that the loss of flying decoys is also penalized (via the survivability of effectors).

Again, one sees a corresponding decline in cost and an increase in lethality, yielding an increased total score. Using the EW aircraft causes another increase in the survivability. However, this time, the cost *does not* decrease. It increases substantially. While the overall survivability of the formation is increased, the individual aircraft still can be shot down. This includes the EW aircraft. Due to the aircraft's very high cost, it heavily impacts the score. However, using the EW aircraft increases the lethality score by a *factor of ten*.

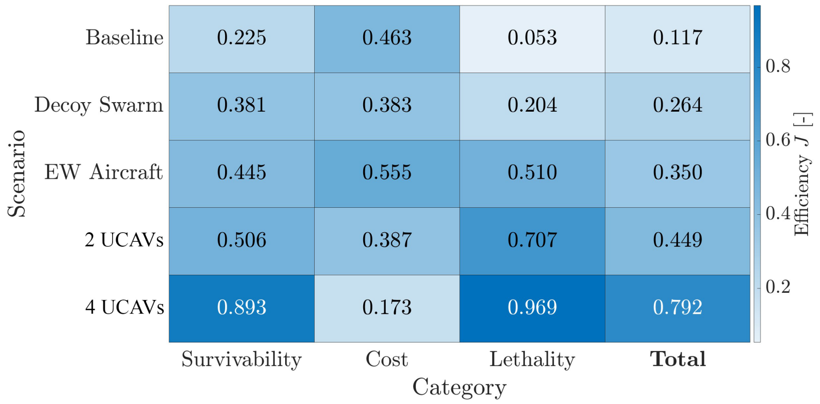


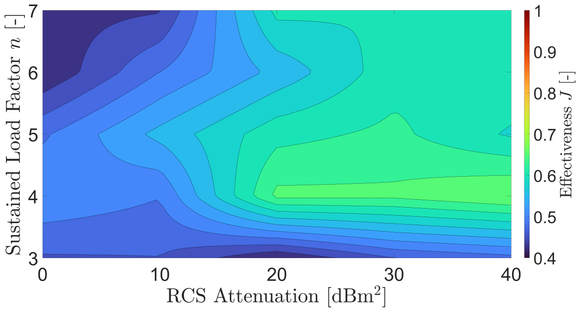
Figure 10 – Mission effectiveness scores of the reference cases

Next is the inclusion of two exemplary UCAVs. As one can see, using two UCAVs increases the survivability score by 33% over the use of flying decoys, while the cost stays almost identical. The lethality score is increased by a factor of 3.5. The use of four UCAVs improves these results even further, doubling the EW aircraft survivability score. The cost is reduced to almost a third of the plain two-ship formation, even though the acquisition costs are significantly higher. The lethality score almost reaches unity, showing that the mission is nearly always successful. In rare cases, one or two Red tanks do survive, which slightly decreases the score. Using two UCAVs almost *quadruples* the total mission effectiveness compared to the standard two-ship formation. Four UCAVs increase the total score by almost a *factor of seven*.

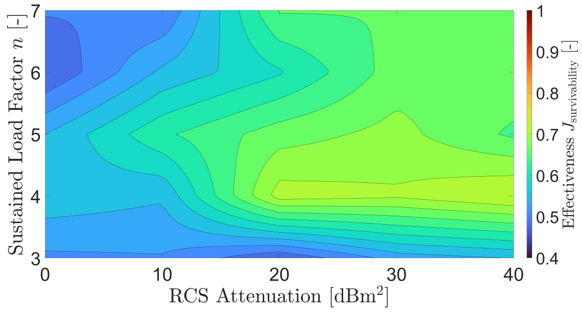
Figure 11 shows the simulation results for the scenario using two UCAVs carrying two ARMs each. As can be seen in Figure 11a, the total mission effectiveness shows a strong dependency on UCAV RCS and sustained load factor. An initial decrease in RCS yields a stark increase in effectiveness. However, there is almost no further improvement beyond an RCS attenuation of 20 dBm^2. The same trend can be observed for the sustained load factor of the UCAV. Increasing the sustained load factor from 3 to 4 g yields a significant jump in effectiveness. Beyond that point, no further improvements can be observed. Additionally, at the low end of RCS attenuation, an increased sustained load factor has a *negative* impact on effectiveness. This effect can be explained by an increasing UCAV size with increasing SEP, increasing the RCS. As can be seen, these trends are also mirrored in the survivability, cost, and lethality score (Figure 11b, Figure 11c, Figure 11d).

To gain a better understanding of these results, one can also look at the lower-level MoEs. Figure 12 shows the attrition of command fighters and UCAVs, depending on UCAV RCS and sustained load factor. Figure 12a shows the UCAV attrition. As can be seen, it is dominated by the UCAV RCS. There is a slight increase in attrition with increasing SEP, but as discussed, this can be explained by an RCS increase due to increased airframe size. It also can be seen that for RCS attenuations of 20 dBm^2 and higher, no UCAV is destroyed anymore.

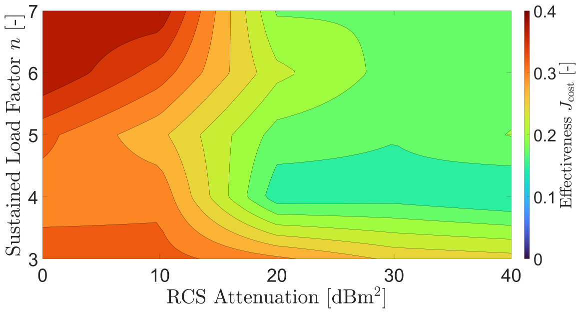
A different trend can be observed when analyzing Figure 12b, which shows the attrition of the fighter. Surprisingly, there is a significant dependency on UCAV SEP when the UCAV has an attenuated RCS. To understand this trend, one has to observe the active simulation. The trend can be attributed to *Emergent Behaviors*. As was shown in Figure 6, the RCS of the UCAV is not smooth but has sharp spikes. This means that when flying turns and following the terrain, the RCS perceived by the hostile radar changes and can peak. In many cases, this is not a problem, as SAM 1 requires a minimum "sensor time on target" before ordering a launch. The majority of the UCAVs turn fast enough to avoid



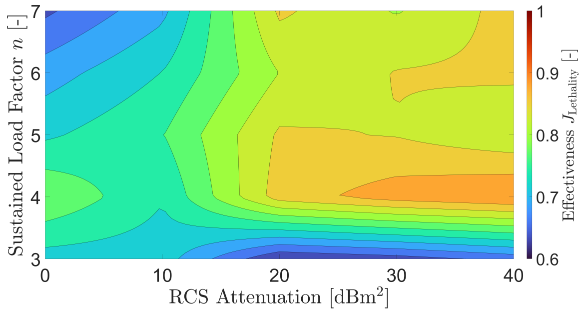
(a) Total effectiveness score for two UCAVs with two anti-radiation missiles each



(b) Survivability score for two UCAVs with two anti-radiation missiles each

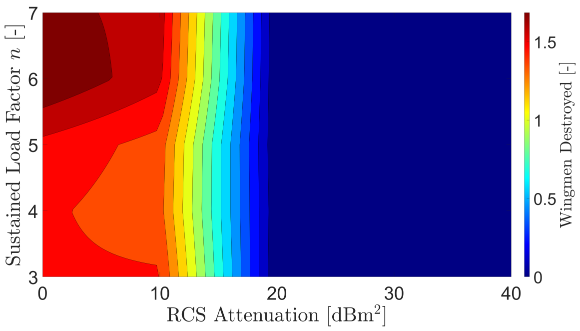


(c) Cost score for two UCAVs with two anti-radiation missiles each

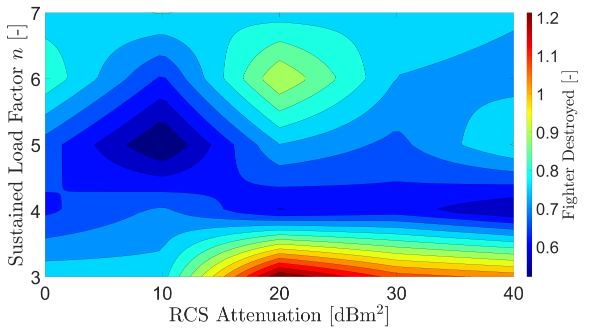


(d) Lethality score for two UCAVs with two anti-radiation missiles each

Figure 11 – Simulation results for the scenario using two UCAVs total carrying two ARMs each. Sustained load factor and RCS attenuation are varied.



(a) Number of UCAVs destroyed for two UCAVs with two anti-radiation missiles each



(b) Number of fighters destroyed for two UCAVs with two anti-radiation missiles each

Figure 12 – Attrition of command fighter and UCAVs depending on UCAV RCS and sustained load factor. Two UCAVs with two anti-radiation missiles each.

lock and launch. However, the UCAV with the lowest SEP turns just slow enough for SAM 1 to launch a missile. The radar lock of the UCAV is broken as soon as it turns, as the perceived RCS decreases. Unfortunately, the missile is already in flight. SAM 1 then reassigns the missile to the next available target: the command fighter. This means that the UCAV *actively increases* the number of missiles fired at the command fighter, *decreasing* its survival rate. Overlaying the trends observed, one finds the same pattern as shown in Figure 11a.

From this point on, the results are shown in clusters of four, as this makes a direct comparison more straightforward, and most results show the same or similar trends. Figure 13 compares the total mission efficiency results for the different simulation cases. Results are shown for two and four UCAVs carrying two and four ARMs.

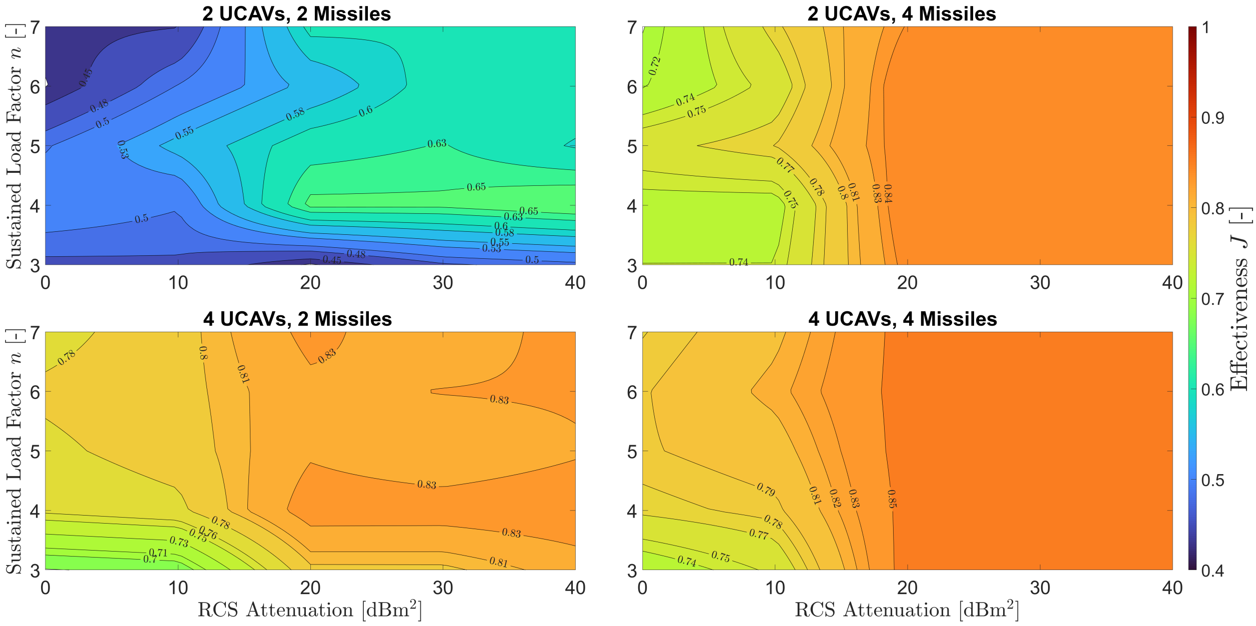


Figure 13 – Comparison of total mission effectiveness for varying UCAV designs and fleet compositions

As can be seen, when deploying two UCAVs, the total mission effectiveness increases significantly. Improvements can be seen over the entire design space. Again, the results show a strong dependency on RCS. The sustained load factor only makes a difference when there is little radar cross-section attenuation. A decrease in effectiveness can be seen for high and low sustained load factors, with a local maximum of around 5 g. The effect can likely be attributed to the increase in RCS with increasing SEP and the previously discussed emergent behaviors for low SEP.

Keeping the total number of missiles constant by doubling the number of UCAVs but halving the load-out of each UCAV yields improvements for low RCS attenuation at a high sustained load factor. The effect of increasing RCS with increasing load factor almost disappears. However, the effectiveness reduces at high values of RCS attenuation. Lastly, doubling the number of missiles carried with four UCAVs and 4 ARMs each maximizes mission effectiveness, showing a plateau beyond an attenuation of 20 dBm^2. For lower attenuation values, effectiveness is higher for larger values of SEP.

Interestingly, the UCAVs seem to perform better when carrying more missiles, even if the total number of missiles is kept constant. Furthermore, penalties for low RCS attenuation can be compensated for by increasing the number of UCAVs and increasing their SEP, which increases the UCAV survival rate. When fewer UCAVs are used, a lower SEP is beneficial. These results are mostly mirrored in the survivability and cost scores, shown in Figure 14 and Figure 15, respectively. However, for survivability and cost, two UCAVs carrying four ARMs each perform best, followed by four UCAVs with four missiles and four UCAVs with two missiles.

The reason for the preference for larger loadouts is likely found in the behavior of the UCAV. When launching missiles, the UCAVs stick to a salvo interval, i.e., they are waiting for a given time before

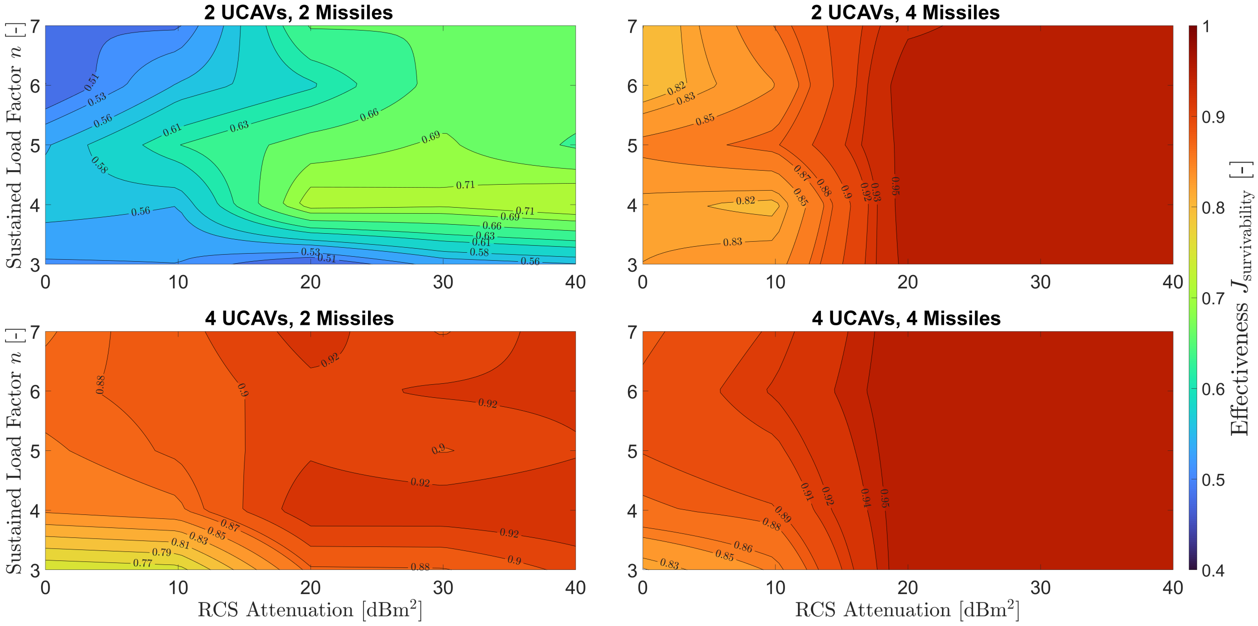


Figure 14 – Comparison of fleet survivability score for varying UCAV designs and fleet compositions

launching another missile. Due to that, UCAVs carrying more missiles tend to stay in the fight for longer while closing the distance to the SAMs. Since the UCAVs are evading most missiles, more SAMs are "wasted" before the command fighters return to engage. This decreases the number of missiles that can be fired at the command fighter, increasing their survival rate. Having more UCAVs increases the number of "sacrificial targets", yielding a slightly better survival score. However, this also implies that more UCAVs are destroyed, which increases the cost slightly.

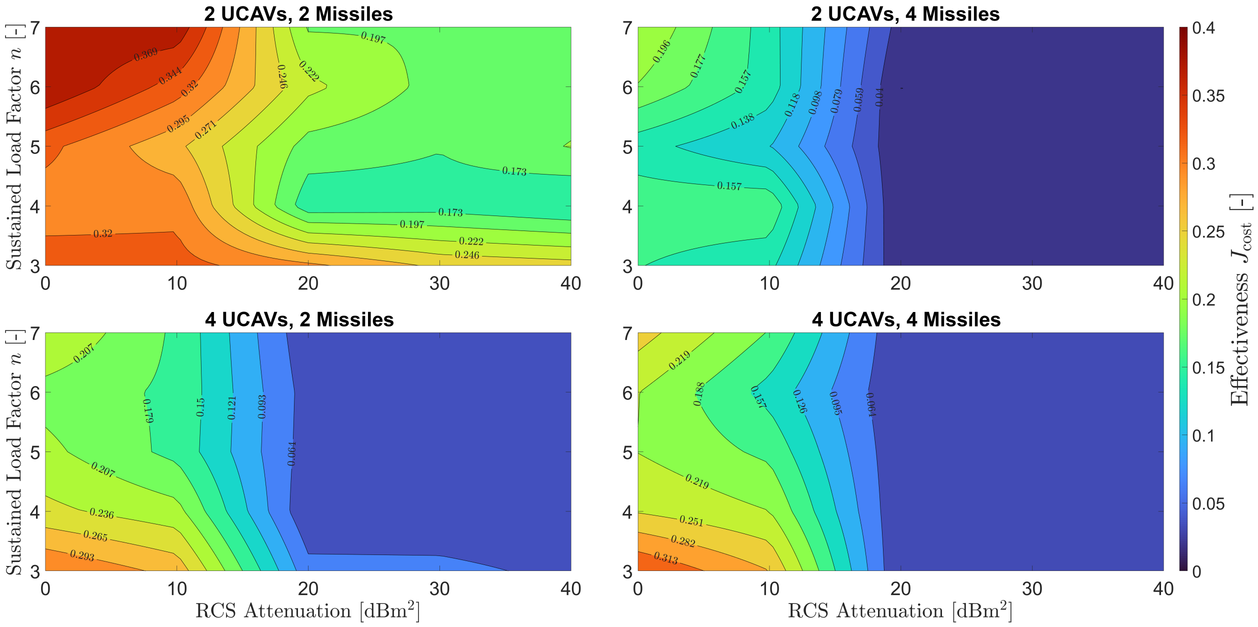


Figure 15 – Comparison of fleet cost score for varying UCAV designs and fleet compositions

Figure 16 shows a different picture when looking at the lethality score. The results for four UCAVs with two missiles each show an almost perfect lethality score that stays almost constant with RCS attenuation. A very low and a very high SEP slightly decreases the score. The results for the other fleet compositions mostly mirror what has been seen before.

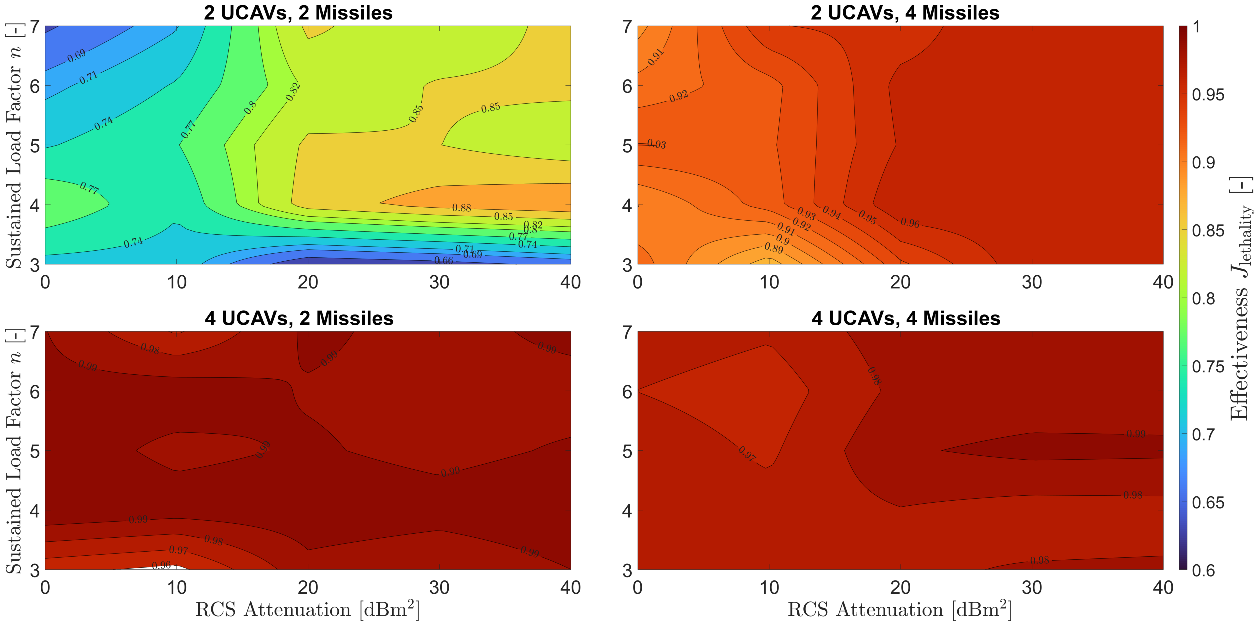


Figure 16 – Comparison of fleet lethality score for varying UCAV designs and fleet compositions

4 Conclusion

While massive efforts are undertaken to design and build networked UCAVs, the proposed benefits have mostly been hypothetical because the few flying prototypes are still in the early stages of field testing. However, evaluating their effectiveness using knowledge-based engineering and agent-based modeling reveals significant advantages of the concept. Including networked UCAVs into strike aircraft groups significantly increases the fleet's total effectiveness, even compared to advanced tactics. This increase is due to increased survivability, which decreases the replacement costs. Furthermore, lethality is increased. The radar cross-section of the UCAVs is a driving factor. For maximum effectiveness, the UCAV should be designed for low observability. The radar cross-section reduction can be limited to treatment with radar-absorbing materials and minor shape optimization to yield an RCS attenuation of 20 dBm^2 compared to 4th generation fighters. This reduction slightly exceeds the stealth properties of generation 4.5 fighter aircraft like the Eurofighter *Typhoon* and Dassault *Rafale*. The ability to fly very hard maneuvers is not an advantage during a SEAD mission. Optimal results are achieved when the UCAV's maneuverability is balanced. Very agile UCAVs, capable of flying sustained turns of 6 g or more, become too large, which is penalized by the accompanying increase of RCS. On the other hand, less nimble UCAVs become a burden, as they actively increase the threat exposure of the command fighter. A deeper understanding of optimal effector loadouts can also be gained. When deciding whether to use fewer UCAVs with more missiles or more UCAVs with fewer missiles, larger loadouts are preferred. A lack of stealth properties can partly be compensated for by deploying more UCAVs and increasing their specific excess power. If the UCAV is stealthy, more UCAVs do not necessarily yield a better mission outcome.
The findings show that the analysis of the larger System of Systems using agent-based modeling has immense potential to become a crucial element for the design of modern combat aircraft. Future research should expand on the presented work by analyzing different CONOPS, like deploying smaller UCAVs as scouts that share sensor data with their command fighter. Also, the use of UCAVs for air-to-air combat should be investigated. Then, the sum of the presented results and the suggested topics would allow to assess future implementations of multi-role capabilities, using varying UCAV types and quantities.

Appendix

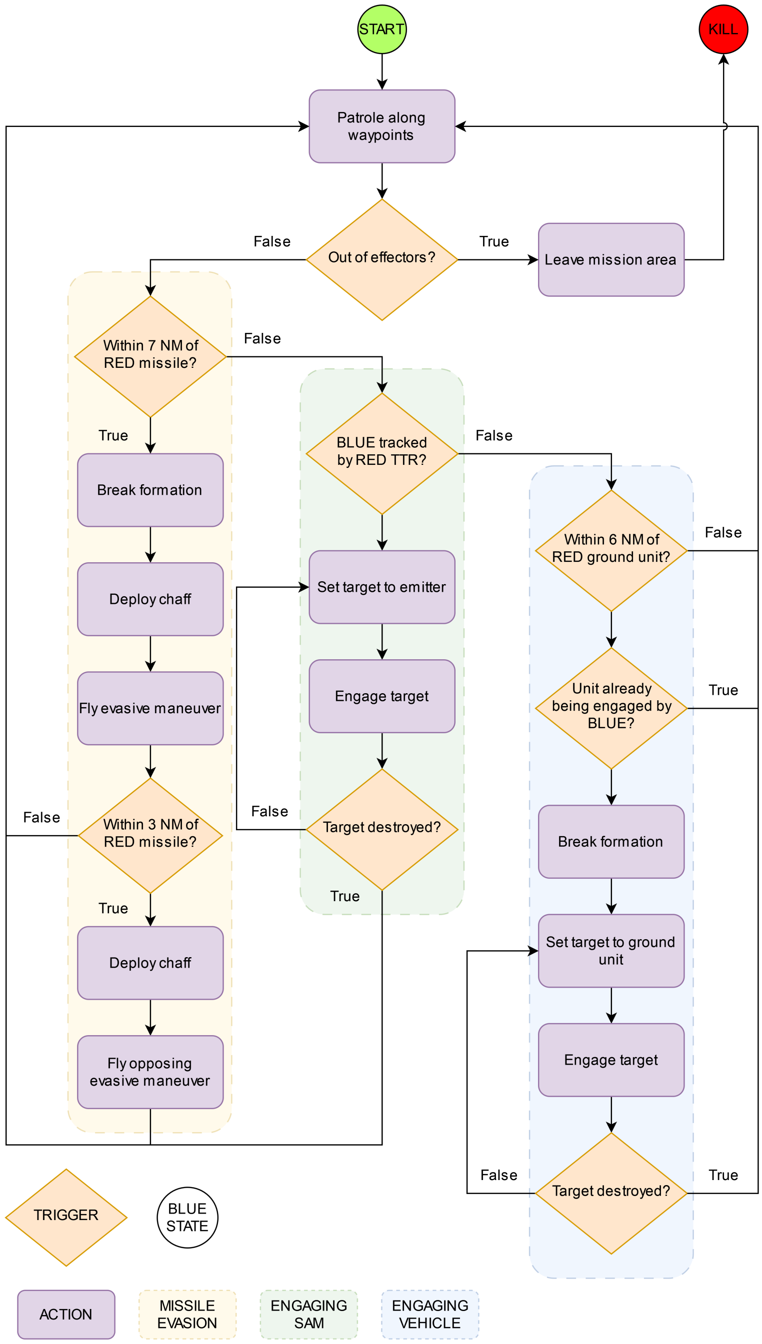


Figure 17 – Behavior of the individual Blue fighter agents [23]. "Kill" indicates that the agent will be removed from the simulation by setting their state to "killed". When all agents of a team are "killed", the simulation is reset and restarted.

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