AIRCRAFT LEVEL EVALUATION AND SOS ASSESSMENT FOR AN AIR INTERDICTION MISSION UNDER OPERATIONAL CONSTRAINTS

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Abstract

Modern combat vehicles are becoming increasingly expensive due to extensive requirements of multirole warfighting capability. The multirole capability requires several weapons, sensors, communication systems and avoidance subsystems. That leads to non-stealthy, inefficient, and heavier platforms. Thus, there is need to understand the effect of individual platform design and technologies on a multi-vehicle battlespace. Multi-level system dependencies impact performance and effectiveness. This necessitates a holistic System of Systems (SoS) design and assessment methodology. With an SoS battlespace simulation we can evaluate the impact of individual platforms or weapons on an individual mission scenario level. This paper presents an extension to further use cases of a simulation embedded SoS framework, developed at the DLR Institute of Systems Architectures in Aeronautics. The framework spans along equipment, weapons, sensors, subsystems, systems, SoS, mission thread. and mission scenarios/operations. This paper focuses on the evaluation of a counterland Air Interdiction (AI) mission with suppression of enemy air defense aspects including the following:

- Obtain a set of aircraft requirements under operational constraints by analyzing the outcome on the battlefield
- Study the impact of different strike group sizes and weapon numbers on the mission outcome in a AI scenario
- Evaluate impact of the individual vehicle performance mapped to a multi vehicle capability
- Demonstrate robustness of the framework across various mission types

A Design of Experiment is conducted over system (aircraft), weapon and concept of operations level, evaluating influence of aircraft specific excess power, weapon carriage, radar cross section and strike group size. The results are evaluated via SoS-level measures of effectiveness such as survivability and weapon usage.

Keywords

Conceptual Fighter Aircraft Design; Mission Effectiveness; System of Systems

1. INTRODUCTION

The security situation around the globe is evolving rapidly. The German federal ministry of defense identifies new trends of potential hostile powers and trends of own aerial weapon systems. The efficiency of german weapon systems is challenged by proliferation of modern weapon systems denying access and usage of the airspace by hostile forces. Additionally, a reduction of North Atlantic Treaty Organization (NATO)'s number of flying weapon systems, personal, and ammunition is anticipated, together with a smaller freedom of action, as well as reduced redundancy and resilience needs to be envisioned. One part of the solution needs to be technological advantage [1]. In order to identify the technologies and platform designs to gain said advantage, the battlefield needs to be considered as a whole. The mission outcome heavily depends on complex interactions not only between friendly and hostile forces but also between all members of friendly forces itself. To full fill its task in that collaboration a clear Concept of Operations (CONOPS). Derived from that the determination of technical requirements for individual platforms within the battlefield is depended on accurate modeling of capabilities and interdependencies. With more and more tasks to fulfill, the list of requirements today's air combat fighter aircraft have to meet is growing. Air forces try to fill immediate capability gaps by modernization of existing legacy platforms. One example is the Eurofighter ECR with additional systems for Eelectronic Warefare (EW) and Suppression of Enemy Air Defense (SEAD) missions [2]. Nevertheless also new designs like the F-35 are affected, as they were designed to fit a vast variety of mission profiles. These aircraft are equipped with more and more sensors, weapons, and communication systems, all under the consideration of stealth properties. However, a design satisfying this extensive list of requirements, will be less agile, less stealthy, heavier as well as more complex and expensive [3] [4]. To this

Weapon system	Delay in delivery [mths]	Cost increase [%]
A400M	195	18
Eurofighter w/ AESA	63	33
PEGASUS	20	0.4
MALE RPAS	10	2
NH90 NTH (Sea Lio)	4	7
NH90 MRFH (Sea Tiger)	0	4

Table 1. Delays and cost increases in major Bundeswehr armaments projects [6]

day, defense projects of the German Bundeswehr experience significant delays and cost increases [5]. Statista lists the latest numbers on that issue. Table 1 shows these densed to aerospace related projets.

One way to reduce cost is the development of unmanned platforms designed for individual roles supporting manned aircraft. By the vision of most experts representing states, industry, and research, next generation air dominance platforms will be supported by loyal wingmen or remote carriers to satisfy all necessary requirements [7], [8]. These concepts require accurate Top Level Aircraft Requierment (TLAR) definition and benefit from a close link between conceptional platform design and operational analysis. Therefore a framework is needed that can evaluate various air combat scenarios and create a sustain link to aircraft design. A review of former research goes back to the early applications of multi-agent simulation to support mission planning [9]. Agent based simulation has also been explored in a vehicle design concept in many different ways [10]. Advances in modeling approaches and corresponding computational, analytical, and conceptual frameworks provide new opportunities for directly connecting a conceptual aircraft design to expected mission effectiveness using operations analysis. Braafladt developed a framework for evaluating the effect of aircraft performance and mission requirements for an Air Interdiction (AI) mission [11]. Biltgen already identified modeling and simulation as enabling techniques to determine the impact of candidate technologies with respect to capability-based Measures of Effectiveness (MoE). He integrated this technique within a ten-step methodology process for quantitative technology evaluation for Systems of Systems [12], [13]. Gao explored ways to determine System of Systems (SoS) contribution and proposed the Mission Success Space (MSS) for the evaluation on aircraft contribution effectiveness based on the thought of inverse design [14], [15].

The goal of this research is to create a deeper connection between the conceptual aircraft design and the operational analysis. Furthermore, methods of mission evaluation and visualization for a quick analysis of mission results for combat aircraft focusing on ground targets and threads are explored. The German Aerospace Center (DLR) Institute of System Architectures of Aeronautics has developed a SoS Air Combat Framework for the integration of mission evaluation in the conceptual aircraft design process [16]. While that work was focused on Air-to-Air Combat this paper extends the framework by the application of an air-to-ground use case with an AI mission with SEAD elements. The red forces of that framework are remodeled with Surface to Air Missiles (SAM) sites for ground based air defense. The framework needs to be able to:

1) Obtain a set of aircraft design requirements under operational constraints by analyzing the outcome on the battlefield
2) Study the impact of different force (number of vehicles) and weapon ratios to the mission outcome in a AI scenario
3) Evaluate effectiveness or impact of the individual vehicle performance mapped to a multi vehicle capability
4) Evaluate mission success criteria and explore visualization techniques under the influence of individually weighted MoEs
5) Demonstrate robustness of the framework across various mission typ

A Design of Experiment (DoE) will be conducted by varying TLARs via Red vs Blue teams battle simulations in order to be able to identify a combination to maximize mission success for a given counterland AI scenario inspired by [14] and [11]. A variety of MoEs will be applied to interpret the results.

2. SYSTEM OF SYSTEMS AIR TO GROUND COMBAT FRAMEWORK

The focus of this paper is the improvement of fighter aircraft conceptual design processes via operational analysis as an integral part of the design process for a classic air-to-ground scenario. An early implementation of the operational environment can help to predict TLARs necessary for mission success. This needs to be conducted based on quantifiable measures and aims for minimizing expensive developments on already developed aircraft. Therefore, the modeling and simulation design framework implemented and tested for this paper includes mission simulation as an integral part of conceptual fighter design. Figure 1 visualizes the vision of air combat vehicle design and strike group composition process, where the simulation drives the design. For various scenarios including relevant technologies, environmental conditions and equipment, simulations can be performed to identify the most efficient and robust fleet, aircraft design, and and subsystem-level parameters. Also SoS parameters such as strike group size, combinations, and distribution can be investigated for their impact on the scenario outcome in this framework.

Notice that the missions are based on blue vs red scenarios. In real world situations, the knowledge of the hostile team is based on intelligence information. This knowledge is extremely important for the success of the mission, as adjusted capabilities would normally result in adjusted measures by the adversary side. Therefore, the outcome of the mission depends heavily on the assumption of fixed red capabilities. This knowledge needs to be assumed to a certain degree for the test of the framework. For this work red performance parameters and capabilities do not adjust to the varied blue. The framework is derived from the previous work on air-to-air combat [16] along with the tool workflow in Figure 2.

To structure the SoS design, a framework is developed to define the key variables of the design, construct the SoS model SoS model, perform the simulations, and analyze the output data to constrain the design space. Platform design, strike group design, CONOPS and mission simulation can build an iterative loop. Optimization was not studied or implemented in this work, as design space exploration was applied. The connection between operational analysis and conceptual design are established via input and output files. The initial point of this work is the set of requirements and capability definitions to select necessary systems and equipment and perform the aircraft design process. Please refer to Subsection 2.2 for more details. With accurate models of the platforms they can be assigned to fleet compositions. Based on the capabilities and the fleet composition a CONOPS can be derived. From a general CONOPS the behavior of all individual agents can be derived, further explained in Subsection 3.4. All that will be implemented in the operational analysis consisting of mission simulation and result interpretation. The results of the design space exploration should offer insights into a suitable set of requirements to full fill the mission successfully. Figure 2 translates the framework that into a tool workflow.

Based on a first set of initial TLARs and with it equipment description, a baseline platform is designed via VAMPzeroF (Subsection 2.2). The aircraft design tool delivers the necessary performance, payload, geometry for the simulation tool Modern Air Combat Environment (MACE). Within MACE a mission is constructed based on the reference mission of the TLARs and including resulting aircraft model. The MACE Evaluation Tool reads the output logfiles created by MACE and converts it in a JMP® readable format for the final data analysis. We used JMP® for data analysis of the mission data points [17]. The simulation results allow to draw a conclusion on a refinement of the TLARs [16].

2.1. Operational Analysis via Agent Based Modeling (ABM)

To conduct a representative operational analysis, the set up of a suitable scenario is necessary. Various factors need to be considered. ABM was chosen for modeling and simulation. It offers several advantages for the modeling of SoS problems:

- Obtain a set of aircraft design requirements under operational constraints by analyzing the outcome on the battlefield that can be drawn back to individual behavioral decisions of agent or design choices.
- Provides a detailed, micro-level understanding where individual decisions and interactions lead to critical emerging behavior
- Offers to test effects of different parameters, policies, or interventions
- Explore "what-if" scenarios and counterfactuals, helping to understand how different decisions or actions might have influenced outcomes

Within military simulation ABM accommodates for movement, sensing, and interacting behaviors of the aircraft and defense systems. Besides the the operational environment like landscape and weather several details about the involved platforms, their behavior and interactions between platforms of either team, to hostile platforms and to the environment needs to be considered and modeled sufficiently. These points are summarized in Section 2 as platform design, fleet design and CONOPS, which have to be modeled to a degree suitable to the challenge at hand.

For ABM the commercially available software, MACE created by Battlespace Simulations Inc was applied. MACE is a physics-based, full spectrum Computer Generated Forces (CGF) and Semi-Automated Forces (SAF) application with a large and user-extensible order of battle, capable of many-on-many simulation. MACE can simulate advanced, 5th generation systems including low observable platforms and Active and Passively Electronically Scanned Arrays as well as highly contested battlespaces. MACE supports the Distributed Interactive Simulation (DIS) architecture including simulation management, entity state, fire, detonate and emissions Protocol Data Unit (PDU)s. MACE supports both ground-based and airborne entities, weapons, and electronic warfare [18].

In MACE aircraft performance parameters are stored in XML-files using an energy based aerodynamic model for aircraft flight. Flight envelope borders are described by fixed values for maximum speed, altitude and G force. Minimum speed is calculated via the know lift function via aircraft weight W, lift coefficient C_L, air density ρ and wing area S. The main parameter modeling aircraft flight performance is the Specific Excess Power (SEP) calculated by mach number Ma speed of sound c, thrust T, W, zero-lift drag coefficient $C_D i$ and the load factor n displayed in Equation 1. Additionally, MACE considers fuel consumption via fuel-burn look- up based on Mach number, altitude, configuration and weight.

$$(1) \quad SEP = Ma \times c \times \left[\frac{T}{W} - \frac{C_{D0} q S}{W} \times \frac{\frac{C_{Di}}{C_L^2} n^2 W}{qS} \right]$$

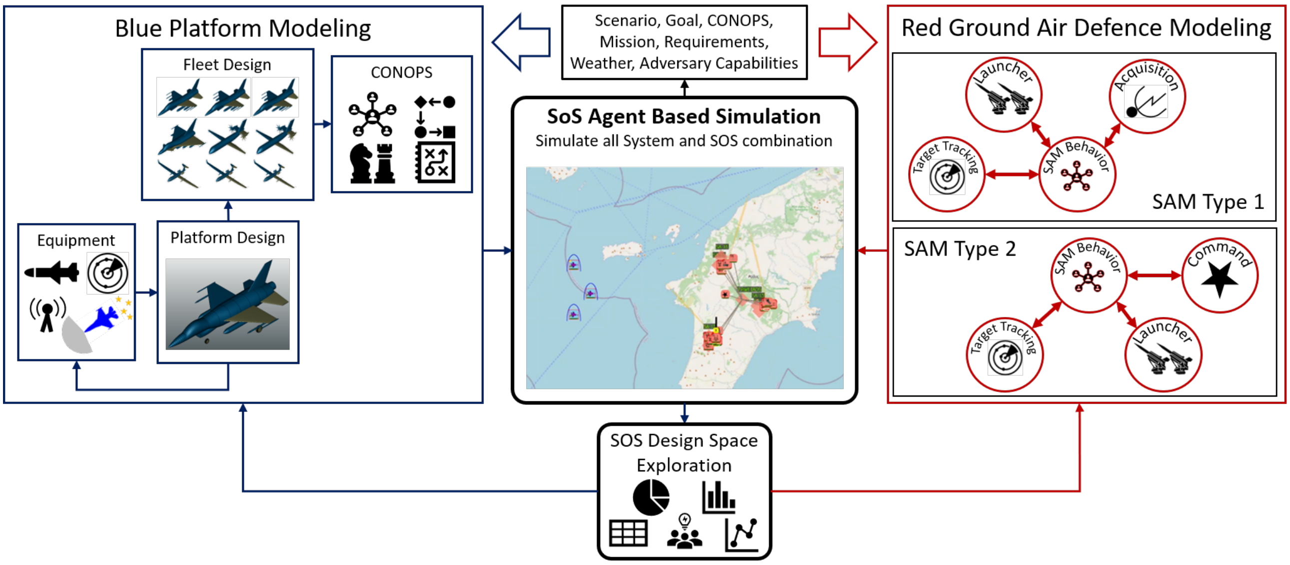


Figure 1. Framework for SoS driven combat aircraft design with focus on ground based threats

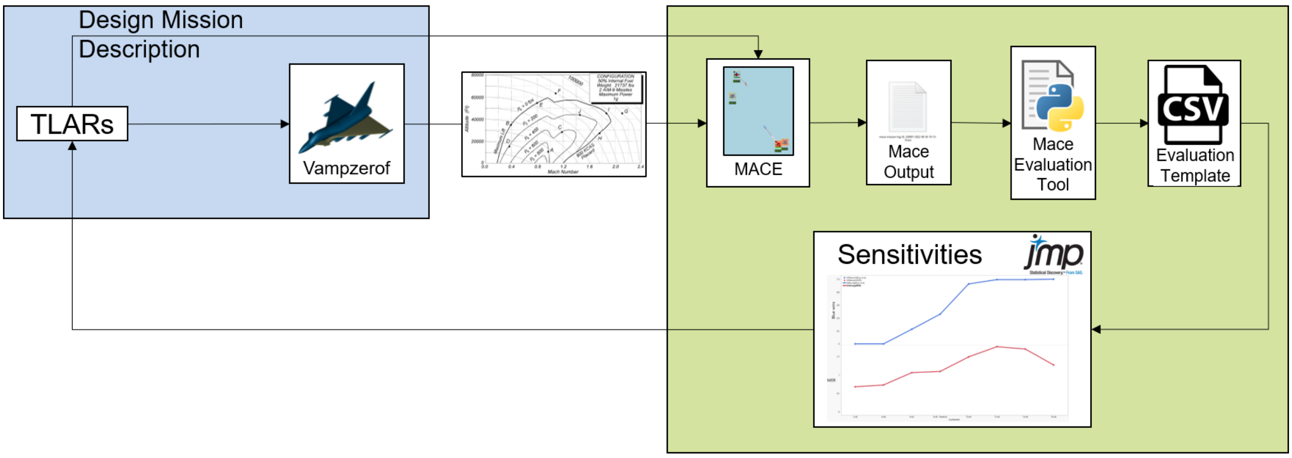


Figure 2. Workflow for the sensitivity study of this paper [16]

MACE is able to model both ground-based and airborne entities, weapons, electronic warfare, datalinks, and Integrated Air Defense Systems (IADS) Integrated Air Defense Systems. MACE can simulate either an entire IADS or provides directly various autonomous SAM Sites. An IADS is a collection of sensors and weapons that communicate (share information) to provide defense against airborne threats. Therefore, IADS as well as autonomous SAM sites can consist of:

- Early Warning Radar
- Command Posts or Sector Operations Centers
- Acquisition Radar
- Height-finding radar
- Target-tracking Radar
- Launcher/Transportable Erector Launcher Site

Additionally provides the following platforms:

- SAM Sites
- Autonomous SAM Sites
- Anti-Aircraft Artillery (AAA)

MACE runs the Radar Range Equation (Equation 2 to calculate maximum detection range R_{max} for all the radar systems in the IADS. It does this in real time for all agents versus all operating radar sites, using mode-specific frequencies and aspect-dependent Radar Cross Sesction (RCS) values.

$$R_{max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}} \tag{2}$$

A visualisation of a Radar Plot visualized in MACE can be found in Figure 3.
It shows that MACE uses a 360ř description broken down to different frequencies for RCS modelling.
Platforms: air: location,speed,altitude, flight performance, weapon load,

2.2. Conceptual Fighter Design

The initial design of combat aircraft typically does not rely on fully defined specifications. The processes

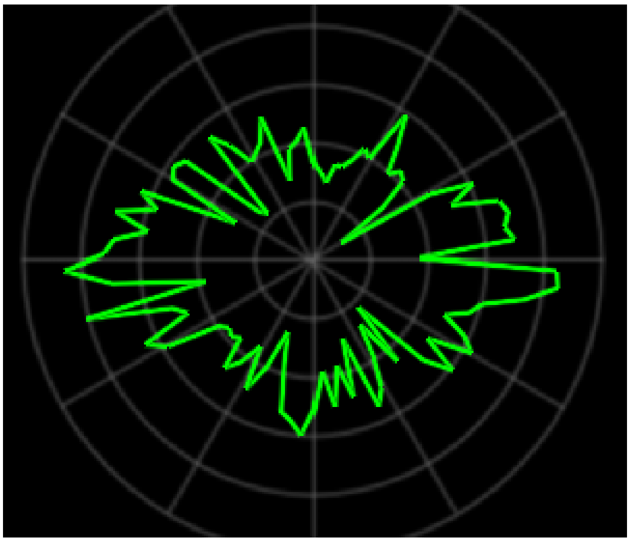


Figure 3. Radar plot visualisation in MACE [Quelle]

of establishing the key design parameters to achieve the optimal configuration are interdependent. New weapon systems will have to fulfill the same tasks previous generations had to. Therefore, also future combat aircraft design needs to account for certain attributes [19]:

- Lethality
- Manoeuvrability
- Handling qualities
- Range
- Persistence
- Visibility
- Stealth
- Resilience

During this paper the focus will lay on lethality, manoeuvrability and stealth attributes. These will from the system requirements serving as input to the aircraft design process. Derived from the attributes this research evaluates the effects of weapon load, RCS and SEP requirements on the mission outcome of a AI mission. The aircraft serving as a reference in the study is F-18 similar aircraft described in Subsection 3.2. Due to the high complexity of accurate RCS determination,RCS evaluation is detached from the aircraft design process. This study treats RCS as an operational requirement to investigate the impact in the operational theater. A valid assumption is the application of coating to the baseline aircraft in order to influence the radar signature [20].
The DLR Institute of Systems Architectures in Aeronautics in-house fighter design tool VAMPzeroF drives the overall aircraft design used for the platform design in this study [21]. VAMPzeroF is an automated Python tool for the initialization and synthesis of fighter aircraft configurations. The software is largely knowledge-based and consists handbook methods of handbook methods and empirical correlations (such as [22] or [23]). Previous work focused on the output of flight performance parameters for the implementation into MACE. That included information about flight envelope borders, SEP, fuel burn, as well as fuel and empty weight. During this work the output was expanded to platform description including equipment lists and RCS.
The output of the conceptual design process is a fully converged aircraft with geometrical dimensions, flight envelope borders, SEP, fuel burn, as well as fuel and empty weight. The converged aircraft also takes a correct allocation of the weaponry into consideration.
The conceptual design results provide a connection between system requirements and the definition of the input parameter necessary for the modeling and simulation process to conduct the operational analysis. Creating a link between aircraft requirements and expected mission effectiveness at this early stage in the design process provides a mechanism to improve the analysis of the requirements. Further information to the aircraft serving as a baseline for this study is presented in chapter Subsection 3.2.

3. TEST OF THE SOS DRIVEN COMBAT AIRCRAFT DESIGN FRAMEWORK

To validate the modeling framework, a test scenario was executed. This scenario involved exploring the design space by considering variable ranges outlined in Subsection 3.5. The selected ranges were primarily chosen notional, with some limitations imposed by modeling constraints. The choice of the particular DoE was made to accommodate discrete payload weight considerations and to sample various conceptual design requirements within the interior of the space.
The chapter includes a description of the mission design, the platform types interacting with the mission as well as their respective behavioral logic.

3.1. Mission Design

To set up an agent-based simulation in MACE, a mission scenario is needed. The scenario is centered around a counterland AI mission with elements of SEAD and Destruction of Enemy Air Defense (DEAD). The operational scenario includes that assumed reconnaissance shows the presence of tanks of the red team. The exact number and composition of these red units is unknown. The mission goal is to neutralize the red assets. Since the number and exact position of the red tanks is unknown, long-range precision-guided munitions, like cruise missiles, are not an option. Large-scale bombardments are not an option either, because the risk of damage to the infrastructure and civilian casualties is too high. Thus, a strike group of aircraft is tasked to identify and neutralize any the mobile armor elements.
The baseline mission consists of three fighters.
The armor elements are represented by four tanks, which are spread throughout the airport area. SAM systems are placed to protect city and assets. They are referred to as SAM-1 and SAM-2 (see Subsection 3.3).

In direct proximity to the armor elements, two SAM-1 are placed. Additionally, a SAM-2 is placed along the route of the fighters toward the mission area. Lastly, a second SAM-2 is placed outside the mission area, such that the fighter sortie route leads through the engagement zone of the SAM site. All enemy assets are placed such that it is impossible to hit multiple targets with a single effector.
The terrain is urban with green patches and minor hills (up to 50m) providing good vision to the radar systems of the SAM sites. There is no clutter in the form of grey team members (uninvolved vehicles etc.). The mission area is constrained by a bounding box of 60 nautical miles in latitude and 55 nautical miles in longitude. Maps of the mission and target area are shown in Figure 4 and Figure 5, respectively.
To constrain the mission, multiple termination criteria are set. Firstly, the mission is terminated if either all blue or all red units are removed. Secondly, blue aircraft are removed if they used up all their effectors (see Subsection 3.4). Lastly, the maximum mission duration is set to 15 minutes, to ensure termination of the simulation. The vast majority of runs is terminated far sooner, either because all units of a team were removed, or because the strike aircraft used up all their effectors.

3.2. Baseline Aircraft

An F-18 similar aircraft, shown in Figure 6 functions as the baseline for all sensitivities during this study. The requirements of the baseline aircraft are shown in Table 2. They are based on literature research [24] [25] and are used as the starting point for the DoE.

Item	Requirement
Weapon load	2 Air-to-Ground missiles, 4 GPS-guided bombs, 578 rounds of ammunition
Takeoff distance	1200 m
Landing distance	890 m
Super Cruise	Mach 1.4 at 12000m with mission fuel mass
SEP	134 m/s at 305m (Mach 0.9, mission fuel mass)
Sustained Turn	3.4 g at 4100m (Mach 1.1, mission fuel mass)
RCS	F-18 similar RCS

Table 2. Performance and payload requirements

The RCS description used as a baseline for the variation is derived from publicly available information assigned to the reference aircraft within the MACE simulation. Variations reference to delta values of the baseline RCS.
The board gun is not used by the agents during the mission simulation but considered for the aircraft design process.
Mission Analysis within in the conceptual design context includes fuel consumption for thrust and aerodynamics based on a design mission from [26] visualized in Figure 7

3.3. SAMs

This subsection gives a detailed description of the two SAM systems. A summary of the specifications can be found in Table 3.

	SAM 1	SAM 2
Radar	Pulse Doppler + PESA	Pulse Doppler + CW
Max detection range [NM]	54	32
# Missiles	8	3
Missile max speed [Ma]	2.8	1.75
Missile max load factor [g]	30	19
Max engagement range [NM]	7	15

Table 3. Summary of SAM specifications

SAM 1

SAM-1 is an autonomous system, which incorporates a central vertical missile storage and launcher as well as target acquisition, tracking, and missile guidance radar, in one mobile self-propelled vehicle. It is designed to engage targets at low to medium altitudes, ranging from aircraft over small Unmanned Aerial Vehicle (UAV)s and ammunition, like short-range ballistic missiles and cruise missiles. The vehicle is tracked and features a movable turret, which is built around the central launcher.
The Target Acquisition radar (ACQ) is a rotating pulse Doppler system. It has a maximum detection range of 54NM. The Target Tracking Radar (TTR) features a Passive Electronically Scanned Array (PESA) that is mounted to the front of the turret. It has a maximum detection range of 33NM. The PESA gives SAM-1 a fast and highly accurate tracking capability. It is also less detectable compared to some other systems (see SAM-2).
SAM-1 carries eight missiles, with a maximum range of seven nautical miles. Due to the missiles' high maximum load factor, thrust vector control, and high speed (see Table 3), they are very maneuverable and can change course mid-flight. The missiles are guided by commands from the vehicle. SAM-1 can engage two targets simultaneously and fires salvos of two rockets at a time.
The combination of radar systems and capable missiles, creates a good representation of a modern SAM system. Two SAMs of this type are placed in the center of the target area (see Figure 5).

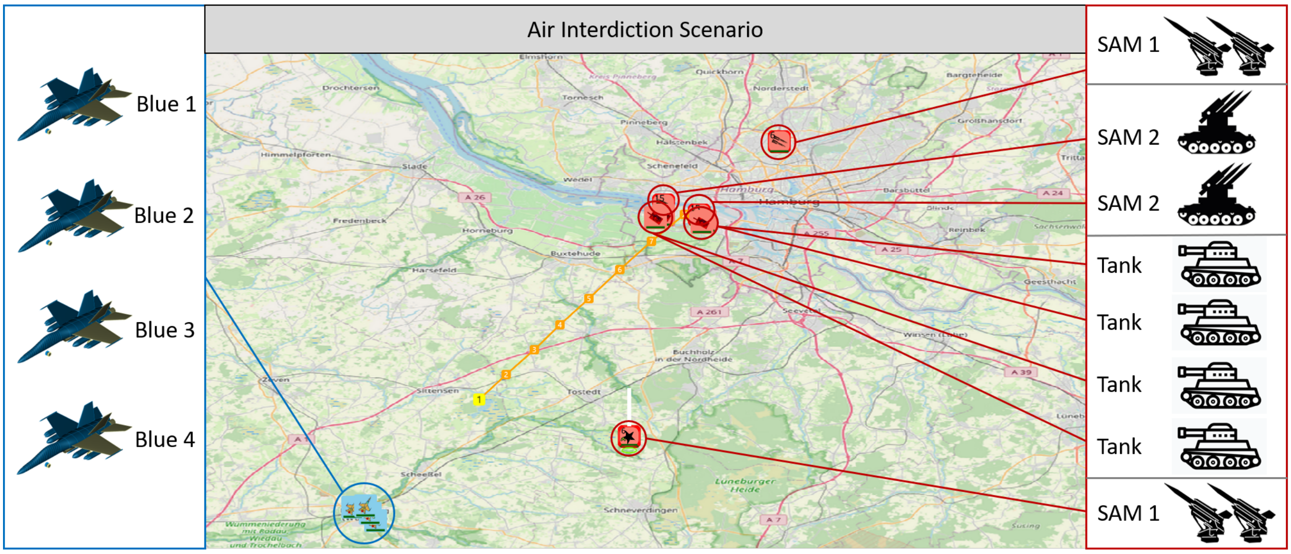


Figure 4. Overview of the entire mission area


Figure 5. Overview of the target area

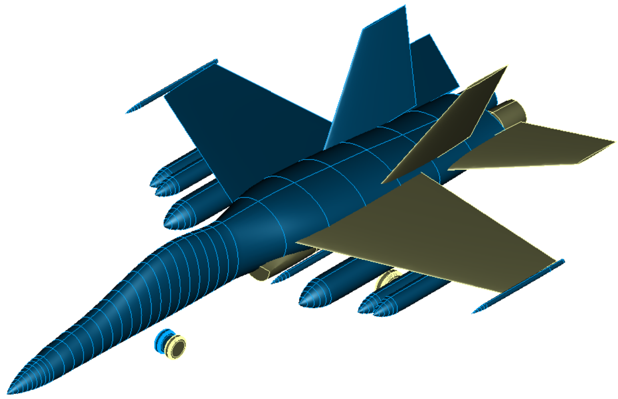


Figure 6. F-18 similar aircraft functioning as a baseline

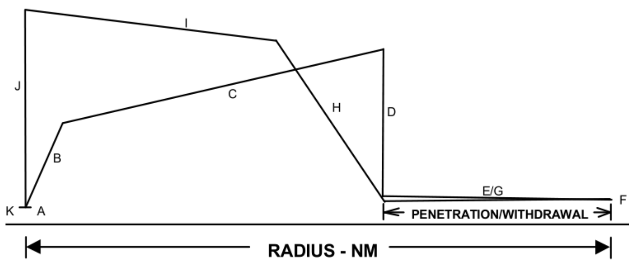


Figure 7. Mission profile for mission analysis during conceptual design [26]

SAM 2

SAM-2 differs drastically from SAM-1 within its functionality. SAM-2 consists of three tracked vehicles: a launcher, a radar, and a command vehicle. Like SAM-1, the system is designed to engage targets at low to medium altitudes. However, it is only able to fight aircraft.
The radar vehicle houses a rotating pulse Doppler ACQ as well as a separate pulse Doppler TTR. Both radars have a maximum detection range of 32NM. Additionally, the TTR includes a Continuous-Wave radar (CW) for missile guidance. A CW radar illuminates the target with a constant beam. It is significantly less accurate than the PESA of SAM-1. Furthermore, it is highly detectable.
The launcher carries three missiles with a maximum range of 15NM. The combination of a lower speed and the low load factor (see Table 3) leads to low maneuverability. The missiles are semi-actively guided by radar, i.e. they are homing at the missile guidance radar's echo reflected by the target. SAM-2 can only engage one target at a time.

Due to the used missile and radar technology, SAM-2 is a good approximation of old and very proliferated SAM systems. One SAM of type 2 is placed along the route of the aircraft and another one is placed north of the target area (see Figure 4).

3.4. Agent Behavior

This subsection describes the behavior of the agents in the simulation, contributing by their behaviour to the mission outcome. Therefore, the logic of aircraft and SAMs are described in detail in the following chapter.

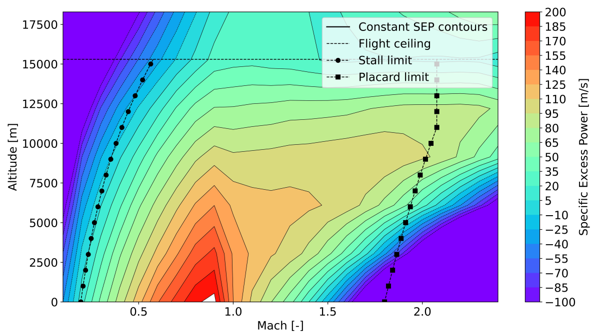


Figure 8. SEP of the reference aircraft at 1g, plotted over Mach and Altitude

Aircraft

The behavioral logic for aircraft is assigned to all blue aircraft in the same manner. The highly dynamic manner of the endgame small details can lead to large variations. A detailed describe of each step is necessary. A graphical representation of the aircraft agent behavior can be found in Figure 9, in the form of a logic diagram.
The blue aircraft follow a fixed route into the mission area, which is defined by waypoints. The route leads in a straight line, from the starting position to the target area. When the last waypoint is reached, they return to the first waypoint to start over. The waypoints are marked in orange in Figure 4.
The fighters enter the mission area at an altitude of 1000ft Above Ground Level (AGL). Their speed is set to 300kts. They form up to a wedge formation and move to the first waypoint while accelerating to 650kts. Along the route, they try to keep a constant flight altitude of 1000ft AGL. This behavior was chosen to mimic a terrain following and low-level flight, as used when penetrating enemy air space.
Apart from that, the behavior of the blue agents is scripted using triggers and actions. Each trigger is checked with a fixed rate of 60Hz (in mission time), which effectively restarts the agent behavior loop. This is done for each agent individually.
The first trigger is used to define the base task of the aircraft. It is checked whether there is any red ground target within a radius of six nautical miles of the aircraft, that is not being engaged already. If there is, the aircraft will break formation, set the red ground unit as a target and engage. The aircraft continues engaging the target until the target is destroyed. If the target is destroyed, the aircraft returns to the route and proceeds to the next waypoint. The "not engaged" condition is included to implement communication and task distribution between the aircraft. It effectively prevents that all aircraft engage the same target. The distance of six nautical miles was chosen to delay the target acquisition. This distance is significantly less than the viewing distance at the given flight altitude (~40 NM). However, at this range, it would be impossible for the pilot to positively identify a target by eye. Thus, a shorter distance was chosen. The exact

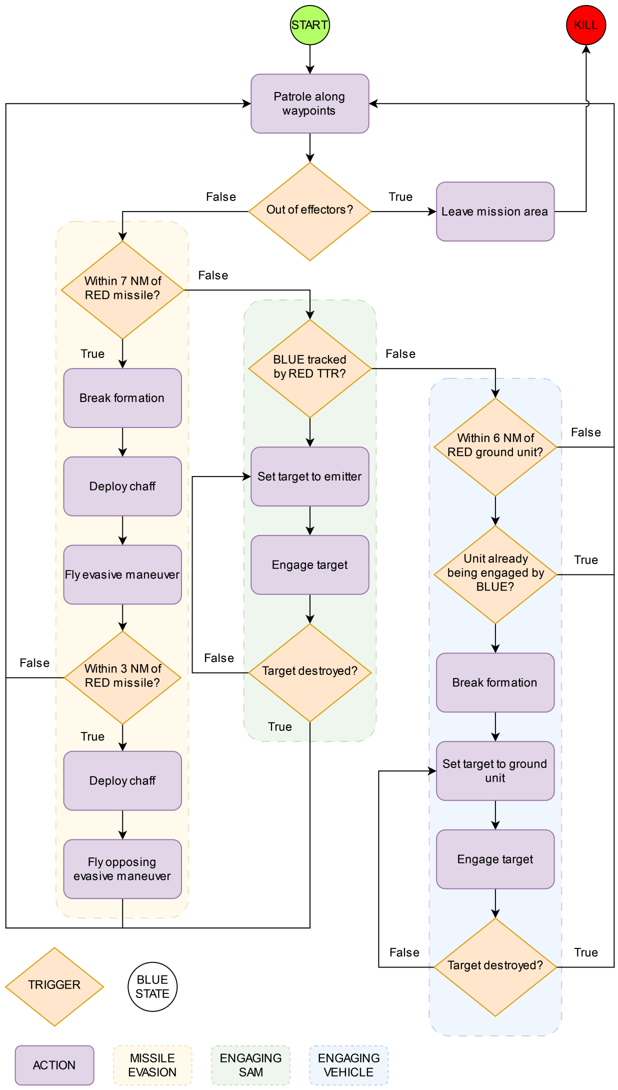


Figure 9. Logic diagram of the aircraft behavior

value was defined during early trials, as a means of "calibrating" the simulation.
The second trigger creates the SEAD/DEAD behavior. It is checked, whether the aircraft is being tracked by a red TTR, by polling the aircraft's Radar Warning Receiver (RWR). If the RWR indeed warns that the aircraft is being tracked by a red TTR, the target of all aircraft is set to the red emitter, i.e. the red radar site. This implements collaboration of the aircraft and ensures that the aircraft team up, to engage a high-priority target. When the TTR trigger is activated, it disables the normal ground engagement trigger, to prevent an interruption of the SEAD/DEAD behavior. This also gives the task a higher priority over the ground engagement. Apart from that, the behavior of engagement is identical to the behavior discussed previously. Again, if the assigned target is destroyed, the aircraft returns to the route. Furthermore, the ground engagement trigger is re-enabled.
The third trigger gives the aircraft the ability to evade incoming red missiles. The trigger checks whether there is a red missile within seven nautical miles of the aircraft. If there is a missile within the given ra-

dius, the aircraft breaks formation, deploys countermeasures in the form of chaff, and flies an evasive maneuver. The maneuver is defined as a 120-degree turn at maximum load factor. After the maneuver, a fourth trigger checks if a missile is within three nautical miles. If there is, the aircraft again deploys chaff and flies the evasive maneuver in the opposing direction so that it flies an S-curve. The maneuver is shown in Figure 10.

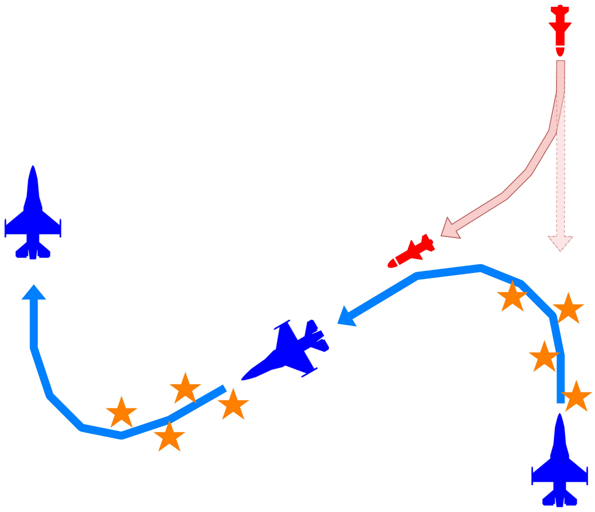


Figure 10. Evasive maneuver performed to evade SAM

The combination of the two triggers gives the basic ability to evade the missile and to check if the first maneuver was successful. When the missile evasion triggers are activated, the triggers for the ground engagement and SEAD/DEAD elements are disabled. This is done to give priority to the "survival" actions. If the missile evasion was successful, the aircraft returns to the route and all triggers are re-enabled. The distances of seven and three nautical miles were determined based on initial trials, to calibrate the survival rate for the baseline mission.
Lastly, a fifth trigger checks whether the aircraft used all onboard effectors. If it did, the aircraft turns west and accelerates to Mach 1.5. As soon as it left the predefined mission area, the aircraft is removed from the simulation. This behavior also is triggered after 15 minutes of mission duration.

SAMs

The SAM systems behave in a simpler way when compared to the aircraft. Both types of SAM turn on their ACQ at the start of the mission. If the ACQ identifies a target and the target is within engagement range, the SAMs switch over to the TTR. When a targeting solution is generated and the missiles are launched, the missile guidance radar is turned on as well, if applicable.
Neither SAM type discriminates between aircraft and missiles. However, only SAM-1 engages incoming missiles, as SAM-2 is not able to create a target track for blue missiles, due to a worse radar system.

3.5. Design of Experiment

The goal of this test case is a proof of concept to assure that the framework is able to produce meaning full results. It is expected that results analysis should be able to identify driving and less relevant parameters for the mission success as well as to reveal tendencies introduced by varying parameter over SoS and aircraft level.
As mentioned before, this study focuses on the parameters SEP, RCS, strike group size, and Air to Ground Missiles (AGM) loadout. These parameters are varied during the experiments. For the mission, a formation is assembled, consisting of a varying amount of identical aircraft. If an aircraft design aspect is varied, it is changed for all aircraft within the formation. The Ranges applied to the DoE are presented in Table 4.

Variable	Range
SEP	134m/s to 254m/s
RCS delta	+5dBm^2 to -15 dBm^2
AGM loadout	2, 4, 6
Strike group size	3, 4

Table 4. DoE variable ranges

The RCS of the baseline aircraft is varied in steps of 5RCS of the baseline aircraft is used as a reference. Three aircraft receive an RCS attenuation (-5, -10, and -15dBm^2), while one aircraft receives an amplification of 5dBm^2. This yields five experiments concerning the RCS. The minimum value of -15dBm^2 is based on experiments concerning RAM coatings and is deemed achievable [27].
Next, the SEP of the baseline aircraft is altered. As a reference point, the initial phase of the mission is chosen. At speed and altitude en route to the mission area, the baseline aircraft has an SEP of 194m/s. From here, the SEP is varied in steps of 30m/s. Two aircraft receive a lower SEP (134 and 164m/s) via VAMPzeroF. Two aircraft receive a higher SEP (224 and 254 m/s). The upper limit is determined by the aircraft design tool's limit to converge to a meaningful aircraft design. The lower limit is choosen in a way the SEP is the driving factor in the sizing process, hence blow the minimum value the other TLARs become the driving factor for the aircraft design. Again, this yields five experiments concerning SEP.
The aircraft formation composition is varied by building one formation of four aircraft (as in the baseline mission) and one formation of three aircraft. This yields two experiments involving the formation composition.
Lastly, the loadout of the aircraft is varied. As the focus lies on the SEAD/DEAD elements of the mission, the aircraft receive varying amounts of AGMs. The baseline aircraft each carry two AGMs, one set of aircraft carries four, and another set carries six. This results in three experiments capturing the payload configuration.

The DoE is conducted as a full-factorial study, i.e. there is an experiment for every possible combination of parameters. This results in 150 distinct simulations. All results are averaged over 60 runs, as determined in Subsection 4.1, resulting in 9000 simulation runs.

4. RESULTS AND DISCUSSION

This section discusses the results of the DoE described before. That includes uncertainty analysis in order to assure confidence of the numbers and the reduction of randomization effects. During the study the focus lays on survivability and how effective the mission was conducted in terms of used equipment with reference the the varied parameters.

4.1. Uncertainty Reduction

To reduce uncertainty effects affecting the mission outcome the plugin architecture of the simulation was used to loop missions until convergence is reached. Figure 11 and Figure 12 shows the investigations conducted to determine the number of repetitions necessary.

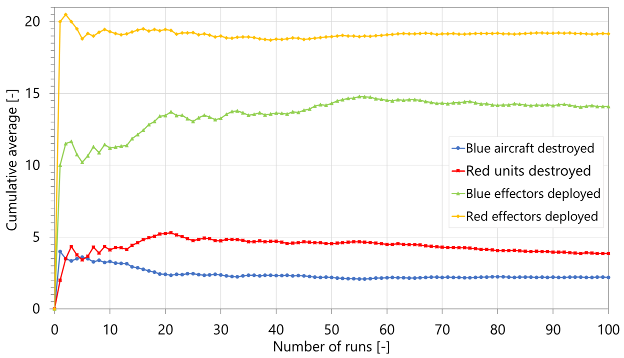


Figure 11. Standard deviation of all previous runs for each run

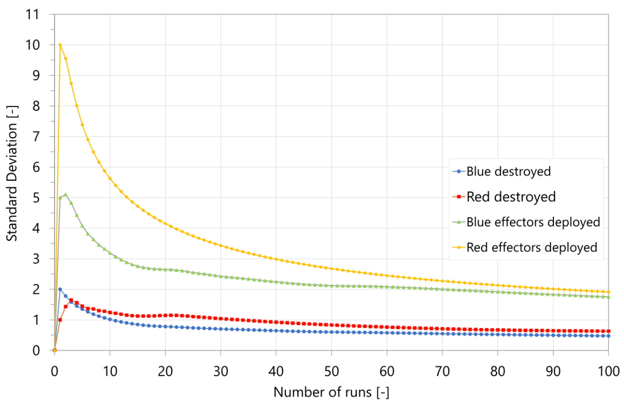


Figure 12. Convergence of results. Shown is the cumulative average over the number of runs conducted.

Tests conducted on the scenario revealed that approximately 60 repetitions of each mission were required to effectively capture the inherent randomness and reach a stable state while minimizing run time. Red platforms destroyed shows a stable decrease instead of convergence to one value. Investigation shows AGM kills also converge, the effect can be tied back to a decrease of hit to launch ratios of the laser guided bombs. Although, even much higher repetition numbers do not lead to convergence of that parameter, the development is stable and not random. Therefore effects of aircraft design changes also reflect in a meaningful manner on the red platforms destroyed parameter. The variation of near the chosen amount of simulation runs per mission was considered acceptable, especially because the tendency of this study to focus on the blue team.

4.2. Measures of Effectiveness

Conceptual aircraft design typically uses Measures of Performance (MoP), e.g. weight, sustained g level turn capability, RCS or SEP. On SoS level MoEs represent metrics or numerical indicators of the SoS level capabilities. Accordingly, the subsequent analyses will make use of MoEs proposed by [11] and [12]. This study will concentrate on MoEs relevant for survivability, sustainment mission success and affordability:

- Survivability S = Percentage of surviving blue platforms
- Lethality L = Percentage of destroyed red targets
- AGM = Number of blue AGMs launched

All these MoEs are derived from the mean of all runs conducted per mission. Inspired by [28] these three MoEs form a combined MoE to provide a single numerical value to capture the mission success. In the following the Mission Success Rate (MSR) represents that value. Several considerations are taken in the selection process of the input parameters for the MSR, placing focus on the survivability, sustainment and target success. The three selected parameters are the converted mission goal to represent the success to destroy as many red targets as possible. While doing the chance for each platform to survive and the number of AGMs used represent survivability and costs of the operations. The combined MoE is then formulated by addition of weights to resemble their relevance for complete mission success in Equation 4.

$$MSR = w_1 \times S + w_2 \times TL + w_3 \times \frac{AGM_{launched}}{AGM_{carried}} \quad (3)$$

The default weights consist of:

$$w_1 = 0.60; w_2 = 0.20; w_3 = 0.2 \quad (4)$$

Prioritizing survivability with 60% over 20% weighting of lethality and 20% weapon usage indicates the importance of protecting the expensive platform and its pilot. AGM usage is included to reward an efficient execution of the mission.
Affordability is determined by calculating the cost estimate, taking into account mission losses and the quan-

tity of weapons utilized by the blue side. To arrive at these cost estimates, the data from Table 5 are used.

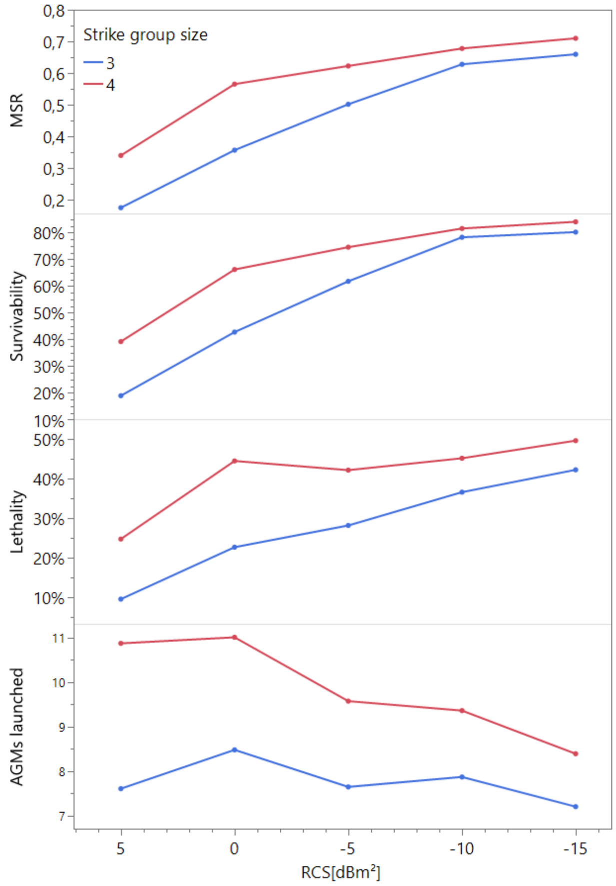
Entity	Acquisition cost [$Millions]
F-18	29.00 [29]
F-35	90.09 [11]
AGM	0.316 [30]
GPS-guided Bomb	0.022 [31]

Table 5. Acquisition cost data

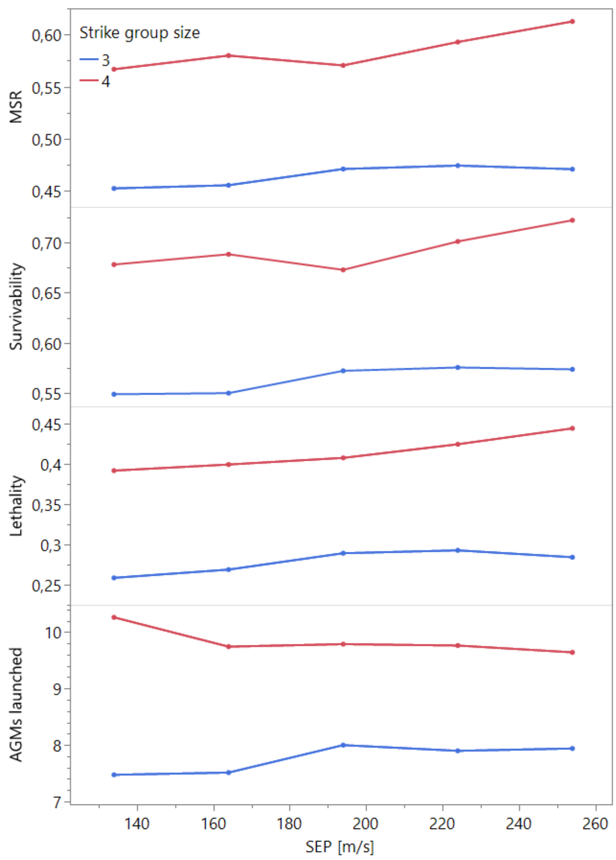
A notional mapping approach was selected for the cost of blue platforms through linear interpolation. The authors do not claim this as an accurate modelling approach of real life costs for fighter aircraft, but it gives quick estimation of the acquisition costs of an individual aircraft tailored to its performance. A platform with the highest RCS the lowest SEP and AGM load value has the lowest cost. A platform with the lowest RCS, the highest SEP and AGM load has the highest cost. A uniform impact of cost was distributed over the three impact parameter.
As previously mentioned, the authors have established the default weighting factors and cost distribution notionally. They may be selected differently by others. In the subsequent sections, we will delve into additional design considerations, where we will explore various sets of priorities. This shift in focus will emphasize aspects such as lethality, for example, trade-offs between different design points are discussed.

4.3. Results

The tested framework describes the transfer of design information, starting from requirements and progressing through the generation of input data for conceptual design, then reviewing the outcomes of the conceptual design phase, followed by the preparation of inputs for operational analysis, and ultimately leading to the determination of resultant MoEs described in the chapter above. This sequential flow enables the ability to trace back through each stage, facilitating an analysis of sensitivities and interdependencies among variables at every step. All numbers show the average of all respective missions.
The effect of RCS and SEP on the MoEs with different strike group sizes are exemplarily presented in Figure 13, with limited TLAR variations.
The metricises show, that larger strike groups and decreasing RCS result in an improved MSR, survivability and lethality. The number of launched AGM is diminishing. Nevertheless, both strike group sizes perform better overall with decreasing RCS. Low RCSs allow the aircraft to approach their target closer and increase the chance to destroy it, with smaller number of attacks. For the mission investigated here, the framework allows to identify the SEP to have less impact on all MoEs, even though a small positive impact is notable. Note that maneuvers are fixed for the CONOPS applied here. Different maneuvers might lead to a higher impact of SEP.



(a) Sensitivity of RCS variation



(b) Sensitivity of SEP variation

Figure 13. Sensitivity of RCS and SEP variation and the impact of different strike group sizes on MoEs

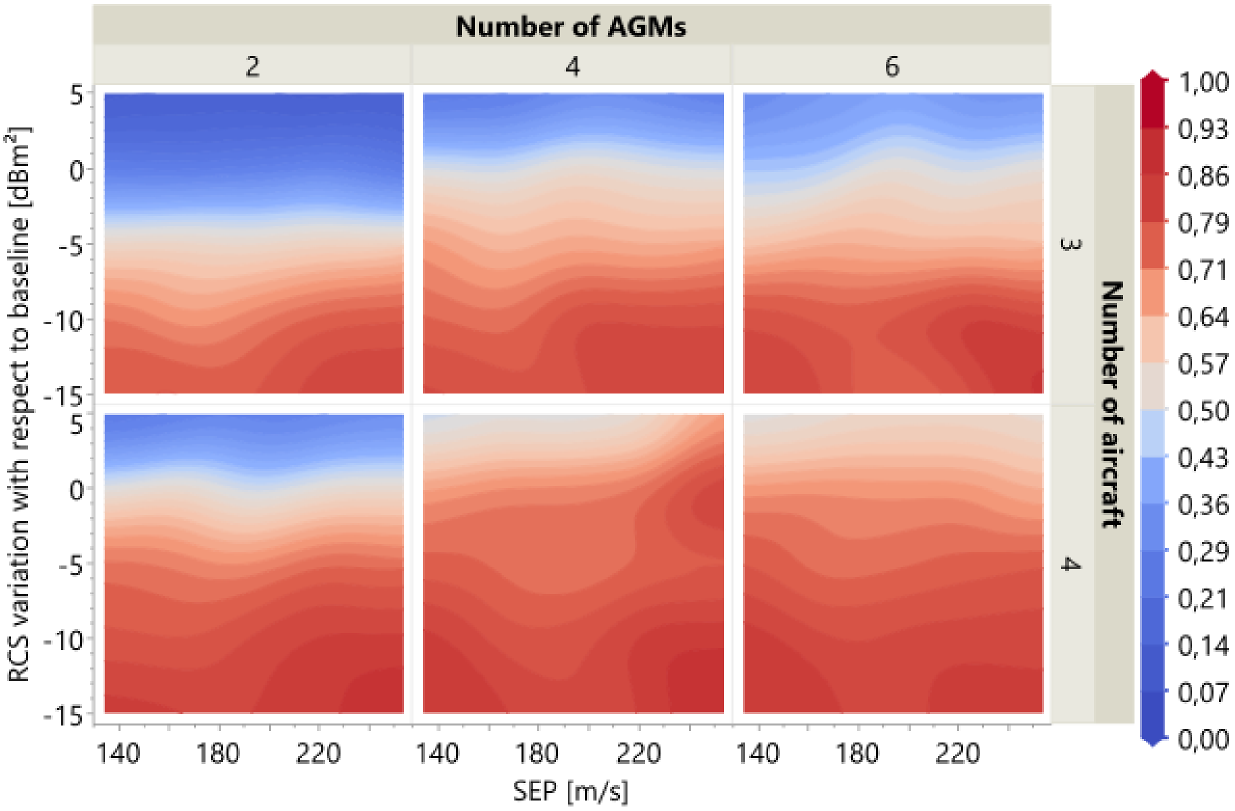


Figure 14. Investigation of the optimal top level aircraft requirements depending on the strike group size.

The TLAR sweep is presented in Figure 14, Figure 15 and Figure 16. Note that the colour gradients are not set for quantitative comparison, but are meant to show the qualitative trends in this figure.

In order to find a robust optimal with respect to survivability, the variation of SEP and RCS over strike group sizes as well as AGM loaded are presented in Figure 14. The colour gradients represent the survivability and therefore the number of surviving blue aircraft divided by the number of initial blue aircraft.

As expected the blue team looses less aircraft with smaller RCS and higher SEP due to lower traceability by the hostile ground threats and higher accelerations and climb ability to evade hostile missiles. Although this graphic confirms the low impact of SEP the optimum can always be found in the lower right corners. While a design payload with four AGMs increase survivability compared to two AGMs, the strong increasing size and weight of the aircraft result in a survivability decrease to six AGMs. For the effect of the strike group size the evaluation shows as expected that the number of forces play a significant role on the battlefield in gaining an advantage. Nevertheless in the region of the high observable aircraft designs and low AGM design numbers more aircraft can also lead to more casualties.

The effects of RCS over SEP with different strike group sizes and AGM load on the replacement costs are presented in Figure 15.

The graphic shows that the highest mission costs are mainly driven by the aircraft design. The loss of one individual aircraft is much more expensive than the excessive use of weapons can be. Indicated by the highest cost numbers in each right top corner shows the interaction of aircraft acquisition cost based on performance and aircraft losses. While the highest acquisition cost would be found at low RCS and high SEP numbers, the mission replacement costs maximises for high RCS and high SEP. That is an expression of the high survivability of low RCS platforms and the small impact of SEP. With decreasing RCS the development of mission cost becomes flatter. In low RCS regions the survivability dominates over the growing cost of individual aircraft via SEP. Looking at the other parameters, the effect of the increasing AGM design load results in increasing mission cost. Reason is the higher usage of missiles and higher aircraft cost. The strike group size does not have an unique impact, but is related the RCS. Using highly observable platforms the strike group has a positive effect on cost, due to higher survivability, despite the higher weapon usage. Low observable platforms can lead to higher mission costs with increased strike group size. Even though the survivability is increasing the chance that one aircraft loss occurs is higher. That has a high impact in design regions that often end up without any aircraft losses.

The investigation of weighting criteria for the mission evaluated shows the effect of varied priority in mission evaluation. Note that the priorities does not reflect on the agent behavior. The presented optimal TLARs are established on a MoE as defined by the authors, representing their earnest endeavor to formu-

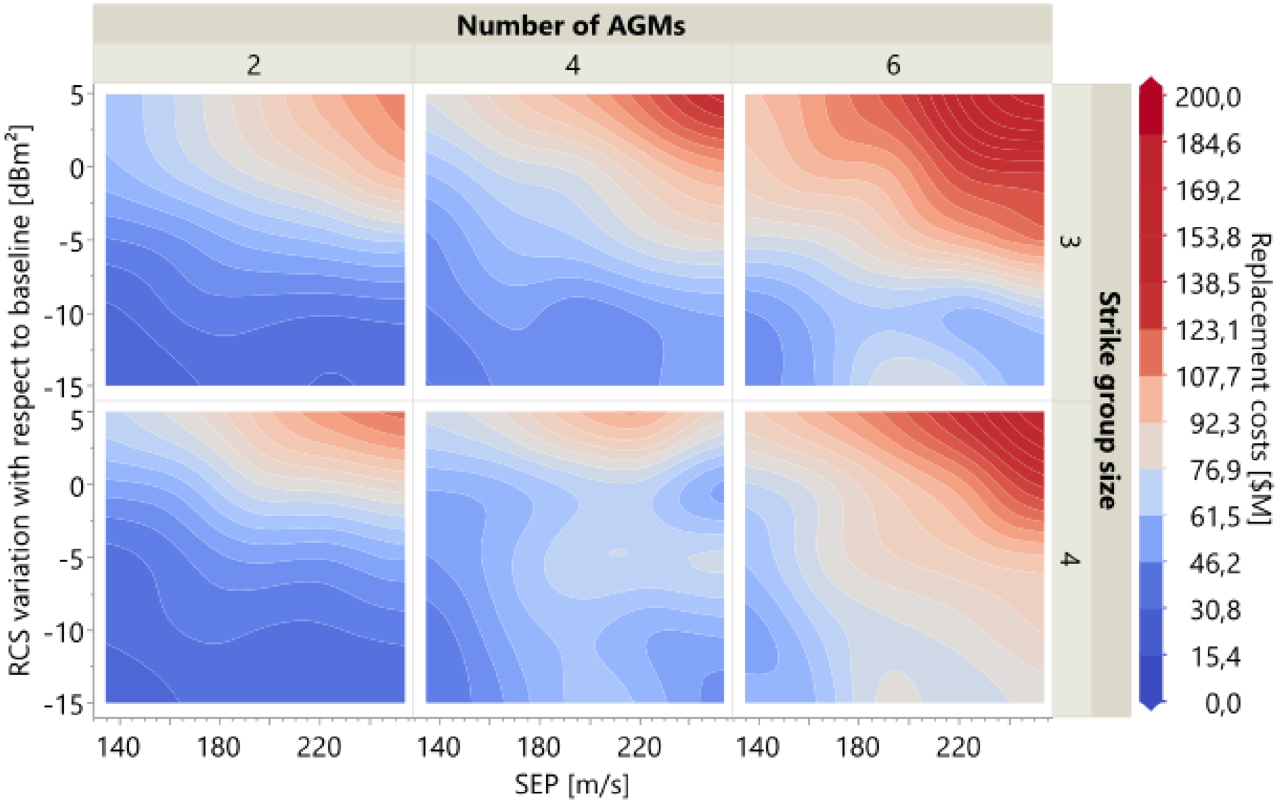


Figure 15. Trade-off between RCS, SEP, strike group size and cost.

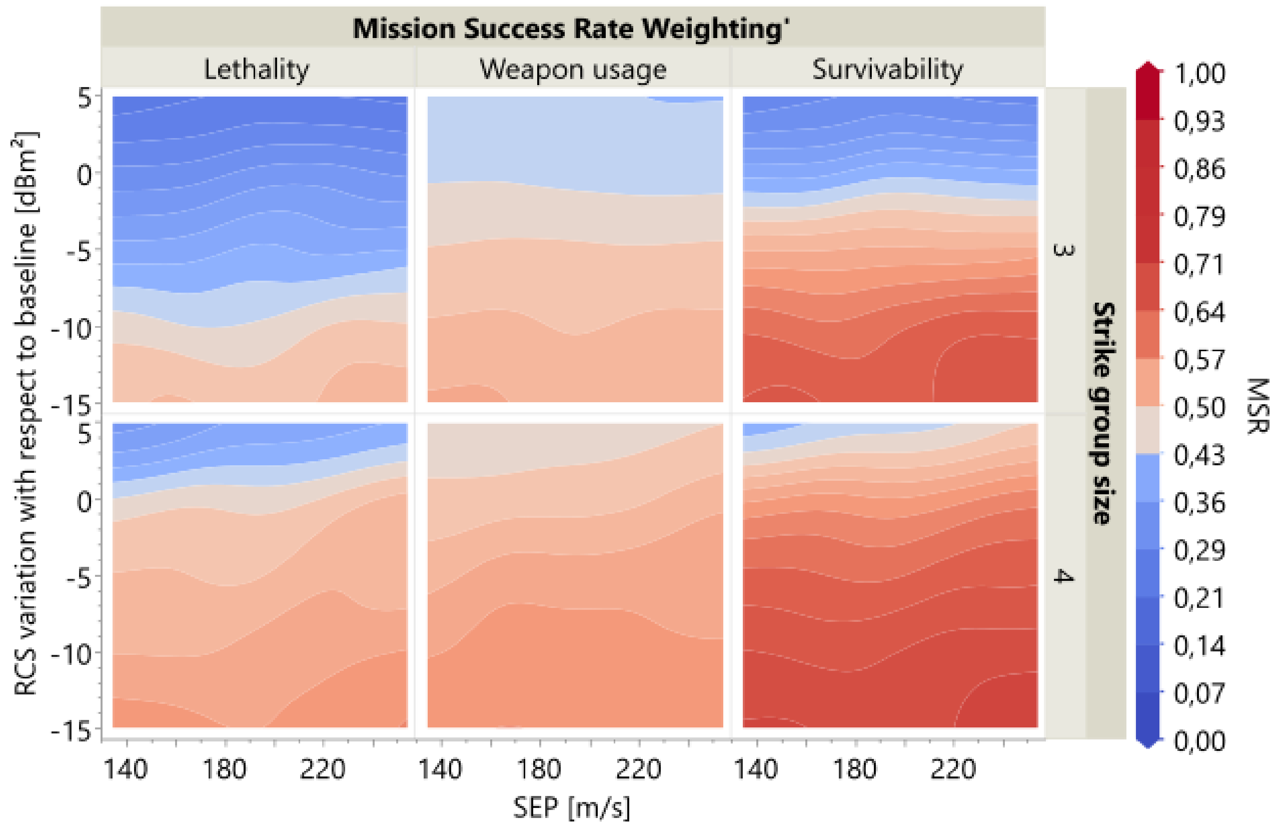


Figure 16. Investigation of different weightings regarding the combined MSR (Survivability: $w_1 = 0.60, w_2 = 0.20, w_3 = 0.2$; $Equal : w_1 = 0.2, w_2 = 0.2, w_3 = 0.6$; $Lethality : w_1 = 0.2, w_2 = 0.60, w_3 = 0.2$).

late a straightforward and logical set of criteria for MoE. It's important to note that others may identify alternative criteria for inclusion or may assign varying levels of importance to them. Figure 16 shows the effect of strike group size, AGM design load, RCS and SEP on MSR as calculated by Equation 4 in Subsection 4.2. A high MSR in the weapon usage column symbolizes a minimized use of bombs and AGMs.

Comparing the the priorities shows that all are dependent on RCS. Prioritizing survivability is achieves the best MSR, but also shows higher dependency on aircraft design parameters, especially RCS. A minimized weapon usage shows the most uniform result distribution over all parameters, being influenced the least by the aircraft design. Within the used mission setup and aircraft design lethality shows the lowest MSR values. Last, the strike group size shows an increase of MSR over all priorities.

This small study is presented to demonstrate the capability of the framework: The optimal concepts can be derived based on various developer or operator priorities.

5. CONCLUSION AND OUTLOOK

This paper builds upon an previously developed SoS framework within the DLR Institute of Systems Architectures in Aeronautics, enhancing its capabilities for the design and assessment of fighter vehicle architectures and strike groups to air-to-ground scenarios, further MoEs and evaluation methods. It highlights the integration of ABM into the SoS simulation-driven design process to improve the aircraft design. The framework is designed to capture the dependencies of various systems and their multilevel dependencies. As a practical demonstration, the authors successfully evaluated the performance of a fighter aircraft similar to the F-18 in a counterland AI scenario, involving complex agent behaviors and a comprehensive analysis with over 900 data points. The study reveals intricate interactions between fighter vehicle architectures, TLARs, agent behavior, and strike force sizes, offering proof of concept for a holistic evaluation framework within the context of SoS by combining insights from various fields. It demonstrates the robustness of the framework across multiple mission scenarios.

Significantly, the research clarifies how mission performance parameters such as survivability, replacement cost and MSR vary in response to factors like strike group size, TLARs, design specifications, and subsystem equipment variations. Multiple homogeneous fleets with varying strike group sizes were created and assessed using Agent-Based Simulation, taking into account TLARs, equipment, collaboration and behavioral aspects. These sensitivities were evaluated using a set of the authors best attempt to formulate a suitable set of MoEs. Different users might choose mission or cost priorities differently. The results suggest that, among all the trade-offs considered, low RCS has the highest impact on the battlefield. Furthermore, increased weaponry and a higher strike group size lead to increased mission success but can also result in high losses of blue aircraft. The most significant effects occur within the strike group size change from three to four. Combining high strike group sizes with high RCS aircraft shows increased number of lost aircraft increase despite the increased mission success. That is also visualized in the replacement cost, which are mainly driven by the cost of the single aircraft. In the mission at hand, bigger strike group sizes have also a negative impact on mission costs in certain design regions. Overall the study shows, that the choice of aircraft design specifications, especially RCS and number of carried weapons, needs to be made carefully, as it influences mission outcomes to a high degree. A TLAR selection tailored to specific mission scenarios, informed by SoS evaluation, can make a noticeable difference. Nevertheless the evaluation of this specific scenario also shows less influential parameters. Assessing the mission at hand the SEP shows only a small positive effect on MSR compared to the other varied parameters. It can also lead to higher losses and with it cost in certain design regions due to the increased size of the aircraft. It is important to mention that different mission designs and maneuvers might lead to a higher SEP impact on mission performance. That needs to be investigated in the future.

The paper acknowledges certain limitations, such as not considering real-world tactics, coordinated shots, and electronic warfare in depth or only addressing them in a simplified manner. The authors recognize the need to expand the simulation capabilities to confidently apply the framework in larger-scale research projects.

They study shows the importance of minimizing the RCS for mission success. For this paper the RCS was not determined based on changes within the aircraft geometry but purely handled as a direct input. For future research a link needs to be established between the geometry of the aircraft and a sufficient RCS determination.

In general future research goals include addressing these topics more comprehensively and further extending the framework. With respect to mission priorities introduced in this paper coming evaluations should have implications of priorities not only on evaluation but also agent behavior. Beyond that collaboration aspects and mission planning alongside tactics, communication as well as guidance and control are desired to be evaluated in the future. Finally the authors aim to cover additional use cases and subjects like crewed-uncrewed teaming, heterogeneous fleets, and design methodologies of loyal wingmen and remote carrier.

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