Design of Loyal Wingmen and Their Integration into a Strike Aircraft Group

A System of Systems Approach

Felix Kuhnert

TU Delft

Design of Loyal Wingmen and Their Integration into a Strike Aircraft Group

A System of Systems Approach

Thesis report

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Felix Kuhnert

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Thesis committee:	
Chair:	Dr.ir. M.F.M. Hoogreef
Supervisors:	Dr.ir. R. Vos
	P. S. Prakasha
	T. Dietl
External examiner:	Dr.ir. J. Ellerbroek
Place:	Faculty of Aerospace Engineering, Delft
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Student number:	4353811

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Preface

> Wer aber den Frieden will, der rede vom Krieg.
> *He who wants peace must speak about war.*
>
> *Walter Benjamin*

When discussing military technology, strategies, or the defense industry, one often encounters the Latin phrase "*Si vis pacem, para bellum*". If you want peace, prepare for war. The translation implies that war, or at least a threat thereof, is a necessity to preserve peace. Large parts of the public resent this sentiment. Instead, many prefer to completely exclude this sentiment and the thought of war from the public discourse.

However, simply not talking about war does not lead to peace. Instead, society forgets about the consequences and becomes woefully unprepared. The German philosopher Walter Benjamin found this troubling. After witnessing WWI, he felt there could be no peace after the nightmares and terrors of the war. In his opinion, the only way of ensuring peace and avoiding another war is to talk about it and the suffering it brings. The tragedy of war must be remembered, and mankind must be aware of the consequences to understand that war must be *the very last resort*. Consequentially, Benjamin adapted the original quote to "*Wer aber den Frieden will, der rede vom Krieg*". He who wants peace must speak about war.

This thesis does speak about war. It should not be understood as glorifying war and conflict but as the opposite. As a society, we must stay open-minded, and we cannot avoid the topic if we want to prevent terrible suffering. We owe it to our ancestors and the victims of war and terror worldwide. Lest we forget.

Felix Kuhnert
Hamburg, August 2024

Contents

Nomenclature

List of Abbreviations

CAS Close Air Support

CF Command Fighter

CPACS Common Parametric Aircraft Configuration Schema

DARPA Defense Advanced Research Projects Agency

DLR German Aerospace Center

DoE Design of Experiment

EW Electronic Warfare

FCAS Future Combat Air System

IADS Integrated Air Defense System

J-UCAS Joint Unmanned Combat Air Systems

KBE Knowledge-Based Engineering

LCS Littoral Combat Ship

MANPADS Man-Portable Air-Defense System

MDO Multidisciplinary Design Optimization

MoE Measure of Effectiveness

MoP Measure of Performance

MSF Mission Success Function

MSS Mission Success Space

MTOM Maximum Takeoff Mass

NGF New Generation Fighter

OEM Operative Empty Mass

RC Remote Carrier

RCS Radar Cross-Section

SAM Surface-to-Air Missile

SEAD Suppression of Enemy Air Defenses

SEP Specific Excess Power

SoS System of Systems

SoSE System of Systems Engineering

TLAR Top Level Aircraft Requirement

TSFC Thrust Specific Fuel Consumption

UAV Unmanned Aerial Vehicle

UCAV Unmanned Combat Aerial Vehicle

β Factor

γ Factor

σ Algebraic Sign (+/-)

List of Symbols

a Time of Target Acquisition

b Wingspan

J Mission Effectiveness

j Measure of Effectiveness

$j_{\text{attrition}}$ MoE for Attrition

j_{cost} MoE for Cost

j_{effector} MoE for Effector Attrition

j_{fighter} MoE for Fighter Attrition

$j_{\text{lethality}}$ MoE for Lethality

j_{SAM} MoE for Lethatlity Against SAMs

$j_{\text{survivability}}$ MoE for Survivability

j_{tank} MoE for Lethatlity Against Tanks

j_{wingman} MoE for Wingman Attrition

L_{tot} Aircraft Overall Length

$n_{\text{effector,carried}}$ Number of Effectors Carried

$n_{\text{effector,expended}}$ Number of Effectors Expended

$n_{\text{fighter,destroyed}}$ Number of Fighters Destroyed

$n_{\text{fighter,total}}$ Number of Fighters Total

$n_{\text{SAM,destroyed}}$ Number of SAMs Destroyed

$n_{\text{SAM,total}}$ Number of SAMs Total

$n_{\text{tank,destroyed}}$ Number of Tanks Destroyed

$n_{\text{tank,total}}$ Number of Tankss Total

$n_{\text{wingman,destroyed}}$ Number of Wingmen Destroyed

$n_{\text{wingman,total}}$ Number of Wingmen Total

$P_{\text{PL,max}}$ Maximum Power Consumption of the Payload

P_{S} Probability of Survival

$PROG_{100}$ Dry Thrust-to-Weight Ratio

q_{ssk} Single Shot Survivability

r_{d} Reciprocal of Mean Time of Detection

r_{k} Average Rate of Fire

s_1 Time Spent Within Detection Envelope

s_2 Time Spent Within Lethal Envelope

T/W_{dry} Dry Thrust-to-Weight Ratio

T/W_{wet} Wet Thrust-to-Weight Ratio

V_{max} Maximum Flight Speed

w Weight of Measure of Effectiveness

W_{avion} Avionics Weight

W_{ECS} Environmental Control System Weight

w_{effector} Weight for MoE for Effector Attrition

W_{elec} Electrical Systems Weight

w_{fighter} Weight for MoE for Fighter Attrition

W_{PL} Payload Weight

w_{SAM} Weight for MoE for Lethality Against SAMs

w_{Tank} Weight for MoE for Lethality Against Tanks

w_{wingman} Weight for MoE for Wingman Attrition

A Aspect Ratio

AUW Aircraft Unit Weight

n Load Factor

List of Figures

List of Tables

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 [1], UCAVs like *Predator*, *Reaper*, and *Global Hawk* revolutionized modern warfare. Engineers and military decision-makers had long envisioned UCAVs replacing manned fighter aircraft [2], 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” [3]. The *Unmanned Tactical Aircraft* concept they described back in 1995 is nowadays known as the *Loyal Wingman*.

The advantages of a Loyal Wingman are manifold:

- Wingmen 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 a Loyal Wingman is highly networked with the Command Fighter, the concept also brings additional benefits [4, 5]:

- Using sensor fusion, the Wingman can increase the situational awareness of the command fighter pilot.
- The pilot’s workload could be decreased, increasing their effectiveness. For example, the Wingman 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 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 some ethical concerns.

Recognizing these advantages, many countries have initiated the development of Loyal Wingmen. Notable examples include the XQ-58 *Valkyrie* by Kratos Defense and the MQ-28 *Ghost Bat* from Boeing Australia.

While significant efforts have been undertaken to develop Wingman 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. This thesis seeks to contribute to the finding of such a proof of concept. Furthermore, an attempt is undertaken to gain insight into the ”optimal” design and requirements for a Loyal Wingman and Wingman Concepts of Operations (CONOPS). To do so, this paper presents a novel approach for designing and evaluating novel aircraft configurations operating as an element of a larger System of Systems. This is done by combining System of Systems Engineering with Knowledge-Based Engineering and Agent-Based Modeling in the form of combat simulations.

Part I of the thesis presents the majority of the work as a scientific paper. The paper describes the problem and methodology applied to close the identified gap in the literature. Furthermore, steps are undertaken to validate the methodology. Additionally, a comprehensive result analysis is performed, and conclusions are presented.

Part II presents the results of an extensive literature survey, which was performed to support Part I. The literature research covers the historical development of UAVs and UCAVs, touches upon modern aircraft design methods, and examines the peculiarities of designing unmanned aircraft.

Lastly, Part III provides further work which was performed in support of Part I. This includes the selection of an appropriate aircraft tail configuration, a tradeoff for choosing the wing's Aspect Ratio, and an extensive explanation of the *Fuzzy Analytic Hierarchic Process* that is applied in Part I.

Part I

Scientific Article

Design of Loyal Wingmen and Their Integration into a Strike Aircraft Group: A System of Systems Approach

Felix Kuhnert*
Delft University of Technology, Delft, 2628 CD, The Netherlands

Manned-Unmanned teaming with Loyal Wingmen is part of every current future fighter concept. However, while much effort is put into design and research, it remains to be seen whether the inclusion of Wingmen 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 Wingmen 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 derived Measures of Effectiveness of Mission Effectiveness, Survivability, Cost, and Lethality. The performance of formations including Wingmen is compared to the performance of modern tactics. The results show significant improvements in mission outcomes when Wingmen are deployed. Optimum results are achieved with Wingmen featuring slightly reduced Radar Cross-Section and balanced Specific Excess Power. The Concept of Operations has an effect, too. Fewer Wingmen carrying a larger number of weapons yield higher overall survivability than more but smaller Wingmen. The inverse holds for overall lethality. The results provide valuable insights into the optimal design and function of the Loyal Wingman concept.

I. Introduction

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*Student, Faculty of Aerospace Engineering

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

Fig. 1 Render of a Loyal Wingman developed by Airbus *

While significant efforts have been undertaken to develop Wingman 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 the Wingman concept. Examples are the control algorithms [6], decision-making [7], or the design of the UCAV [8]. However, as others have shown [9, 10], 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 Loyal Wingmen, examples of such SoS analyses exist [11–13] but are of low fidelity and have little connection to aircraft design aspects. A publication that stands out was written by a working group at the Airbus Future Projects Office. The group applied agent-based modeling to a combat scenario and concluded that including Loyal Wingmen offers a "force multiplication" [14]. However, they do not share any results apart from the conclusion. Thus, the proof of concept of the Loyal Wingman is still missing. Whether the inclusion of Wingmen yields a better mission outcome remains to be seen. Also, it has yet to be shown if the Wingman concept brings the advantages it promises. Lastly, it remains unclear what a Wingman 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 Loyal Wingman and Wingman 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 Loyal Wingmen have on a strike aircraft group's effectiveness?*

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

Question 2 *What is the optimal design of a Loyal Wingman for a given combat mission?*

Question 3 *What is the ideal tactic for using Loyal Wingmen, 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 Loyal Wingmen are designed based on the TLARs using the Knowledge-Based Engineering (KBE) tool *VAMPzeroF*, 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*† (MACE).
- A parameter study is conducted by deploying the varying Wingman 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 Measures of Effectiveness (i.e., Mission Effectiveness, Survivability, Cost, Lethality), varying designs are compared to each other and to established baselines to conclude on Wingman design, CONOPS, and the concept's validity.

*https://www.airbus.com/en/newsroom/press-releases/2024-06-unmanned-escort-for-manned-fighter-jets-airbus-presents-new-wingman

†https://www.bssim.com/mace/

Neither of the steps listed above is unheard of. However, a combination of the individual steps is rare. Furthermore, this method has not yet been applied to the analysis of the Wingmen concept, Remote Carriers, or Mannend-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 System of Systems.

The steps outlined above also serve as the structure of Section II, which covers the methodology. Section III treats the validation of the outlined methods. The results are presented in Section IV. Section V details the conclusions drawn from the discussion of the results.

II. Methodology

This section shows and explains the methodology. Section II.A describes the scenario and how it is derived. Section II.B shows the steps of UCAV design, while Section II.C provides an insight into the agent-based model and the software used. Section II.D shows the Design of Experiment. Lastly, Section II.E presents the definition and derivation of the Measures of Effectiveness.

A. Scenario

To assess the potential benefits of wingman integration, a scenario that challenges the individual aspects addressed by Wingmen 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 Wingman and the pilot.

When thinking about dangerous missions, the first type that comes to mind is the Supression 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 [15]. 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 Wingmen. Thus, the scenario is constructed around Red (enemy) SAM systems.

Another potential benefit of Wingman integration that is brought up frequently is the task distribution between Wingman 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 Wingman 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, the 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.

B. Wingman Design

This subsection is further subdivided into smaller elements. Section II.B.1 explains how the TLARs are derived, while Section II.B.2 goes into the details of the airframe design and *VAMPzeroF*. Section II.B.3 explains how the airframe cost is determined, and Section II.B.4 shows the radar cross-section derivation.

1. Requirements

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

- The Wingman should be interoperable with existing systems of European countries' air forces to facilitate integration and alignment of capabilities.

- The Wingman should operate like a "normal" fighter aircraft to reduce the need for additional support systems. Some concepts include catapult launches, deployments from larger carrier aircraft, or parachute recoveries. These CONOPS are purposefully excluded to limit the scope of this work.
- The Wingman 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 Wingman should be designed with stealth capabilities in mind to follow the design trend of 5^{th} and future 6^{th} generation fighter aircraft. Unfortunately, to analyze radar cross-sections, higher fidelity tools are needed that 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 "deadly sins" of RCS design (e.g., by storing the payload in internal bays).

Now, a set of functions and requirements can be derived from the scenario. First of all, to challenge the potential benefit of the Wingman of reducing the risk to the pilot, it shall perform the dangerous SEAD/DEAD elements of the mission. Based on this, the Wingman's mission profile can be determined. The military standard MIL-STD 3013B of the U.S. Department of Defense [16] provides a mission profile for a SEAD mission. It can be seen in Figure 2. The standard places the *Penetration/Withdrawal* segment at an altitude of 20,000 ft.

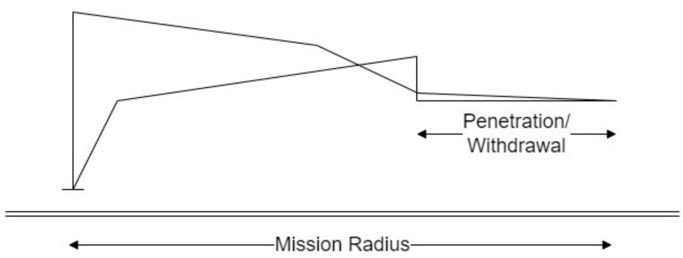


Fig. 2 Mission profile of a SEAD mission, adapted from MIL-STD 3013B[16]

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 3.

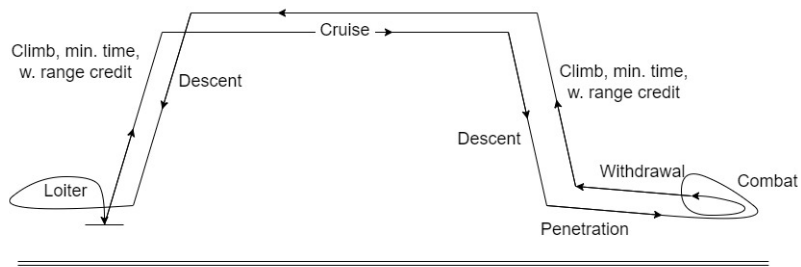


Fig. 3 Adapted *Interdiction HI-LO-LO-HI* profile from MIL-STD 3013B [16]

Having the mission profile, the individual segment lengths of the profile can be fixed. Since the Wingman 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 [17]. Accordingly, the Wingman shall also have a combat radius of 1390 km. Due to the lack of better values, cruise speed and altitude are fixed at Mach 0.8 and 10,000 m, respectively. Following MIL-STD 3013B, the radius of the *Penetration* and *Withdrawal* segments is fixed at 50 nmi (~ 90 km). The flight speed during those segments is Mach 0.8. However, based on the initial MACE trials, the flight altitude for airspace penetration provided by MIL-STD 3013B (2000 ft / 600 m) is deemed too high and reduced further to 500 ft (~ 150 m). Climb profile and loiter times are constrained according to the MIL-STD as well.

Following the argument of the Wingman 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 [18]. 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 [19]. This length is taken as takeoff and landing field length requirement for the Wingman.

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. Varying the sustained load factor also addresses the commonly used requirement for Specific Excess Power (SEP).

Another driving requirement is the Wingman's payload configuration. Given that the Wingman shall perform the SEAD role, its loadout shall consist of modern Anti-Radiation Missiles (ARMs). As one could imagine varying combinations of the number of Wingmen in formation and the number of missiles per Wingman, the number of missiles carried is also given as a range (2 and 4). Additionally, the Wingman 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.

Table 1 List of Wingman requirements

Requirement	Value
Combat Radius (HI-LO-LO-HI) [km]	1390
Cruise Altitude [m]	10,000
Cruise Mach Number [-]	0.8
Penetration Radius [km]	90
Penetration Flight Altitude [m]	150
Penetration Mach Number [-]	0.8
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]

2. Airframe Design

Following the establishment of requirements, one can continue with the aircraft design. The KBE tool *VAMPzeroF* [20] 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, Raymer, Torenbeek, and Airbus. 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 [21], this was done by generating a model of the F/A-18C *Hornet* in Air Interdiction configuration, using reference data from Jane's [22] and declassified manuals [23].

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" [4]. 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. Also, by subtracting the pilot's weight, weight savings of 266 kg can be achieved.

Next, the weights of the avionics W_{avion} are adjusted. Gundlach provides tables listing the weights of individual components for each UAV size category. The components included are autopilot, air data system, GPS antenna, onboard processors for signals intelligence (SIGINT), inertial navigation system, line-of-sight (LOS), and satellite communications. Out of the provided range, the heaviest element is always chosen. Because the avionics are a vital element, without which the Wingman cannot function, double redundancy is also implemented. The *signal* wiring harness is assumed to weigh 35% of individual components, again, the highest value from the range provided by Gundlach. A complete list of uninstalled component weights is given in Table 2. Gundlach provides weights in imperial units. Here, for consistency's sake, they are provided in SI units, rounded to the closest half number. Exact values are used in the implemented methods.

Table 2 List of avionics component weights as chosen from Gundlach's suggestions

Component	Uninstalled Weight [kg]
Autopilot	90.5
Air Data System (Boom)	9.0
GPS Antenna	0.5
INS (Northrop Grumman LN-100G)	10.0
SIGINT Processor	81.5
LOS Communications (L-3 Mini TDCL Transceiver)	8.5
SATCOM (based on Global Hawk UHF)	38.5 + 6.0 + 6.5 + 1.5 + 3.5
Signal Wiring Harness	89.5
Total	345.5

The avionics weight can now be used to determine the weight of the electrical systems W_{elec}. Gundlach provides the relation for the weight in lb, as given in Equation 1. $P_{\text{PL,max}}$ is the maximum power consumed by the electronic payload in W. The payload is assumed to consume a maximum power of 2000 W. L_{tot}, and b are the overall length and wingspan of the UCAV measured in ft. Again, double redundancy is implemented afterward.

$$W_{\text{elec}} = 0.003 \cdot (P_{\text{PL,max}} + 15 \cdot W_{\text{avion}})^{0.8} \cdot (L_{\text{tot}} + b)^{0.7} \tag{1}$$

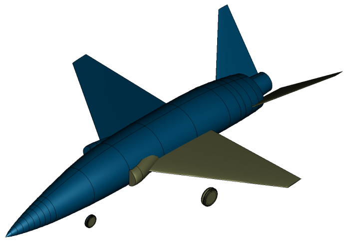
Finally, the last weight group, the Environmental Control System (ECS), can be modified. Initially, one may think that no ECS is needed, considering there is no pilot. However, the rather extensive avionics suite needs considerable cooling, too. For a UCAV, Gundlach refers to the "General Dynamics method" presented by Roskam [24]. It is given by Equation 2, where W_{ECS} is the ECS weight, and W_{PL} is the payload weight. Both are given in lb.

$$W_{\text{ECS}} = 202 \cdot \left(\frac{W_{\text{avion}} + W_{\text{PL}}}{1000}\right)^{0.75} \tag{2}$$

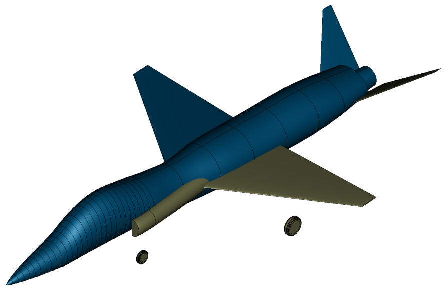
After implementing the new knowledge base, the Wingman designs can be generated. An exemplary Wingman (dubbed *Atreus*) can be seen in Figure 4a. The Wingman shown is designed for a sustained load factor of 7 g (14 g instantaneous) while carrying 2 ARMs in an internal payload bay. The afterburning turbofan is placed centrally inside the fuselage, with S-ducts concealing the fan blades. A dorsal, buried inlet as utilized on stealth aircraft like B-2, B-21, or X-47 had been preferred for its stealth properties. However, vortices can be shed from the fuselage during high-load maneuvers, making intake placement difficult. 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 3.

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 4b. As can be seen, the resulting aircraft is significantly longer than the Wingman. This is due to the additional volume required by the cockpit. While the Wingman'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 10952 kg, with an OEM of 6221 kg. So, indeed, assuming identical requirements, the manned fighter is about *10% heavier* than a comparable Wingman. It should be remembered that this result does not account for potential weight savings because of increased attritability/reduced



(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 Wingman

Fig. 4 Comparison of Wingman and manned fighter

Table 3 Key metrics of the exemplary Wingman. 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	Value
MTOM [kg]	9949
OEM [kg]	5858
W/S [kg/m^2]	485
T/W$_{\text{dry}}$ [-]	0.43
T/W$_{\text{wet}}$ [-]	0.64
V$_{\text{max}}$ [m/s]	386
Service Ceiling [m]	22,000
Length [m]	11.0
Wing Span [m]	9.6
Payload Mass [kg]	1036

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.

3. Airframe Cost

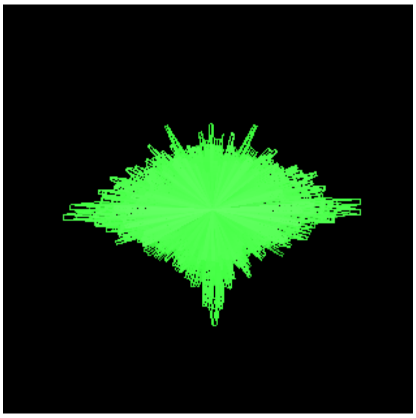
The airframe cost is determined by following a publication by the RAND corporation [25]. The authors conducted an exhaustive study of jet-powered fighter jets, ranging from F-4 *Phantom*, over F-111 *Aardvark*, to F-14 *Tomcat* and F-18 *Hornet*. The result was a collection of Cost Estimation Relations (CERs) that account for many parameters, like complexity and production methods. This paper uses their CER for the program cost, as given in Equation 8, 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 Wingman has a unit cost of 32,110,000 USD.

$$PROG_{100} = 550AUW^{0.812} \tag{3}$$

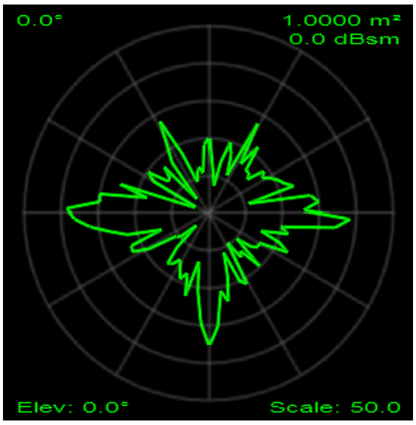
4. Radar Cross Section

As mentioned before, *VAMPzeroF* cannot generate radar cross-sections of 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 is shown in Figure 5. Figure 5a shows a three-dimensional view of the RCS, while Figure 5b shows a two-dimensional "slice".

While the F-18 looks considerably different than the designed Wingman, it is the available aircraft that comes closest. Thus, the Wingman RCS is modeled based on the MACE F-18 RCS. However, it is modified: to depict the impact of Wingman 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[‡]. 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 Wingman size. While this method provides results that are far from accurate, previously, it was applied by other authors, too [10].



(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.

Fig. 5 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 Wingmen 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 [26]. Beyond that shape modification would be necessary.

The MACE F-18 has an all-band average cross-section of 47 m^2. The exemplary Wingman RCS is reduced to 26 m^2 due to the scaling. Applying the RAM attenuation, the Wingman RCS reduces to 2.6, 0.26, 0.026, and 0.0026 m^2, respectively.

C. Agent-Based Modeling

Again, this subsection is split into smaller elements. Section II.C.1 explains the features and function of MACE, while Section II.C.2 explains how the scenario and DoE are implemented in MACE.

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

[‡]While RCS is commonly measured in m^2, it is unrelated to the physical size 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.

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.[27]

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.

Unfortunately, MACE's implementation has some side effects that must be addressed. MACE is a real-time application in Microsoft Windows. Other computer processes can influence MACE's execution. For example, a background process might be started, which requires additional resources. This can delay the execution of MACE, leading to a delay in agent reaction. This introduces some variance, even though the simulation is deterministic. Additionally, the simulation is hardware-intensive, especially for more complex scenarios and large agent numbers. Increasing the computational effort worsens the occurring variance. Because of this, attention has to be paid to the convergence of the simulation and Design of Experiment (DoE).

2. Scenario in MACE

Now that the scenario is known and the Wingmen 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 6

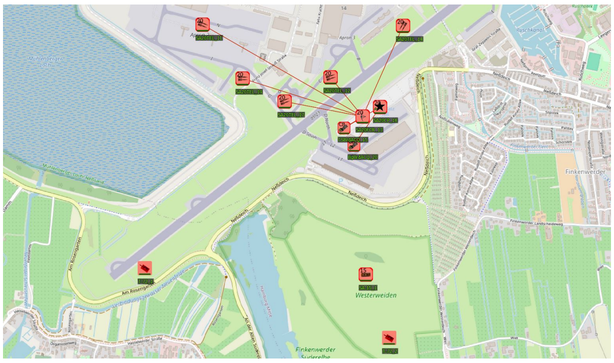


Fig. 6 Distribution of Red team in the mission area, as implemented in MACE

Blue Team To establish a baseline for comparison and to show the effects of differing Wingman CONOPS, multiple Blue teams are needed. For the baseline, the Blue team consists of *two Hornet*-like aircraft (*Blue-1* and *Blue-2*), based on the previously generated model shown in Section III.A.

For the baseline, the Blue fighters 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 (~ 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 18.

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 7. 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.

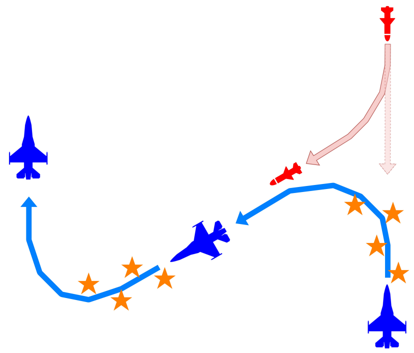


Fig. 7 Evasive maneuver of a Blue fighter. Countermeasures are depicted by stars. [21]

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 baselines to evaluate how the use of Wingmen holds up against more modern tactics.

Baseline 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 Baseline 2, *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.

Baseline 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 Wingman can be implemented into the MACE scenario. To gain some initial results separate from the parameter study, two Wingman cases are implemented: one where each manned fighter receives one Wingman and another case where each fighter receives two. The Wingman 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 Wingmen successfully destroy the SAMs, the fighters return, and the Wingmen return to formation. If the Wingmen run out of effectors, they act as decoys while the fighters return and engage. If the Wingmen are destroyed, the fighters also return and engage. The exemplary Wingman from Section II.B.2 is utilized (7g sustained turns, 2 internal ARMs, 10 dB RCS attenuation).

D. Design of Experiment

As mentioned, this study aims to conduct a parameter study that varies TLARs and Wingman 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 Wingmen are manually replaced by the 50 distinct Wingmen designs.

Table 4 Summary of DoE variables

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

As mentioned in Section II.C.1, the inherent nature of MACE introduces variance, which has to be accounted for. Thus, each of the 100 simulations has to be repeated until the results converge. To determine how many simulation runs are needed, one can visually inspect a convergence plot of a sample mission. It is shown in Figure 8. The figure shows the *cumulative* average μ over the number of runs N. Cumulative average means that $\mu = f(N)$ is the average of N runs. Four separate indicators are examined: the number of Command Fighters, Wingmen, SAM 1, and SAM 2 destroyed per mission. As can be seen, the sample mission was repeated 300 times. At around 110 repetitions, the results stabilize and converge to the mean. To have an extra margin, the number of simulation runs per case is set to 120.

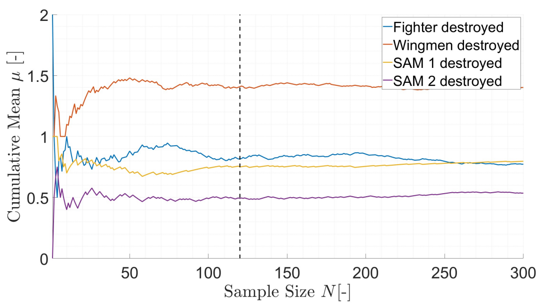


Fig. 8 Convergence plot of the results of the combat simulation

The study comprises 12000 separate runs, with 100 simulation cases à 120 repetitions. With one mission taking ~2.5 minutes[§], it requires 500 hours of computational time or ~21 days.

E. 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 4. 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.

$$J = \sum_{k=1}^{N} \sigma_k w_k j_k \tag{4}$$

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 [28]. The approach, dubbed *Fuzzy AHP*[¶], 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 Wingman is that it reduces the risk to the Command Fighter. Cost is also a recurring theme in the arguments for including Wingmen. While it was shown earlier that a Wingman 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, Wingmen, 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, Wingmen, effectors, and fuel. The cost of training a pilot is factored in as well[‖]. 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.

Using the three criteria, the quality integral can be described by Equation 5, where $j_{\text{survivability}}$ can also expressed as the complement of attrition $j_{\text{attrition}}$. This is done because the number of entities destroyed is a direct result of the simulation, which does not require extra manipulation.

$$J = w_{\text{survivability}} \cdot j_{\text{survivability}} - w_{\text{cost}} \cdot j_{\text{cost}} + w_{\text{lethality}} \cdot j_{\text{lethality}} \tag{5}$$

The MoE of attrition is expressed by Equation 6, where j is the ratio of entities of the type destroyed to the total number of entities of that type. In the case of the effectors, j expresses the number of effectors expended to effectors carried. Thus, j expresses the utilization of the resource. The individual contributions are listed in Equation 7. As can be seen, more weights are assigned to the Command Fighter, Wingman, and effectors. These weights are also determined using Fuzzy AHP, which allows the expression of the importance of the fighter and *pilot* relative to the others.

$$j_{\text{attrition}} = w_{\text{fighter}} \cdot j_{\text{fighter}} + w_{\text{wingman}} \cdot j_{\text{wingman}} + w_{\text{wighter}} \cdot j_{\text{wingman}} \tag{6}$$

$$j_{\text{fighter}} = \frac{n_{\text{fighter,destroyed}}}{n_{\text{fighter,total}}}, \qquad j_{\text{wingman}} = \frac{\mathrm{n}_{\text{wingman,destroyed}}}{n_{\text{wingman,total}}}, \qquad j_{\text{effector}} = \frac{\mathrm{n}_{\text{effector,expended}}}{n_{\text{effector,carried}}} \tag{7}$$

As with survivability, it makes sense to express the costs as a fraction. It is decided to evaluate cost as the ratio of the replacement cost to the *maximum* replacement cost. The costs are highest in the case of total attrition of the largest strike group of the most expensive Wingmen, carrying the maximum amount of weapons. The MoE of cost can be

[§]In mission time, the simulation takes ~ 17.5 minutes. However, thanks to an event-based and variable simulation speed, the simulation can be significantly sped up when the teams are not in contact.

[¶]AHP: Analytic Hierarchic Process

[‖]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.

formalized using Equation 8, where $cost_i$ is the cost of the individual item, be it Command Fighter, Wingman, pilot training, effector, or fuel.

$$j_{\text{cost}} = \frac{1}{cost_{\text{max}}} \sum_{i=1}^{k} cost_i \tag{8}$$

Lastly, $j_{\text{lethality}}$ is expressed similarly, as shown in Equation 9 and Equation 10.

$$j_{\text{lethality}} = w_{\text{SAM}} \cdot j_{\text{SAM}} + w_{\text{tank}} \cdot j_{\text{tank}} \tag{9}$$

$$j_{\text{SAM}} = \frac{n_{\text{SAM,destroyed}}}{n_{\text{SAM,total}}}, \qquad j_{\text{tank}} = \frac{n_{\text{tank,destroyed}}}{n_{\text{tank,total}}} \tag{10}$$

Table 5 lists the costs of individual items. A report from the RAND Corporation [29] lists the costs for training an F-22 pilot at 10.9 million USD, 10.2 million USD for an F-35 pilot, and 9.2 million USD for an F-15C pilot. Thus, the costs for pilot training are assumed to be 10 million USD.

Table 5 Costs of individual items, based on real-life counterparts

Item	Unit Price [$]
Command Fighter	62810000
EW Fighter	88950000
AGM	110000
ARM	870000
TALD	18000
Fuel (per kg)	0.6755
Pilot training	10000000

Seethaler, Strohal, and Stütz suggested that the weights be assigned *in a group* by providing a questionnaire to Subject Matter Experts (SMEs) [28]. The SMEs received an explanation of the criteria, method, and matrices in which they could assign linguistic variables. The SMEs were not in contact with each other and devised weights separately.

III. Validation

This section is divided into smaller parts, covering the validation of conventional fighter design in *VAMPzeroF* (Section III.A), Wingman design validation (Section III.B), cost validation (Section III.C), and RCS validation (Section III.D). Section III.E shows the validation of the Fuzzy AHP method.

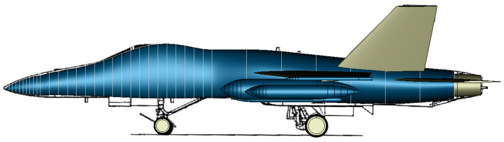
A. *VAMPzeroF* Calibration

As mentioned in subsubsection II.B.2, *VAMPzeroF* was calibrated using the model of a F/A-18C with Air Interdiction loadout for previous work. The side and top views are shown in Figure 9a and Figure 9b. For method validation, the model renders are laid over scale drawings of the F/A-18C. As can be seen, the resulting geometry comes remarkably close to the shape of the real-life fighter. The only notable difference is the absence of wing strakes in the *VAMPzeroF* model. While the strakes heavily impact the stall and turn performance, the effects are assumed to be minimal during initial design stages, as *VAMPzeroF* only analyses steady flight at low angles of attack.

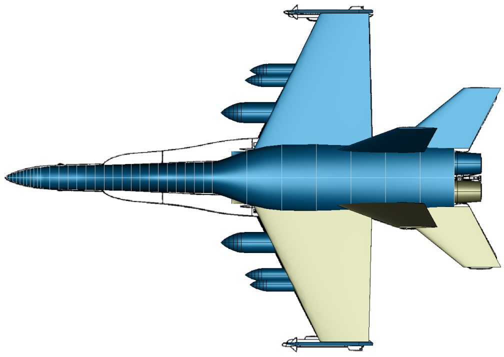
Table 6 compares Operating Empty Mass (OEM) and Maximum Takeoff Mass (MTOM) for further validation. As can be seen, the results are within 2-3% of the actual values, while the defining geometry is close to identical to the real aircraft. It can be concluded that *VAMPzeroF* provides good results for conventional aircraft.

B. Wingman Validation

Unfortunately, it is not easy to validate the Wingman design. Little to nothing is known about existing Wingman concepts. According to Janes [30], the Kronshtadt *Grom* (a comparable Russian Concept) has a Maximum Takeoff Mass of 7000 kg, with a slightly heavier payload (1300 kg). However, according to Janes, *Grom* 's mission radius is considerably smaller. Table 7 compares *Grom* to two different Wingman designs. One Wingman is designed for a



(a) Side view of the F/A-18C model generated by *VAMPzeroF*. Scale drawing in the background for geometry validation.



(b) Top view of the F/A-18C model generated by *VAMPzeroF*. Scale drawing in the background for geometry validation.

Fig. 9 F/A-18C model generated using VAMPzeroF

Table 6 Comparison of the *VAMPzeroF* F/A-18C to reference values

	MTOM [kg]	OEM [kg]
F/A-18C [22]	23541	10810
VAMPzeroF model	23134	10851

sustained load factor of 7 g, while the other is designed for 3 g. As can be seen, the 3 g Wingman 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 Wingman.

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

Parameter	Atreus 7g	Atreus 3g	*Grom* [30]
MTOM [kg]	9949	8090	7000
OEM [kg]	5858	4461	?
Range [km]	2780	2780	1600
Internal Payload [kg]	1036	1036	1300
Top Speed [Ma]	1.15	1.0	0.8
Wing Span	10.0	7.9	9.6
Length	13.8	10.5	11.0

C. Airframe Cost Validation

To validate the cost element of the design, one can look at other modern aircraft. The F/A-18-E *Super Hornet* is chosen. The *Super Hornet* is a very modern aircraft featuring extensive computer systems, avionics, and elements of stealth design. Furthermore, it was not included in the dataset on which Equation 3 is based. According to Boeing, the F/A-18E has an empty mass of 14552 kg [31]. The United States Navy lists the unit cost as 67.4 million 2021 USD [32], equivalent to 75.8 million 2023 USD. Equation 3 predicts a cost of 69.8 million 2023 USD. This difference is sizable. However, it must be noted that Equation 3 only accounts for program costs, so no profit margins are included. Including a profit margin increases the unit price, making the difference smaller.

It can be concluded that the results produced by the implemented cost estimation are only indications. However, estimating the cost of an aircraft is known to be complicated. This is to the extent that even aircraft manufacturers themselves are struggling struggle to find good estimates.

D. RCS Validation

While RCS analysis is deemed out of scope, one can compare the results to known values of real-world aircraft. To this end, Table 8 provides values for the *frontal* RCS of selected combat aircraft. The data was gathered by a group of researchers from the Hellenic Air Force [33] during an extensive literature review. It has to be mentioned that the frontal RCS is generally lower than the average cross-section. As can be seen in Table 8, the different listed radar cross-sections place the Wingman between an F-16 and stealth fighters like the F-117 and F-35. Thus, the method is yielding the desired effect of covering every design between a "normal" and a stealth fighter.

Table 8 Selection of frontal RCS of varying combat aircraft [33]

Aircraft	Frontal RCS [m^2]
C-130 *Hercules*	80
F-15 *Eagle*	10-25
F-16 A	5
Eurofighter *Typhoon*	0.1
B-2 *Spirit*	<0.1
F-117A *Nighthawk*	<0.025
F-35 *Lightning II*	0.0015-0.005
F-22 *Raptor*	0.0001-0.0005

E. MoE Weights Valdiation

It is hard to validate the expressions for Measures of Effectiveness. However, one can inspect the results of the implemented method for consistency, specifically the results of the Fuzzy AHP approach. The responses of the individual SMEs are shown in Figure 10. Each figure also includes a row with the arithmetic mean of the responses, which will be used as the final weight.

Figure 10a 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.

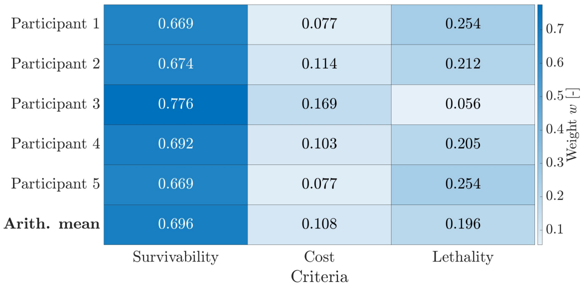
Figure 10b shows the weights for the individual constituents' survivability. The results show similar trends to the general criteria. Generally, the survival of Command Fighters and pilots is significantly more valued than that of Wingmen. Only Participant 5 is an outlier. Effectors only play a minor role.

Lastly, Figure 10c shows the weights for the lethality subcriteria. All Participants agree that the destruction of SAMs has absolute priority over the destruction of tanks.

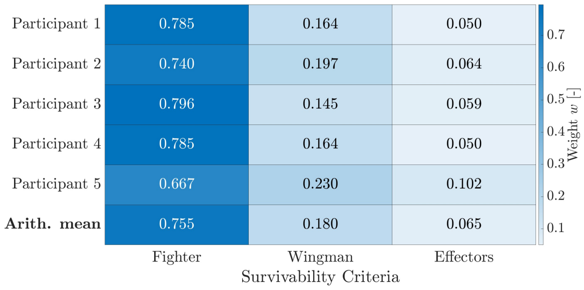
Even though determining weights is a highly subjective subject, the individual SMEs' results are in good agreement. Smaller differences can be seen but the spread is still low. This can be taken as an indicator that Fuzzy AHP and the use of linguistic variables are very robust methods, providing meaningful results.

IV. Results

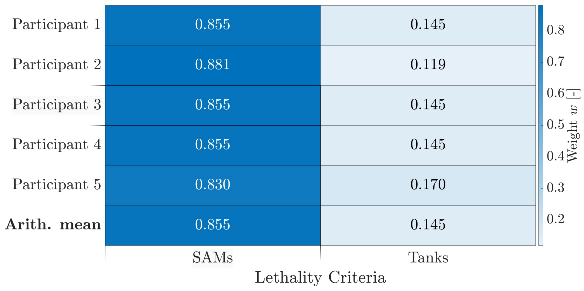
The results of the established baselines can be seen in Figure 11. As can be seen, the two-ship formation of Command Fighters has a low score for survivability. Since the cost score is related to the replacement cost, the cost score is relatively high (the cost score has a *negative* contribution). The 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



(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.

Fig. 10 Weights determined via Fuzzy AHP

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*.

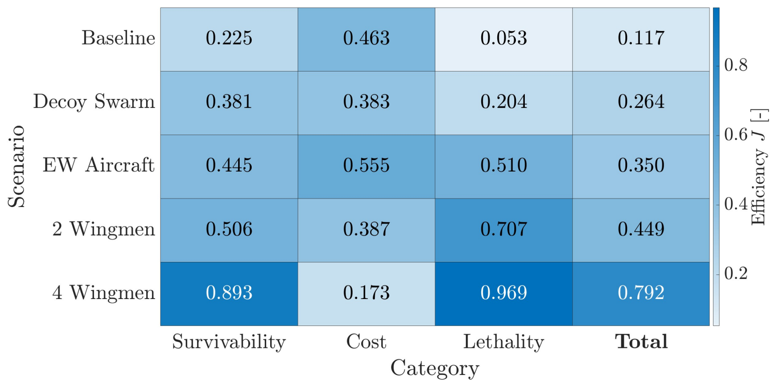
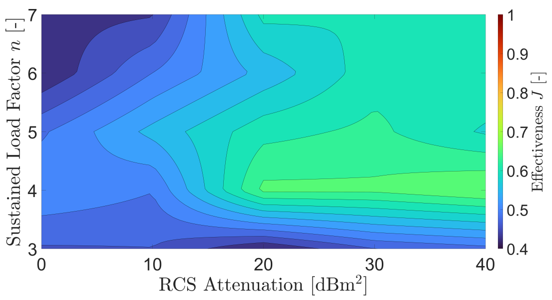


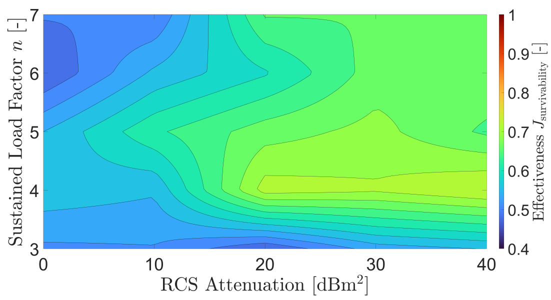
Fig. 11 Mission effectiveness scores of the baselines

Next is the inclusion of two exemplary Wingmen. As one can see, using two Wingmen increases the survivability score by 33% over the use of flying decoys, while the cost stays almost identical. The lethality score is increased by 347%. The use of four Wingmen 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 Wingmen almost *quadruples* the total mission effectiveness compared to the standard two-ship formation. Four Wingmen increase the total score by almost a *factor of seven*.

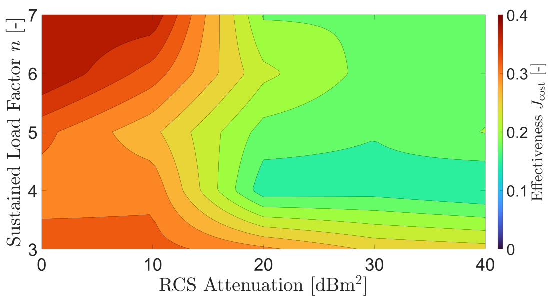
Figure 12 shows the simulation results for the scenario using two Wingmen carrying two ARMs each. As can be seen in Figure 12a, the total mission effectiveness shows a strong dependency on Wingman RCS and sustained load factor. An initial decrease in RCS yields a stark increase in effectiveness. However, 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 Wingman. 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 Wingman size with increasing SEP, increasing the RCS. As can be seen, these trends are also mirrored in the survivability, cost, and lethality score (Figure 12b, Figure 12c, Figure 12d).



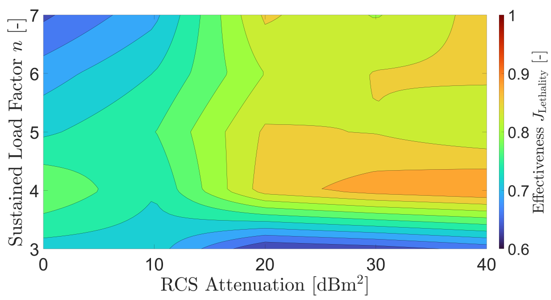
(a) Total effectiveness score for two Wingmen with two anti-radiation missiles each



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



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

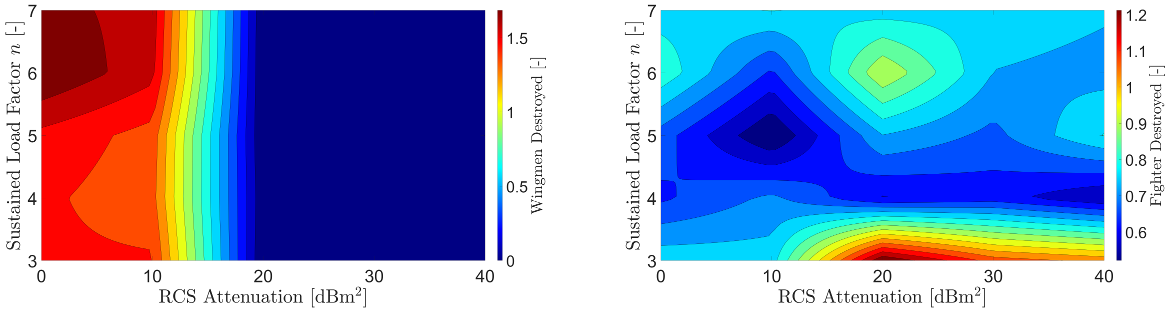


(d) Lethality score for two Wingmen with two anti-radiation missiles each

Fig. 12 Simulation results for the scenario using two Wingmen total carrying two ARMs each. Sustained load factor and RCS attenuation are varied.

To gain a better understanding of these results, one can also look at the lower-level MoEs. Figure 13 shows the attrition of Command Fighters and Wingmen, depending on Wingman RCS and sustained load factor. Figure 13a shows the Wingman attrition. As can be seen, it is dominated by the Wingman 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 Wingman is destroyed anymore.

A different trend can be observed when analyzing Figure 13b, which shows the attrition of the fighter. Surprisingly, there is a significant dependency on Wingman SEP when the Wingman 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 5, the RCS of the Wingman 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 Wingmen turn fast enough to avoid lock and launch. However, the Wingman with the lowest SEP turns just slow enough for SAM 1 to launch a missile. The radar lock of the Wingman is broken as soon as it turns, as the perceived RCS decreases. Unfortunately,



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

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

Fig. 13 Attrition of Command Fighter and Wingmen depending on Wingman RCS and sustained load factor. Two Wingmen with two anti-radiation missiles each.

the missile is already in flight. SAM 1 then reassigns the missile to the next available target: the Command Fighter. This means that the Wingman *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 12a.

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 14 compares the total mission efficiency results for the different simulation cases. Results are shown for two and four Wingmen carrying two and four ARMs.

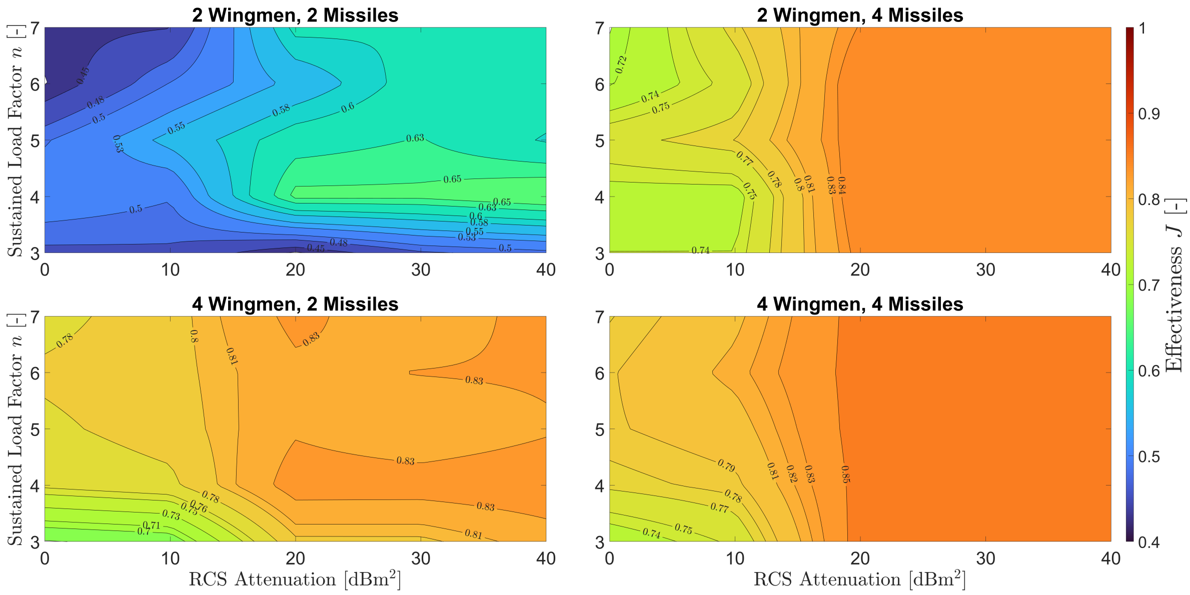


Fig. 14 Comparison of total mission effectiveness for varying Wingman designs and fleet compositions

As can be seen, when deploying two Wingmen, 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 Wingmen but halving the loadout of each Wingman 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 Wingmen 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 Wingmen 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 Wingmen and increasing their SEP, which increases the Wingman survival rate. When fewer Wingman are used, a lower SEP is beneficial. These results are mostly mirrored in the survivability and cost scores, shown in Figure 15 and Figure 16, respectively. However, for survivability and cost, two Wingmen carrying four ARMs each perform best, followed by four Wingmen with four missiles and four Wingmen with two missiles.

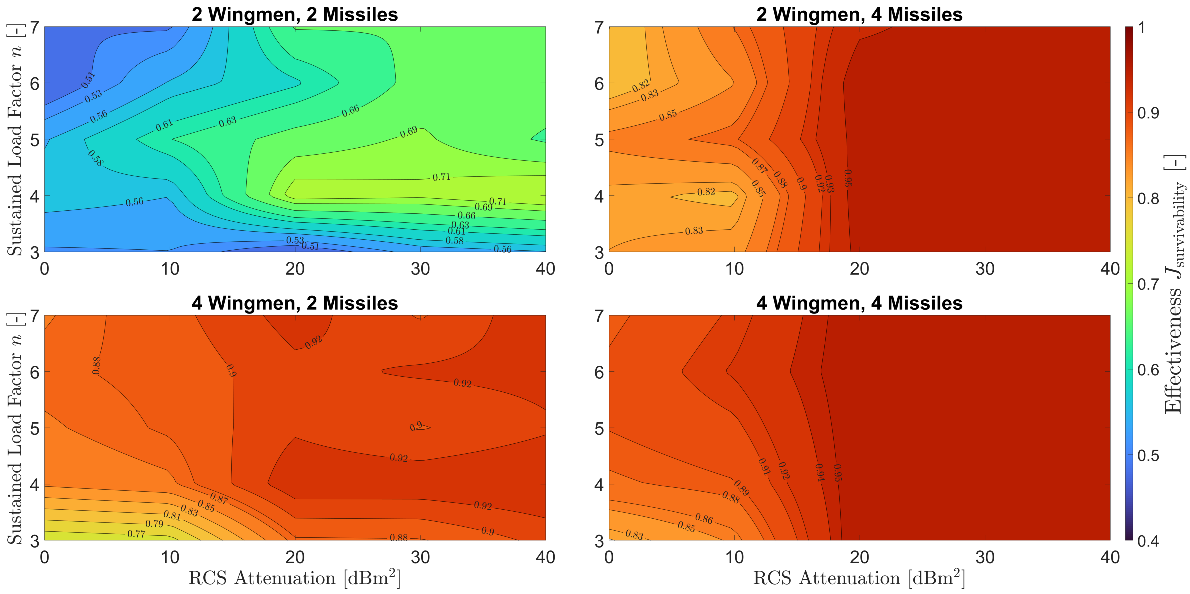


Fig. 15 Comparison of fleet survivability score for varying Wingman designs and fleet compositions

The reason for the preference for larger loadouts is likely found in the behavior of the Wingman. When launching missiles, the Wingmen stick to a salvo interval, i.e., they are waiting for a given time before launching another missile. Due to that, Wingmen carrying more missiles tend to stay in the fight for longer while closing the distance to the SAMs. Since the Wingmen 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 Wingmen increases the number of "sacrificial targets", yielding a slightly better survival score. However, this also implies that more Wingmen are destroyed, which increases the cost slightly.

Figure 17 shows a different picture when looking at the lethality score. The results for four Wingmen 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.

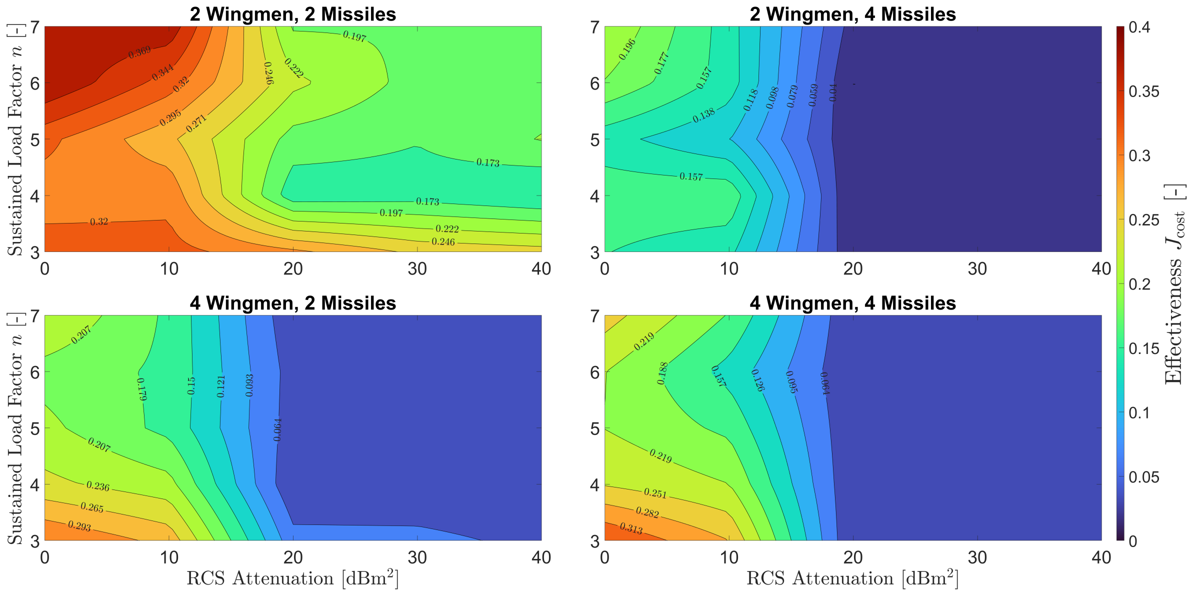


Fig. 16 Comparison of fleet cost score for varying Wingman designs and fleet compositions

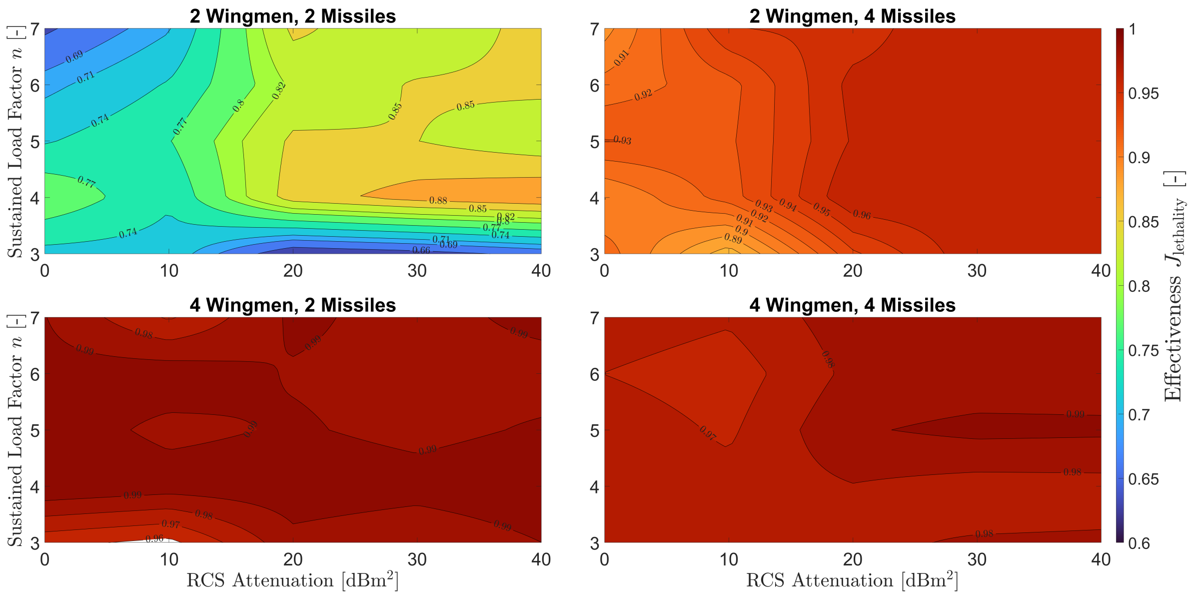


Fig. 17 Comparison of fleet lethality score for varying Wingman designs and fleet compositions

V. Conclusion

The discussion of the results showed many interesting trends. The findings can be used to revisit and answer the previously posed research questions. As a reminder, they are listed below.

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

Question 2 *What is the optimal design of a Loyal Wingman for a given combat mission?*

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

Comparisons between the established baselines allow answering Question 1. Including Loyal Wingmen significantly increases the fleet's total effectiveness, even when compared to advanced and modern tactics. This is due to an increase in survivability, which in turn decreases the replacement costs. Furthermore, lethality is increased. Overall, it can be concluded that the inclusion of Wingmen is highly beneficial.

Also, Question 2, which poses the question of what a Wingman should look like, can be answered. Based on the total effectiveness, it becomes apparent that the radar cross-section of the Wingmen is a driving factor. For maximum effectiveness, the Wingman should have a reduced radar cross-section. The reduction can be limited to treatment with radar-absorbing materials and minor shape optimization to yield an RCS attenuation of 20 dBm^2. This would reflect the stealth properties of modern generation 4.5 fighter aircraft like the Eurofighter *Typhoon* and Dassault *Rafale*. Beyond that, reductions in RCS do not yield an improvement. However, the outcome might differ if the Wingmen escort modern stealth fighters instead of conventional non-stealth aircraft. Differences could also be seen when operating *behind* Red lines, where detection must be avoided at all costs.

The results also show that the ability to fly very hard maneuvers is not an advantage for a SEAD mission. Optimal results are achieved when the Wingmen's maneuverability is balanced. Very agile Wingmen, 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 Wingmen become a burden, as they actively increase the threat exposure of the Command Fighter.

The question for an ideal loadout builds the bridge to Question 3. Regarding total mission effectiveness, survivability, and cost, the Wingmen perform better when carrying more anti-radiation missiles. When deciding whether to use fewer Wingmen with more missiles or more Wingmen with fewer missiles, larger loadouts are preferred.

The lack of stealth properties can partly be compensated for by deploying more Wingmen and increasing their Specific Excess Power. If the Wingman is stealthy, more Wingmen do not necessarily yield a better mission outcome.

Lastly, it can be concluded that the presented methods provide interesting results and help better understand novel aircraft concepts and their CONOPS. While the individual fighter design tools have limited fidelity, they provide outcomes that would otherwise be unobtainable and partly also unexpected. The results show that the analysis of the larger System of Systems via the use of agent-based modeling has immense potential to become a critical element for the design of modern combat aircraft.

Appendix

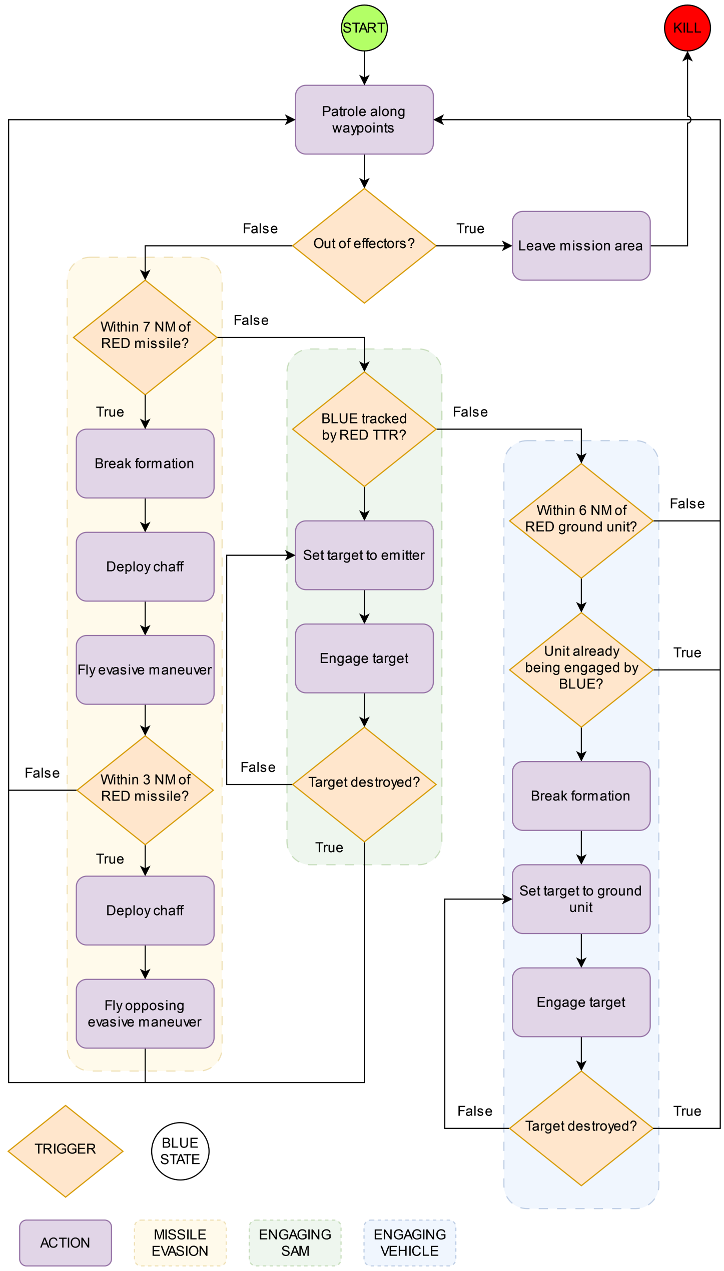


Fig. 18 Agent behavior of the Blue fighters [21]

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Part II

Literature Review

*This part has been assessed for the course AE4020 Literature Study.

3

Unmanned Combat Aerial Vehicles and Loyal Wingmen in a System of Systems

3.1. Introduction

Over the last century, aircraft developed significantly. Especially when it comes to military aviation the development was, and still is, astounding. While early periods were shaped by biplanes mostly made of wood, rope, and cloth, nowadays far supersonic and super-maneuverable aircraft made of composites are not a rarity. In recent years, especially Unmanned Combat Aerial Vehicles (UCAVs) have been met with interest. Aerial combat by nature is connected with very high risks for the pilots. UCAVs offer an alternative. Besides the obvious fact that they are unmanned, they promise to bring many advantages, like lower cost and higher performance. The latest state-of-the-art concepts are known as *Loyal Wingman*, UCAVs that accompany and support manned fighters. Pilots will be able to designate tasks to the UCAV, while they focus on different tasks. This tremendous development arc that aircraft have undergone from WWI until today, is described in Section 3.2.

With the development arc of aircraft, the design methods had to evolve as well. Many traditional and conventional design methods are still being used today. Some modifications have been made, to adapt the design methods to modern technologies and concepts, but the core idea and function stayed the same. With the introduction and proliferation of more powerful computers, approaches have been developed to optimize and automize the design process. Methodologies like Multidisciplinary Design Optimization (MDO) and Knowledge-Based Engineering (KBE) have the potential to drastically improve aircraft design. However, they are not industry standard, as of yet. More recently, efforts have been undertaken, to combine aircraft design with operational analysis using modeling and simulation. The techniques harness a System of Systems approach and attempt to follow a more holistic path. Methods from all the previously mentioned areas, from the standpoint of UCAV design, are introduced in Section 3.3.

This document proposes a project in which traditional design methods are combined with KBE and a System of Systems approach, to enhance and support the design of UCAVs designated as Loyal Wingmen. The goal is to gain more insight into and experience with the design of UCAVs. Especially the inclusion effects, design requirements, and use strategies of Loyal Wingmen are of interest. The identified research gap and proposed research questions are provided in Section 3.4. Section 3.5 covers the research plan.

Finally, Section 3.6 provides a short conclusion.

3.2. Development of UAVs

To work on the design of Unmanned Combat Aerial Vehicles, one first has to know the origins and understand the development. Thus, this chapter gives a brief overview of the history of the concept. Section 3.2.1 describes the very early drones of WWI and WWII. Section 3.2.2 covers a part of the developments of the Cold War. The first "modern" UAVs are introduced in Section 3.2.3. Section 3.2.4 discusses the introduction of the UCAV, while Section 3.2.5 covers the latest developments: the concept of the *Loyal Wingman*.

3.2.1. Early Beginnings

The concept of Unmanned Aerial Vehicles (UAVs) is not new. First UAVs were developed during WWI and were referred to as "flying torpedoes". The models were very crude, flying a simple course, stabilized by gyroscopes, then cut power when a previously determined number of engine revolutions was reached. Loaded with explosives, the aircraft were then supposed to fall onto the target. Many trials were conducted, some of them very successful, some of them not so much. None of the concepts saw service during the war.[1]

After the war, the interest in UAVs dwindled. However, the British found that they were excellent aerial targets, for the training of anti-aircraft gunners. During the 1930s, manned aircraft like the Fairey III (dubbed "Fairey Bee") or de Havilland Tiger Moth ("Queen Bee") were modified for this purpose. In that context, the term "drone" (a male bee) was coined for a UAV.[1]

However, the idea of the flying torpedo did not die. Towards WWII, further successful tests and developments in radio technology led to an increased interest again. During WWII it was realized that having a combat drone would be invaluable to strike heavily fortified German positions of major strategic importance, like U-boot bunkers.[1]

The American Interstate TDR-1 was the first assault drone that saw operational deployment. The TDR-1 was an almost conventional-looking twin-engine propeller aircraft, fitted with radio remote controls, TV cameras, and a radio altimeter. The take-off was remotely controlled by a ground crew. When airborne, the controls were handed off to the crew of an already airborne Grumman TBF *Avenger*. Then, the controller guided the TDR-1 to its target via a display that showed the TV signal from the drone. The TDR-1 was deployed in the Pacific by the US Navy, to strike ships, radar stations as well as anti-aircraft sites. Only a small number of drones were used, with limited success.[6],[1]. A picture is shown in Figure 3.1.

Figure 3.1: Interstate TDR-1 in flight, USN

Source: `http://www.designation-systems.net/dusrm/app1/bq-4.html`

Following a similar approach, the United States Army Air Force deployed remote-controlled B-17 bombers during *Operation Aphrodite*. The bombers were stripped of all unneeded hardware and filled with explosives. Cameras provided a view of the instrument panel and bomb sight. Attacks were conducted against German V-1, V-2 and V-3 sites. However, all were unsuccessful.

3.2.2. Cold War

After the war, the pattern repeated, and interest in assault drones dwindled. In August 1952, during the Korean War, a handful of remote-controlled Grumman F6F *Hellcat* fitted with bombs, were used against

North Korean targets like bridges and power plants. Those attacks were not very successful either, so UAVs continued to only see use as target practice.[7] A contributing factor was the beginning development of reconnaissance satellites, together with improving intercontinental ballistic missiles, as well as cruise missiles. In fact, it was believed that the combination would lead to the complete obsolescence of even manned aircraft [2].

However, the interest in UAVs rose drastically around 1960 when Gary Powers' U-2 was shot down over the Soviet Union and Powers was captured and trialed. UAV development experienced another boost during the Cuban Missile Crisis when Rudolf Anderson's U-2 was shot down over Cuba.[1],[7],[2]

One of the UAVs that gained a lot of attention, was the Ryan Model 147. It was based on an aerial target, the Ryan *Firebee*. The *Firebee* stemmed from the early 1950s and was a small, jet-powered, subsonic, and swept-wing UAV.[1] Early Model 147 versions, named *Firefly*, were just *Firebee* drones fitted with cameras, a gyroscope, and an altimeter. This enabled the drones to fly a straight path over the target and to return to a designated recovery location. Since they only were modified aerial targets, they did not have a landing gear and had to be air- or JATO-launched. Recovery was solved using parachutes and mid-air capture of the UAV. During early tests in 1962, the drones showed to have stealth properties; several air-to-air missiles missed the drones and F-106 *Delta Darts* struggled to achieve a radar lock. An improved version was able to cruise at an altitude of 62,500 ft (10,000 ft higher than the initial models) and was equipped with a Doppler navigation system, as well as a contrail suppression system, to improve the stealth properties.[2] The Model 147 saw its first use after the Gulf of Tonkin incident in 1964. Now named *Lightning Bug*, it overflew mainland China, delivering high-resolution imagery [1],[2]. Alone in the time from 1965-66, the Lightning Bug flew 160 sorties [2]. Ryan Aeronautical manufactured over 20 different versions of the Lightning Bug and it saw prolonged use till the late 70s. Alone during the Vietnam War, it flew $\sim$ 1100 sorties [1]. Some versions were used as bait to collect intelligence on enemy SAMs. Others were able to detect and avoid SAM sites to gather SIGINT behind enemy lines [2]. A picture of a high-altitude version of the Lightning Bug is shown in Figure 3.2a.

Another UAV of that time was the Lockheed D-21. It was carried and launched by a version of the A-12 (CIA version of the SR-71 *Blackbird*). The UAV was powered by a ramjet, enabling it to fly at speeds over Mach 3 at very high altitudes. It was equipped with cameras, which were jettisoned together with the avionics, after flying over an area of interest. Then, the package slowly descended on a parachute and was captured in flight.[7] After initial successes during testing, a D-21 collided with its carrier aircraft. At a speed of Mach 3 and an altitude of 80,000 ft, both aircraft broke up and crashed into the Pacific. As a consequence, Lockheed canceled the program.[2] Later, the program was revived as the D-21B. The D-21B was carried and launched by a modified B-52 bomber. From 1969 on, it was deployed four times, to overfly Chinese facilities. The missions were only partially successful.[2],[8] A picture is shown in Figure 3.2b.

(a) Ryan Model 147H. Picture taken by Clemens Vasters.

Source: `https://www.flickr.com/photos/clemensv/6586644087/`

(b) D-21 on its carrier aircraft, CIA

Source: `https://commons.wikimedia.org/wiki/File:LockheedM21-D21.jpg`

Figure 3.2: Two Cold War era UAVs

In the 1970s and 1980s, many higher-performing UAVs were developed and tested. Efforts were undertaken to design high altitude, long endurance (HALE) vehicles, that provided real-time and beyond line-of-sight surveillance. Examples were the Defense Advanced Research Projects Agency (DARPA) *Condor* [9] and *Amber* [10]. Neither UAV saw active use beyond prototype testing and not a lot is known about either since both projects were classified. However, they are mentioned due to their importance as stepping stones for modern UAVs.[7],[2] Some drones of that era *did* see operational use, like the Israel Aerospace Industries *Scout* [11] and *Pioneer* [12]. Similar to their classified competition, they were able to provide real-time surveillance. However, they were relatively small, and range, payload, as well as speed, was limited.[7],[2]

3.2.3. Post-Cold War

Till the 1990s, there was a major technical capability gap. Reconnaissance aircraft could not overfly targets in heavily contested or denied airspace. Satellites removed the risk component but only provided episodic coverage due to the periodicity of their orbit. Drones like the *Lightning Bug* were more flexible, but generally also only overflew the area of interest in a straight line and returned. Later UAVs like the *Pioneer* were able to loiter over the targets, but range and endurance were limited. All these problems were addressed by the General Atomics RQ-1 *Predator* and Northrop Grumman RQ-4 *Global Hawk*.

Predator is a medium altitude UAV (service ceiling of 25,000 ft) with a range of 400 nm. While the cruise speed of 70 kts is rather low, it has an endurance of up to 40 hours.[13],[14] The drone has a rather unconventional design, that directly stems from *Amber* [10]. Its fuselage is very narrow, with a sensor package mounted under the nose. The nose of the UAV also houses a small satellite dish that is used for communication. The wings are unswept and have a high aspect ratio. Furthermore, the designers gave the drone an inverted V-tail and a tail-mounted pusher propeller which is powered by a reciprocating engine. Due to its tricycle landing gear, it can operate operate from normal runways, without requiring carrier aircraft. *Predator* is a remotely piloted UAV, that is controlled by operators on the ground, via satellite connections. It saw its first use in 1995 when it was deployed to the Balkans. Loitering over targets, it was able to provide imagery using cameras operating in the visual and infrared spectrum, as well as with a Synthetic Aperture Radar (SAR). Considering that *Predator* also was the first deployed UAV to use the Global Positioning System (GPS), this was a breakthrough for UAV development and a novelty, closing the capability gap.[2] A picture of *Predator* can be seen in Figure 3.3a.

The Northrop Grumman *Global Hawk* is a significantly higher-performing UAV. The shape is similar to the *Predator*. However, it is significantly larger and heavier. Unlike *Predator*, the *Global Hawk* is powered by a jet engine, which allows the drone to cruise at higher altitudes (service ceiling of 60,000 ft) and higher speeds (350 kts). Range and endurance are higher, too. At a range of 3500 nm, it can loiter a full day over an area of interest [2]. Maximum ranges of 12300 nm and maximum endurance times of over 34 hours are reported [14],[15]. Similar to *Predator*, *Global Hawk* has unswept wings with a high aspect ratio and a (non-inverted) V-tail. It also has a tricycle landing gear and is remotely piloted. However, *Global Hawk* can also operate fully autonomously, which includes locating and landing at friendly airfields [2],[14]. The system saw its first use in 2001 [15],[14]. The *Global Hawk* is shown in Figure 3.3b.

3.2.4. The Age of the UCAV

Soon after the successful adaption of the *Predator*, it was realized that aerial platforms loitering above a target could have more uses than just providing intelligence. Besides giving situational awareness, the UAV already was used to identify and designate potential targets, which then were engaged by other ground- or air-based assets. If the drone was armed, targets could be engaged without delay and potentially endangering friendly units. As a consequence, in 2001, attempts were undertaken to equip *Predator* with weapons.[16] The wing span was increased by two meters to account for additional payloads and pylons were mounted to the wings. Initial trials were conducted using laser-guided AGM-114 *Hellfire* missiles. Initially intended as a helicopter-born anti-armor missile, it was small, lightweight, and precise. Test firings showed promising results and by 2002, the modified Predator entered service with the model designation MQ-1B.[16],[17] General Atomics developed the idea further and designed a ”Hunter-Killer”. The goal was to design a UAV that could ”prosecute critical emerging time-sensitive targets” [16]. The result was the MQ-9 *Reaper*. The Reaper shares many design aspects of the *Predator*. However, it is significantly larger and heavier due to the seven hardpoints for weapons and increased payload capacity. Additionally, it is powered by a turboprop, which allows for a cruise speed of 240 kts at a range of 1000 nm with a service

(a) *Predator* flying low over the ground, USAF

Source: `https://www.af.mil/News/Photos/igphoto/2002864353/mediaid/5461034/`

(b) *Global Hawk* in flight, USAF

Source: `https://www.af.mil/News/Photos/igphoto/2000581685/`

Figure 3.3: Two modern UAVs

ceiling of 50,000 ft. The first tests were conducted in 2001. *Reaper* entered service in 2007.[16],[18]. An armed *Reaper* is shown in Figure 3.4.

Figure 3.4: Armed MQ-9 *Reaper* in flight, USAF

Source: `https://www.919sow.afrc.af.mil/News/Photos/igphoto/2002715932/`

During the development of the previously shown drones, it became clear that UAVs could be very capable tools and a competition to conventional aircraft. In the case of surveillance aircraft like the Lockheed U-2, UAVs even were able to completely replace the manned aircraft. Seeing this, efforts were undertaken to expand the capabilities of UAVs. Hence, in 1997, "DARPA announced an Advanced Technology Demonstration [...] for an “Uninhabited” Combat Aerial Vehicle [...] for Suppression of Enemy Air Defenses (SEAD)” [2]. The UCAV was born. In 1999, Boeing was chosen as the main contractor, and their demonstrator, the X-45, underwent testing with the US Air Force.[2] The US Navy soon started testing another demonstrator, the X-47 from Northrop Grumman. The programs later were consolidated under the name Joint Unmanned Combat Air Systems (J-UCAS) [19]. The program was canceled in 2006 [20].

The X-45 followed a significantly different design philosophy than earlier UAVs. Being designed for SEAD missions and precision strikes, the drone was designed as a stealthy flying wing. The tail-less aircraft is powered by a fuselage-buried turbofan engine, with the air inlet on the upper side of the fuselage. Thrust vectoring is used for yaw control. The Ordnance is housed in two internal cargo bays and the conventional tricycle landing gear is stored in the fuselage as well. First test flights were conducted in 2002.[19],[21],[22],[23] While many details are still classified, the X-45A is reported to cruise at an altitude of 45,000 ft at a speed of Mach 0.75 [19]. The X-45A is shown in Figure 3.5a. A fully operational version, the X-45B was supposed to enter service with the US Air Force. However, it was canceled in favor of the X-45C, a larger version of the X-45A/B. The X-45C features an increased wing span, payload capacity as well as range. With the new design came a new wing shape, too.[19] Pictures of the X-45C are rare and only show mock-ups or renders, but it seems to be very similar or identical to the Boeing *Phantom Ray*. It is shown in Figure 3.5b. After the cancellation of the J-UCAS program in 2006, there were very few publications about the X-45 and/or *Phantom Ray*. It is possible that development continued in a different form but was classified.

(a) X-45A during early test flights at Dryden Aeronautical Test Range, NASA

Source: `https://www.dfrc.nasa.gov/Gallery/Photo/X-45A/HTML/ED02-0295-5.html`

(b) *Phantom Ray* at Dryden Aeronautical Test Range, NASA

Source: `https://commons.wikimedia.org/wiki/File:Phantom_Ray_(ED11-0128-181).jpg`

Figure 3.5: Two versions of the Boeing UCAV

The X-47 followed a very similar design approach to the X-45 but was more targeted at the US Navy. Like the X-45A, it is designed as a tail-less flying wing with stealth properties. In contrast to the X-45, the planform resembles a diamond or arrow tip shape. The turbofan engine is buried in the fuselage. Ordnance and tricycle landing gear are stored in the fuselage as well. Since the X-47 is supposed to operate from aircraft carriers, the landing gear is heavier and stronger and the drone is equipped with an arrestor hook. First test flights were conducted in 2003.[22],[24] A picture of the X-47A can be seen in Figure 3.6a. With the cancellation of J-UCAS, also the X-47 program was stopped temporarily. However, the program soon continued as a pure Navy project and the X-47B was developed. As with the X-45C, size, payload, and range were significantly increased. Also, the wing shape changed again and the planform of the X-45A was adopted.[20] The X-47B was the first drone to demonstrate autonomous catapult-assisted takeoffs from an aircraft carrier, autonomous aircraft carrier landings as well as autonomous aerial refueling [25]. The X-47B is reported to cruise at altitudes above 40,000 ft at speeds of Mach 0.7 [26]. The X-47B can be seen in Figure 3.6b.

Two very similar UCAVs were developed in Europe: the *Taranis* (BAe) and *Neuron* (Dassault). Based on the very little information available, their design, performance, and roles are very similar to the X-45/X-47.[27],[28]

While the UAVs brought many advantages, they also brought some disadvantages and ethical issues, especially UCAVs. In many cases, remotely piloted vehicles are controlled from ground stations far away from the mission area. This implies, that all communication and control has to be transmitted via satellite links, which places restrictions on bandwidth and creates a delay. As a result, the situational awareness of the controlling crew is rather limited and the delay becomes problematic in quickly developing combat situations. Next to the logistical concerns, the deployment of weapons via UCAVs creates ethical issues. Due to the distance of the crew to the combat situation, the psychological barrier to the deployment of weapons may decrease. Furthermore, the decreased situational awareness can lead to a lack of information, resulting in misidentifications of targets. When the UCAV is operating completely autonomously, the ethical problems are heavily amplified.[29],[30]

(a) X-47A at rollout, DARPA

Source: `https://commons.wikimedia.org/wiki/File:X-47A_rollout.jpg`

(b) X-47B during aerial refueling, USN

Source: `https://commons.wikimedia.org/wiki/File:X-47B_receiving_fuel_from_a_707_tanker_while_operating_in_the_Atlantic_Test_Ranges.jpg`

Figure 3.6: Two versions of the Northrop Grumman UCAV

3.2.5. The Loyal Wingman

While the previously described developments were aiming to replace manned combat aircraft, another thought was developed in parallel. In 1995, engineers at Lockheed came up with a UCAV concept that would "[...] complement, not compete with, existing manned and unmanned systems" [3], a system that would "operate as an element of [a] system of systems" [3]. The idea was, to distribute the tasks between UCAV and manned aircraft. What the engineers at Lockheed described, is known as the *Loyal Wingman*, nowadays. Newer concepts envision mostly autonomous, network-enhanced UCAVs, that can take orders from the human pilot, or autonomously communicate and organize in a swarm with more UCAVs. Also, sensor fusion plays a vital role in newer concepts. The individual Wingmen often are referred to as Remote Carrier (RC). Smaller RCs could act as forward-deployed sensor platforms, while Heavier RCs could carry weapons. The Loyal Wingman concept has many advantages, that mostly match the advantages of "conventional" UCAVs [3],[4]:

- UCAVs and Wingmen can take over the dangerous parts of missions. For example, they could provide SEAD capabilities, while allowing human pilots to stay at a safe distance. Due to that, there is no risk of loss or capture of pilots, which enables the use in many situations unthinkable for manned aircraft.
- The use of UCAVs has the potential to be a lot cheaper than the use of manned aircraft. UCAVs themselves tend to be lighter, and smaller. Hence, they tend to be cheaper. Additionally, the crew needed to support UCAVs does not need to undergo in situ flight training, further reducing cost. Lastly, UCAVs can be designed to be *attritable*, which means that it is expected to lose the vehicle during combat, eventually. This drastically reduces the design lifetime of the UCAV, reducing the cost further.
- UCAVs are not hindered by human limitations. While the attention span and mission duration for a human pilot are limited, a UCAV does not suffer from these constraints and can loiter for days on end, provided it does not run out of fuel. Furthermore, nowadays, during maneuvers, the pilot is what limits the load factor. Without the physiological constraint, in principle, the UCAV can fly harder and more demanding maneuvers, only limited by the structural design.

Due to the networking with manned aircraft, the Loyal Wingman also brings three additional benefits [4],[5]:

- Due to sensor fusion, they can increase the situational awareness of pilots.
- Wingmen have the potential to reduce the workload of the pilot, increasing the pilot's effectiveness. As an example, the Wingman could protect the manned aircraft from hostile fighter aircraft, so the pilot can focus on a reconnaissance mission.
- In contrast to drones like *Reaper*, which are controlled from a distance, there is still a human in the

loop, who is witnessing the situation in person. This removes many logistical, as well as technical problems, but also ethical concerns.

As such, it is not surprising that many countries started developing their own visions of the Loyal Wingman. Prominent examples are the MQ-28 *Ghost Bat* developed by Boeing Australia, the Turkish *Kizilelma* made by Baykar, and the Russian *Grom* and *Molniya* from Kronshtadt.

Kizilelma is a medium-sized UCAV with reported stealth properties. It is powered by a fuselage-buried turbofan engine and bears a heavy resemblance to the Chinese Chengdu J-20. Like the J-20, the *Kizilelma* features slightly canted canards, side-mounted air intakes, and a V-tail. It is a subsonic UCAV, with a cruise speed of Mach 0.6 and a top speed of Mach 0.9. Ordnance is stored inside the fuselage's internal cargo bay. It has a conventional tricycle landing gear and is capable of operating from *Anadolu* class assault ships. A combat radius of 500 nm and a service ceiling of 30,000 ft are provided. It is designed for Close Air Support (CAS), SEAD, and air-to-air combat.[31],[32] The Baykar UCAV is shown in Figure 3.7b.

Grom looks significantly different compared to the Turkish concept. *Grom* has a slender fuselage with a lambda wing. As with many of the designs previously discussed, the engine is buried with a dorsal air intake and ordnance is stored in an internal payload bay. The V-tail is heavily canted. The cruising speed is reported to be around Mach 0.65 with a top speed of Mach 0.8. The range is given with a maximum of 430 nm (800 km). Supposedly, *Grom* is also able to carry multiple smaller drones, called *Molniya*. The purpose of *Molniya* is unknown, but based on the Loyal Wingman concept, they could either be used as sensor platforms or as effectors. Like previous UCAVs, Grom seems to be designed for SEAD.[33] *Grom* is shown in Figure 3.7a

Ghost Bat slightly differs from the other concepts. Like the other concepts, it has a fuselage that is shaped such that stealth properties seem likely. It features a lambda wing, side-mounted air intakes. and a buried turbofan engine, as well as a V-tail. However, the MQ-28 does not carry weapons but has an internal cargo bay in the nose, that is used for sensor and electronic warfare packages. The range is given with over 2000 nm.[34] The *Ghost Bat* is shown in Figure 3.8

Also, Airbus is working on its own version of a Loyal Wingman. There is not a lot of information available. However, it seems that the concept is centered around a new generation fighter aircraft (NGF), heavier Loyal Wingmen, and a combination of small and medium-sized RCs. The project goes by the name FCAS.[35],[36]

It must be noted that many of the systems have not reached the testing phase yet. The systems that have, are only in the very early testing phase. Because of that, there exists no proof of concept or of the benefits of a Loyal Wingman.

(a) Kronshtadt *Grom* at Army 2022, TurDef

Source: `https://www.turdef.com/article/kronstadt-begins-building-the-grom-combat-drone`

(b) Kizilelma on display, DefenseMirror.com

Source: `https://www.defensemirror.com/news/32644/Second_Prototype_of_Bayraktar__Kizilelma__Jet_powered_UAV_Assembled__First_Flight_in_2023`

Figure 3.7: Two modern Loyal Wingmen

Figure 3.8: MQ-28 during high-speed taxi tests, Boeing Australia

Source: `https://www.boeing.com/defense/MQ-28/`

3.3. Design Methods

Now, that there is an overview of the historical development of UAVs and the current state of the art, one can look at the corresponding design methods. UCAV-specific design aspects are shown in Section 3.3.1. Section 3.3.2 discusses newer, computer-aided approaches. A relatively new aspect referred to as System of Systems Engineering is presented in Section 3.3.3, together with agent-based modeling. In Section 3.3.4, alternate simulation approaches are discussed, as well as efforts to evaluate the contribution of Loyal Wingmen.

3.3.1. Systems Engineering

Looking at the individual UAV concepts, they appear unconventional, due to the stealth features and the lack of a cockpit. However, the designs do not drastically differ from current generation fighter aircraft. For example, *Kizilelma* resembles a scaled-down and cockpit-less version of a Chengdu J-20 or Lockheed F-22. As such, one could argue that conceptional design methods as established by Roskam and Raymer are still applicable, provided some modifications are made.

”The most obvious difference between an unmanned aircraft and a manned aircraft is the lack of a pilot or other flight crew” [4]. A logical conclusion would be, that all crew-related subsystems as well as pieces of inventory can be excluded from the design, but the rest of the design steps remain valid. For a reconnaissance aircraft of the size of the Cessna O-2, Gundlach estimates that the removal alone leads to a weight difference of 555 lbs when compared to a UAV fulfilling the same task [4]. These differences would amplify during the design process, due to the iterative nature and the snowball effect. He bases this estimate on the weight breakdown provided in Table 3.1. While this is just an exemplary comparison, some aspects might be exaggerated. For example, a UAV does not need cabin environmental systems (simply because there is no cabin), but it might very well need air conditioning or other cooling systems for the significantly larger amount of electronic/computer hardware. However, the general argumentation and tendencies remain valid.

Table 3.1: Weight breakdown highlighting differences between manned aircraft and UAVs. Table is only based on the accommodations of crew (manned aircraft) and specialized computer hardware (UAV).[4]

	Weight [lb]		
Component	Manned	UAV	Notes
Crew	320	0	2 Crew
Windows	20	0	
Furnishing	60	0	Fixed Seats
Doors	30	0	
Controls	20	15	For Manned Aircraft: Interface For UAV: Actuators
Environmental Controls	30	0	
Survival Kit	10	0	
Instrumentation and Avionics	100	15	Guidance, Navigation, Autopilot
Communications for Command&Control and Payload	0	10	
Electrical subsystems	10	5	
Total	600	45	

When looking at fighter aircraft, the differences become even larger. For example, Raymer estimates the weight of the uninstalled avionics alone to be between 800 and 1400 lb, while furnishings for two crew members weigh over 430 lb [37]! Additionally, the fuselage volume of a manned aircraft tends to be larger than that of a comparable UAV, because of the inclusion of the crew. This results in larger wetted surface areas and thus, more drag, increasing weights further.[4] Gundlach estimates, that ”the weight associated with humans on board an aircraft could approach 2000–3000 lb per person on a tactical military aircraft” [4].

A group of researchers from Iran highlighted another potential weight saving. Since there is no crew on board, there also is no need for a pressurization of the fuselage, which allows for a local reduction of the safety factor from 2.0 down to 1.5. With the assumption that only the cockpit is pressurized and that the cockpit occupies a third of the fuselage, they arrive at a fuselage weight that is 8.3% lower than that of a manned fighter aircraft.[38] During the early design stages, effects like this should be accounted for as well.

Looking at these findings, one can conclude that a UCAV has the potential to be significantly lighter than a manned aircraft fulfilling the same role, which could lead to major cost reductions. Also, transport and storage could be improved, due to a reduced aircraft size. The size might also positively impact possible stealth properties.

3.3.2. KBE and MDO

Due to the inherently multi-disciplinary nature of aircraft design, the design process is very complex. It lends itself to the application of Knowledge Based Engineering (KBE) and Multidisciplinary Design Optimization (MDO). In KBE, design rules and processes are formalized such that they can be included in purpose-built software applications. If well-built, these design tools can accelerate the design process drastically or even fully automate it. In MDO, software tools are used to optimize a given system. Various numerical methods allow for the creation of multi-variate optimization problems. For example, one can set up a program, that minimizes the fuel weight of a given aircraft, by varying the wing geometry and profile. If set up correctly, the tool can pick a near-optimal combination of parameters from the design space.

An example of a well-established KBE tool for the design of fighter aircraft was developed by the German Aerospace Center (DLR), called *VAMPzeroF*. VAMPzeroF is a parametric design tool, that executes aircraft sizing based on the well-known design methods. The structure of the program is shown in Figure 3.9.

Via an input file, the user provides the general configuration of the aircraft (e.g. fighter with canards and delta wing) and Top Level Aircraft Requirements (TLARs, e.g. range, endurance, ultimate load factor). It is also possible to provide multiple different mission profiles with different payloads and flight profiles. VAMPzeroF automatically determines the mission that constrains the design and sizes accordingly. The configuration input is used to define the rough geometry of the aircraft. The TLARs are used to conduct a constraint analysis, using wing- and thrust-loading curves. Then, the combination of both is used to

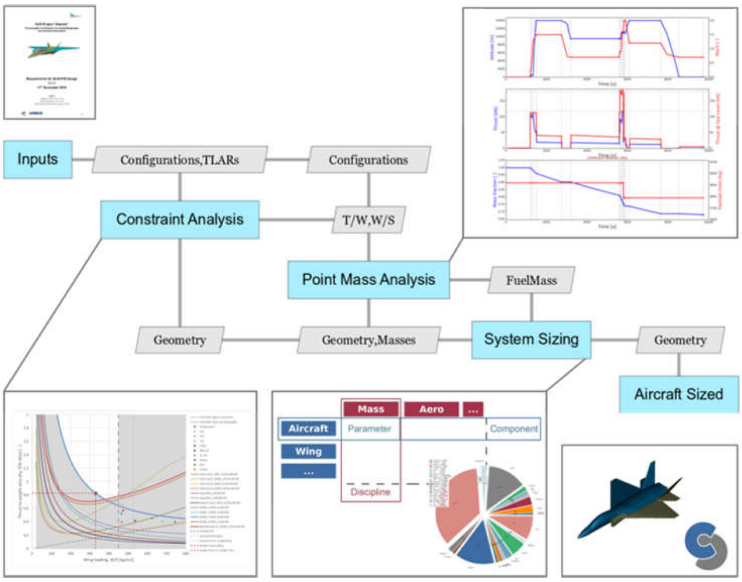


Figure 3.9: Program structure of VAMPzeroF [39]

conduct a First and Second Order Weight Estimation, based on established and validated design methods (e.g. Raymer, Roskam, Torenbeek). During this process, VAMPzeroF utilizes modules containing varying disciplines, like aerodynamics for lift and drag calculations, propulsion modules for fuel consumption and thrust curves, or atmospheric models. The resulting design is used to update the initial weight estimates and the process is repeated iteratively until it converges onto a fixed design. Tool outputs are V-n diagrams, weight breakdowns, performance metrics, as well as a 3D model of the aircraft in CPACS format. The tool was validated using multiple existing fighter aircraft (F-16, Eurofighter Typhoon, F-22). The resulting aircraft models were very similar to the real-world counterparts and key parameters like Maximum Takeoff Weight (MTOW), Operative Empty Weight (OEW), and fuel mass came within less than 1%, compared to the real values.[39]

The design capabilities of VAMPzeroF are a great help during the conceptual design phase because the tool converges within minutes and the results can be analyzed almost immediately. The benefits become significant, if VAMPzeroF is used to perform trade studies. For example, it is possible to compare different configurations (e.g. canards vs V-Tail, delta wing vs conventional) for different payload configurations and missions.[39] Studies like this easily can result in dozens to hundreds of designs, which makes a ”manual” design process with following performance analysis impossible. This capability of rapidly performing design trade-offs and also substantiating them with quantitative data is invaluable for the design of novel or unconventional aircraft concepts, like UCAVs. Unfortunately, VAMPzeroF does not include a complete knowledge base for UCAV design, yet.

An example of the results of a trade-off study using VAMPzeroF is shown in Figure 3.10. The different colors correspond to different payload configurations. As can be seen, the ”red” configuration results in the highest MTOW due to high supersonic drag during parts of the mission.

A tool similar to VAMPzeroF was developed by a group of researchers at Cranfield University, called *GENUS*. Like VAMPzeroF, it uses KBE. However, MDO capabilities were also implemented. For example, the tool includes optimization methods for elements like aerodynamic performance, or stealth characteristics. Also, it includes an external tool for the analysis of the Radar Cross-Section (RCS) of the aircraft, called POFACETS. In contrast to VAMPzeroF, it also already includes a knowledge base for UCAV design, based on Gundlach.[40],[41],[42]

A design of a fifth-generation unmanned strike fighter, designed using *GENUS* is shown in Figure 3.11.

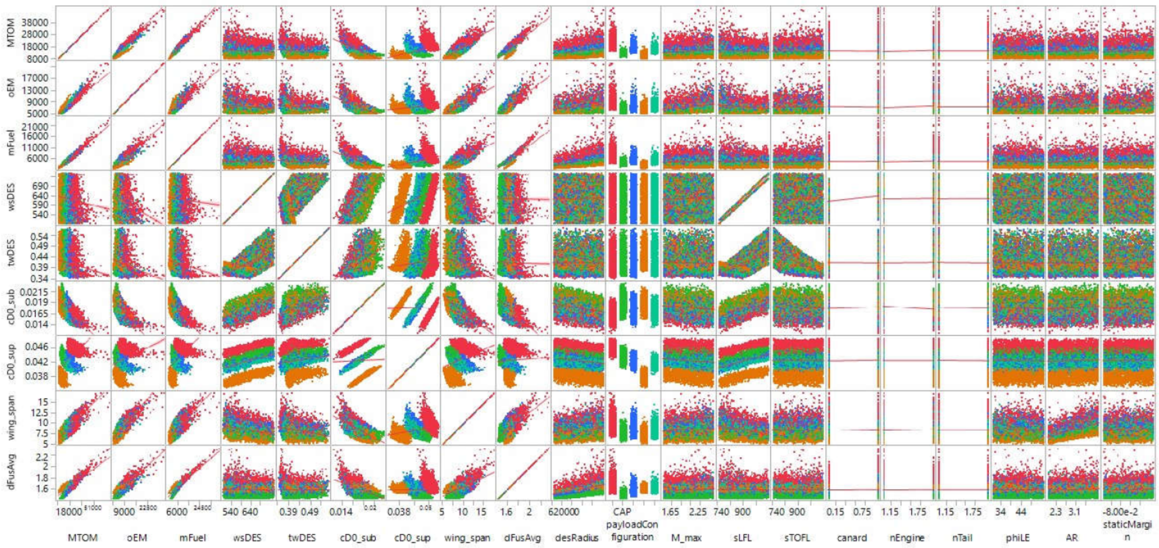


Figure 3.10: Example of a large-scale trade study conducted using VAMPzeroF [39]

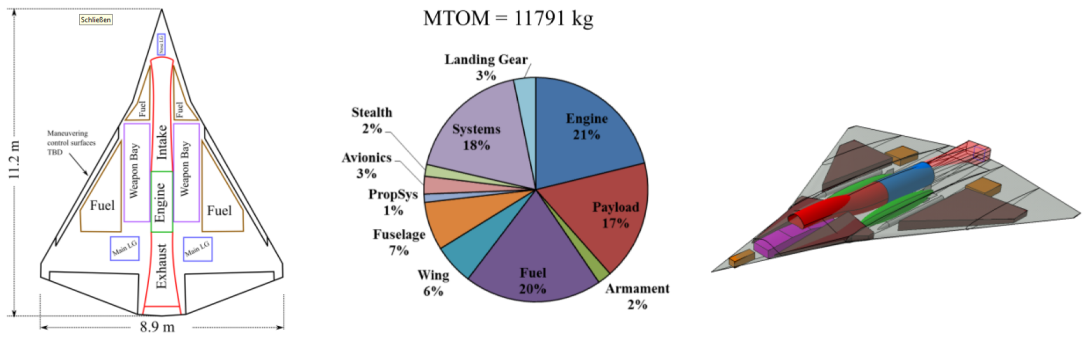


Figure 3.11: A UCAV design generated with GENUS [40]

3.3.3. System of Systems Engineering

However, also methods like KBE and MDO are reaching their limits when constrained to the traditional design methods. In the case of the Loyal Wingman, the UCAV, and the manned aircraft are both *operationally independent* and *possess managerial independence*. With the term of operational independence, one means that the Wingman and the manned fighter both can function as a standalone system. Both systems can perform a mission autonomously, e.g. they can take off, fly to a target, engage, and return. Managerial independence means, that both systems also make their own decisions, e.g. they perform individual actions based on rules of engagement. The systems are independent of each other and geographically separated. Yet, they interact, communicate, collaborate, and influence each other, leading to effects that are hard to predict and cannot be explained by a pure addition of the effects of the individual systems. When referring to the resulting effects, one speaks of *Emergent Behaviors* [43].

When independent systems are forming a larger system, that performs better or is more effective than the sum of its constituents, one often labels it as a System of Systems (SoS). Maier defines five inherent characteristics of such a System of Systems [44]:

- Operational independence
- Managerial independence
- Geographical distribution
- Evolutionary development
- Emergent behaviors

According to Maier, the first two items are necessary but also sufficient criteria for a System of Systems, while a mix of the other three requirements often is found as well [44].

DeLaurentis later on extended the list by [45]:

- Networks. The constituents are interconnected and can interact.
- Heterogeneity. Individual systems differ significantly from each other.

Based on this, a larger system of Loyal Wingman and manned aircraft possesses four out of the five characteristics as described by Maier. Both points listed by DeLaurentis are fulfilled as well. The point of *evolutionary development* refers to the ability to adapt to future changes of the System of Systems, for example including a third, alternative concept, or replacing elements of the SoS. At this stage, it is hard to determine whether such an SoS possesses the trait of evolutionary development. However, at the conceptual stage, there is no reason why the SoS should *not* be able to adapt to future changes. As such, it is valid to see the combination of Loyal Wingman and manned aircraft as a System of Systems.

When designing elements of a Systems of Systems (e.g. a UCAV), one quickly realizes that a combination of many different means can lead to the same effects. Thus, one can argue that for a successful design process, one has to address the problem on the System of Systems level and cannot solely focus on the constituent systems. To that end, it was suggested to move away from Measures of Performance (MoPs, e.g. the Specific Excess Power of an aircraft at pre-defined speed and altitude), towards a capability-focused approach with Measures of Effectiveness (MoEs) [46],[47]. In this context, a capability is defined as ”the ability to achieve a desired effect under specified standards and conditions through combinations of means and ways to perform a set of tasks” [48].

When looking at MoEs, measurements like *Mission Success Rate* or *Survival Rate* are of interest. The MoEs bring multiple advantages. For example, using MoEs allows optimization of the systems such that they achieve maximum performance in reaching a certain goal while staying flexible regarding performance requirements. Biltgen and Mavris propose a quantitative method for technology evaluation, based on MoEs, using *Modeling and Simulation*. In their example, an *agent-based simulation* is set up. In an agent-based simulation, individual entities (agents) can make decisions based on their own logic, interact with other entities, and react to external stimuli. In their case, the simulation is centered around a military conflict. Generic models of aircraft and enemy ground targets, including air defenses, serve as agents. The friendly aircraft are tasked to destroy the ground targets, based on a predetermined military doctrine. Aircraft and weapon parameters can be varied to model a broad spectrum of systems. A wide range of values for multiple parameters is fed into the simulation, to see their effect on the MoEs. In the provided example, this includes parameters like aircraft top speed (Mach 0.72 - Mach 4), Thrust-to-Weight Ratio (0.35 - 1.5), and Munition Range (10 - 1200 nm). Because the agent-based simulations are very resource- and time-intensive, the results are then used to create surrogate models, which in turn can be used to predict the effectiveness of new systems (e.g. the effectiveness of aircraft with a top speed of Mach 6), without having to rerun the simulation.[46],[47]

The proposed approach allows to evaluate which system parameters have the biggest effect on the desired MoEs, which then can be used to establish or refine design requirements. For example, one could analyze how high the Specific Excess Power (SEP) of an aircraft should be for a given mission, to achieve a maximum mission success rate, *before* the aircraft is designed. In theory, this could enable the design of ideal systems. However, the proposed approach is also lacking in one regard: It is not connected to the actual design of the aircraft. The simulation could indicate that an aircraft with a top speed of Mach 6 is required, while it might not be possible to design such an aircraft while satisfying the remaining requirements. The previously proposed approach is more of an additional step before the normal Systems Engineering Methods.

A method of including the operational analysis into the design process is discussed in a later paper. The authors suggest a framework, that connects classical conceptual design methods and operational analysis via modeling and simulation [49]. To begin, a Python-based aircraft design tool is developed, that is similar to the previously discussed VAMPzeroF. Using the strength of such a KBE tool, input parameters are varied to generate a wide range of aircraft designs. Then, a military scenario is built in the agent-based simulation tool AFSIM, which allows the modeling of complex scenarios on a mission level. In the mission, a formation of blue (friendly) aircraft is tasked with the destruction of red (enemy) high-value targets, which are protected by an Integrated Air Defense System (IADS). This is schematically shown in Figure 3.12

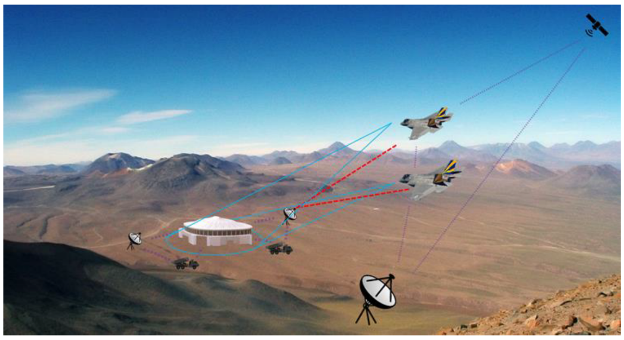


Figure 3.12: Mission setup in AFSIM [49]

The previously generated aircraft designs are taking over the role of the blue aircraft. *AFSIM* then is used to also implement ranges of operational parameters (e.g. amount of weapons, speed during engagement, flight altitude). Furthermore, the Radar Cross-Section of the aircraft is coupled to the wing area of the aircraft. This way, in a large Design of Experiment (DoE), 5000 distinct combinations are created, consisting of varying aircraft designs and operational aspects. Each of the 5000 cases is repeated 100 times to account for random variations of the result. After that, the results are evaluated.[49]

Figure 3.13 shows some of the results of the DoE. It can be seen that in this specific scenario, the lower the RCS of the aircraft, the fewer blue (friendly) aircraft are being destroyed. Similarly, the lower the maximum Mach number, the more aircraft are destroyed. Also shown is a coupling between the payload weight (i.e. the amount of weapons) and the number of red units destroyed The results show that the proposed framework allows for coupling of the design and operational analysis so that the physical design can be evaluated based on predetermined MoE.

Another group of researchers at the German Aerospace Center (DLR) followed a very similar framework approach. For the conceptual aircraft design, VAMPzeroF is used. As in the previous papers, the design tool is used to generate a range of different aircraft designs, all based on the General Dynamics F-16, which are then implemented into an agent-based simulation software. In this case, some of the varied parameters are the drag coefficient, OEW, and Thrust Specific Fuel Consumption (TSFC). A reduction in either allows to simulate the impact of new technologies (e.g. a reduction of OEW can simulate weight reductions due to new production techniques). Furthermore, the amount of weapons carried and the combat radius are varied.[50] An example aircraft generated by VAMPzeroF, including performance metrics, is shown in Figure 3.14.

Next, the resulting aircraft are implemented into a scenario in the simulation tool *MACE*. MACE allows the generation and simulation of a wide range of combat scenarios. The user can build up missions in any part of the world, by placing entities in a three-dimensional space, built on OpenStreetMaps and topological data. A large variety of weapon systems is modeled, including common Air-to-Air, Air-to-Ground, and Surface-to-Air systems. MACE models aerodynamics, control systems, and electromagnetic emissions in the visual, infrared, and radio spectrum. This includes but is not limited to, Radar Line-of-Sight calculations, Radar Cross Section, Radar Refraction, Infrared Signatures and Countermeasures, as well as modeled weapon sensors and PID controls of the individual systems. This way, any scenario can be modeled, while keeping a high flexibility, fidelity, and realism. The tool also allows the scripting of the logic of each entity, based on patterns and external stimuli. Communication between agents is supported as well, e.g. via Link-16.[51]

Using MACE, an offensive counterair mission is modeled, where a formation of blue aircraft is tasked to intercept and destroy a red formation. MACE is also used to implement differing tactics, like engagement types, number of blue aircraft, and the use of Link-16 for target track exchanges.[50]

The group uses the same framework in another paper, to simulate an air interdiction mission, with the McDonnell Douglas F/A-18 as reference aircraft. In this paper, the number of aircraft, loadout, RCS, and SEP were varied.[52] A schematic depiction of the scenario is shown in Figure 3.15

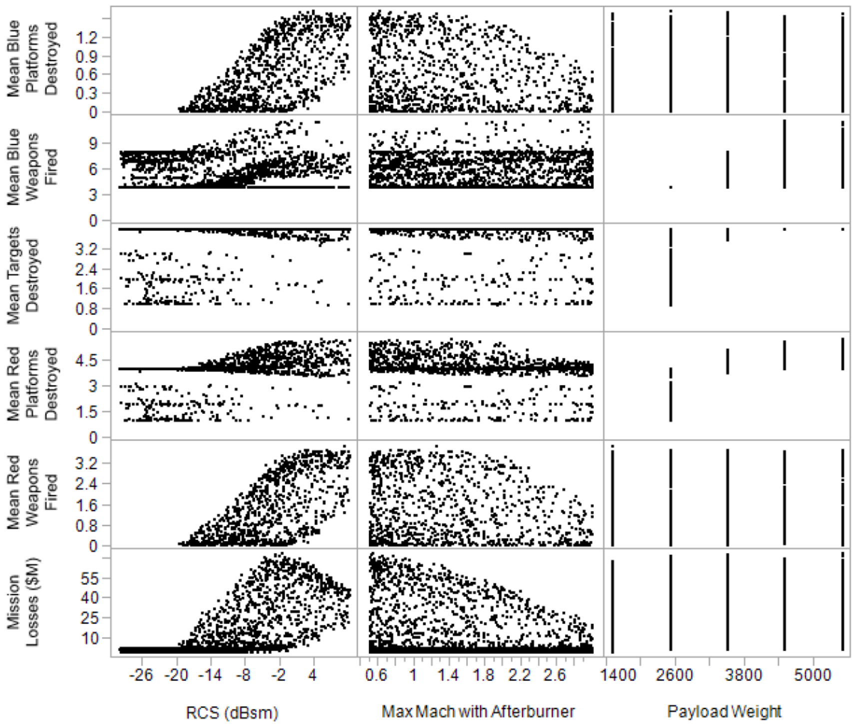


Figure 3.13: Results showing the coupling between aircraft design parameters and MoEs [49]

The three papers demonstrate effectively how operational analysis and conceptual design can be linked and integrated into a larger framework. This approach promises massive efficiency increases during the early design stages, as informed decisions can be made before a concept is chosen and requirements are set in stone. However, all the papers lack in one aspect: They do not harness the full potential of a System of Systems approach, since they only model homogeneous fleets. For the design and analysis of a Loyal Wingman, the simulation of heterogeneous fleets is necessary.

A paper that treats the simulation of heterogeneous fleets and their emergent behaviors using agent-based modeling was written by a group of researchers at Purdue University [53]. The group simulated the behavior and interactions of a fleet of so-called Littoral Combat Ships (LCS). The LCS is a ship concept that uses different payload packages, to achieve different goals in coastal waters. For example, one ship can be configured for anti-submarine warfare, while others are geared for surface warfare or mine clearing. The team used the MATLAB-based simulation tool *Discrete Agent Framework* to model a scenario including different versions of LCS, including friendly helicopters and varying enemy threats. Initial simulations showed major flaws in the implemented tactics, that led to the destruction of a large part of the blue fleet. The flaws were based on non-intuitive agent actions caused by Emergent Behaviors. Based on the results, the tactics were modified, which prevented losses and led to a complete elimination of the red threats.[53] While the experiment is a good demonstration of the implementation and analysis of heterogeneous fleets, it covers the wrong combat domain when it comes to the design of UCAVs.

3.3.4. Alternate SoS Simulation Methods

When it comes to the analysis of a System of Systems, agent-based simulation models are favored, since they capture the essence of an SoS best. In many cases, the agents possess operational and managerial independence, are (virtually) geographically distributed, and can interact and communicate with each other, leading to Emergent Behaviors. Alternate simulation models exist, like *System Dynamics* or *Discrete Event Simulations*.

In the case of *System Dynamics*, the Systems, often even the entirety of the System of Systems, are described by mathematical models capturing the behavior. Depending on the fidelity, the models can become very complex and involve feedback loops. While rarely used for problems as complex as a System

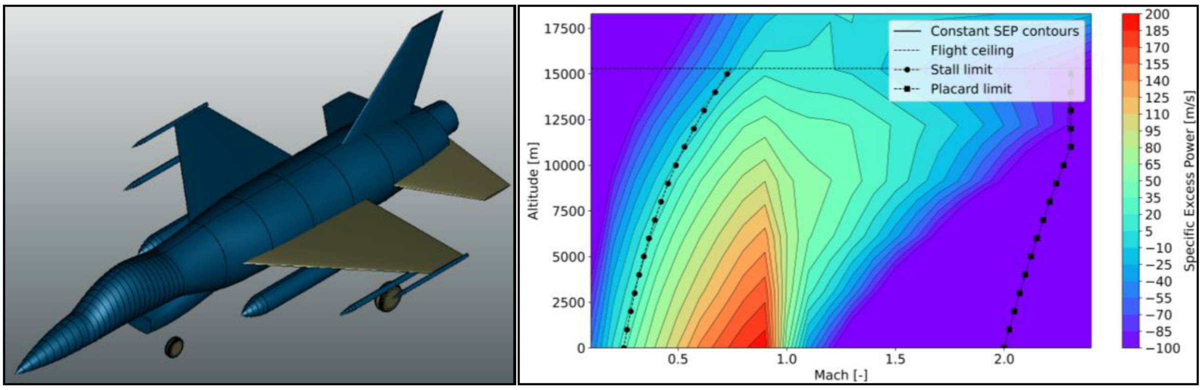


Figure 3.14: F-16 and doghouse plot designed using VAMPzeroF [50]

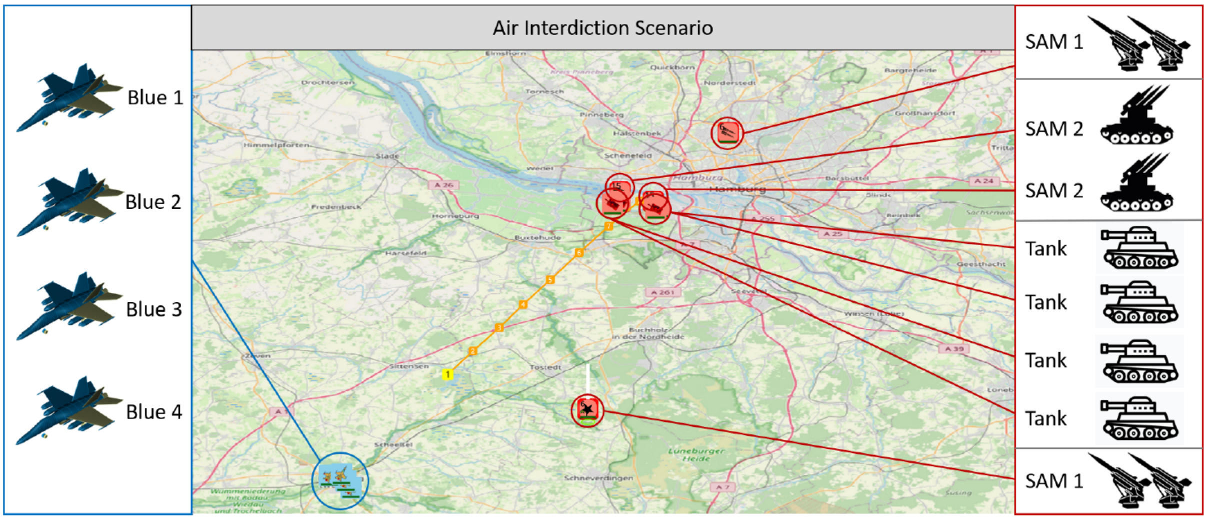


Figure 3.15: Air interdiction mission modeled in MACE [52]

of Systems consisting of multiple aircraft, there are existing examples. Lunsford and Bradley utilized the System Dynamics approach, to evaluate strategies of increasing the survivability of a cargo aircraft under enemy fire. The work is centered around *Lethal Envelope Theory*. A schematic representation in shown in Figure 3.16.

The aircraft is following a simple flight path. Along the path, a manportable air-defense system (MANPADS) is placed. When the aircraft enters the detection envelope, after time r_{d} the MANPADS begins targeting the aircraft, which takes time a. After time s_1 the aircraft enters the lethal envelope of the MANPADS and remains in there for time s_2. When the MANPADS has acquired the target, it fires at the aircraft, which has probability q_{ssk} to survive the shot. The survival probability P_{S} is given by Equation 3.1, where β and γ are given by Equation 3.2, and Equation 3.3, respectively. It is a pure correlation between the time spent in the envelopes and the single-shot survivability.[54]

$$
\begin{aligned}
P_{\text{S}} =& e^{-(s_2-a)r_{\text{d}}} + \frac{1}{2}\sqrt{q_{\text{ssk}}}r_{\text{d}}e^{-(s_2-a)r_{\text{d}}} \times \left((1+\sqrt{q_{ssk}})\frac{e^{(s_2-s_1)\beta}-1}{\beta} - (1-\sqrt{q_{\text{ssk}}})\frac{e^{(s_2-s_1)\gamma}-1}{\gamma}\right) \\
&+ \sqrt{q_{\text{ssk}}}\left(1-e^{-(s_1-a)r_{\text{d}}}\right) \times e^{-2r_{\text{k}}(s_2-s_1)} \\
&\times (\sinh(2r_{\text{k}}\sqrt{q_{\text{ssk}}}(s_2-s_1)) + \sqrt{q_{\text{ssk}}}\cosh(2r_{\text{k}}\sqrt{q_{\text{ssk}}}(s_2-s_1)))
\end{aligned}
\tag{3.1}
$$

$$
\beta = r_{\text{d}} - 2r_{\text{k}}(1-\sqrt{q_{\text{ssk}}}) \tag{3.2}
$$

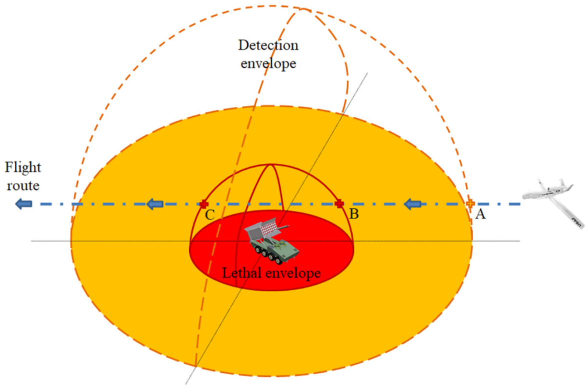


Figure 3.16: Lethal Envelope Model [54]

$$\gamma = r_{\mathsf{d}} - 2r_{\mathsf{k}}(1 + \sqrt{q_{\mathsf{ssk}}}) \tag{3.3}$$

Then, *Monte-Carlo simulations* are performed, including several different tactics to increase survivability. Armoring (reducing the velocity while increasing q_{ssk}), increasing the initial flight speed, accelerating due to fuel dumping, and swarm tactics with UAVs are implemented. In the given case, Loyal Wingmen are used that try to intercept the missile, by serving as decoys.[54] Some of the obtained results are shown in Figure 3.17. While it is possible to use the proposed method to quickly evaluate new tactics, the model is crude, even though it is mathematically complex. Values like the single-shot probability of survival rely on educated guesses and many influencing factors are excluded.

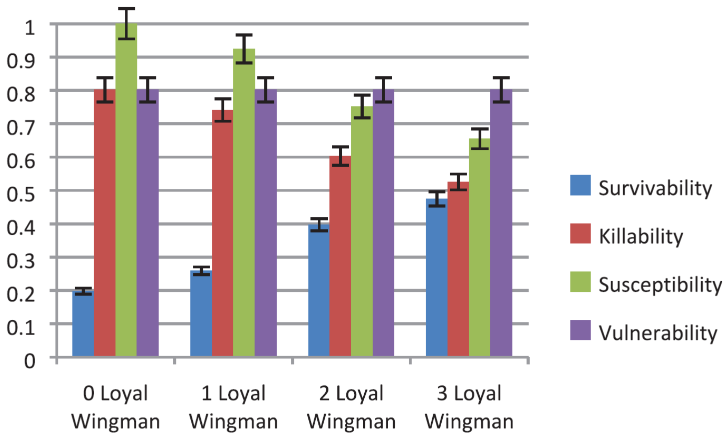


Figure 3.17: Aircraft survivability with varying amounts of Loyal Wingmen in a Lethal Envelope Model [54]

When looking at *Discrete Event Simulations*, the models are less mathematical. Systems are modeled like a flow chart or decision tree, often including probabilities. For example, one could model the previous Lethal Envelope example as follows: When the aircraft enters the Detection Envelope, there is a chance to be detected. If it is detected, there is a chance that it will be engaged, and another probability that it will be hit by a missile. This way, large scenarios can be "played through". However, this method still relies on predetermined probabilities and requires a thorough analysis of possible options. Emergent Behaviors are almost impossible to create because all possibilities are predefined.

A mix of agent-based modeling and discrete event simulations was applied by a group of Chinese researchers from Beihang University. The authors set up a simulation in the commercial software AnyLogic. First, a military scenario is established: a heterogenous fleet consisting of fighters, Loyal Wingmen, and an electronic warfare aircraft, are tasked to destroy military targets, which are protected by air defense systems. All units are set up as individual agents. However, their actions are modeled as discrete events with probabilities. When the manned fighters detect an enemy radar site, they fall back and send the Wingmen to destroy the sites. The Surface-to-Air Missile (SAM) sites have a fixed probability of detecting and engaging the aircraft. In turn, the Wingmen decide to fly evasive maneuvers with a certain probability, where success is fixed with a predetermined rate. Aircraft and UCAV designs are kept fixed, as well as the tactics used. The only parameter varied is the RCS of the UCAV. Due to the probabilistic nature, the simulations are repeated thousands of times. Then, the results are fitted with normal distributions. Based on the distributions, confidence intervals are established, which in turn are used to construct what they call a *Mission Success Space* (MSS).[55] An example of such an MSS is shown in Figure 3.18.

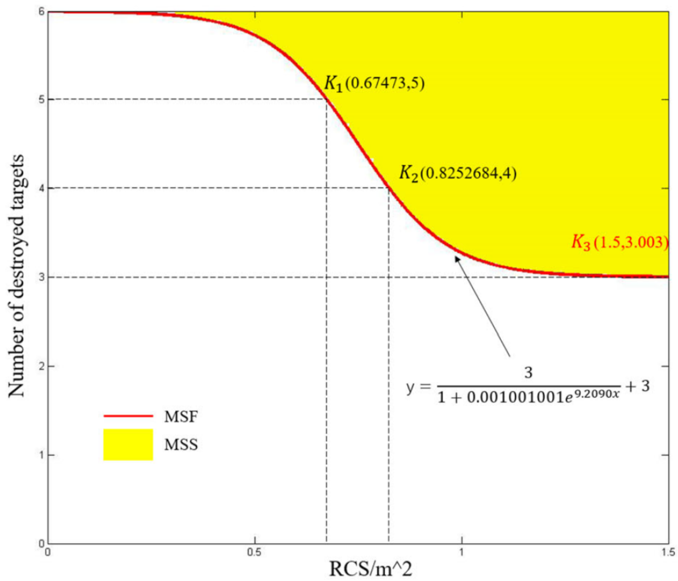


Figure 3.18: Mission Success Space for stealth UCAV design [55]

The idea behind the MSS is, that based on different definitions of success, a requirement for a parameter like the RCS can be derived. For the given example, if success is defined as ”four targets destroyed”, then the Wingman is required to have an RCS of 0.83 m^2 or less. RCS values smaller than the given value, result in a mission success, while higher values lead to a failure. The authors call the boundary between success and failure *Mission Success Function*. It is shown as the red curve. The yellow area signifies the *Mission Success Space*.[55] The idea of a Mission Success Space is interesting because it enables inverse aircraft design, i.e. the aircraft design can be used to discover and define requirements. However, as with the System Dynamics example, in the current form, the results rely on educated guesses, and many influencing factors are excluded.

3.4. Problem Statement

In the previous chapters, relevant literature regarding the history of UAVs and UCAVs was reviewed, including design methodologies and novel approaches. Section 3.4.1 reflects upon the covered literature and identifies the research gap. In Section 3.4.2, research questions are developed, based on the previously identified gaps.

3.4.1. Reflection

As was seen in Section 3.2, the idea of Unmanned Aerial Vehicles is not new. The first UAVs were designed over a century ago. However, only from the 1960s on, breakthroughs were achieved. In the new millennium, the first UCAVs were deployed, which sparked developments in many different directions. In the last ten years, UCAVs developed from a replacement of manned fighters, towards autonomous fighting and sensor platforms which are supposed to support manned fighters. State-of-the-art concepts, like the *Kizilelma* were introduced in Section 3.2.5.

The use and deployment of UCAVs promises many benefits. However, for a successful UCAV design, the conventional aircraft design methods have to be modified, as highlighted in Section 3.3.1. Especially the design of novel aircraft configurations like the Wingmen can profit from the application of MDO and KBE. Two software tools that can accelerate and heavily impact the design process were introduced as well (Section 3.3.2).

Since UCAV concepts like the Loyal Wingman are supposed to act in a larger System of Systems, one also cannot get around the use of System of Systems Engineering. Some novel and promising frameworks were introduced in Section 3.3.3, that connect the conceptual aircraft design using design tools and operational analysis via the use of agent-based simulations. The methods offer a completely new approach to the exploration of the design space and aid in trade-off processes. Lastly, attempts to evaluate the contribution and influence of Loyal Wingmen, as well as deriving design requirements were introduced, too (Section 3.3.4).

However, up to this day, it is unclear how Emergent Behaviors in a heterogeneous aircraft fleet containing Wingmen could look like. It is unclear, whether Loyal Wingmen actually contribute as much as the concept promises. Also, no one was able to quantify the effects in a meaningful way. Many methods that could aid in this were introduced, but most of them are more or less disconnected.

3.4.2. Research Questions

Based on the previously identified research gap, the proposed work aims to combine KBE design tools with the design of UCAVs and to connect them to operational analysis using agent-based simulations. This then is used to evaluate the design and contribution of Loyal Wingmen. The objective is to aid and improve the design of UCAVs designed as Loyal Wingmen, and to provide insights into the requirement definition. Another goal is to learn about the emergent behaviors of an SoS consisting of UCAVs and manned fighters and to establish whether the inclusion of Loyal Wingmen is beneficial in the first place.

Thus, based on the previously established goals, the following main research question is posed:

What are the effects of the inclusion of Loyal Wingmen into a heterogeneous combat aircraft fleet on its Measures of Effectiveness?

Secondary questions are:

What is the optimal design of a Loyal Wingman for SEAD missions, and what is the ideal fleet composition?

And

What is the ideal use tactic for Loyal Wingmen, within a heterogeneous fleet, during a SEAD mission?

3.5. Research Plan

To answer the previously determined questions, first, a Loyal Wingman has to be designed. This will be done using the Python tool VAMPzeroF. At the current moment, the tool can design various fighter aircraft, but no UCAVs. As such, the tool will have to be modified, by adding appropriate design rules. This mostly involves the modification of weight estimates, as discussed previously, but also altered aerodynamic approximations and characteristics of the Radar Cross Section. In large parts, this will be based on the work of Grundlach. The resulting design will be validated by comparing it to existing UCAV designs.

Next, the generated aircraft will be implemented into an agent-based simulation. For this, the tool MACE from Battlespace Simulation Inc. will be used. As described previously, MACE is a physics-based simulation tool, that allows the generation and simulation of a wide range of combat scenarios. The user can build up missions in any part of the world, by placing entities in a three-dimensional space, built on OpenStreetMaps and topological data. The wide variety of modeled weapon systems and platforms allows for a high-fidelity simulation of multi-domain warfare. MACE will be used to build up a scenario, similar to the one shown in Figure 3.15. MACE will also be used to implement logic and strategies used by the agents.

To analyze the Measures of Effectiveness, an experiment must be designed, centered around the SEAD mission. Varying aircraft designs in varying constellations with different payloads and tactics will be combined in a large, full-factorial Design of Experiments (DoE). Some parameters of interest are the maximum load factor of the UCAV, the sustained turn performance, the RCS of the UCAV, the number of missiles the UCAVs carry, as well as the number of Wingmen. Also, baselines will be established to compare the performance of a heterogeneous fleet to a conventional formation of manned fighter aircraft (potentially also with advanced countermeasures like ALE-50 towed decoys). Some MoEs of interest are survival rate and combat effectiveness.

MACE is a deterministic simulation tool, but due to the real-time implementation in Windows, variations are to be expected. This implies that there is a variance in the results, but also a mean. Thus, each simulation is repeated multiple times, until the results of each individual experiment converge. This minimizes variance and increases the accuracy of the mean.

Proper logging of all events within the simulation will be achieved by writing C# plugins, that anchor into MACE. The output will be in the form of log files, which then are consolidated into a single Excel sheet, by a third tool, a self-written Python program. The resulting Excel file can be analyzed using the tool JMP Pro, which combines statistical analysis tools with virtually endless plotting options.

The function of each tool and the individual steps were already validated and documented during a six-month internship.

A listing of all file types, their purposes and storage methods can be found in Table 3.2.

The work can be separated into five distinct major work packages, which are as follows (corresponding times in weeks in brackets):

- Preceding Literature Research (16). An in-depth literature review builds the basis for this work.
- Planning ($\sim$3). Generation of work breakdown structure, Gantt chart, project planning, and management.
- Aircraft Design (10). Includes the adjustments of VAMPzeroF, definition of requirements as well as the generation and adjustment of the different UCAV designs. In case design or VAMPzeroF modifications fail, Alternate aircraft models can be used, as long as the performance specifications match.
- Agent-based modeling (15). Setting up the simulation in MACE, scripting the agent logic, defining scenarios, running the simulations, and simulating the results.
- Documentation (12). Writing a thesis report, including the final presentation.

The work packages were generated using a top-down approach. Time estimates (in weeks) are based on the previous, comparable project. A Gantt chart was created to create an overview. The used tool (the Gantt Project) also allowed to factor in weekends and public holidays, to arrive at a final and detailed planning, including exact deadlines. Milestones are accounted for and included.

Dependencies are mostly linear and direct, i.e. one task depends on the previous and cannot be started before that. In this version of the report, the final Gantt chart is omitted due to limitations in paper size.

Table 3.2: Types of data generated during the project, including their purpose and storage

Type of data	Format	How will data be collected	Purpose of processing	Storage location	Who will have access
VAMPzero input files	.xml	Files will be created manually and contain mission profiles and top level requirements, config. constraints	Input files used by VAMPzeroF to initiate the design	Local hard drives of workstation and personal computer, as well as secure network drive of institute	Small group within the department (4 people)
VAMPzero output files	.xml	Design in CPACS format, including CAD files, SEP and fuel burn look up tables, generated by VAMP	Documenting the design, the latter points serving as input to MACE.	Local hard drives of workstation and personal computer, as well as secure network drive of institute	Small group within the department (4 people)
MACE mission logs	.txt	Automatically generated by MACE	Documenting each mission, including the individual actions, for evaluation	Local hard drives of workstation and personal computer, as well as secure network drive of institute	Small group within the department (4 people)
Results table	.xlsx	Generated by MaceDataProcessor, self-written Python tool	Consolidating data from log files	Local hard drives of workstation and personal computer, as well as secure network drive of institute	Small group within the department (4 people)
Results, graphs	.png/.jpg	Result analysis via JMP Pro	Result analysis	Local hard drives of workstation and personal computer, as well as secure network drive of institute	Small group within the department (4 people)

3.6. Conclusion

A project centered around the System of Systems driven design of UCAVs, specifically Loyal Wingmen, is proposed. During the project, the already existing KBE fighter aircraft design tool VAMPzeroF will be modified to facilitate the design of UCAVs. Then, the generated designs will be included into agent-based simulations, using the tool MACE, developed by Battlespace Simulations Inc. The resulting log files will be processed via a self-written Python tool, MaceDataProcessor. The final results will be analyzed using JMP Pro.

The proposed project has the potential to significantly advance the field of UCAV design. The use of KBE tools and agent-based simulations will provide a comprehensive analysis of the performance and benefits of UCAVs in a heterogeneous aircraft fleet. The insights gained from this project can help in developing novel aircraft design strategies and could potentially lead to the adoption of the Loyal Wingman in future military operations. Overall, this project could be a step towards enhancing the capabilities of aircraft fleets.

Part III

Supporting Work

4
Tail Configuration and Sizing

During the very early stages of conceptual aircraft design, the designer must choose the tail configuration. This decision is impactful, and the tradeoff is nontrivial. Fortunately, KBE tools like *VAMPzeroF* make it possible to generate designs for varying configurations quickly and efficiently to see the impact directly. The tradeoff for the presented UCAV is explained here.

A conventional tail configuration serves as a logical starting point. The Wingman with a conventional tail is shown in Figure 4.1. The shown configuration leads to an MTOM of 10541 kg. It is a proven design, simple in production, and straightforward from a control point of view. However, the horizontal and vertical tails form a perfect retroreflector due to the 90-degree angles, i.e., any incoming radar wave will be reflected directly back to its source. This effect results in a significantly increased Radar Cross-Section. As outlined in Section 2.2, the Wingman should be designed with stealth capabilities in mind, so the RCS properties of the conventional tail constitute a significant drawback.

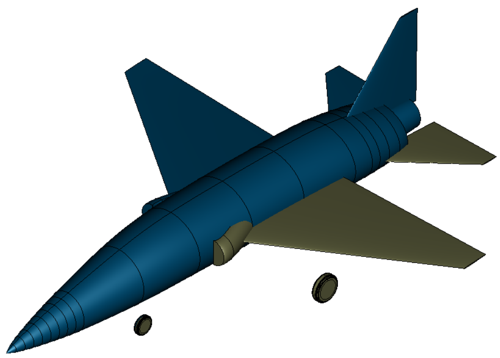


Figure 4.1: Wingman with a conventional tail configuration

Some Wingmen are sized for extreme maneuver loads. During those maneuvers, vortices are almost certainly shed from the fuselage, reducing the effectiveness of the vertical tail. To reduce the impact, the vertical tail can be shifted further outboard. Consequentially, the following tail configuration tested is a twin-vertical tail used on fighter aircraft like the F-15 *Eagle* or F-14 *Tomcat*. The resulting Wingman design is shown in Figure 4.2. This Wingman version has an MTOM of 10446 kg, almost 100 kg less than the weight of the conventional tail Wingman. The reduced weight makes this tail configuration more attractive. However, it suffers from the same RCS properties as the conventional tail.

To improve the stealth properties, the vertical tails can be canted as seen on fighter aircraft like the F/A-18 *Hornet*, but also rather unconventional aircraft like the SR-71 *Blackbird*. The resulting design is shown in Figure 4.3. The canted tails slightly increase the MTOM to 10485 kg. The weight increase stems

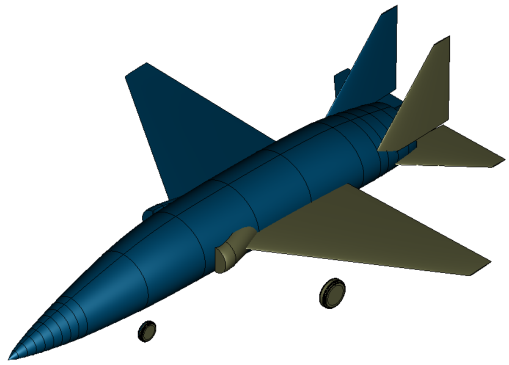


Figure 4.2: Wingman with a twin-tail configuration

from an increase in fin area, as the *projected* surface area needs to stay constant. However, the canted twin-tail configuration is still lighter than the conventional tail configuration. Furthermore, it solves the problem of vortex shedding and radar signature, making it the most suitable configuration so far.

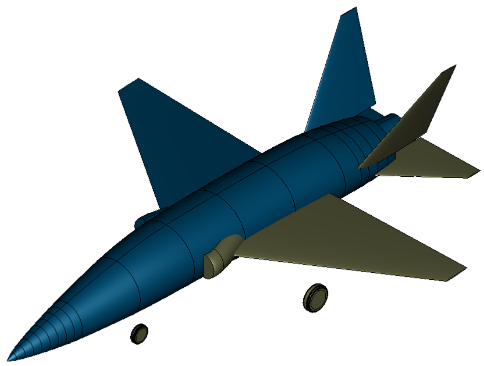


Figure 4.3: Wingman with a canted twin-tail

The last tail configuration tested is a V-tail, also known as a butterfly tail. The configuration is shown in Figure 4.4. With a V-tail, the MTOM reduces to 9949 kg, which is 600 kg lighter than the weight of the conventional tail Wingman. Like the canted twin-tail, it also solves the issues of vortex shedding and radar signature. However, the configuration also brings two disadvantages. The UCAV becomes far more vulnerable since only two tail surfaces exist. If either surface is damaged, the aircraft becomes either hard to control or completely uncontrollable, leading to attrition. This is likely the main reason V-tails are seldom seen in the design of manned combat aircraft despite their demonstrated advantages. However, this increased vulnerability could be accepted considering that the Wingman is *unmanned*. The second drawback of the V-tail concerns the flight dynamics. Due to the placement of the tail surfaces, a coupling between yaw and roll is occurring. When yawing to the right, the aircraft experiences a negative rolling moment, i.e., it banks out of the turn, and the turn becomes uncoordinated. Fortunately, using modern fly-by-wire controls, one can compensate for this by simultaneously deflecting the ailerons. As both drawbacks of the V-tail are deemed tolerable for the design of the Wingman, the V-tail configuration is selected, leading to the design presented in Part I.

At this point, an oddity of twin-tail configurations should be mentioned. It is universally accepted that twin-vertical tails are more effective than single fins. The increased effectiveness allows reducing the size

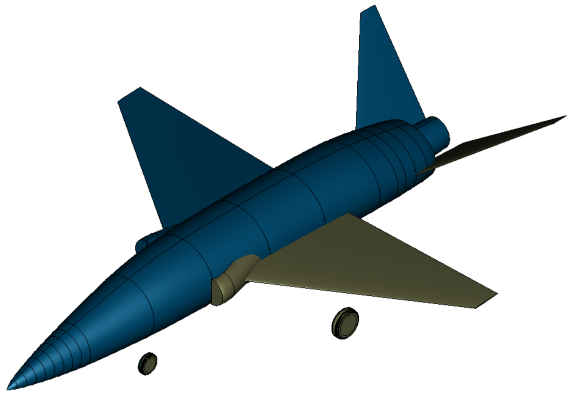


Figure 4.4: Wingman with a V-tail

of the individual fins, leading to a lower overall height and reduced bending moments. The lower height makes twin-tails especially attractive when strict hangar height constraints are given, like on aircraft carriers. While this tail configuration is not uncommon, quantitative expressions for the increase in effectiveness are incredibly challenging to find. A literature research leads to the following estimate from Whitford [56]:

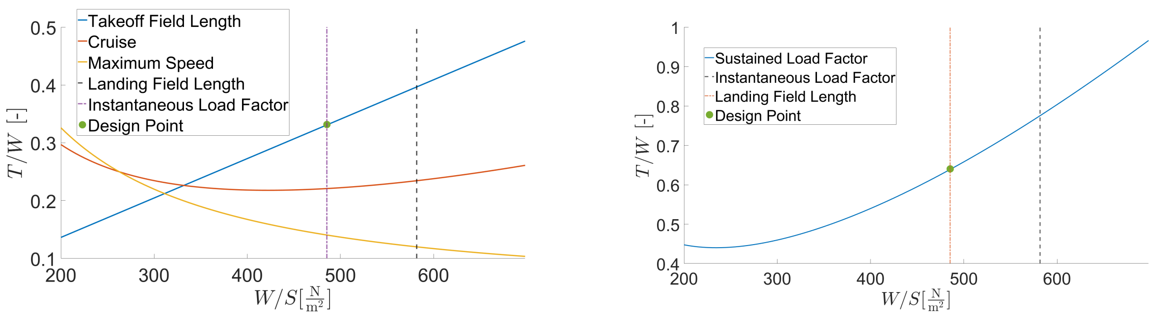
"[...] increasing the area of a single fin by 30% could increase directional stability by 55%, giving a relative efficiency of 120%. Doubling the fin area by the use of twin fins increased directional stability by only 20%, however, giving a relative efficiency of just 70%."

This means that by adding a second fin of identical size, the directional stability increases by 20%. Alternatively, when keeping the directional stability constant, the surface area of the individual fins can be reduced by ~17%. As *VAMPzeroF*'s knowledge base did not include rules for twin-tail configurations, the given relation is implemented for sizing.

5

Wing Aspect Ratio Trade

Another important tradeoff is the one for the wing's Aspect Ratio A. Commonly, this tradeoff is performed based on constraint diagrams, like the ones shown in Figure 5.1. The designer generates constraint diagrams for multiple Aspect Ratios and chooses A to minimize the Thrust-to-Weight Ratio T/W while maximizing the Wing Loading W/S.



(a) Constraint diagram for dry thrust

(b) Constraint diagram for wet thrust

Figure 5.1: Constraint diagrams for the exemplary Wingman

Constraint diagrams can become rather complex, especially for designs with many performance requirements. In those cases, KBE tools like *VAMPzeroF* allow the tradeoff to be performed based on the final MTOM. This method was selected for the Wingman design. Wingmen designs for varying sustained load factors and the number of ARMs carried are created for a range of Aspect Ratios. The results for the Wingman carrying two missiles are shown in Figure 5.2. As can be seen, towards low Aspect Ratios, the MTOM increases rather quickly. Wingmen designed for higher load factors are consistently heavier. Towards higher Aspect Ratios, the MTOM quickly converges, and differences between the different Wingmen become smaller. Beyond Aspect Ratios of 5, further weight reductions become marginal.

Figure 5.3 shows the results for Wingmen carrying four missiles. The same trends can be observed as in Figure 5.2. However, the divergence towards lower Aspect Ratios is more extreme, and the separation between the different Wingmen becomes larger.

Upon closer inspection, one realizes that some sample points are missing. This is because *VAMPzeroF* could not always converge onto a consistent design. Considering the need for reliable convergence, the Aspect Ratio of 5 is infeasible. Instead, an Aspect Ratio of 4.5 is selected for all Wingmen. The resulting weights are very close to configurations with a higher Aspect Ratio (e.g., 5.5) but result in a smaller Wingman regarding overall length and wingspan.

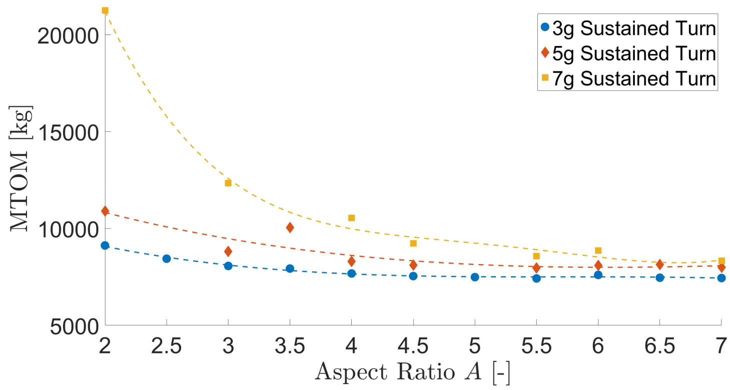


Figure 5.2: Wingman weight for varying Aspect Ratios. The Wingman is carrying two ARMs and is sized for three different sustained turns.

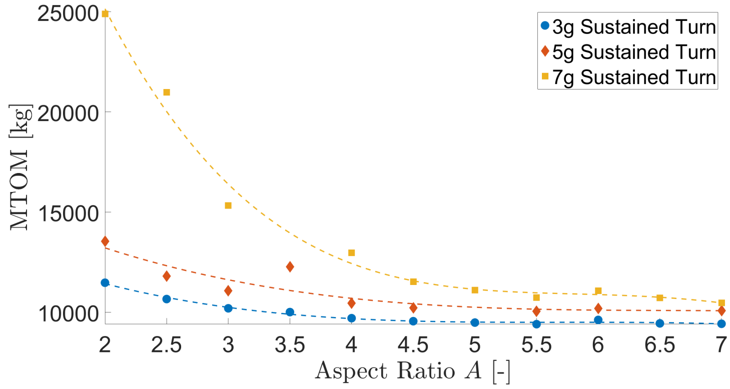


Figure 5.3: Wingman weight for varying Aspect Ratios. The Wingman is carrying four ARMs and is sized for three different sustained turns.

6
Fuzzy AHP

The *Fuzzy Analytic Hierarchic Process* described in Section 2.2 can initially seem obscure. Thus, this chapter is used to show the details of the procedure.

Assuming one wants to express the mission efficiency as the sum of a system's survivability, cost, and lethality, as previously done in the quality integral (Equation (6.1)), one can compare and rate each measure relative to the others. For example, one could give survivability a relative weight of 6 compared to cost. The reciprocal weight of cost compared to survivability is 1/6. Doing this for all three measures, one receives nine relative weights that can be written in matrix or table form, as shown in Table 6.1. As can be seen, the relative comparison of a measure to itself yields the value of one, so the entries on the diagonal are always unity.

$$J = \sum_{k=1}^{N} \sigma_k w_k j_k \tag{6.1}$$

Table 6.1: Example relative weights using AHP

Parameter	Survivability	Lethality	Cost
Survivability	1	2	6
Lethality	$1/2$	1	3
Cost	$1/6$	$1/3$	1

Further following the approach, one can determine the individual weights w by treating it as an Eigenvalue problem, as shown in Equation 6.2, where λ_{max} is the principal Eigenvalue. Normalizing the principal Eigenvector so that its elements' sum is unity yields a vector where the entries are the individual weights.

$$A\vec{w} = \lambda_{\text{max}}\vec{w}, \qquad A = \begin{pmatrix} 1 & 2 & 6 \\ 1/2 & 1 & 3 \\ 1/6 & 1/3 & 1 \end{pmatrix}, \qquad \lambda_{\text{max}} = 3, \qquad \vec{w} = \begin{pmatrix} 0.6 \\ 0.3 \\ 0.1 \end{pmatrix} \tag{6.2}$$

While this provides a method of determining weights, one might have realized that one still, more or less arbitrarily, assigns a number, which can be challenging. Thus, in *Fuzzy* AHP, one uses *linguistic variables*. For example, survivability can be an ”absolutely dominant” criterion over cost. *After* the relative importance is defined, *sets* of numerical values are assigned to each linguistic variable. The used assignments are listed in Table 6.2. As can be seen, the sets are partly overlapping and hence account for the uncertainty of the assignment (hence the name ”fuzzy”).

One can create a new matrix for each value from (l, m, u), yielding three matrices, three Eigenvalue problems, and three vectors with weights. Using a ”defuzzification function”, one can convert the three sets into one final result. The defuzzification function is given in Equation 6.3.

Table 6.2: Linguistic variables and assigned tri-angular fuzzy set [57]

Linguistic variable	Triangular fuzzy set (l, m, u)
Absolutely dominant	(8, 9, 9)
Very much more	(6.5, 7.5, 8.5)
Much more	(5, 6, 7)
Substantially more	(4, 5, 6)
Significantly more	(3, 4, 5)
Slightly more	(1.5, 2.5, 3.5)
Equivalent	(1, 1, 2)

$$defuzz(l, m, u) = \frac{1/3 \cdot (-lm + um - l^2 + u^2)}{u - l} \tag{6.3}$$

As this chapter and Section 2.2 showed, applying Fuzzy AHP provides a robust method to reliably quantify *subjective* priorities in an unbiased and systematic manner.

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