Fighter Design and Fleet Effectiveness Evaluation via System of Systems Battlespace Simulation

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With ever-increasing regional conflicts and demand for military deterrence and peace, there is a need for highly capable, agile and multirole manned and unmanned fighter. Due to difficulty in prediction, uncertain needs drive more and more capabilities in a specific vehicle leading to bigger, more expensive and harder to upgrade multirole fighter aircraft. Today's fighter aircraft operate in a highly agile environment, fulfilling a wide set of roles like air superiority, aerial reconnaissance, forward air control, electronic warfare, etc. To fulfill these tasks, several kinds of weapons, sensors and communication systems are necessary. That results in a larger airframe and also in a higher total weight. Next generation fighters will not incorporate all of the systems for the specific roles. Instead the systems responsible for the abilities are spread over several smaller unmanned platforms which are linked to the manned fighter by network connections. The fighter itself can be lighter and more agile, and the abilities can be upgraded by additional platforms. The increased complexity of the battlespace increases the scope for evaluating requirements, conceptual design of new fighter aircraft, unmanned aerial vehicle, mid-air refueling tanker, etc. Using a System of Systems (SoS) Battlespace simulation driven aircraft design approach helps to simulate multi-platform interaction and account for numerous uncertainties in the development of future battle systems. For this reason, this research focuses on developing a SoS framework for fighter evaluation and design with three different aspects:

- **Linking conceptual fighter aircraft design & weapon performance to a large multi vehicle battle scenario via agent-based simulation**
- **Analyzing the sensitives of technology, vehicle design, fleet composition, interoperability and weapon selection as well as evaluating requirements**
- **Obtaining a set of aircraft level parameters for the fighter aircraft that produce improved SoS-level Measures of Effectiveness (MoE) during a Counter-Air Fighter Sweep mission such as blue win rate, Survivability and weapon usage**

Herein, a baseline aircraft and its sensitivity trade-offs modelled. The mission performance is evaluated by formulating different measures of effectiveness. In summary, this study demonstrates the need for system of systems simulations to derive adversary and operations-tailored vehicles and fleets.

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I. Nomenclature

ABS = Agent-based Simulation
AFSIM = Analytic Framework for Simulation, Integration and Modeling
API = Application Programming Interface
BAAINBw = Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support
BSI = Battlespace Simulations Incorporated
CAF-DMO = Combat Air Forces Distributed Mission Operations
CGF = Computer Generated Forces
BVR = Beyond Visual Range
DoE = Design of Experiments
EM = Energy-Maneuverability
FCAS = Future Combat Air System
IADS = Integrated Air Defense System
IR = Infrared
LPI = Low Probability of Intercept
MACE = Modern Air Combat Environment
MER = Mission Efficiency Ratio
MoE = Measure of Effectiveness
OCA = Offensive CounterAir
PDU = Protocol Data Unit
RC = Remote Carrier
SAF = Semi- Automated Forces
SoS = System of Systems
SEP = Specific Excess Power
SISO = Simulation Interoperability Standards Organization
TLAR = Top Level Aircraft Requirement
WEZ = Weapon Engagement Zone

II. Introduction

With evolving regional conflicts between competitors on peer-to-peer level [1], the development of new weapon systems needs to improve capability sets. New technologies within topics like electronic attack, radar, imagery, weapons and communications enable new options on a contested battlefield. But new combat vehicles are becoming more expensive due to extensive requirements of multirole war fighting capability. This multirole capability requires several weapons, sensor & communication systems and avoidance subsystems. That leads to large non-stealthy, inefficient, bigger and heavier platforms [2]. While a solely performance optimized individual system, does not guarantee maximum overall mission effectiveness, a fitting combination of fleet, technology and operational tactics can effectively lead to air superiority. Highly integrated operations within a System of Systems (SoS) context with Remote Carrier (RC), legacy fighter and other platforms airborne and on ground lead to new tactical opportunities, visualized in Fig. 1. Additionally, the issues of maintenance, training and upgradability is cumbersome for such heavily equipped multirole combat vehicles. Lastly, the operation of expensive platform inhibits high risks since one lost aircraft becomes very costly. Thus, there is a need for modern combat vehicles to be lean and capabilities distributed across multiple smaller agile platforms or Mother - Children roles; i.e. Loyal Wingman or RCs. Therefore, the effectiveness of a multi vehicle battlespace and the impact of individual platforms or weapons applied to joint operations needs to drive the vehicle design, weapons & subsystem integration as well as fleet operations.

In the past the analysis of SoS problems via agent-based simulations (ABS) in military contexts emerged to a beneficial capability to evaluate different platforms, technologies or weapons. Several organizations like NATO [3], USAF [4] or Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw) [5] mention or apply ABS in an applicant environment. Several researchers used SoS methods and tools to address individual research topics like Decoy operations [6], maneuvering [7] or tactical formations [8].

In a bigger picture, Conner [9] developed a methodology to evaluate the benefits of a particular weapon systems and analyze new missile concepts of aircraft launched missiles using AFSIM (Analytic Framework for Simulation, Integration and Modeling). On vehicle level Biltgen [10] [11] already identified modeling and simulation as an enabling technique to determine the impact of candidate technologies with respect to capability-based Measures of Effectiveness (MoE). He integrated this technique within a ten-step methodology process for quantitative technology evaluation for systems-of-systems. Talley [12] proposed a multi-level robust design process, which contains operational environment, scenario level and intermediate levels. While they focused on missions of a single design object via ABS, Frommer [13] suggested a process that involves the design new aircraft in fleet by considering the objectives and constraints on SoS level for consisting a search and find and suppression of enemy air defense operations via a framework including surrogate models for metrics such as capability and cost.

All these publications describe platform by surrogate models or on sizing level. Therefore, the focus of this Academic Research study is to develop a SoS framework which is able to;

1) Link conceptual fighter aircraft design & weapon performance to a large multi vehicle battle scenario via agent-based simulation
2) Analyze the sensitives of technology, vehicle design, fleet composition, interoperability and weapon selection as well as analyses sensitivity for Top Level Aircraft Requirements (TLARs) and evaluating requirements
3) Obtain a set of system level (aircraft level) parameters for the fighter aircraft that produce improved SoS-level MoE during a counterair fighter sweep mission such as blue win rate, Mission Efficiency Ratio (MER), Survivability and weapon usage

Fig. 1 Illustration of a future SoS air combat scenario [14]

Parametric studies at aircraft, weapon and multiplatform level will be performed via Red vs Blue teams battle simulations on platform level (multiple payload configurations, aircraft range, aircraft speed) collaboration level (Communication J3 & Link 16 data link effectiveness, maneuvering), fleet level (number of aircraft), technology level (empty weight) for a standard counterair scenario inspired by [15]. A variety of MoEs will be applied to interpret the results.

The research team at DLR – Institute of Systems Architectures in Aeronautics is working on a simulation embedded SoS framework. The framework spans along components, weapons, sensors, subsystems, systems, SoS, mission thread and mission scenarios/operations. The integrated vehicle design and technologies can be designed with varied fidelity and battle scenario simulated.

III. System of System Air Combat Framework

To structure the SoS design, a framework is developed to establish the key variables of the design, construct the SoS model, execute the simulations, and analyze the output data to constrain the design space. Fig. 2 depicts the vision of the combat vehicle design and fleeting where the simulation drives the process. For various scenarios spanning multiple technologies, environmental conditions and equipment distributions, simulations can be performed to identify the most efficient and robust fleet, aircraft design, and the SoS level parameters that respectively constitute them. SoS parameters such as the fleet size, combinations, and distribution and their impact on the combat outcome can be investigated in this framework. Notice that the missions are based on blue vs red scenarios. In real live the knowledge of the adversary team is based on intelligence information. This knowledge is highly critical for mission success. Therefore, the mission outcome is highly sensitive to the assumption of red capabilities.

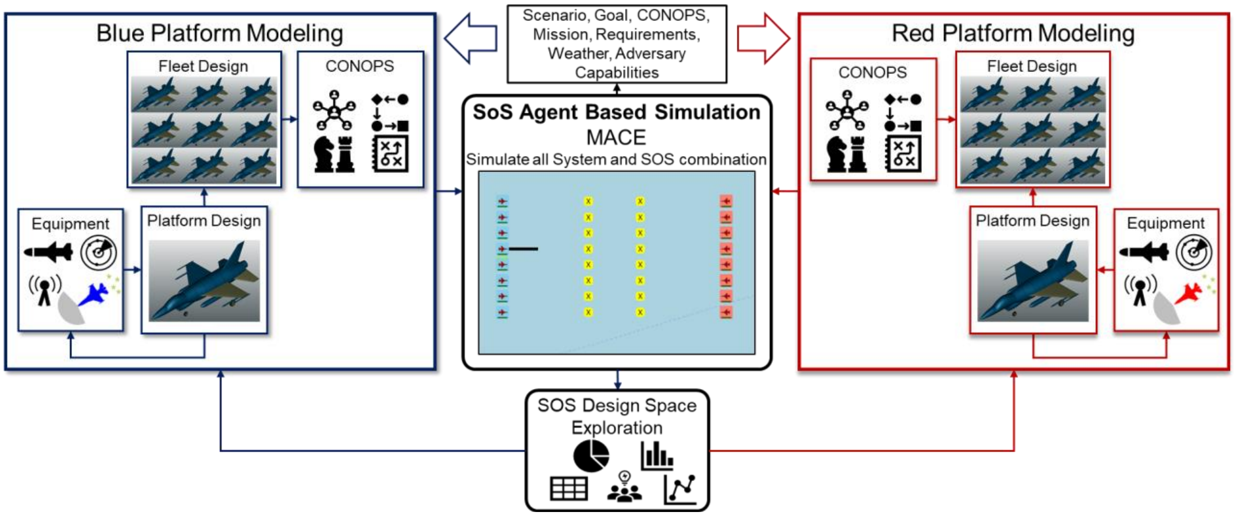

Fig. 2 Original framework for SoS driven combat aircraft design

While Fig. 2 visualizes the framework Fig 3 presents the tool and data workflow as applied to the sensitivity and trade studies conducted for this paper.

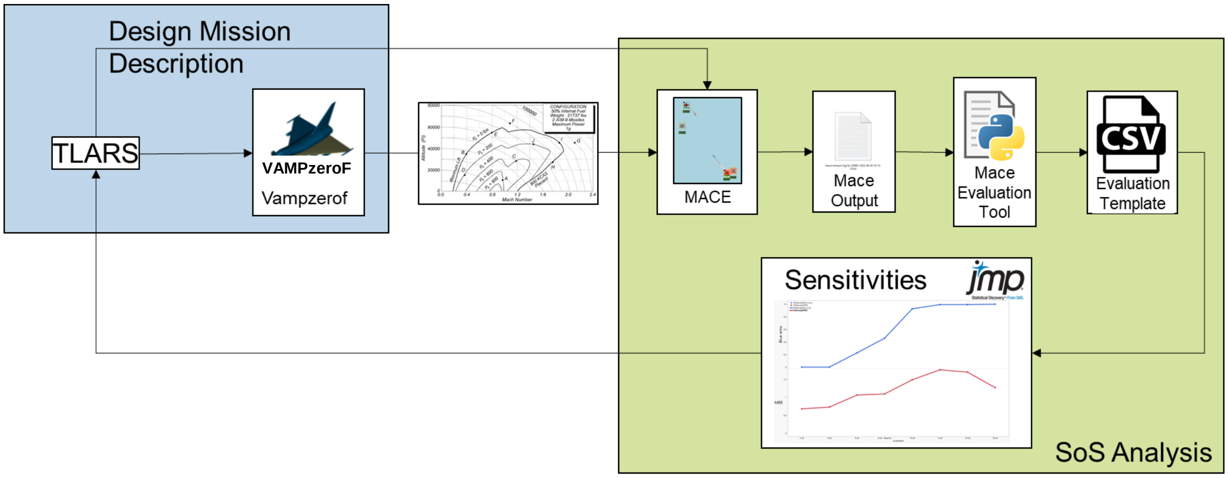

Fig 3: Workflow for the sensitivity study of this paper

Based on a first set of initial TLARs, a baseline platform is designed via VAMPzeroF (III.B Platform Design). The aircraft design tool delivers the necessary performance, payload, and geometry for the simulation tool MACE (Modern Air Combat Environment) (III.A Multi Agent-Based Simulation). Within MACE a mission is constructed based on the reference mission of the TLARs and including resulting aircraft model. The MACEDataProcessor (MDP) reads the output logfiles created by MACE and converts it in a JMP readable format for the final data analysis. The simulation results allow to draw a conclusion on a refinement of the TLARs.

A. Multi Agent-Based Simulation

Agent-Based Simulation was performed via the commercially available software, Modern Air Combat Environment or MACE created by Battlespace Simulations Inc. MACE is a physics-based, full spectrum Computer Generated /Semi- Automated Forces (CGF/SAF) application with a large and user-extensible order of battle, capable of many-on-many simulation yet having high fidelity at the engagement level with publicly available information on platforms and weapon systems [16]. MACE can simulate advanced, 5th generation systems including low observable platforms and Active and Passively Electronically Scanned Arrays (AESA and PESA radar) as well as highly contested battlespaces. MACE supports the Distributed Interactive Simulation (DIS) architecture including simulation management, entity state, fire, detonate and emissions Protocol Data Units (PDUs); MACE complies with the Simulation Interoperability Standards Organization (SISO) standards and Combat Air Forces Distributed Mission Operations (CAF-DMO) extended DIS standards, thereby enabling participation in distributed mission operations. MACE supports both ground-based and airborne entities, weapons, electronic warfare, datalinks, and Integrated Air Defense Systems (IADS). The entire battlespace is modeled to high degree of fidelity. RF emissions are modeled to the pulse level, and signal propagation over terrain and attenuations by atmospheric effects are modeled in real time. Aircraft countermeasures, to included chaff, multi-frequency IR flares, Radar Absorbent Materials (RAM), 3D radar cross sections, and Low Probability of Intercept (LPI) radar systems are also modeled, allowing for a very high-fidelity representation of present-day large force contested airspaces. MACE also has a robust Application Programming Interface (API), allowing for the third-party extension of MACE's inherent capabilities.

In MACE Aircraft Performance parameters are stored in XML-files using an energy maneuverability (EM) based aerodynamic model for aircraft flight. The model is described via flight envelope borders and Specific Excess Power (SEP). Flight envelope borders are described from EM principles by fixed values for maximum speed, altitude and G force. Minimum speed is calculated via the know lift function in Eq. (1) via aircraft weight W, lift coefficient C_L, air density ρ and wing area S. The main parameter modeling aircraft flight performance is the (SEP) [16] influenced by Mach number Ma, speed of sound c, thrust T, aircraft weight W, zero-lift drag coefficient C_{D_0}, dynamic pressure q, wing area S, induced-drag coefficient C_{D_i}, lift coefficient C_L and load factor n displayed in Eq. (2).

$$v = \sqrt{\frac{C_L \frac{\rho}{2} S}{W}} \tag{1}$$

$$SEP = Ma \times c \left[\frac{T}{W} - \frac{C_{D_0} q S}{W} - \frac{\left(\frac{C_{D_i}}{{C_L}^2} \right) n^2 W}{qS} \right] \tag{2}$$

Additionally, MACE considers fuel consumption via fuel-burn look- up based on Mach number, altitude, configuration and weight.

1. *Mission Setup*

The scenario setup in this mission forms an offensive counterair (OCA) operation described as fighter sweep. By the definition of the US Air Force a fighter sweep mission is an offensive mission by fighter aircraft to seek out and destroy enemy aircraft or targets of opportunity in a designated area [17]. Therefore, the target of this paper's scenario is to achieve air superiority over a defined battlespace by one team. Air superiority is defined by the US Air Force as the degree of control of the air by one force that permits the conduct of its operations at a given time and place without prohibitive interference from air and missile threats [17]. This can be reached by controlling the airspace without threats from hostile aircraft. Following that, we define a win as one team surviving with at least one aircraft, while all enemy aircrafts are either destroyed or withdrawn from the battlespace. Draws are possible if no aircraft of either team is left within the defined battlespace. In the baseline scenario visualized in Fig. 4, eight blue fighters are facing two red fighters where all the fighter jets are of the same type and equally equipped.

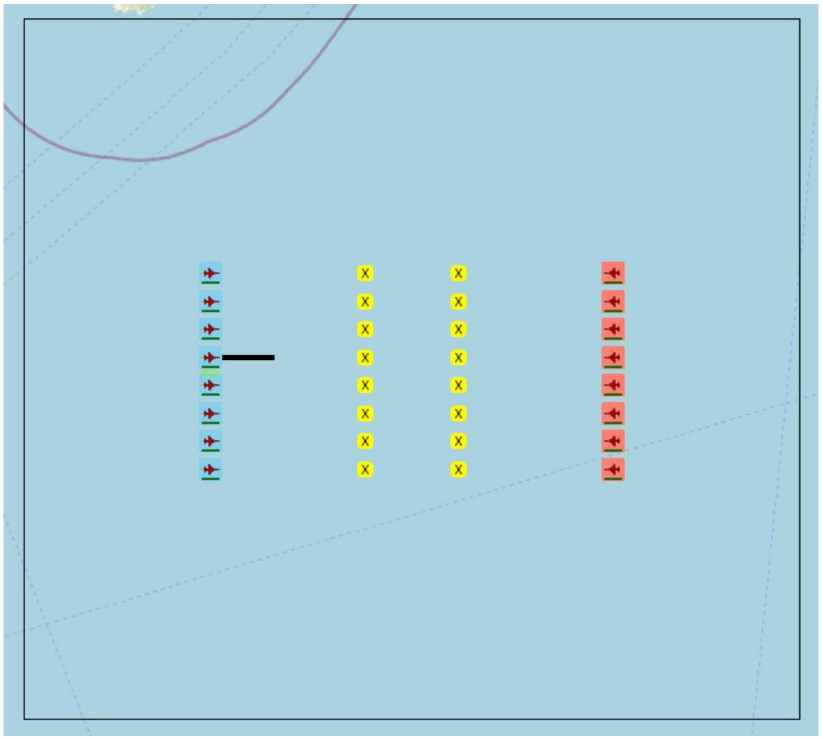

Fig. 4 Scenario Set-up: Red and Blue team and contested battlespace

The aircraft models used with in the simulation are similar to the General Dynamics F-16 CD “Fighting Falcon” (based on publicly available information). During the Design of Experiments (DoE), number and equipment of the red team fighters and their equipment stay the same. Only the composition of the blue team changes by varying number of blue aircraft, weaponry, equipment and flight performance.

The contested battlespace of the scenario is located above a sea and it spans over an area of 110 km x 125 km. The aircraft of both teams are located equally spaced from the center of the battlespace to west and east and are facing each other in a distance of 64 km. The aircraft’s side abreast separation is 4,4 km. All aircraft start at 7000m altitude and Mach 1.14 speed. The base scenario consists of two aircraft for each team which are identically equipped.

The base equipment in terms of weapons are 2 PW-211 and 2 PW-113. The PW-211 and PW-113 are generic models of a AIM-120 AMRAAM type similar missile and respectively a AIM-9 Sidewinder type missile based on publicly available information. The PW-211 is a Medium-Range Air-to-Air Missile whereas the PW-113 is a Short-Range Air-to-Air Missile. Furthermore, the aircraft is equipped with a board gun with 511 rounds. For defending themselves a total of 60 Chaffs and 30 Flares are carried on each aircraft. All Data-Links of the aircraft are disabled in the baseline scenario. Fighters of one team are not able to share information (e.g. of opponents’ location) with each other. The efficiency of Link-16 capabilities are exploited via sensitivities as described in chapter IV.

Although this research replicates real world maneuvers, topics like real world tactics coordinated shots and cooperative targeting, electronic warfare is not considered or in a simplified manner.

2. *Agent Behavior*

Each combat vehicle is an agent with a logic modeled as shown in an overview in Fig. 5 and each individual in Fig. 6, Fig. 7, Fig. 11 and Fig. 12. The mission starts with all agents proceeding to the waypoints. If there are hostile aircraft left the agent will set their target fly in their direction and start to engage them. Each dotted white logic block is necessary in each phase of the mission, therefore each of the logics described below will be performed from the start and enabled again once all actions of the logic are performed. That means the logics for defensive maneuvers, target destroyed or conflicts with the battlespace borders are always active and overturn the attack and engagement logics. Each agent only attacks its assigned target and takes shots based on an internal logic created within MACE based on the Weapon Engagement Zone (WEZ) of the selected weapon, visibility and orientation to the hostile aircraft. The agents act only on their own behavioral logic but not coordinated as a group. The mission finishes and restarts when all agents or all agent of one team are destroyed.

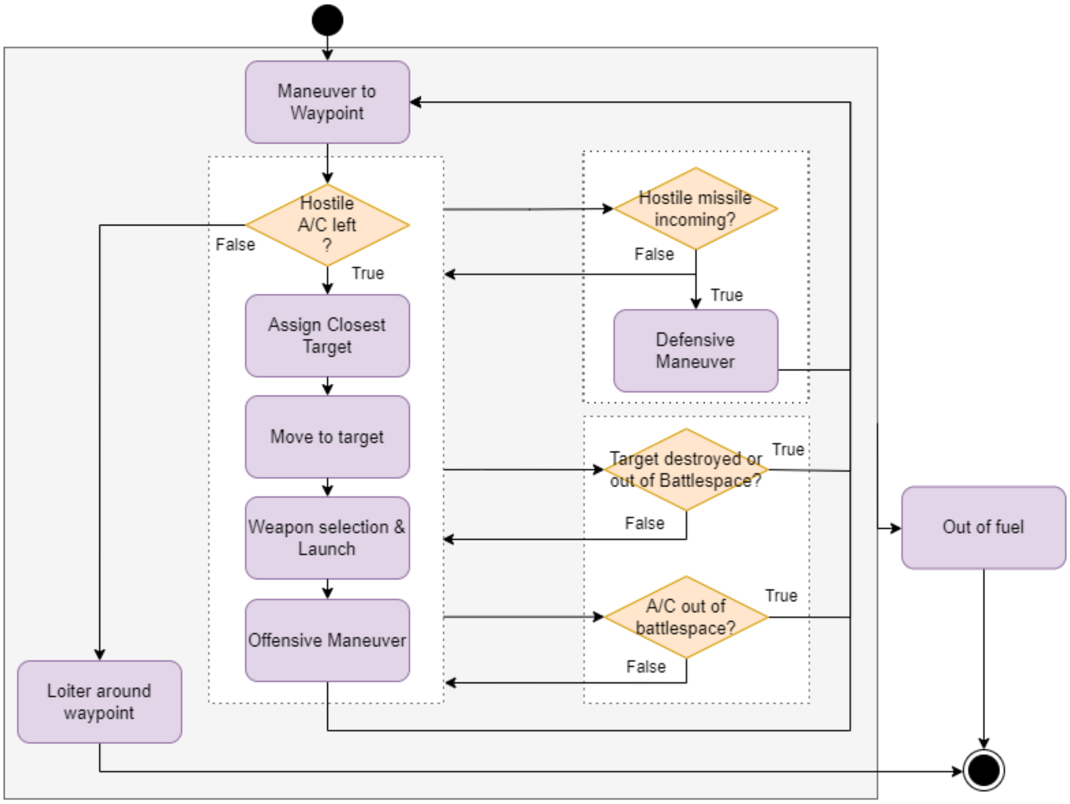

Fig. 5 Agent Behavior during a Fighter Sweep Scenario

Assign closest target

At the beginning of the simulation, the fighter jets search for their closest air enemy using their onboard radars, the APG-68, based on representative radar signal parametric data available within the public domain. To assign the closest target it is required that the fighter jet as well as its closest enemy needs to be inside the contested battlespace. When the closest enemy is found, the aircraft marks it as its target and heads towards it. The logic for this maneuver is shown in Fig. 6. If the targeted aircraft is within the WEZ, the aircraft shoots a missile, based on proficiency settings. The WEZ is specific for each missile type and is dependent on the aircrafts heading towards its hostile aircraft, the flight velocity and the altitude. It describes the range to a target, where a certain missile can be used. In contradistinction to the short-range missile PW-113, the medium-range missile PW-211 has a larger WEZ. Therefore, it can be fired from a greater distance to the target. The board gun has the shortest WEZ.

When datalinks are enabled within the scenario, datalink track contributions from aircraft of the same team can affect the "assign closest target" behavior. The PW-211 is capable of engagement on datalink contributions alone, meaning the launching platform is not required to acquire the target platform with their own radar before employing a Beyond-Visual-Range (BVR) weapon. The blue team exchanges target tracks between members of the own team via Link16 radio. That gives each platform a better understanding of the battlespace, even if its radar is not facing in the correct direction. The tracks can be used in multiple ways. For simplification we use it only for assigning a new target. Potential is there for target sorting and coordinated shots. In our scenario blue platforms rank all incoming and own tracks to hostile aircraft by distance. They select the track with the closest distance as the new target. That is similar to the way explained above, but each platform has higher awareness of all hostile platforms around. The higher track confidence leads to earlier shots and more efficient assignment of the next target.

Defensive evasion maneuver against PW-113 or PW-211

As a defensive maneuver against PW-113 missiles the aircraft releases flares, when the missile is closer than 5.5 NM. Additionally, a certain probability is implemented to simulate the pilots' reaction time The fighter turns away 135° to its enemy and releases flares (see Fig. 8). If the platform beats the missile and escapes out of a 4 NM radius, the fighter maneuvers to the next waypoint and searches for new targets to attack. The logic (see Fig. 6) for PW-211 missiles is the same as for PW-113 missiles except releasing chaffs instead of flares.

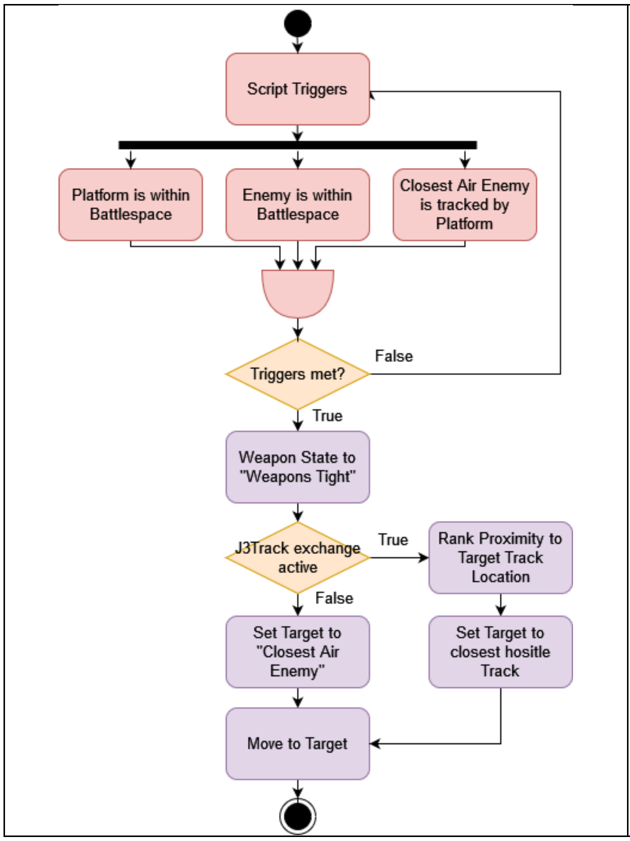

Fig. 6 Logic for assign closest target

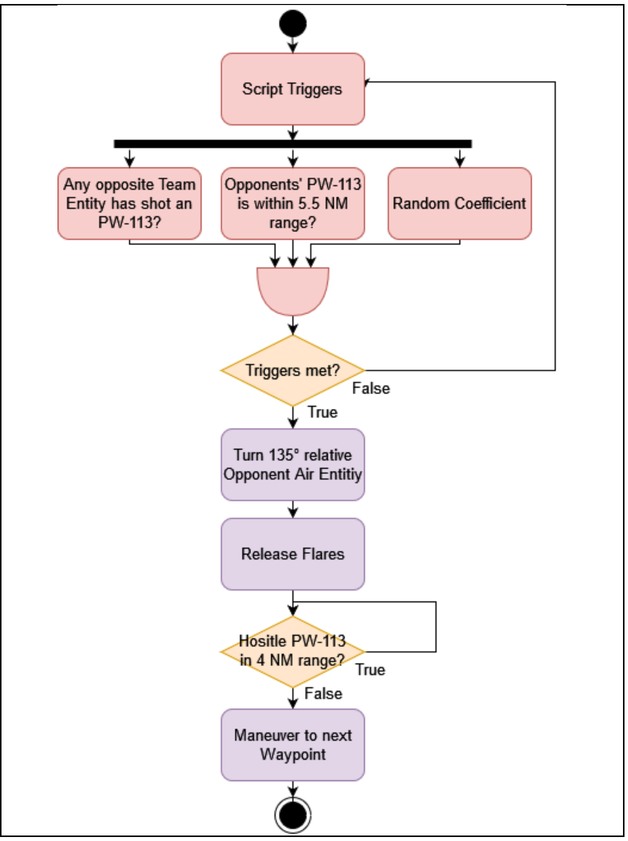

Fig. 7 Logic for defensive evasion maneuver

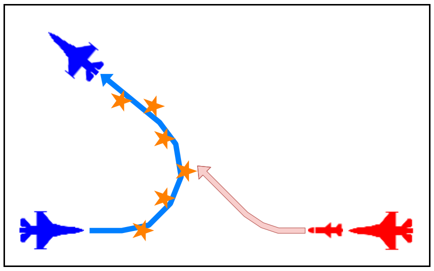

Fig. 8 Schematic of defensive evasion maneuver

Offensive Maneuver

Depending on the type of the missile shot, an aircraft will perform a fixed maneuver. Since the PW-113 is an infrared (IR) guided fire and forget missile, once it is launched the attacking aircraft performs a basic turn around named "launch & leave maneuver". The maneuvers consist of the missile launch and a 120° turn. The maneuver schematic is visualized in Fig. 10.

After a PW-211 missile is shot, the fighter jet will perform a "crank maneuver" which is shown in Fig. 9. The attacking aircraft seeks to minimize its own downrange travel toward the target aircraft while keeping its radar on the target. The aircraft turns 50° left or right depending on the orientation to the target after the missile is fired. Until the target is near the border of the aircraft's radar scan volume the attacker will maintain this geometry until the radar seeker head of the missile turns active, continuously supporting the missile and feeding it with the latest radar position of the target. After the seeker head of the missile turns on its terminal guidance radar, called "Pitbull", the aircraft turns away from the target to arrest its downrange travel entirely and potentially defeating any inbound missile shots from the target. The missile will home in on the target without further support from the launching aircraft. The logic of this maneuver is presented in Fig. 9.

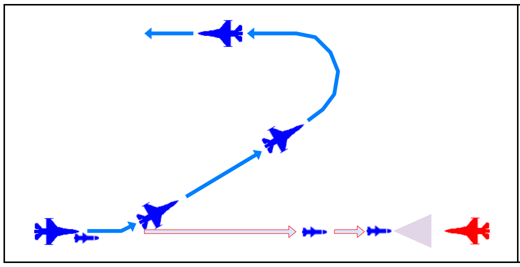

Fig. 9 Schematic of crank maneuver

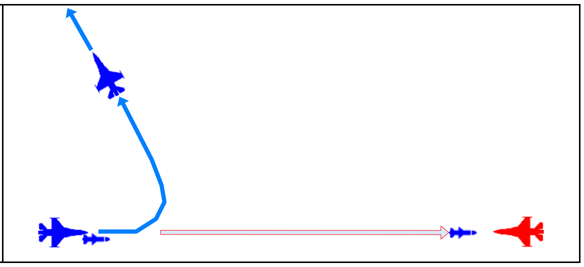

Fig. 10 Schematic of Launch & Leave maneuver

Weapon Selection

Constraints were applied to weapon selection based on engagement geometry. The PW-211 is the weapon of choice for engagements Beyond Visual Range (BVR), taken to be any engagement in which the range to the priority target was greater than 10 nautical miles. Within 10 NM, the PW-113 is given priority, given that it is an IR guided missile that can be cued visually via the modeled Helmet Mounted Cueing System in MACE (i.e. the "Visual Observer" equipment in MACE). The gun is prioritized for very close engagements in which the engagement geometry has collapsed significantly, or in which the attacker has attained a distinct offensive advantage at very close range within the target's rear quarter "control zone", the region in which an attacker who rendezvous with range, aspect, and closure under control cannot be denied an offensive advantage by the defender. The logic is shown in Fig. 12.

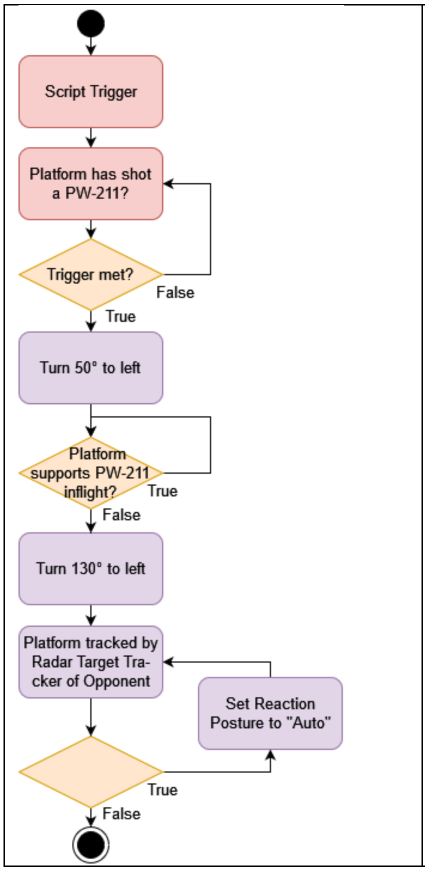

Fig. 11 Logic for offensive crank maneuver after PW-211 Shot

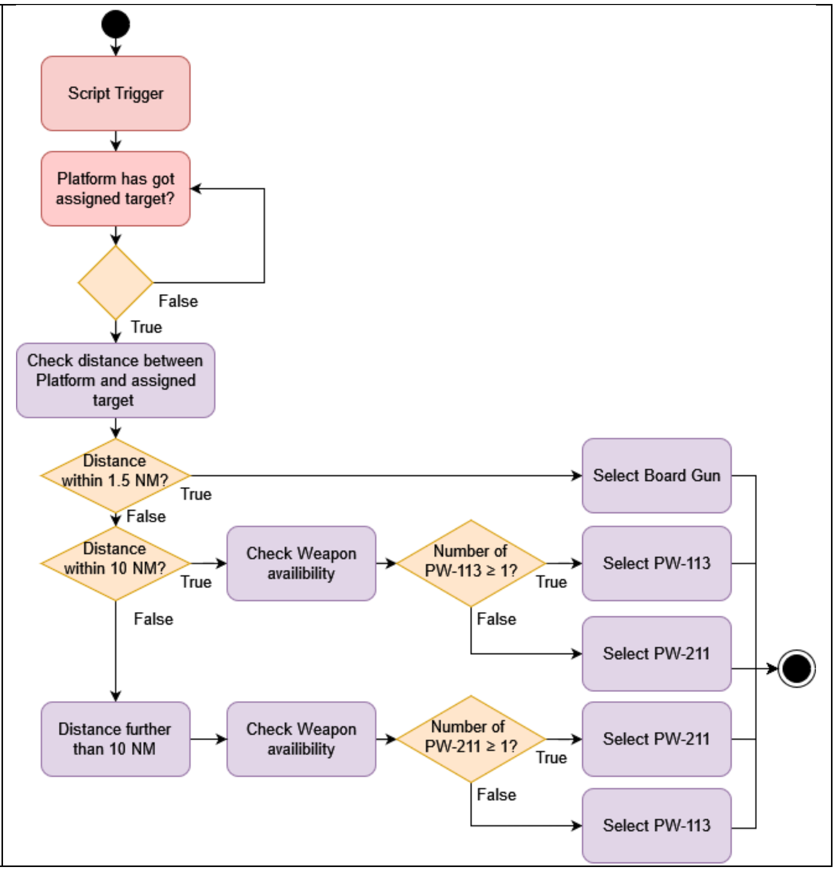

Fig. 12 Logic for weapon selection

Out of fuel

The big limitations of fuel capacity of fighter aircraft, make the modeling of fuel restricted behavior necessary. The "Out of fuel" procedure addresses that problem by excluding a platform from the scenario that reaches a low fuel threshold. At the beginning of the simulation all red and blue aircraft are filled with 2353 kg of fuel. That measure helps to replicate the impact of higher or lower fuel consumption between the platforms. After reaching 1587 kg an aircraft is excluded from the scenario and is counted as a lost platform. We choose the threshold via analysis of the Baseline Scenario with Force Ratio = 1, as this is the most critical scenario in terms of mission time. With the threshold mission duration of that scenario stays below 13min in most cases.

Although this research replicates real world maneuvers, topics like real world tactics, coordinated shots, and cooperative targeting, electronic warfare are either not considered or are only addressed in a simplified manner.

B. Platform Design

The DLR Institute of Systems Architectures in Aeronautics in-house fighter design tool VAMPzeroF drives the overall aircraft design used for the platform design in this study [18]. VAMPzeroF is an automated tool for the initialization and synthesis of military aircraft configurations. For this work we implemented the option to create an additional MACE readable output as XML file. The file contains information about flight envelope borders, SEP, fuel burn, visualized in Fig. 13, as well as fuel and empty weight. An F-16 similar aircraft, shown in Fig. 13 functions as the baseline for all sensitivities during this study. Since the DoE in this study is performed in order to refine the Aircraft Design itself, every single sensitivity is determined with an own design. As a consequence, the used platform is optimized on a specific payload configuration or range resulting in a different aircraft.

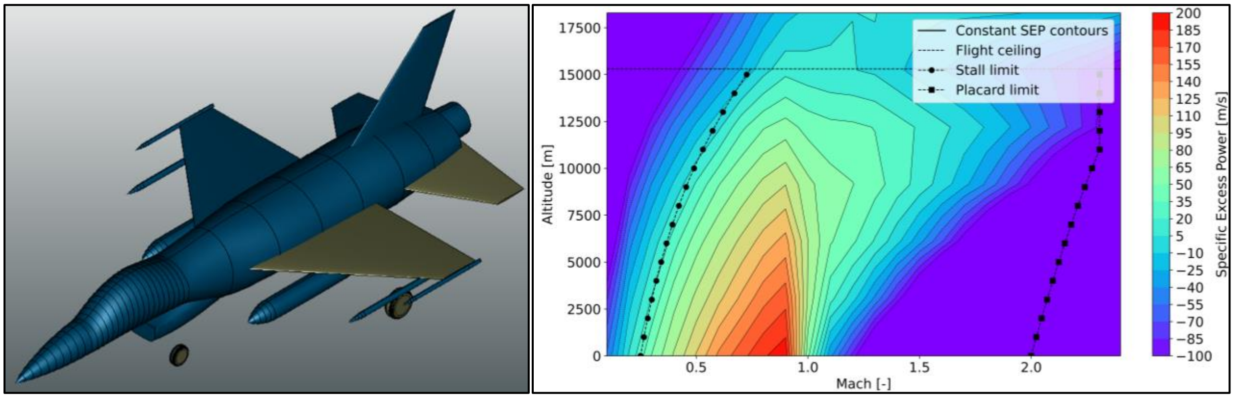

Fig. 13 F16 similar aircraft with 1g flight envelope

IV. Trade Off Study or Sensitivity at Multiple Levels

A large-scale DoE is created for the blue team to evaluate the sensitivity at multiple levels shown in Fig. 14. This study will be addressed to platform, tactics, collaboration, MoE and fleet composition. The question for an ideal combination of vehicle and fleet sizes is addressed by analyzing SoS metrics. During the study we took a closer look at the effects of technology factors of mass, fuel flow and aerodynamics. Additional trades were conducted for weapon numbers, combat radius and J3 Track exchange via Link 16 data radio. Apart from the J3 Trade all sensitives were performed as design points for the aircraft concepts. E.g. weapon numbers were not varied on the same aircraft but as design requirements resulting in an adjusted design concept. All trades were analyzed over a fleet number variation of the blue team. We used JMP® for data analysis of the in total 252 mission data points [19].

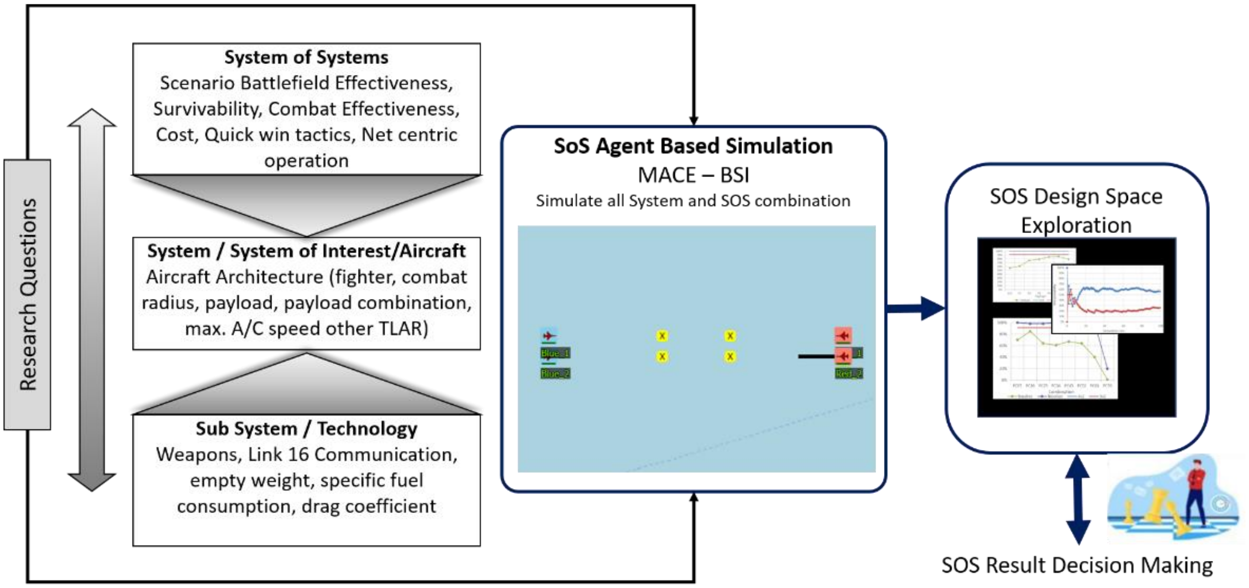

Fig. 14 Sensitivity or tradeoff at multiple levels

A. Technology and TLAR Trades

The following subchapters state the aircraft parameters; This displays the trends between the aircraft. The simulation calculates the fuel burn and SEP via look-up tables given for a wide range of configurations, altitudes and Mach numbers. The role rate is a global factor per model MACE uses for the full flight envelope.

The technology trades were performed via factors on empty weight (OEM), thrust specific fuel consumption (SFC), and aerodynamics in the form of a factor on the system level drag coefficient (CD). Based on the baseline model we created new models for individual variation of the factors on OEM, SFC and CD by +10 % and -10%. We chose those numbers to generate a clear effect within the simulation, but keeping in mind a realistic goal for the future. Wing loading and thrust to weight ratio are kept constant throughout the trades. The relevant data to distinguish the aircraft models including the baseline can be found in Table 1. The weapon number trades were conducted similar as before on vehicle design level. The number of weapons is increased stepwise from two to eight per missile. The aircraft parameters are shown in Table 2. The range trade was conducted similar as before on vehicle design level. Therefore, the combat radius was increased to the aircraft parameters are shown in Table 3.

Table 1: Aircraft Model Parameters for Technology Trades

	- 10%			Baseline	+ 10%		
	CD	SFC	OEM		OEM	SFC	CD
Aircraft Model	PWF-10	PWF-20	PWF-30	PWF-01	PWF-12	PWF-22	PWF-32
MTOM [kg]	14999	15086	15668	16925	18228	19135	21259

Table 2: Aircraft Model Parameters for Weapon Number Trades

Aircraft Model	PWF-01	PWF-44	PWF-46	PWF-48
MTOM [kg]	16925	19907	23074	26566
Weapon carried	2 PW-211 2 PW-113	4 PW-211 4 PW-113	6 PW-211 6 PW-113	8 PW-211 8 PW-113

Table 3: Aircraft Model Parameters for Range Trades

Aircraft Model	PWF-50	PWF-01	PWF-52
MTOM [kg]	13824	16925	21224
Combat Radius [km]	800	1200	1600

B. J3 Track Exchange via Link 16 Radio

This study should show the additional capabilities of exchanging J3 Tracks between blue platforms. All aircraft are equipped with Link 16 Radios. This system enables the capability to exchange Link 16 messages. During this analysis we show effects of surveillance track exchange. In a real-world situation it should increase situational awareness of the individual platform, leading to improved mission performance. Without this exchange of J3 Tracks the platform finds their next target via the “Assign closest target” procedure in chapter III.A.2. With J3 Tracking enabled new targets are assigned via the “Assign J3 target” procedure. We make use of MACE design as a framework by implementing a C# self-programmed logic via the MACE API using the exchanged tracks to hostile aircraft. The results depend heavily on how the platforms make use of the additional information. Therefore, it is important to acknowledged that the assign closest target procedure also includes hostile platforms the blue agent cannot track. That tends to too efficient assignment of new targets. The pure exchange of J3 Tracks without appropriate use does not lead to improved mission performance. The flight performance of the platforms exchanging tracks is the same as the baseline model PWF-01.

C. Uncertainty Analysis

Before performing the DoE, the necessary number of runs per scenario has to be determined. Fig. 15 shows the evaluation of the blue win rate of the baseline scenario in order to determine how many runs are necessary to obtain reliable results.

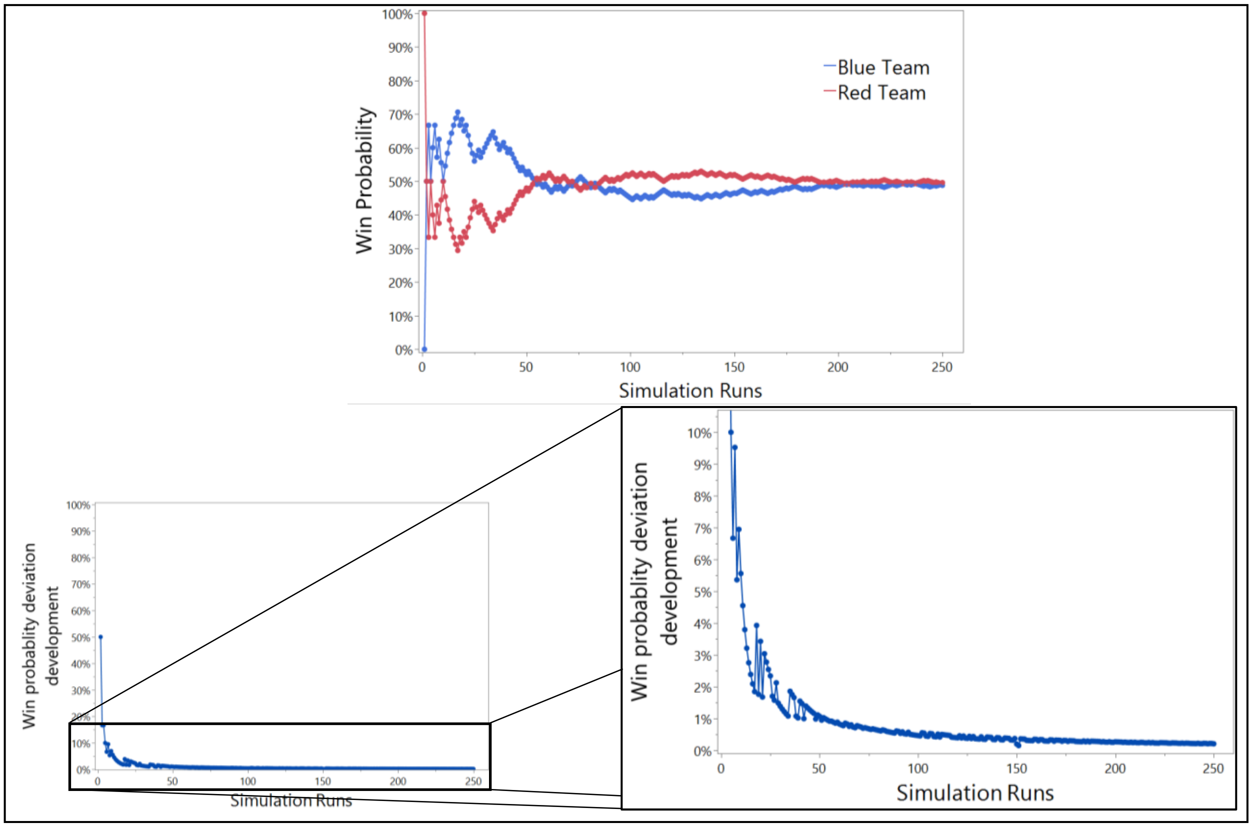

Fig. 15 Number of runs evaluation based on blue win probability

The development of the blue and red win probability is displayed over the number of simulations for the 8vs8 Baseline scenario. in the upper part of the figure. Red and blue win probabilities will not add up to 100% as draw results are possible if both teams lose all their respective aircraft. It shows that a minimum amount of runs of around 50 is necessary. The lower part of the figure shows the deviation of the blue win probability between two runs calculated after each other. To reach consistent results a consistent deviation of below 0.5% is desired. This value is reached for the first time after 96 runs and continuously after 107 runs. The evaluation confirms the experience from other scenarios that a doubled amount of runs result in a halved deviation. Following that logic, a deviation in the area of 0.25% can be reached after 200 runs. This assumption is confirmed by this evaluation. Due to the fact that the best result quality can be obtained by running the scenarios in real time speed 150 runs are chosen for the conducted DoE in this paper as a trade between desired accuracy and available runtime.

V. Results

The results provide observations made during this SoS driven fighter aircraft design and force ratio exploration. As described in chapter IV, several multi-level sensitivity studies regarding force ratio/SoS, aircraft/System/System of Interest, and the subsystem level are provided and discussed in the following sections. Each sensitivity study emphasizes the need for analyzing fighter operations and design from a SoS perspective, while checking for robustness of the framework.

Note that the DoEs are only performed for the blue team. The DoE contains of 216 data points with 150 runs per data point. The results show either the mean or the median value over 150 runs. The trade between precision of the results and the simulation time results in individual data points fitting not perfectly in the overall trend. We expect this problem to resolve by the adding additional runs to gain an even more precise picture for future studies. For the purpose of this paper the results are sufficient to show a general effect of different measurements on the battlefield. The red team remains with the baseline version A/C throughout the whole DoE. The conducted DoE will be investigated with MoEs as proposed by [10]. This study will concentrate on:

1) Blue Win Rate
2) MER (Mission Efficiency Ratio)
3) Weapon usage
4) Duration of Conflict

The success criteria considered for the mission is the blue win rate. A win is defined as one team being able to survive the adversary team. That can be reached by destroying all hostile aircraft. The second way how a team can lose aircraft are fuel kills. Platforms are taken out of the mission after hitting a low fuel threshold as described in chapter A.2.

MER symbolizes survivability and is shown in Eq. (3). MER is based on [20] and was adjusted to the scenario presented in this paper.

$$MER = \frac{Red\ Losses}{Blue\ Losses} \tag{3}$$

We evaluate weapon usage broken down the different missiles launched and GAU shots fired.

The Results will be presented over the force ratio as described in [21], is defined in Eq. (4). The force ratio is varied by the blue platform number.

$$Force\ Ratio = \frac{Blue\ Units}{Red\ Units} \tag{4}$$

The mission duration is the measurement for quick win measures. It states the time between mission start and the kill or detonation of the last entity of one side (red or blue). That includes platforms and missiles.

A. Technology Trades

The effects of the technology trades for OEM, SFC and CD with different force ratios on the blue win rate and MER are exemplarily presented in Fig. 16 and Fig. 17. The development of the duration of conflict is visualized in Fig. 18. These numbers show the median of all respective missions.

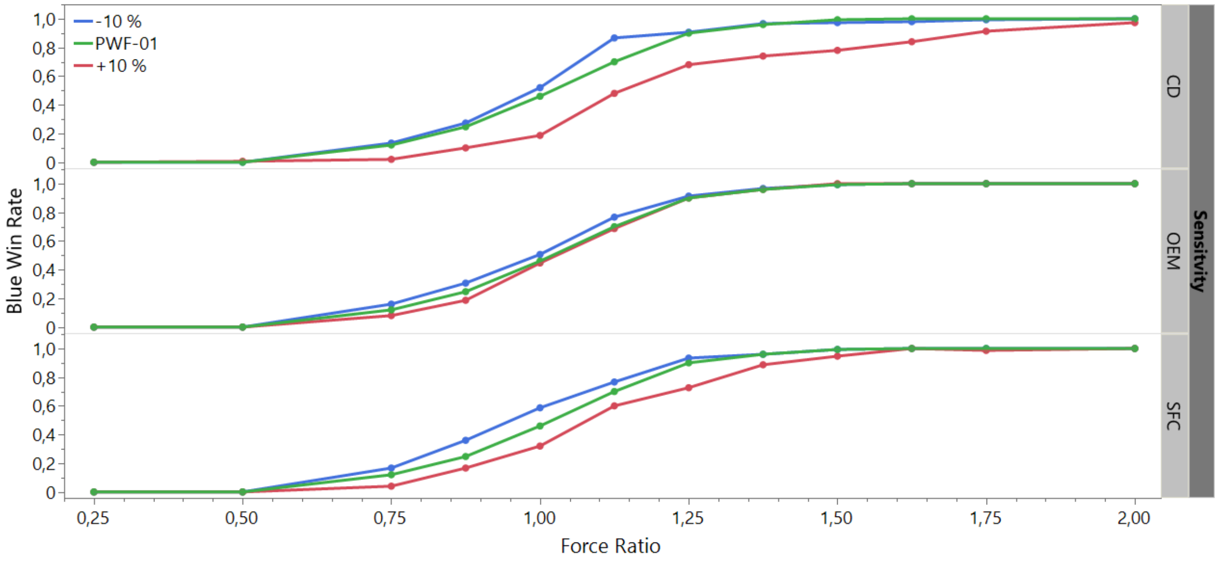

Fig. 16 Blue **Win Rate for technology trades**

As expected the blue win ratio is growing from 0 to a 1,0 over the course of the force ratio growing in sigmoid function manner. Starting from force ratio 1.0 the blue win rate grows for higher and declines for lower force ratios until reaching 0 respective 1,0. Most runs of all trades in this paper reach 1,0 starting by force ratio 1.5 and fall to 0 at 0.5. It can be replicated that each sensitivity of CD, OEM and SFC has an effect on the blue win rate in the expected way. The curves of the fighter with 10% decrease of these parameters show an increase in blue win rate. The adjusted fighters have advantages in SEP and fuel burn. That leads to less kills by fuel and higher chances to evade attacking missiles. The inverse effect can be observed for CD, OEM and SFC increased by 10%. The blue win rate declines over the course of the force ratio. These aircraft do not have an energy advantage anymore and die, because they hit the fuel threshold earlier.

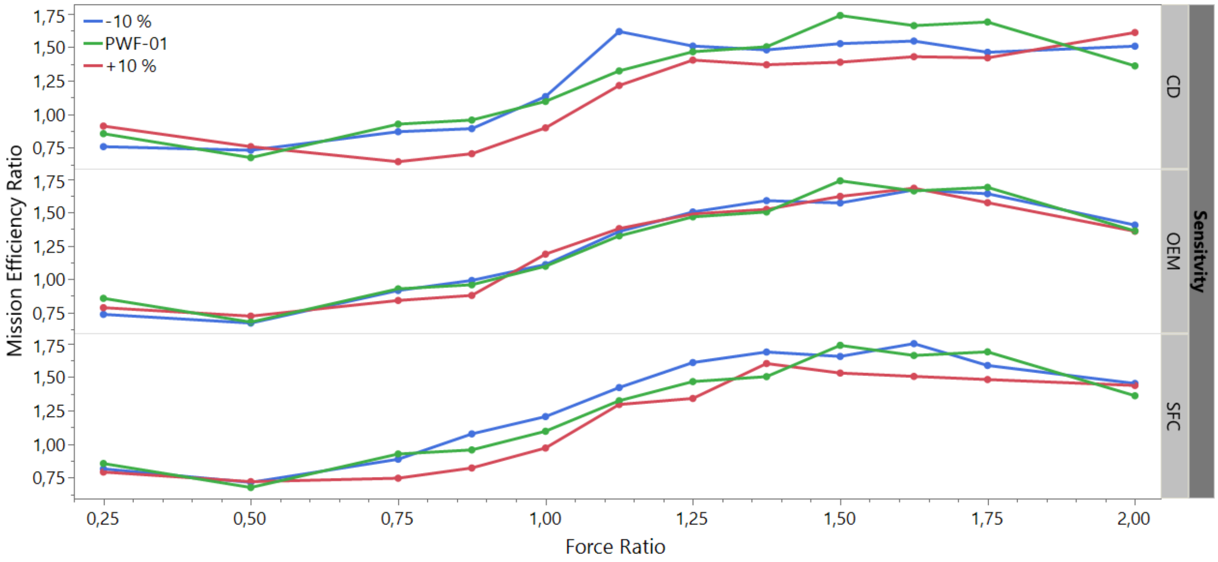

Fig. 17 MER for technology trades

The MER development over the force ratio has similarities but also differences from the blue win rate. It varies between 0.648 to 1.75 and grows in general between force ratios 0.5 to 1.375 similar to the blue win rate. The difference between the two is the existence of minima and maxima. The location of the minima depends on the sensitivity but varies between 0.5 and 0.75 as well as respective for the maximum around 1.5. The rise between force ratios 0.5 and 1.75 is confirmed by the Lanchester Square Law [22]. The Lanchester Square Law is a mathematical formula for estimating the relative strength between military forces [22]. The extreme force ratios considered in this study show some deviation from the law. That can be led back to the limited number of weapons used and to how the individual mission plays out, increasing the existing bias by starting every simulation with the same aircraft locations. The MER confirms the impression of the blue win rate in general. The improvements in CD, OEM and SFC lead to a higher MER compared to the degraded models indicating improved survivability. The Baseline PWF-01 shows some inconsistencies especially in higher force ratio regions. The equal performance of blue and red platforms leads to stronger randomized behavior in the MER outcome. There is a tendency to clearer results for platforms with different capabilities. Since the blue and red team use the same aircraft model in this runs lower level MoEs like blue units lost need more time to converge and show unexpected development for some data points.

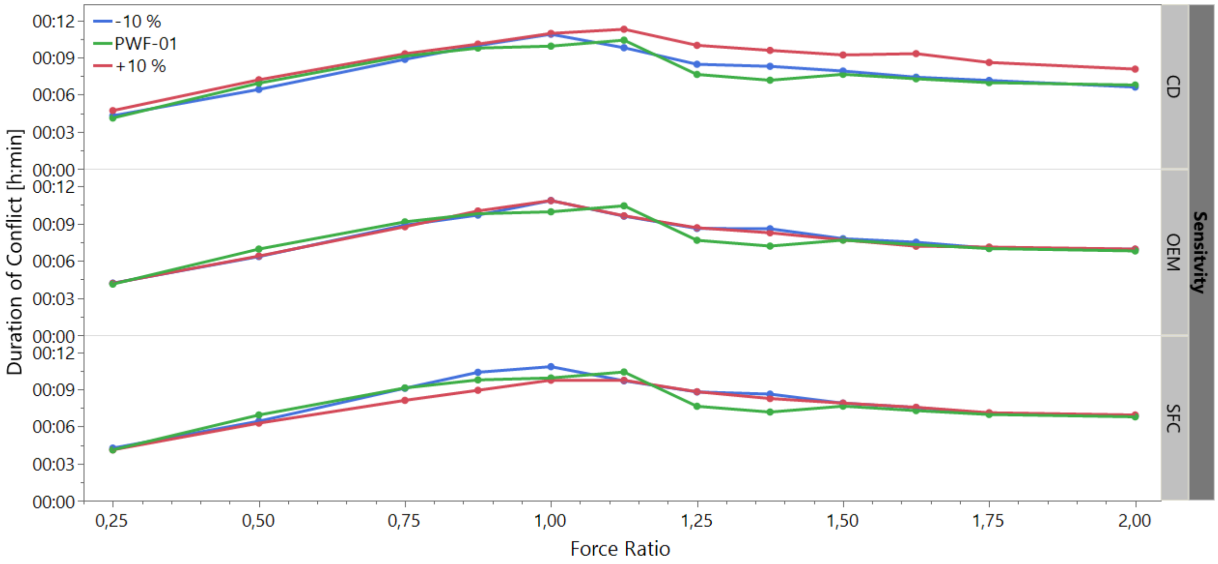

Fig. 18 Mission duration of technology trades

The median of the duration of conflict varies between 4 min and 11:18min. The duration of conflict is influenced by the advantage of either one team. Conflicts lost by blue tend to take longer for low force ratios and lower aircraft performance. Missions won by blue take more time in contested situations around force ratio 1.0 and increased aircraft performance. High force ratios usually even out the differences in mission performance but the significantly worse performance of the PWF-32 extends the mission time. The maximum varies around the force ratio of 1.0 depending on the trade. That was expected as no clear dominance of either side occurs. In general, lower fuel burn tends to extended duration of conflict. Better and worse flight performances shrink mission durations compared to the baseline. The CD sensitivity shows the highest maximum mission duration, followed by OEM and SFC. Comparing the data points there is a relation between increased gun usage and mission duration, due to the limited number of missiles. The longer a conflict takes the higher the chance the GAU comes to use. There is no clear trend on the OEM and SFC trade, although the improved performance of the PWF-20 compared to the baseline increases the duration for lower force ratios.

B. Weapon Number Trades

In Fig. 19 the blue force ratio variation is displayed and its effect on the win rate, MER and blue units lost for the weapon trade. The weapon usage is analyzed in Fig. 20, while Fig. **21** shows the mission duration for the weapon trade. The numbers are divided in PW-211, PW-113 and board guns shots for the three models PWF-01, PWF-44, PWF-66, PWF-88 with different weapon load. They are presented over the growing force ratio.

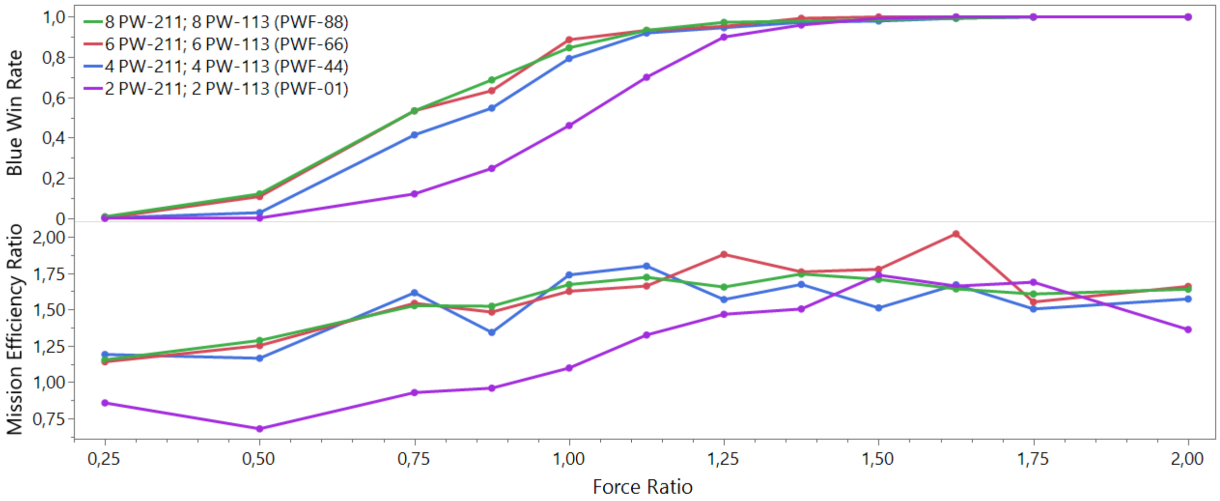

Fig. 19 Blue Win Rate and MER for weapon trades

This study shows the strong influence on weapon numbers on the scenario outcome. All runs with additional missiles have increased mission performance. It shows in the blue win rate as well as survivability. The biggest influence can be observed between force ratios 0.5 and 1.375, the by number most contested region. The significant step occurs between the PWF-01 and PWF-44. There is another increase to PWF-66 but the step to PWF-88 does not result in notable additional wins. While the extra missiles increase survivability between force ratios 0.75 and 1.375, there is no clear improvement above PWF-44. No other trade has such significant effect also on low force ratios. The worse flight performance especially in the subsonic region and fuel burn do not have a high influence beyond the availability of additional missiles.

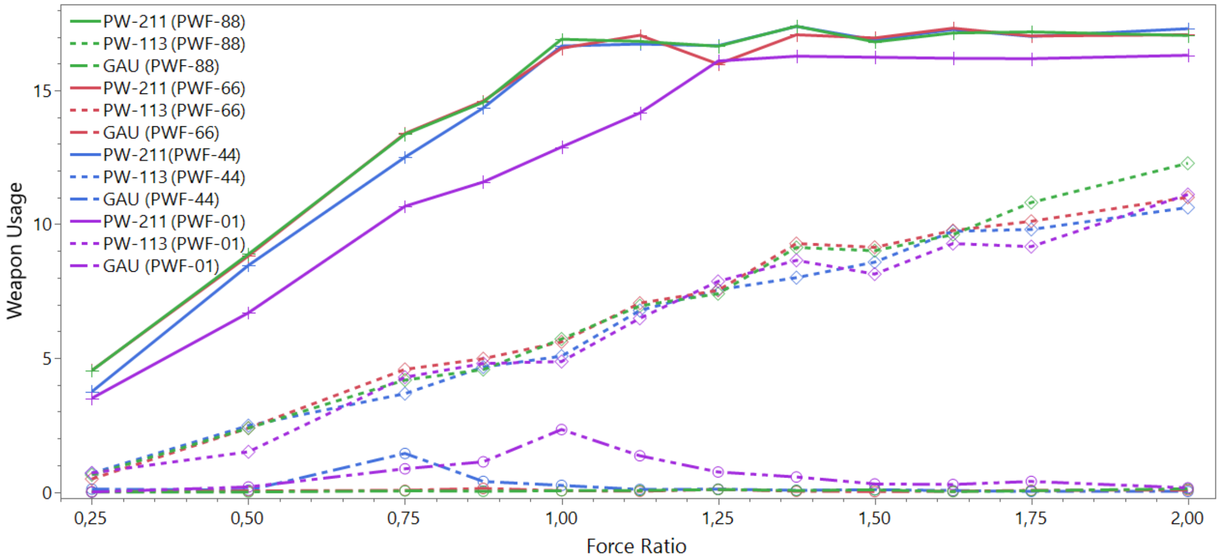

Fig. 20 Blue Weapon usage analysis for weapon number trades

In general, the results show a clear dominance of the PW-211 missiles. The majority of the scenario takes place in the BVR region. Real world trends collected in [15] confirms that Air-to-Air Combat is mainly staged in the BVR region. The shorter-range PW-113 missiles is the preferred weapon of closer engagements as the Gun is the least selected weapon and even not used in many scenarios. While the PW-113 number grows continuously, PW-211 launches approach a number slightly over 16 for the PWF-01. Nevertheless, a board gun can still be a valuable support. The agents use the board guns especially in force ratios around one as there is a higher chance of scenario development towards close encounters. The gun usage development differs the general trend of growing number of missiles launched. That can be drawn back to the growing number of blue aircraft, each bringing additional weapons to the arena. The agents do not communicate missile launches. Each platform takes an individual decision independent from their teammates. There seems to be a trend to higher launch numbers of PW-211 for closer platform ability encounter. The baseline scenario shows the highest numbers in many scenarios. Over all force ratios the availability of more missiles leads to more PW-211 launched. That is the reason for higher win rates in that region. In the lower force ratio region there is another but much smaller increase from PWF-44 to PWF-66. The importance of the PW-211 can also be argued via the PW-113 numbers. Even though PWF-44, PWF-66 and PWF-88 carry more PW-113 there is no trend of increased usage of that missile over the course of the force ratio. The higher the missile load the lower the force ratio becomes for competitive scenarios with a balanced win percentage. That can be also visualized via the maximum gun usage at lower force ratios of PWF-44 than PWF-01. Additional gun usage decreases with increasing missile numbers. Starting with PWF-66 the blue team does not use the GAU anymore.

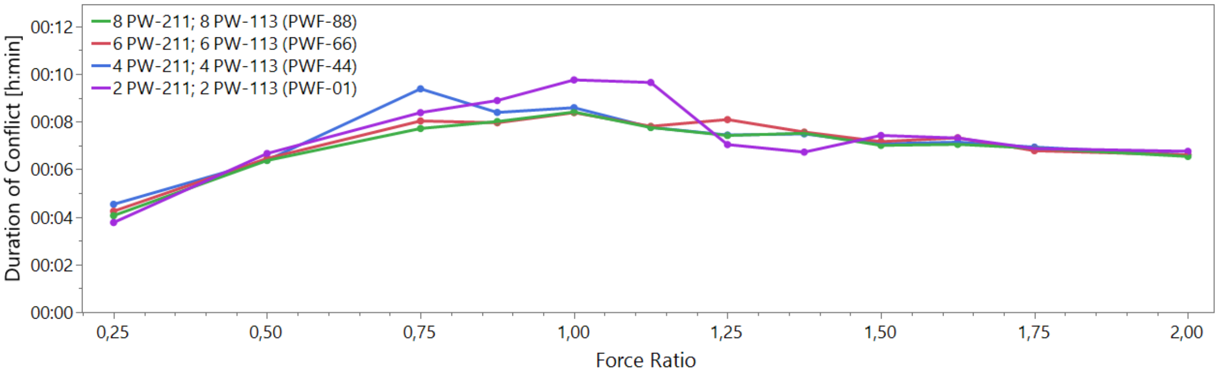

Fig. 21 **Mission duration for weapon number trades**

The maximum mission duration moves with higher missile availability to lower force ratios. In general, the biggest pact shows between force ratios of 0.5 and 1.125. On top the moving maximum there is the tendency to lower mission times with higher missile numbers up to a certain point. PWF-88 does not show a significant effect compared to PWF-66.

C. Combat Radius Trades

Fig. 22 presents the blue force ratio variation and its effect on the blue win rate and MER for the combat radius trade. Fig. 23 shows the conflict duration for the combat radius trade. Considered are the models PWF-50 with a Combat Radius of 800km, the baseline PWF-01 with 1200km and the PWF-52 with 1600km. They are presented over the growing force ratio.

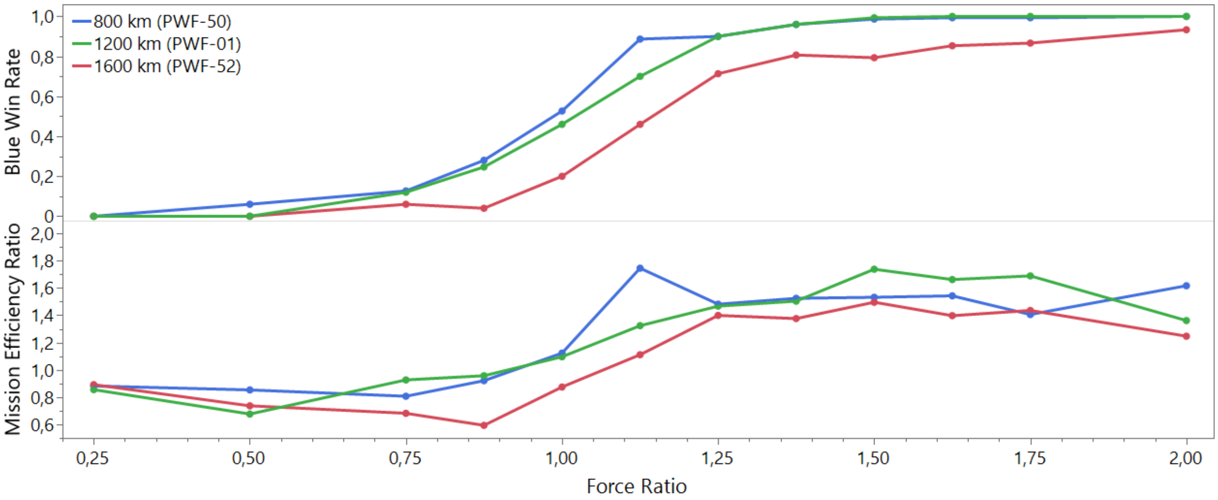

Fig. 22 Blue Win Rate and MER for combat radius trades

Higher combat radius leads to bigger and less maneuverable aircraft with higher fuel burn. That leads to the expected result. The smaller the combat radius the higher is the win percentage in our scenario. Besides being hit more easily the PWF-52 and PWF-01 compared to PWF-50 die earlier for fuel purposes. MER and blue aircraft destroyed develops alongside the blue win rate. It has to be noted that all aircraft start the mission with the same amount of fuel. In the presented scenario a smaller combat radius can increase effectiveness and survivability. For higher force ratios the smaller combat radius does not gain any advantage over the baseline. The force ratio is now dominant over the performance difference between PWF-50 and PWF-01. The PWF-52 with a higher combat radius shows a worse mission performance for all force ratios. The start with the same fuel mass withdraws the natural advantage of the PWF-52 of higher fuel capacity. Therefore, only the higher fuel burn plays a role. The SEP advantage of bigger aircraft with higher combat radius do not lead to a positive result in mission performance and does not dominate the battlefield.

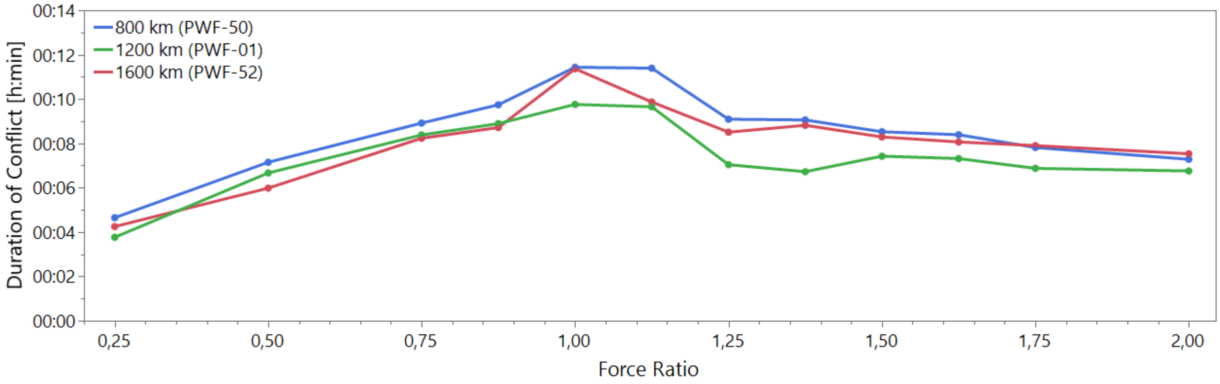

Fig. 23: Mission duration for combat radius trades

The combat radius has no big impact on the force ratio of the mission end time maximum. But overall the PWF-50 increases the duration of conflict. The lower fuel burn let the blue team survive longer, increasing mission time. Duration of conflict is slightly higher for PWF-52 for force ratios below 1.0. The higher maneuverability keeps the blue platforms alive longer, the gap grows for higher force ratios. The higher fuel burn dominates that region.

D. J3 Track Exchange Trade

The J3 Track Exchange Trade shows the effect on applying J3 track locations into the selection of assigning new targets. It does not show effects of the exchange of the information itself. Notably difference can only be generated by meaningful usage of the track information. Fig. 24 shows the blue win rate and MER for the J3 track exchange trade.

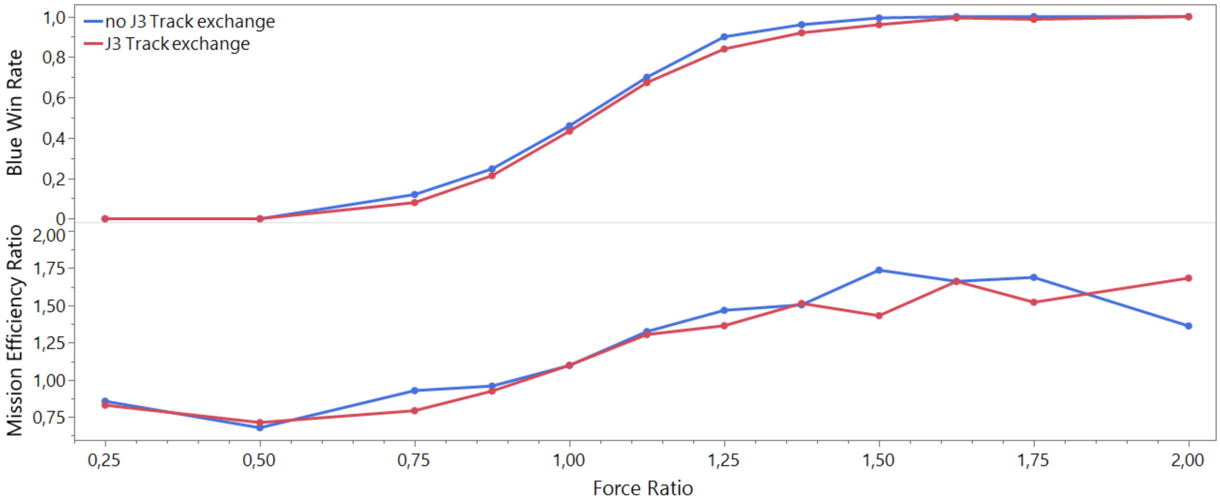

Fig. 24 Blue Win Rate and MER for J3 Track Exchange Trade

Counterintuitive the additional capability of J3 track exchange via Link 16 radios lead to slightly worse results. Reason for that lays in the procedure for new target assignments. Within the scripted behavior J3 Tracks only have influence on the assignment process. The assignment of closest air enemy is an idealized way assuming all hostile aircraft locations are known. The new target assignment procedure used for the J3 Track exchange trade considers only known track locations, while "assign closest enemy" considers all hostile platforms. That aspects leads to less efficient choices for the next target in situations where not all target tracks known or have sufficient accuracy. As a result, the blue win rate is smaller and der MER is higher overall force ratios than without J3 Track exchange. However, the differences in mission performance are very small.

VI. Discussion and Outlook

This paper presents a SoS framework for the design and assessment of fighter vehicle architectures and fleets. It provides a glimpse into using MACE within SoS simulation driven vehicle design processes. The framework allows to capture the interconnectivity of the involved systems and their multilevel interdependencies. As a demonstration, we performed a successful multilevel evaluation of a F16 like fighter aircraft in a counterair fighter sweep scenario. The SoS design space exploration and sensitivity trades spans over 216 data points. It shows the complex interaction between fighter vehicle architectures, technologies, subsystems, agent behavior and force ratios. It provides proof of concept of the holistic evaluation framework that can be developed in an SoS context by combining different influences of different fields.

Most relevant, this study helps to clarify how mission performance parameters like win rate and MER varies in relation to force ratio, technology trades, design point and subsystem equipment. variation Several homogeneous fleets to vary force ratios were formed and evaluated via an Agent-Based Simulation under the effect of technology factors, TLARS, equipment and collaboration aspects. These sensitives were evaluated by a set of mission tailored MoEs. Considering all trades additional material, like more fighters or more missiles show the consistent biggest effect on the battlefield. Additional weapons as well as a higher force ratio lead to a higher and more distributed launch options. The highest effects in the trades result between force ratios 0.5 and 1.25. Outside that area the force ratio itself dominates the mission performance far above anything else. Nevertheless, the aircraft design point needs to be chosen wisely as the combat radius shows trade shows. A TLAR selection tailored to specific representative mission scenarios supported by SoS evaluation can make a difference, noticeable in the lower blue win rate of the higher combat radius model. The data presented in this paper lead to the conclusion that a smart selection of TLARs might even offer higher potential on the battlefield than innovations on specific vehicle-based fields. Improved technology factors on aerodynamics, empty weight and TSFC promise improved results on mission level, but neither technology trade show result as promising as the TLAR trades. On the collaboration side, the use of J3 Track exchange heavily depends on how the agents make use of the additional information. Our simplified behavioral logic might replicate more realistic results but leads even to disadvantages in mission performance.

Although this research replicates real world maneuvers, topics like real world tactics, coordinated shots, and cooperative targeting, electronic warfare are either not considered or are only address a simplified manner.

In order to ensure the framework can confidently be used within a bigger scale research project, more simulation capabilities need to evaluated. Future research aims to included additional of the topics listed above, to develop the real-world application further. Additionally, the framework will be expanded to further use cases and topics like air to ground scenarios, crewed – uncrewed teaming, radar cross sections effects, heterogenous fleet and design methodologies. The effect that the development of major MoEs follow mathematical functions, opens up the opportunity to include simple surrogate modeling into the processes. That can be a future application to reduce runtime by reducing the number of simulated scenarios.

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