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Optimizing Threat Response in Integrated Air and Missile Defence Using Multi-Criteria Decision Analysis

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Abstract

Integrated Air and Missile Defence (IAMD) environments are increasingly characterized by high-density saturation attacks consisting of heterogeneous threats such as unmanned aerial systems, cruise missiles, and ballistic weapons. The core operational challenge is the Weapon-Target Assignment (WTA) problem, which involves determining the optimal allocation of defensive resources to incoming threats under strict time constraints. Traditional heuristic approaches implemented in legacy air defence systems rely on simplified rules such as Closest-Threat-First (CTF), which do not fully account for the multi-dimensional nature of modern engagements.
This paper proposes a Multi-Criteria Decision Analysis (MCDA) framework for optimizing WTA decisions in IAMD Command and Control (C2) systems. The model evaluates potential weapon-target engagements using three primary criteria: probability of interception, temporal urgency, and interceptor cost efficiency. A comparative simulation framework based on Monte Carlo methods evaluates the proposed approach against a baseline heuristic model. The results demonstrate that the MCDA-based approach significantly improves defensive efficiency while maintaining resource sustainability.
The presented Python-based simulation environment provides a scalable proof-of-concept for integrating decision-support algorithms into future automated IAMD architectures.

KEY WORDS: *Integrated Air and Missile Defence, Weapon Target Assignment, Multi-Criteria Decision Analysis, Operational Research, Simulation.*

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1. Introduction

Modern air defence systems operate in an increasingly complex operational environment characterized by rapidly evolving aerial threats. Emerging threats include low-cost unmanned aerial systems (UAS), loitering munitions (LM), cruise missiles (CM), ballistic missiles (BM), and other precision-guided weapons (PGW) capable of conducting coordinated saturation attacks. These attacks aim to overwhelm defensive systems by exploiting both quantitative and qualitative asymmetries between offensive and defensive capabilities.

Integrated Air and Missile Defence (IAMD) architectures must therefore process large volumes of sensor data, perform real-time threat assessment, and allocate defensive resources within extremely limited decision timeframes. Within such systems, one of the central operational problems is the Threat Evaluation and Weapon Assignment (TEWA) process. Threat Evaluation determines the relative danger posed by each detected target, while Weapon Target Assignment identifies the most suitable interceptor or weapon system for engagement.

Historically, many operational air defence systems have relied on heuristic decision rules, such as assigning the nearest available interceptor to the closest or most imminent threat. Although such approaches provide computational simplicity and rapid response, they often fail to account for the multi-dimensional nature of modern engagement environments. Important factors such as probability of successful interception, available engagement time, interceptor cost, and inventory management must be considered simultaneously when allocating defensive resources. Overall approach to the air defence modelling and simulation can be found in 1.

The defence of critical assets against airborne threats therefore involves two closely interconnected decision processes: Threat Evaluation and Weapon Target Assignment. See 2 , where is this process comprehensively described and 3 with analytical hierarchic method in decision making process.

Threat evaluation (TE) aims to determine the level of danger each detected target poses to defended assets by integrating sensor observations, kinematic parameters, and contextual information in order to produce a prioritized threat ranking. Previous research by Roux and Van Vuuren 4 introduced a multi-level threat evaluation architecture combining qualitative and quantitative assessments to support command decision-making.

The Weapon Target Assignment (WTA or just WA) problem is typically formulated as an optimization problem in which available weapon systems must be assigned to incoming threats in order to maximize overall defensive effectiveness. The mathematical foundations of the assignment problem were originally introduced in operations research by Votaw and Orden 5, who studied optimal allocation of agents to tasks. Subsequent research by Flood 6 and Manne 7 extended this concept to military applications by modelling the probability of target destruction as a function of assigned weapons.

These early formulations assumed static engagement environments and independent weapon effects. Later developments introduced nonlinear optimization methods, stochastic models, and dynamic decision frameworks capable of representing evolving combat conditions and uncertainty in sensor observations. Despite these advances, practical implementations in operational systems often still rely on simplified heuristic logic due to computational constraints and real-time decision requirements.

To address these limitations, this research proposes a decision-support framework based on Multi-Criteria Decision Analysis (MCDA) for optimizing the Weapon Target Assignment process in Integrated Air and Missile Defence systems. The proposed approach integrates operational research methods with simulation-based evaluation in order to support more informed engagement decisions under complex saturation attack scenarios.

2. Related Works

In 2008, Roux and Van Vuuren 8 developed a general design for a TE system specifically intended for use in the context of Ground Based Air Defence (GBAD), which was intended to assist air force commanders in quantifying the level of threat that enemy aircraft may pose to defended assets (DA). They proposed a model consisting of three levels, each representing a set of qualitative and quantitative mathematical solutions that vary in complexity and sophistication and work in parallel to provide results that, when combined, provide commanders with the desired decision support about the level of threat posed by enemy aircraft to the DA. At the highest level of sophistication, they proposed a probability-based TE model that takes as input data the kinematic data of air attack assets, DA deployment data, information on the enemy's arsenal and doctrine, with the output being a single threat value for each air attack asset relative to each DA – an estimate of the probability that an airborne attack asset will attack and/or destroy a specific DA.

The TE system designed by Roux and Van Vuuren is divided into two basic components in terms of system architecture: the Threat Evaluation Model (TEM) and the Threat Evaluation Fusion Model (TEFM). The results generated by the TEM component are merged by the TEFM component to obtain a single threat value for each threat and to arrive at a clear list of threats ranked by priority (i.e., a list containing the threat value for each threat) with respect to the entire DA set.

Like TE, WTA is also continuously studied and researched by a few research institutions around the world. The development of weapon assignment models (WTA) is an important area of military operational research that deals with the optimal assignment of available weapon systems to individual threats. The basic goal of these models is to minimize the probability of enemy targets surviving or to maximize the effectiveness of the defence system while respecting operational constraints.

The presented paper also extends previous work related to the GBAD modelling and simulation, specifically the C2 procedures 9, and complex GBAD simulator 10 and 11.

3. Main Objective and Overall Approach

The objective of this research is to evaluate whether a MCDA approach can improve the effectiveness of the WTA process within IAMD systems compared to traditional heuristic engagement methods. Conventional decision strategies in air defence often rely on simplified rules that prioritize threats based on limited parameters, such as proximity or time-to-impact. While these methods enable rapid decision-making, they may overlook other critical operational factors, including interception probability, engagement time constraints, and resource efficiency. The proposed MCDA-based approach integrates multiple evaluation criteria into a structured decision framework, enabling more balanced and informed weapon allocation decisions in complex and dynamic threat environments. The selected methodology and criteria reflect trends in recent defence applications, where decision-support systems increasingly consider not only engagement effectiveness but also operational time constraints and the cost efficiency of interceptor usage.

Overall TEWA concept and simulation layout is illustrated in flow diagram, see Fig. 1. Where each step of TEWA process is represented by distinguished model. The process begins with threat detection and evaluation, where sensor data are used to identify and assess incoming threats. Based on this information, the system determines weapon availability and performs weapon assignment, followed by engagement execution and engagement evaluation, representing the operational decision cycle in air defence systems.

In parallel, a simulation-based analytical framework is employed to assess the performance of the decision models. Threat scenarios are generated and their parameters calculated, after which the threats are evaluated and processed by the selected decision model. The decision model considers weapons models and performs weapon assignment within a Monte Carlo simulation environment, allowing multiple engagement scenarios to be analysed. Finally, the outcomes are assessed through performance evaluation metrics, enabling comparison between different decision strategies. This combined operational and simulation approach provides a systematic methodology for analysing and optimizing the WTA process under complex and dynamic threat conditions.

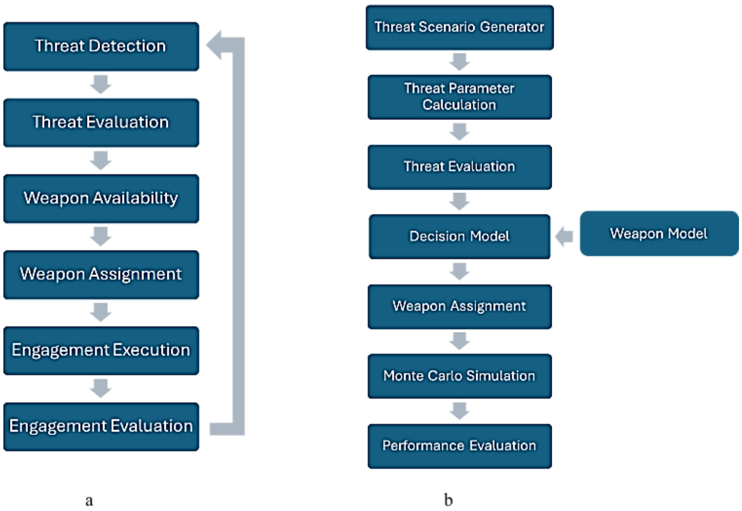

Fig. 1. Flow diagram of a) Overall TEWA procedure and b) Presented simulation

3. Simulation Based Framework and Models Description

This chapter describes each component of the simulation process in detail, including the selected evaluation criteria, parameter settings, and the overall configuration of the Python-based simulation environment, and the entire code is available from12.

Threat Scenario Generator and Parameter Calculation. Is implemented as a configurable module within the Python-based simulation environment and is designed to produce representative sets of incoming threats for subsequent evaluation. Its logic is based on a user-defined catalogue of threat types, where each category is characterized by parameter intervals such as minimum and maximum speed, minimum and maximum cost, and a normalized threat coefficient expressing the relative operational importance of that threat class. Before scenario generation, the input catalogue is validated to ensure consistency of parameters, for example by checking that speed and cost intervals are correctly ordered, see Fig. 2, and that the threat coefficient remains within the [0,1] range. The generator then allows the user to specify the number of threats for each threat type, which makes it possible to construct tailored saturation scenarios with controlled composition. Once generated, the scenario is automatically transformed into a structured threat table, see Tab. 1, and visually summarized using basic exploratory plots, including threat-type frequency, speed distribution, and the relationship between estimated cost and threat coefficient. In this way, the threat scenario generator provides both a reproducible input dataset for the simulation and a transparent mechanism for controlling the diversity and intensity of the analysed threat environment.

All parameters can be easily modified according to specific type of aerial threat. Presented parameters represents average values of generic threat type.

Table 1.

Example of Generated threats parameters

Threat ID	Threat Type	Speed (m/s)	Cost (EUR)	Threat
T001	Drone Class I	32	12000	0,2
T002	Drone Class II	60	45000	0,35
T003	Loitering Munition	55	70000	0,45
T004	Cruise Missile	280	1500000	0,75

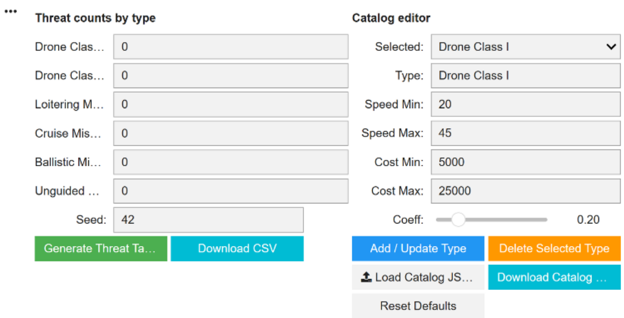

Fig. 2. Threat Scenario Generator GUI

Weapon model. The weapon system (effector) consists of multiple interceptor types with different operational characteristics. Each weapon system is defined by parameters including interceptor velocity *V* [m/s], reaction time *Tr* [s], engagement range *R* [km], probability of hit *Pk*, cost C [EUR]. For example, see 13, where is described comparative analysis of the fighter jets

All parameters can be easily modified according to specific type of effector. Presented parameters represents average values of generic weapon type.

Table 2.

Example of Weapon models parameters

ID	Type	V_{min}	V_{max}	T_{rmin}	T_{rmax}	R_{min}	R_{max}	Pk_{min}	Pk_{max}	C_{min}	C_{max}
0	SHORAD Missile	700	900	3	6	8	20	0,55	0,8	50000	150000
1	MRAD Missile	1000	1400	4	8	20	60	0,6	0,88	150000	500000
2	LRAD Missile	1800	2400	6	12	60	150	0,65	0,92	500000	2000000
3	CIWS Gun	900	1200	1	3	1	5	0,3	0,65	1000	10000

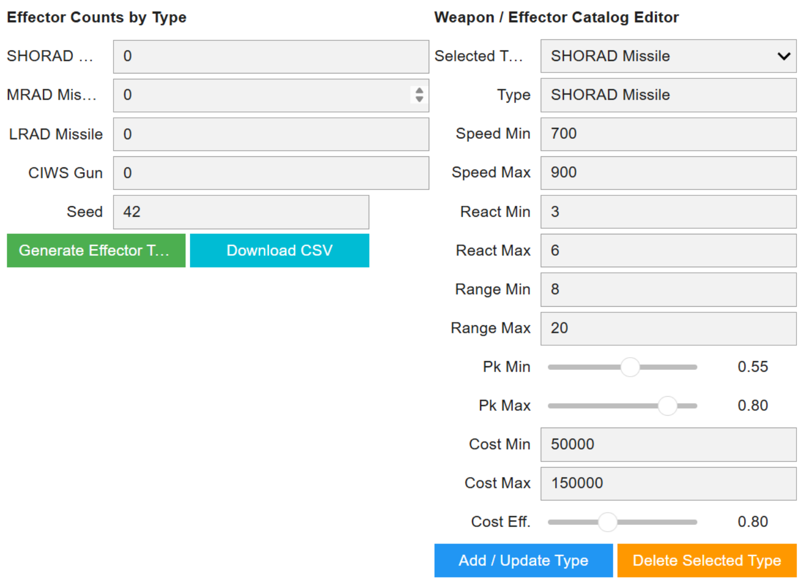

Fig. 3. Weapon model Generator GUI

These parameters determine whether a given interceptor can engage a particular threat within the available time window with defined probability of hit.

The simulation reflects different hit probabilities for different weapon–threat combinations by combining the effectiveness of each effector type with a pairwise suitability modifier and the relative difficulty of the target, see 1. First, each effector is assigned a base single-shot interception probability generated from the parameter range defined for that effector class. This base value is then adjusted by a type-specific modifier representing the suitability of a given weapon type against a given threat type, and further reduced by the threat coefficient, which expresses the relative difficulty or danger of the target. In this way, the model captures the fact that not all weapons are equally effective against all threats, while remaining simple enough for simulation-based analysis.

$$P_{ij} = P_i \cdot M_{ij} \cdot (1 - \alpha K_j) \quad (1)$$

Where:

P_{ij}– probability of interception for effector $i$against threat j
P_i– base single-shot probability of the effector
M_{ij}– type modifier for effector–threat combination
K_j– threat coefficient of threat j
α– scaling factor for threat difficulty

Threat Evaluation and Decision Model

Based on the generated threat scenarios, the threat evaluation and prioritization process is performed. One of the key parameters used in this process is the Time to Impact (TTI), which represents the estimated time remaining before a threat reaches the defended asset. In the proposed model, this parameter is calculated using a simplified approach that assumes a linear threat trajectory directed toward the defended asset and a constant threat velocity. Although this assumption reduces the complexity of the model, it provides a reasonable approximation for estimating engagement urgency within the simulation environment.

$$TTI_j = \frac{D_j}{V_j} \tag{2}$$

Where:

TTI_j– time to impact of threat j [s]
D_j– distance of threat j from the defended asset [m]
V_j– velocity of threat j [ms^{-1}]

The distance value is user-defined based on the scenario and can vary for each threat or threat type.

For each possible combination is computed following parameters:

Time to intercept

$$T_{int} = T_r + \frac{D_j}{V_w} \tag{3}$$

Where:
T_{int}– interceptor engagement time [s]
T_r– interceptor reaction time [s]
D_j– distance to threat [m]
V_w– interceptor velocity [ms^{-1}]
A feasible engagement requires that:

$$T_{int} < TTI \tag{4}$$

If this condition is not satisfied, the engagement option is considered infeasible.

Baseline model - represented by a heuristic Closest-Threat-First (CTF) procedure, which is typical of legacy rule-based air defence systems. In this approach, threats are prioritized primarily according to their proximity to the defended asset, or equivalently according to the shortest remaining time to impact under simplified kinematic assumptions. The nearest threat (4) is evaluated first, and the system assigns the first available feasible interceptor that satisfies the engagement conditions, such as sufficient range and the ability to intercept the target before it reaches the defended asset.

$$j^* = \arg\min_{j \in J} D_j \text{ or } j^* = \arg\min_{j \in J} TTI_j \tag{5}$$

Where:
j^* is the selected threat
D_j is the distance of threat $j$from the defended asset [m]
TTI_j– time to impact of threat j [s]
J is the set of active threats

Multi-Criteria Decision Model (MCDA) - The proposed MCDA model evaluates each possible weapon-target pairing according to three primary criteria:

- Probability of successful interception *Pk*
- Remaining engagement time *Tij*
- Cost efficiency *Cij*

$$U_{ij} = w_1 P_{ij} + w_2 T_{ij} + w_3 C_{ij} \tag{6}$$

Where:
w_1, w_2 w_3 are weight coefficients for each criterion

4. Scenario Layout and Models Verification

The simulation scenario was based on simplified GBAD tactics 14**Error! Reference source not found.** and it was configured as a mixed saturation attack combining low-cost aerial threats with higher-value missile threats to reflect the heterogeneous character of IAMD engagements, see Tab.3 For each iteration, all threat and effector parameters were generated from the previously defined type-specific intervals, ensuring consistency with the threat and weapon catalogues introduced earlier in the paper. Threat urgency was represented by the TTI, while each possible effector–threat pairing was evaluated through time-to-intercept, feasibility, interception probability, and cost-efficiency measures before being processed either by the CTF or by the MCDA assignment model. This scenario layout directly follows the simulation-oriented TEWA structure presented in fig.1.

Table 3.

Scenario layout

Component	Configuration
Total threats per run	20
Threat composition	6 Drone Class I, 4 Drone Class II, 3 Loitering Munitions, 2 Cruise Missiles, 1 Ballistic Missile, 4 Unguided Rockets
Total effectors per run	15
Effector composition	6 SHORAD Missiles, 4 MRAD Missiles, 2 LRAD Missiles, 3 CIWS Guns
Tactical profiles	Aggressive, Balanced, Sustainable
Weight sets	Aggressive: (0,6; 0,3; 0,1), Balanced: (0,5; 0,3; 0,2), Sustainable: (0,4; 0,2; 0,4)
Monte Carlo iterations per profile	150

To ensure internal consistency of the model, a dedicated verification stage was included before the comparative Monte Carlo experiment. Verification focused on five aspects, see Tab.4. First, reproducibility was checked by confirming that identical random seeds produced identical threat and effector tables. Second, generated values were tested against the declared catalogue intervals to verify that speed, cost, range, reaction time, and single-shot interception probability remained within their prescribed bounds. Third, the TTI calculation was verified to ensure that all generated threats had positive, physically meaningful impact times. Fourth, the feasibility logic was checked by confirming that only assignments satisfying both range and time constraints were accepted by either decision model. Finally, the utility formulation was verified by ensuring that feasible pairings generated bounded criterion scores and that infeasible pairings were excluded from the optimization. In the reference implementation all verification checks passed, which supports the validity of the subsequent comparative results.

Table 4.

Verification Table

Verification item	Result
Threat generation reproducibility	Passed
Effector generation reproducibility	Passed
Generated values within declared ranges	Passed
Positive TTI values	Passed
Feasible assignments only	Passed
Utility bounded for feasible pairs	Passed

Note that the presented model uses generic, non-classified parameter sets, the verification process should be interpreted as a check of logical and computational correctness rather than as a validation against operational firing data. The purpose of this stage is therefore to demonstrate that the simulation behaves consistently with the assumptions stated in the methodology and that the observed differences between the baseline and MCDA models arise from the decision logic itself rather than from implementation errors. This is consistent with the paper's stated role as a simulated-based proof-of-concept for automated WTA decision support.

The presented simulation model includes several simplifying assumptions introduced to maintain computational clarity and to provide a transparent proof-of-concept for the proposed MCDA-based WTA framework.

1. Threat motion is modelled as linear and directed toward the defended asset with constant velocity, which enables straightforward calculation of time to impact.
2. Interceptor engagement is represented using simplified kinematic relationships based on reaction time, nominal speed, and engagement range.
3. The model assumes one-shot assignments, independent engagement outcomes, and generic, non-classified parameter ranges for both threats and effectors.

5. Results

The comparative experiment confirmed that the MCDA-based assignment method consistently outperformed the baseline CTF rule under the tested saturation-attack conditions. Overall results are presented in Tab.5 and Tab.6.

Table 5.

Overall results, CTF and MCDA comparison

Metric	CTF baseline	MCDA	Change
Assigned engagements	10,667	11,127	+4,3%
Coverage rate	0,533	0,556	+4,3%
Expected kills	5,907	6,540	+10,7%
Expected leakage	14,093	13,460	-4,5%
Mean time margin (s)	208,308	478,012	+129,5%
Total cost (EUR)	4,266,172,930	4,312,738,931	+1,1%
Cost per expected kill (EUR)	728,327,122	663,783,619	-8,9%
Total utility	4,990	6,430	+28,9%

Table 6.

Weight criteria (profile) comparison – mean utility values

Profile	CTF baseline	MCDA
Aggressive	5,811	7,342
Balanced	4,990	6,430
Sustainable	3,948	4,978

In the balanced profile, the baseline model assigned an average of 10,67 effectors per run, whereas the MCDA model increased this value to 11,13. More importantly, the mean number of expected kills increased from 5.91 to 6.54, corresponding to an improvement of approximately 10,7%. At the same time, expected leakage decreased from 14,09 to 13,46 threats per scenario. These results indicate that the optimized model not only engages slightly more targets but also allocates available interceptors to more effective pairings.

A particularly important result is the difference in engagement timing. The baseline CTF logic produced a mean time margin (disponible time) of 208,31 s, whereas the MCDA model increased the mean margin to 478,01 s. This indicates that the MCDA framework more often selects feasible interceptors with greater temporal reserve, which reduces the risk of last-moment engagements and provides a more robust defensive posture. Although the total average engagement cost increased slightly from 4,27 million EUR to 4,31 million EUR, the cost per expected kill decreased from 728,3 thousand EUR to 663,8 thousand EUR. In other words, the MCDA approach produced a better outcome per cost unit despite a marginal increase in total expenditure.

The same trend was observed across all three tactical profiles. The total mean utility of the MCDA solution was higher than the baseline in the aggressive, balanced, and sustainable configurations. In the aggressive profile, total utility increased from 5,811 to 7,342; in the balanced profile from 4,990 to 6,430; and in the sustainable profile from 3,948 to 4,978. This confirms that the MCDA formulation remains beneficial even when the relative emphasis on interception probability, time, and cost changes. The effect is especially relevant for IAMD decision support, where commanders may need to shift rapidly between highly aggressive and resource-sustainable engagement doctrines depending on operational context. This interpretation is fully aligned with the paper's earlier statement that the MCDA framework should support both effectiveness and cost-aware resource management.

This Fig.4 shows that only a limited subset of weapon–target combinations (in presented scenario layout) have high utility, while most pairings are infeasible or unsuitable, as indicated by the dark purple cells near -1. The highest utility values are concentrated mainly for effectors E007–E012 against threats T001–T013, which suggests that these effectors form the main effective engagement layer in the scenario. Some earlier effectors, such as E001–E006, are useful only against a narrower group of threats, while E013–E015 appear almost entirely ineffective in this run. The final threats, especially T017–T020, can be engaged only by a smaller subset of effectors, indicating more limited defensive options. Overall, the heatmap confirms that the MCDA model clearly distinguishes between feasible and non-feasible assignments and prioritizes those combinations that offer the best balance of interception probability, time margin, and cost efficiency.

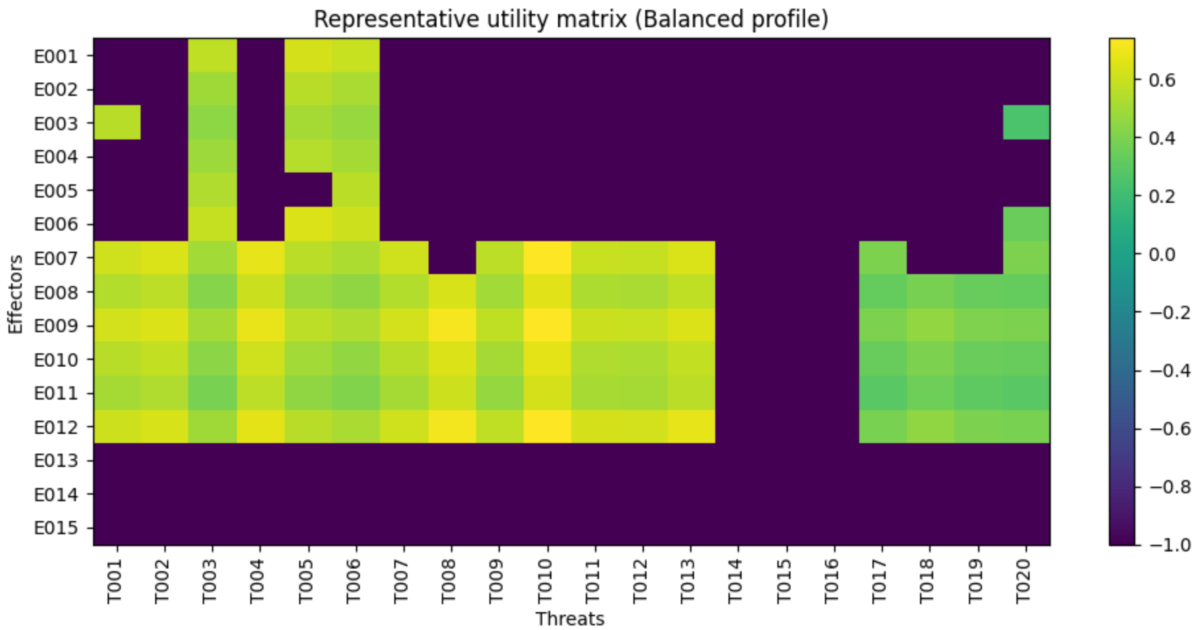

Fig. 4. WTA Scenario Heatmap

6. Results and Conclusion

The results of the presented simulation indicate that the MCDA-based WTA approach provides a measurable improvement over the legacy Closest-Threat-First baseline under generic saturation-attack conditions. The optimized model achieved higher expected kills, lower expected leakage, and better cost-per-kill performance while also significantly increasing the average time margin for feasible engagements. These findings suggest that even a relatively simple multi-criteria utility model can improve both the efficiency and the robustness of defensive decision-making in Integrated Air and Missile Defence systems.

From a methodological perspective, the proposed framework offers two important advantages. First, it remains computationally tractable and can therefore serve as a practical decision-support layer within a Python-based simulation environment or future C2 prototype. Second, it allows explicit tuning of tactical posture through weight coefficients, making it possible to adapt the engagement logic to aggressive or sustainable defence concepts without altering the underlying model structure. This flexibility is particularly important in modern IAMD operations, where commanders must balance immediate lethality against longer-term inventory preservation.

At the same time, the present work should be understood as a proof-of-concept rather than a final operational model. The threat and effector parameters are intentionally generic, the target trajectories are simplified, and the current formulation assumes a one-shot, one-assignment engagement structure. Future work should therefore extend the model toward greater realism by introducing defended-asset prioritization, dynamic re-engagement, inventory depletion across multiple time steps, sensor-track quality, and more detailed pairwise probability-of-kill calibration. Even in its present form, however, the simulation demonstrates that a structured MCDA approach provides a stronger analytical backbone for WTA than traditional heuristic logic alone. This conclusion is consistent with the paper's stated aim of reducing decision latency and supporting more adaptive IAMD command-and-control procedures.

7. Way Ahead

The next phase of research should focus on extending the current proof-of-concept toward a more operationally realistic and analytically rigorous model. One important direction is the introduction of defended-asset prioritization, where threats are evaluated not only according to their own characteristics but also according to the value and vulnerability of the asset they are approaching. This would allow the model to better reflect real IAMD decision-making, in which not all defended objects have equal strategic importance.

A second priority is the incorporation of dynamic engagement logic. The present model assumes a static one-shot assignment, whereas real engagements often follow a repeated shoot-look-shoot cycle in which the outcome of the first engagement influences subsequent decisions. Extending the framework to multiple decision steps, including re-engagement opportunities and inventory depletion over time, would significantly increase its realism and relevance.

Further development should also include a more detailed representation of sensor-track quality, uncertainty, and threat manoeuvrability. In the current model, these effects are represented in a simplified form, but future work should connect the WTA process more closely to the upstream Threat Evaluation process and to the quality of sensor-derived information. Similarly, the current pairwise probability-of-kill formulation could be replaced by a more detailed weapon-type × threat-type effectiveness matrix calibrated from expert knowledge, operational data, or high-fidelity simulation.

Another promising research direction is the integration of the model with advanced optimization and artificial intelligence methods. While the present MCDA approach is transparent and computationally efficient, future work could compare it with machine-learning or reinforcement-learning-based decision policies in order to explore the trade-off between interpretability and adaptive performance. In this sense, MCDA could remain either a standalone decision method or a transparent supervisory layer placed above more advanced automated engagement algorithms.

Finally, the framework should be validated in more sophisticated modelling and simulation environments, including constructive and virtual simulation tools already used in military experimentation. Such a step would allow the proposed decision model to be tested against more complex kinematic, doctrinal, and operational constraints, and would provide a stronger basis for future implementation within real command-and-control support systems.

Overall, the way ahead is therefore not a replacement of the current framework, but its gradual evolution from a generic analytical model into a more realistic and operationally relevant decision-support capability for future IAMD architectures.

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