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Dynamic Non-binary Prioritisation for UTM Resource Allocation

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***Abstract*—Advanced air mobility (AAM) is set to revolutionise aerial operations, with uncrewed aircraft system (UAS) missions varying significantly in societal importance, urgency, and scheduling requirements. Existing regulatory frameworks, however, rely on static and binary prioritisation schemes which fail to address the complexity and diversity of UAS missions. This approach is particularly problematic in federated UAS traffic management (UTM) environments, where no single actor allocates interdependent resources. Notably, such environments often default to a first-come, first-served (FCFS) approach, leading to inefficiencies, delays, and suboptimal scheduling outcomes. This study thereby proposes a dynamic and non-binary prioritisation scheme to address the limitations of conventional static approaches. It defines the requirements and objectives of such a scheme, and contextualises the framework within a federated UTM architecture aligned with global concepts of operations (ConOps). Notably, extensive simulations confirm that non-binary priorities can effectively improve the success rate of socially critical missions in a federated UTM ecosystem. Moreover, focus groups with UTM stakeholders are leveraged to identify generic characteristics that may influence mission priorities, and expert-defined prioritisation functions are derived using a bespoke symbolic regression tool. Supervised learning through a Siamese network is further used to learn priority mappings from pairwise expert decisions. This data-driven technique is identified as a more practical approach to priority mapping, and shown to outperform expert-defined functions even in simple environments.**

***Index Terms*—AAM, prioritisation, resource allocation, UAS, UTM**

I. Introduction

A. UAS traffic management

Emerging advanced air mobility (AAM) operations will transform the aviation industry by introducing a large number of uncrewed aircraft systems (UASs) in potentially unsegregated airspace. This requires robust UAS traffic management (UTM) systems to safely coordinate beyond visual line-of-sight (BVLOS) operations with higher traffic densities, heterogeneous aircraft types, and more diverse airspace users [1], [2]. Limited vertiport landing, takeoff, and charging facilities also impact mission planning, requiring resource allocation mechanisms to extend beyond airspace deconfliction to include ground-based infrastructure [3].

Several UTM concepts of operations (ConOps) have been proposed globally to address these challenges [4]–[8]. In contrast to traditional centralised air traffic management (ATM), UTM is envisioned as a service-based framework, where multiple UTM service providers (USPs) and resource managers (RMs) coordinate airspace access and resource allocation within a federated ecosystem. This decentralised structure introduces complex challenges in ensuring the fair and efficient allocation of interdependent resources while maintaining safety, operational integrity, and overall system efficiency.

B. Priority-based resource allocation

The diverse and cost-effective capabilities of UASs enable a broad range of applications, including cargo delivery, medical transport, infrastructure monitoring, and inspection missions [9]. These operations differ significantly in their urgency, societal importance, and underlying business model, particularly when comparing on-demand services with pre-scheduled operations. Emergency medical deliveries and search-and-rescue missions, for example, require immediate authorisation, whereas pre-scheduled cargo deliveries or routine inspections are often less socially critical and more tolerant of delays.

Historically, static prioritisation has been employed in airspace management to distinguish between critical and non-critical missions, with binary levels often considered for civil operations [10], [11]. ICAO further promotes a first-come, first-served (FCFS) approach, such that the first authorised flight plan secures the intended airspace unless superseded by a higher-priority mission [12]. Such a two-tiered priority hierarchy offers a simple and enforceable scheme, but fails to reflect the diversity and time-varying characteristics of UAS missions. Even within a single domain, such as medical transport, an organ delivery may be more critical than a radio-pharmaceutical transport, which in turn may be more urgent than a routine blood sample delivery. Furthermore, UAS mission criticality is not static, and a delivery or inspection mission may become increasingly urgent as its payload or deadline nears expiration. Moreover, prioritisaiton for UTM must extend beyond airspace management to resolve conflicts for limited ground infrastructure and resources.

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Few works have explored the concept of granular prioritisation for UTM and aerial operations, with most assuming an underlying static and binary framework [13]–[15]. Emami et al. [16] assign dynamic priorities to aircraft based on the aircraft position, velocity, distance to other aircraft, and surrounding weather conditions. This work, however, focuses on improving system efficiency through prioritisation, and does not reflect the societal importance and urgency of aerial operations. Conversely, Pamucar et al. [17] employ fuzzy logic to prioritise transport systems according to expert knowledge, but do not consider dynamic prioritisation amongst different aerial missions. Hlavatá et al. [18] propose a static, non-binary and rule-based prioritisation scheme for UTM, accounting for aircraft types, mission use cases and emergency states. This work, however, fails to consider context- and time-varying factors that may influence the priority of a mission.

C. Contributions

To overcome the limitations of existing prioritisation schemes, this paper proposes a dynamic non-binary prioritisation framework for UTM, designed to extend to crewed and military aircraft for mixed operations in non-segregated airspace. The main contributions of this work are as follows:

- A mission-centric, dynamic, and non-binary prioritisation scheme is developed to capture the time-varying and context-dependent criticality of aerial operations. This framework is aligned with global UTM ConOps, and extensive simulations of a UTM ecosystem are used to validate the feasibility of standardised non-binary prioritisation within a federated resource allocation model.
- Focus groups with UTM stakeholders are used to (a) identify generic characteristics influencing mission priorities, (b) derive priority functions for a set of missions through a bespoke symbolic regression tool, and (c) compile a preliminary dataset of user prioritisation preferences.
- A Siamese supervised learning algorithm is developed to learn absolute priority assignments from pairwise rankings provided by UTM experts, and shown to outperform expert-defined prioritisation rules and functions.

D. Paper structure

Section I introduced the challenges of UTM resource allocation and existing prioritisation schemes. Section II outlines a priority-based decision-making architecture to address these challenges in a federated UTM ecosystem, and Section III defines the requirements and objectives of such a prioritisation scheme. It further discusses algorithmic techniques that may be used to calculate mission priorities. Some of these algorithms are demonstrated in Section IV, in which findings from focus group discussions are also reported. Additionally, simulation results on priority-based resource allocation are used to demonstrate the feasibility of the proposed framework. Finally, Section V summarises the key contributions of this work and outlines potential directions for future research.

II. Priority-driven Resource Allocation

A. Generic UTM architecture

Despite ongoing efforts toward global harmonisation, multiple distinct UTM ConOps have been developed to address regional requirements. The ConOps for European UTM systems (CORUS) [4], for example, introduced U-Space airspace to manage UAS traffic in Europe, where U-Space service providers (USSPs) offer a suite of certified services to operators and other stakeholders. In the UK, the open-access UTM framework [5] was proposed by Connected Places Catapult in collaboration with the UK Department for Transport (DfT), Civil Aviation Authority (CAA), and industry stakeholders. In the United States, the Federal Aviation Administration (FAA), in partnership with NASA, has developed a ConOps for UTM operations in the national airspace [6]. Similarly, the Civil Aviation Administration of China (CAAC) introduced the cvil UAS aviation operation management system (UOMS) for Chinese airspace [7], while the Japan UTM Consortium, in coordination with the Japan Aerospace Exploration Agency (JAXA), has proposed the Japan UTM (JUTM) framework [8]. Several industrial entities have also developed proprietary UTM ConOps to address emerging UAS and AAM operations.

To ensure compatibility across different ConOps, this study adopts the generic UTM architecture depicted in Fig. 1, which abstracts fundamental system components based on similarities between existing ConOps [2], [19], and the harmonisation principles established by ICAO [20] and ISO 23629 [21]. Notably, most ConOps advocate for a federated UTM ecosystem, which fosters market-driven innovation through the cooperative exchange of information and services among UTM stakeholders, according to performance-based standards. The responsibilities of these actors are summarised in Tab. I and hereby discussed.

TABLE I
Stakeholder responsibilities in a generic UTM architecture.

Stakeholder	**Responsibilities**
UTM service provider (USP)	Airspace management and service provision in certified UTM airspace.
Supplemental data service provider (SDSP)	Airspace management and service provision in non-certified airspace, or ancillary service provision beyond the capabilities of a USP.
Air traffic services (ATS)	Airspace management and certified service provision in controlled airspace.
Vertiport manager (VM)	Management of vertiport ground infrastructure and resource allocation.
Geozone manager (GM)	Management of access conditions for designated airspace volumes.
Common information service provider (CISP)	Provision of common information to authorised stakeholders.
UAS operator or command and control centre (C2C)	Mission planning and management, resource booking coordination and vehicle control. The legal entity responsible for a UAS mission.
Uncrewed aircraft (UA)	Mission execution and collision avoidance.

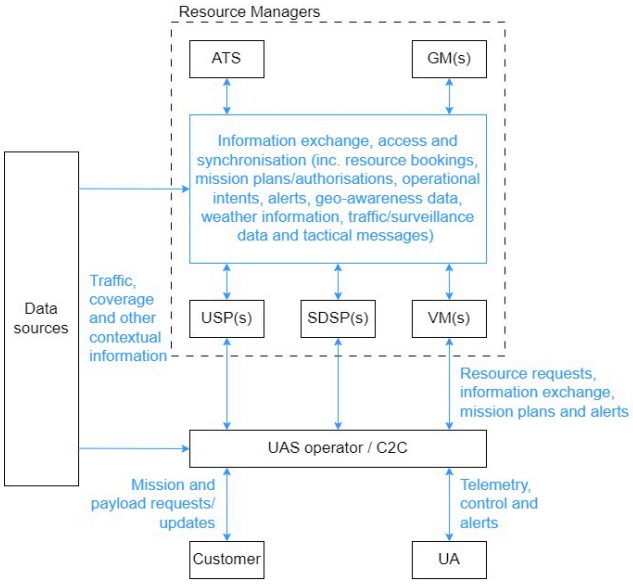


Fig. 1. Typical actors (black) and data flows (blue) in a UTM architecture.

In this framework, UTM airspace management is the responsibility of one or more SPs that authorise and strategically deconflict flight plans. Such entities may include:

- USPs operating in certified airspace, such as USSPs managing U-Space airspace;
- Supplemental data service providers (SDSPs) supporting operations in uncontrolled non-certified airspace;
- Air traffic services (ATS) managing operations in controlled airspace, typically through a USP or SDSP to reduce interactions with UAS operators and minimise excess air traffic control (ATC) workload; and
- Geozone managers (GMs) overseeing access to designated airspace volumes.

Additionally, vertiport managers (VMs) manage bookings of ground infrastructure, such as vertipads, charging stations, and loading or unloading facilities. For simplicity, these entities are collectively referred to as resource managers (RMs).

RMs exchange meteorological, geospatial, aeronautical, and contextual data, as well as tactical messages, bookings, and operational intents. This exchange may occur through a centralised information service provider (CISP) or direct interfaces between stakeholders. Furthermore, RMs may provide additional services such as network identification, flight authorisation, strategic deconfliction, tactical deconfliction, and conformance monitoring. From a resource allocation perspective, the following process occurs:

1) The customer submits a mission request and coordinates payload logistics with a UAS operator.
2) The operator or command and control centre (C2C) plans the mission, before submitting resource booking requests to the relevant RMs. Depending on the implemented UTM model, mission planning and resource coordination may be directly managed by the C2C or facilitated through a USP or SDSP.
3) RMs authorise the requests if they are strategically deconflicted, and reject them otherwise. An alternative plan may also be proposed to the UAS operators.
4) Once airborne, operators and relevant SPs monitor the mission and take required corrective actions while issuing appropriate alerts. This may involve tactical mission replanning or collision avoidance manouevres, whereby RMs must rapidly approve a revised plan or issue a non-conformance alert to accommodate real-time changes.

B. Priority-based decision-making

Multiple federated actors managing interdependent resources requires robust synchronisation and coordination among decision-making processes. This is particularly critical when a single resource (such as an airspace volume) is simultaneously managed by multiple stakeholders (such as multiple USPs). Additionally, tactical rerouting and on-demand missions with short decision-making horizons demand efficient, real-time deconfliction and authorisation mechanisms. This study thereby proposes a standardised prioritisation framework that all stakeholders must adhere to. Under this approach, strategic or tactical resource conflicts are rapidly resolved by assigning the contested resource to the highest-priority mission, even if this requires delaying or revoking an existing lower-priority authorisation. GMs may also issue priority-based access restrictions, allowing only missions exceeding a predefined priority threshold to enter restricted airspace. For instance, airspace above a nature reserve may be restricted to high-priority life-critical or military operations.

In this approach, the UAS operator retains final responsibility of a UAS mission. Mission priority is thereby assigned by the operator, such that no sensitive data, beyond the mission priority number, is disclosed to other stakeholders. This improves mission privacy, increases operational clarity on how to resolve conflicts and prevents airspace managers from monopolising or unfairly restricting airspace usage. Nonetheless, priority assignment must be periodically audited by a certified authority to prevent operator manipulation or misuse.

C. Assumptions

This study assumes real-time synchronisation among stakeholders, ensuring that a resource authorisation of one RM is immediately visible to all others. Additionally, it assumes that suitable interfaces exist to communicate priority levels to airspace users with limited technological capabilities, such as paramotors and general aviation (GA). Moreover, electronic conspicuity (e-conspicuity) is assumed, whereby mission priority may be communicated as part of the e-conspicuity signal. Rules of the air based on mission priorities are also assumed to exist, avoiding ambiguity when resolving tactical conflicts in the absence of a deconfliction SP. In cases where the difference between priority levels of conflicting missions falls below a configurable threshold, a FCFS policy is assumed. Such a buffer accounts for the inherent uncertainty in priority assignment, and helps reduce unfair delays and revocations.

III. Priority Computation

A. Operational objectives

Prioritisation may be used to achieve several objectives, including safety, societal benefit, efficiency, fairness, stability, and profitability. These objectives are hereby described, and their relevance to UTM is summarised in Tab. II:

- **Safety**: Prioritisation can improve safety by reducing ambiguity in real-time strategic and tactical conflict resolution [18]. Specifically, it can reduce the impact and number of catastrophic failures by assigning a higher priority to aircraft experiencing or approaching an emergency state, or to missions with greater associated air and ground risks. However, the fundamental safety of UTM operations should not be contingent on prioritisation. The system must therefore ensure that:
  - Aircraft in an emergency posing a significant risk to human life receive unambiguous priority;
  - Collision avoidance does not rely on priorities if a collision is imminent, ensuring that aircraft do not erroneously assume right-of-way in case of non-cooperative or no radio (NORDO) aircraft; and
  - All operations meet safety assessments from a certified authority, regardless of their priority.
- **Societal impact**: The aim of a mission-centric prioritisation framework is to maximise societal benefit by prioritising missions of high societal value, such as urgent medical and search-and-rescue operations. The social impact of UAS operations, however, varies with time and context, confirming the need for a dynamic prioritisation scheme [22].
- **Fairness**: Prioritisation should ensure mission-level fairness, by preventing an airspace manager from unfairly restricting airspace usage, especially for socially critical missions [18]. Additionally, operator-level fairness can be promoted by prioritising operators who have experienced frequent prior rejections or delays. Booking times may also be defined relative to a reasonable time to book (RTTB) metric, rather than the absolute take-off time, to avoid systematic disadvantages for on-demand services. However, quantifying fairness remains an open challenge and falls beyond the scope of this work [14], [23], [24]. Specifically, simple metrics often fall short in capturing *why* such rejections occurred, which may not be a result of unfair systematic biases.
- **Certainty**: Uncertainty quantification plays an important role in improving the efficiency and determinism of UTM operations [4]. Notably, priority-based decision-making inherently mitigates uncertainty, as missions with greater variability in take-off, landing, and route timing are more prone to conflicts with multiple other missions. Consequently, such missions must have a sufficiently high priority to ensure acceptance. Conversely, prioritisation should also allow an operator to reasonably assess the likelihood that a resource booking or flight authorisation will remain unchanged, based on its assigned priority.
- **Efficiency**: Operational efficiency may be improved by assigning a higher priority to flights experiencing significant delays, missions likely to cause significant knock-on disruptions if delayed, and flights with a higher probability to respect their allocated booking times. Nonetheless, efficiency is likely to be incentivised through additional mechanisms that complement prioritisation, such as reduced costs or taxation for more efficient missions with lower operational uncertainty [25].
- **Environmental impact**: Prioritisation may be used to encourage more sustainable operations. This may include assigning a higher priority to missions with lower emissions, visual impact, noise pollution and/or energy consumption. Nonetheless, sustainability is likely to be incentivised through additional mechanisms that complement prioritisation, such as reduced costs or taxation for operations with a lower environmental impact [26].
- **Profitability**: Economic sustainability is fundamental to UTM, and prioritisation should complement, but not limit, pricing strategies while avoiding monopolisation [27]. In general, prioritisation can be (a) independent of price, whereby SPs charge an unrelated subscription cost; (b) dependent on price, whereby mission priorities are influenced by the price paid by an operator; and (c) related to operator fees, whereby priority assignments are independent of price, but operators must pay a predetermined fee to secure their priority level.

TABLE II
Possible objectives of a prioritisation scheme and their relevance to UTM.

Objective	Relevance	Rationale
Safety	High	Clear priority rules reduce ambguity when resolving real-time conflicts and can mitigate operational risk.
Societal impact	High	Prioritisation should ensure that critical missions succeed through timely authorisation and access to resources.
Fairness	High	Prioritisation should ensure mission-level fairness by preventing unfair airspace restrictions, especially to socially critical missions. It may also promote operator-level fairness by considering historical delays, prior rejections and other contextual data.
Certainty	High	Prioritisation should allow an operator to reasonably assess the likelihood that a resource booking or flight authorisation will remain unchanged, based on its assigned priority.
Environmental impact	Neutral	Prioritisation may encourage more sustainable operations, but will typically complement other mechanisms that encourage reduced environmental impact.
Efficiency	Neutral	Prioritisation can improve efficiency, but will typically complement other mechanisms that encourage more efficient operations.
Profitability	Neutral	Prioritisation cannot undermine resource access for socially critical missions. It will typically complement, but not restrict, pricing mechanisms.

B. Requirements

To ensure practical feasibility and adoption, a prioritisation scheme must satisfy several key requirements. These are hereby discussed and summarised in Tab. III:

- **Explainability**: Prioritisation should be simple, transparent and interpretable, enabling stakeholders to understand how priority levels are assigned. This ensures traceability, promotes stakeholder adoption, and enables post-event audits to verify compliance with regulations [28].
- **Privacy**: Prioritisation should ensure that commercially sensitive and mission-specific details are not exposed to unauthorised entities. Operators should not be required to disclose their identity or payload characteristics to external parties, and only abstracted priority scores should be shared with RMs and SPs [4], [6]. The scheme should also prevent operators from inferring strategic data about competitors in a competitive market.
- **Reliability**: The prioritisation scheme must be robust and formally verified, preventing issues such as cyclic priority fluctuations or deadlocks in resource allocation [29]. Priority assignments should also be deterministic, yielding predictable and repeatable outcomes.
- **Resilience**: Prioritisation should be resilient to strategic manipulation, preventing actors from exploiting loopholes to unfairly increase priority levels [25]. Moreover, the scheme must be resilient to cyber attacks that can lead to potential safety hazards and operational inefficiencies, especially when using priority-based flight rules and deconfliction algorithms [30].
- **Flexibility**: The prioritisation framework should be readily extended to diverse airspace users, including crewed, uncrewed, paramotor and military aircraft, to support mixed operations in non-segregated airspace [4], [6], [20].
- **Interoperability**: The prioritisation scheme should remain compatible with existing regulations, such that emergency missions holding higher priority under current legal frameworks retain their unambiguous priority [11].

TABLE III
REQUIREMENTS OF A UTM PRIORITISATION SCHEME.

Requirement	Rationale
Explainability	Prioritisation should be transparent to encourage stakeholder adoption and ensure traceability.
Privacy	Mission priorities should not expose sensitive mission details.
Reliability	Prioritisation must be deterministic and formally verified to prevent cyclic resource allocation loops or undesirable priority fluctuations.
Resilience	The framework should be resilient to strategic manipulation and malicious attacks.
Flexibility	Priorities should extend to crewed, uncrewed, paramotor and military aircraft, promoting mixed operations in non-segregated airspace.
Interoperability	Prioritisation should be aligned with established legal frameworks.

C. Mapping context to priority levels

The fundamental objective of mission-centric prioritisation is to reflect the criticality and urgency of an aerial mission based on time-varying context and mission-specific heuristics. Fairness, societal benefit, and knock-on disruptions, however, are often hard to quantify and predict. Human expertise and domain knowledge are therefore needed to understand the context of different use cases, and determine the criticality and urgency of a UAS mission in different environments. Consequently, two approaches can be employed to calculate numeric priority levels, as exemplified in Fig. 2 and detailed below:

- **Direct context-to-priority mapping**, in which human experts (or artificial intelligence (AI)-based algorithms) directly assign priority levels based on mission characteristics and environmental context [18]; and
- **Staggered context-to-priority mapping**, in which contextual information is first translated into generic quantitative parameters, such that standardised functions or algorithms can compute a priority value based on these quantitative inputs [16].

D. Algorithmic solutions

As air traffic density increases, traditional human-in-the-loop decision-making processes will struggle to meet real-time operational demands due to cognitive overload [31], [32]. This highlights the need for automated and scalable algorithms to calculate mission priorities and quickly resolve emerging resource conflicts. Several computational approaches have been used in diverse applications to compute mission priorities. These are illustrated in Fig. 3 and their relevance to UTM prioritisation is discussed below.

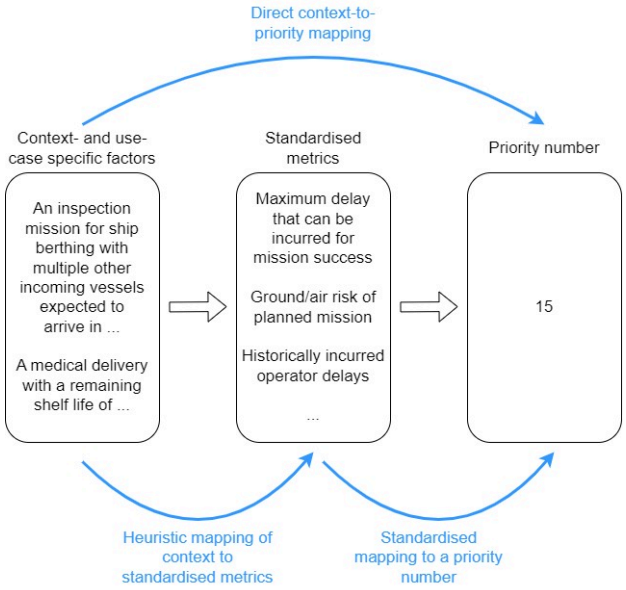


Fig. 2. Approaches to map context- and use case-dependent factors to a priority number.

- **Rule-based classification**: A comprehensive set of predefined rules can be established to map mission-specific and environmental context to standardised parameters or directly to a priority level [18], [33], [34]. This approach follows existing regulatory frameworks and offers a simple, transparent, and easily explainable solution for stakeholders. However, it becomes increasingly challenging and time-consuming to define comprehensive rules as mission diversity increases and more input parameters are considered. Moreover, rule-based techniques are unable to dynamically adjust to unforeseen circumstances, making them unsuitable for real-time, adaptive prioritisation. Despite these limitations, they offer a promising baseline for initial parameterisation, allowing mission characteristics to be mapped to standardised metrics or priorities.
- **Deterministic functions**: Continuous or piecewise mathematical functions and models can map quantifiable mission metrics to a priority level [16], [35], [36]. This ensures a deterministic and explainable prioritisation process, and can serve as a foundational framework for standardisation. However, as the number of relevant mission parameters increases, defining, validating, and tuning such functions becomes increasingly complex.
- **Supervised learning**: Machine learning (ML) models trained on expert decisions can map standardised mission metrics to priority levels, offering improved adaptability and generalisation [37]–[40]. However, their effectiveness depends heavily on the availability of representative, unbiased and well-annotated training datasets, which can be difficult to obtain. Additionally, experts may struggle to assign absolute priority levels, leading to ambiguity in labelled data. This can be mitigated using Siamese learning networks to learn absolute priority mappings from pairwise expert comparisons [41]. Experts must instead decide which of two missions should be prioritised, reflecting a more intuitive decision than assigning direct numerical priority levels [42]–[44].
- **Reinforcement learning (RL)**: RL can be used to assign mission priorities, especially when prioritisation objectives can be encoded as a reward signal [45]–[47]. Different objectives, however, must be statically weighted in a single reward function, unless multi-objective RL (MORL) are employed [48]. Moreover, objectives based on human expertise may be incorporated through RL with human feedback (RLHF) techniques [49] or by identifying quantifiable metrics to reflect these heuristics. Nonetheless, measuring and observing system-wide metrics related to fairness, societal impact and stability will pose significant practical challenges.
- **Fuzzy logic**: Fuzzy logic can help translate human expertise to a set of prioritisation rules, and is often used in uncertain and ambiguous environments [50]–[52]. The effectiveness of a fuzzy logic system, however, depends on well-defined rules and membership functions, which can be difficult to design for complex UTM environments with a large number of input parameters.

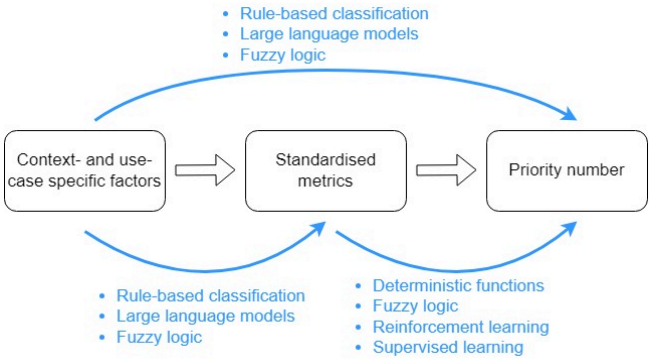


Fig. 3. Algorithms for context-to-priority mapping.

- **Large language models (LLMs)**: LLMs with retrieval-augmented generation (RAG) enable real-time querying of UTM expert data, operational guidelines, and historical decisions to infer mission importance and translate qualitative context into prioritisation decisions [53]. This offers a more generalisable solution, that can adapt to unseen scenarios without the need for re-training. Moreover, LLMs can directly provide natural language explanations for priority decisions, improving transparency and facilitate human-over-the-loop implementations. Multimodal LLMs could also be leveraged to incorporate audio-visual airspace data, ATC workload levels, and real-time sensor inputs that cannot be readily translated to quantifiable metrics [54]. Conversely, LLMs may be used to augment and diversify training datasets for other machine learning algorithms, reducing reliance on manually labelled data [55]. LLM-based prioritisation, however, requires counterfactual guarantees to ensure transparency, accountability, and auditability [56]. It may also suffer from hallucinations, in which the generated output is inconsistent with the provided input [57].

E. Selected approach

Refining prioritisation algorithms falls beyond the scope of this work. Nonetheless, the staggered approach outlined in Fig. 4 was implemented to establish a foundational understanding of deterministic and data-driven prioritisation techniques. In this approach, stakeholder feedback is collected to:

1) Identify a set of generic metrics that can be applied to different use cases and mission contexts;
2) Identify simple classification rules that map mission-specific context to a set of standardised metrics;
3) Compile a preliminary dataset of expert prioritisation decisions; and
4) Derive mathematical functions that map quantitiative metrics to a numeric priority level, using a bespoke priority definition tool. This allows users to define desired priority trends, generates a representative dataset based on these trends, and employs symbolic regression to fit a multivariate curve to the dataset.

The Siamese network depicted in Fig. 5 is explored as a data-driven alternative to mathematical and rule-based prioritisation techniques. Experts are presented with pairs of randomly generated mission contexts and asked to decide which mission should be prioritised. The resulting pairwise dataset is used to train and evaluate the Siamese network through a supervised learning approach. The network consists of two identical neural network instances with shared weights, each processing a different set of mission characteristics as inputs. Each instance outputs an absolute priority value, and the difference between these priorities is passed through a sigmoid function, effectively producing the probability that the second mission should be prioritised over the first. This is compared to the expert pairwise ranking through a binary cross entropy loss function and used to train the neural network.

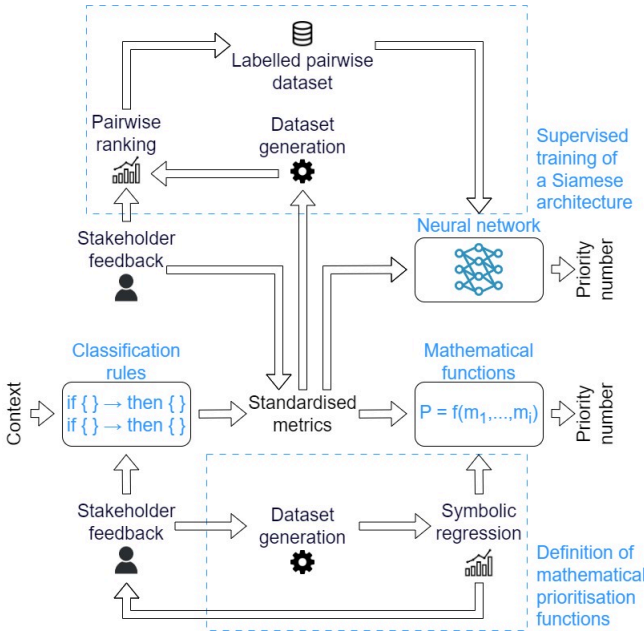


Fig. 4. Overview of the algorithmic solutions used for a preliminary study of dynamic non-binary prioritisation for UTM.

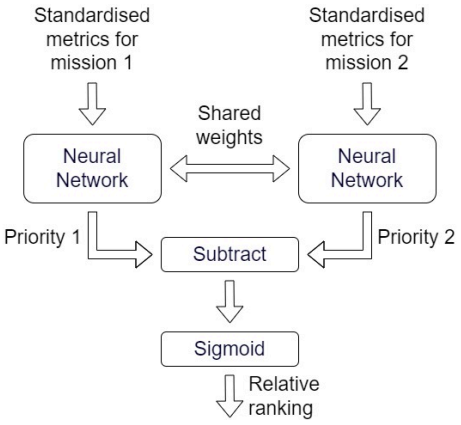


Fig. 5. Architecture of a Siamese network used to learn absolute priority mappings from pairwise expert decisions.

IV. Stakeholder Feedback and Results

A. Methodology

This study introduces the concept of mission-centric, dynamic and non-binary prioritisation for UTM. To better understand the implications and stakeholder expectations of such a scheme, the following data collection and testing is performed:

- The generic UTM architecture discussed in Section II is extensively simulated in AnyLogic to verify that assigning a higher priority to a mission increases its probability of success within the federated framework.
- Focus groups with UTM stakeholders are conducted to identify a preliminary set of standardised metrics to which different mission contexts can be mapped. Such stakeholders include USSPs, SDSPs, CISPs, UAS operators, civil aviation authorities, VMs, GMs and mission- or domain-specific experts.
- Stakeholders are consulted to determine the expected priority ranges for different mission types, providing a reference for subsequent priority calculations.
- A bespoke tool is developed to assist stakeholders in defining, visualising, and testing initial prioritisation functions. This is used within the focus groups to define preliminary prioritisation functions for three distinct types of missions, namely: blood sample delivery, goods delivery, and ship berthing inspection missions.
- Using the same use cases and input parameters, a neural network is trained to generate absolute priority values from pairwise expert comparisons, following the Siamese learning approach detailed in Section III. The collected dataset of pairwise decisions is split into training and testing datasets, ensuring that a portion of the data remains unseen during training for validation purposes. The performance of the trained model is then compared to that of expert-defined functions to evaluate the feasibility of data-driven algorithms for priority calculations.
- All results and stakeholder feedback are analysed to identify key areas for future research.

B. Priority-based resource allocation

The federated UTM ecosystem described in Section II was simulated using a custom agent-based simulation environment in AnyLogic. In this environment, a pre-defined number of customers periodically generate new mission requests, with pseudo-randomised start and destination vertiports, mission characteristics, and desired start times. Each request is sent to a UAS operator, who then retrieves information on existing mission plans from RMs and SPs. Using this information, operators attempt to plan 4D flight paths and ground resource bookings, prioritising non-conflicting routes when possible but overriding lower-priority bookings if no feasible alternatives exist. Operators are also responsible for vehicle allocation, ensuring that fleet schedules remain consistent without empty flights. If an existing authorisation is revoked, the affected operator replans the mission. If no viable alternative exists, the mission is rejected.

Upon receiving a booking request, RMs evaluate the request based on predefined acceptance criteria. Airspace managers approve a request if the proposed flight path remains strategically deconflicted in 4D space and/or does not exceed airspace capacity limits. Similarly, VMs authorise requests only when vertiport infrastructure bookings (including parking bays, final approach and take-off (FATO) areas, chargers, and loading or unloading mechanisms) remain within capacity limits. Whenever a conflict occurs, the lowest-priority mission in conflict is rejected by the RM and re-planned.

Once the mission start time is reached, the UAS executes its flight plan with a predefined level of speed and heading uncertainty. Other non-deconflicted traffic is also simulated, such that the lower-priority mission experiences greater delays whenever a tactical collision avoidance manoeuvre is required. This simulates the impact of priority-based right-of-way rules, but does not specify how such rules should be defined. Upon arrival, the UAS lands and delivers its payload in preparation for the next mission. Vehicle battery life, charging times, ground taxiing, payload handling times, message exchanges, and algorithm execution times are also simulated. However, a comprehensive description of the simulation environment, including its path planning, vehicle allocation, and optimisation algorithms, falls beyond the scope of this paper.

The environment was configured to have six vertiports, each containing two parking bays, three FATOs, three chargers, and three loading and unloading mechanisms, as summarised in Tab. IV. The operational airspace was divided into two airspace volumes, each managed by a separate USP. The simulation further involved 12 customers, each configured to request new missions from one of three available operators with a predefined probability at each timestep. High operational densities and request frequencies were tested, ensuring that a significant proportion of requests had to be rejected to maintain system safety. Specifically, three different request probabilities of 1% ($\sim$ one request every 8 mins), 4% ($\sim$ one request every 2 mins) and 8% ($\sim$ one request every minute) were examined. For simplicity, five distinct priority levels were considered to assess the feasibility of priority-based decision-making in a federated UTM ecosystem. The results obtained after four hours of continuous simulated operations are illustrated in Fig. 6.

TABLE IV
CONFIGURED NUMBER OF ACTORS AND RESOURCES IN THE UTM SIMULATION ENVIRONMENT.

Parameter	**Simulated quantity**
Customers	12
UAS operators	3
USPs	2
Vertiports and VMs	6
Parking bays per vertiport	2
FATOs per vertiport	3
Chargers per vertiport	3
Loading and unloading mechanisms per vertiport	3

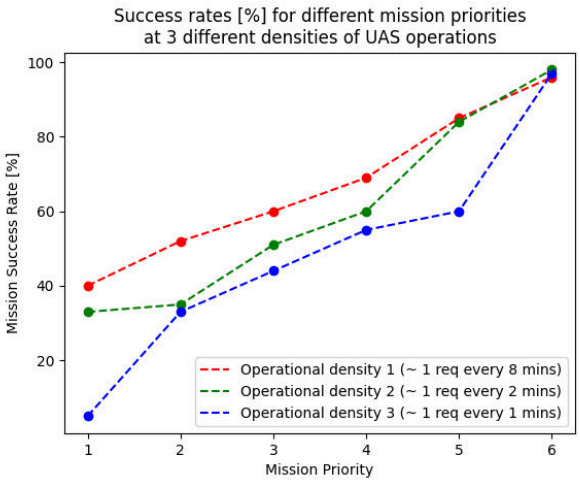


Fig. 6. Data-driven results showing the performance of a priority-driven resource allocation mechanism in a federated UTM ecosystem, for increasingly high operational densities (red to blue).

Despite individual stakeholders managing interdependent resources and operating independent decision-making processes, the use of a standardised prioritisation scheme enabled higher-priority missions to achieve significantly improved success rates across the entire UTM ecosystem. Furthermore, these success rates remained consistent even as operational density increased, demonstrating the scalability of the proposed prioritisation framework. However, this was achieved at the cost of increased rejection rates for lower-priority missions. The high rejection rates for low-priority missions were expected due to randomised mission characteristics (increasing the probability of conflicts occurring), limited resource availability, and high request frequencies. While this stress-testing approach provided valuable insights into system performance, it is unlikely to reflect a practical real-world scenario, where low-priority rejection rates would be significantly lower due to more balanced operational demand and infrastructure scaling.

C. Generic metrics for priority computation

Through focus groups with key UTM stakeholders, a set of generic priority metrics were identified. These metrics are summarised in Fig. 7 and categorised based on whether the mission is grounded, airborne, or experiencing an in-air emergency. For grounded missions, identified metrics included the time to the scheduled or requested take-off time, the maximum allowable delay beyond this take-off time for the mission to succeed, and whether the mission is fully booked and authorised. For airborne missions, stakeholders highlighted the remaining energy reserves, air and ground risk levels, number of remaining viable contingency routes, maximum tolerable delay before mission failure, and whether or not the vehicle is conforming to its flight plan. In the case of an in-air emergency, critical parameters included air and ground risk levels and the time until a catastrophic event occurs, with the prevention of fatalities being the primary consideration.

Beyond these operational parameters, additional fairness, environmental, and efficiency-related metrics were identified for potential inclusion across all mission states. Fairness-related parameters included the RTTB of the mission type, the number of historical rejections experienced by the operator, and the number of prior operator delays. Environmental impact considerations included expected noise and visual pollution as well as forecast energy consumption. Additionally, efficiency-based metrics included the likelihood of adhering to authorised timings and causing ripple-through disruptions. However, these parameters will likely be part of a separate pricing or incentive mechanism that complements, but is not necessarily included within, the prioritisation scheme.

To streamline the definition of prioritisation functions, similar use cases were further grouped into broader categories, as listed in Tab. V. Instead of defining use case-specific functions, this approach enables the development of standardised prioritisation models for each category, ensuring greater scalability and adaptability. This categorisation allows for new use cases and groups to be incorporated as UTM operations evolve, without requiring frequent redefinition of priority standards. Nonetheless, these parameters and groupings should be considered as an initial reference based on stakeholder input and must be refined through further data collection and validation.

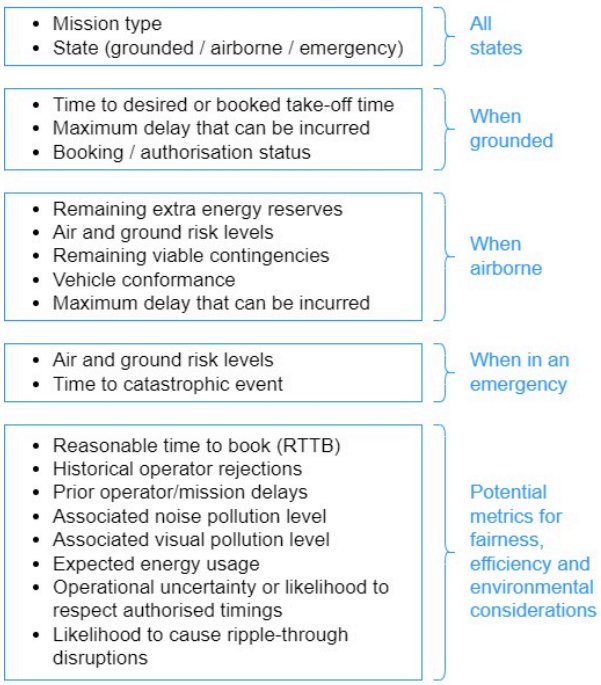


Fig. 7. Generic metrics identified by stakeholders as relevant inputs to a prioritisation scheme, to which context-specific factors of different missions can be mapped.

D. Priority expectations

Further stakeholder feedback was collected to determine the expected priority ranges for different mission types, as depicted in Fig. 8 for an arbitrary numeric range of 0 to 15000. These ranges provide heuristic insights into stakeholder expectations and serve as a benchmark for evaluating the prioritisation functions under development. Notably, some priority ranges exhibited clear separations, indicating that certain mission categories should always be prioritised over others. For example, a grounded search and rescue mission (D1 or D2), which has the potential to save human lives, should always take precedence over an airborne delivery of non-urgent medical supplies (C1). In contrast, several overlapping priority ranges suggest that mission prioritisation is often context-dependent. For instance, if an airborne UAS delivering non-urgent medicine (C1) is in conflict with a consumer goods delivery (B1), priority assignment may vary depending on the real-time mission status, payload conditions, and other operational factors. These results further confirm the need for a dynamic and non-binary prioritisation scheme for UTM.

TABLE V
PRELIMINARY GROUPING OF AERIAL MISSIONS WITH SIMILAR CHARACTERISTICS.

Mission Types	**People on Board**	**Type**
No use case, Standby (Grounded only)	Unpopulated	A
Recreational Filming and Photography, Sports and Event Coverage, Real Estate Photography, Wildlife Monitoring and Conservation, Agricultural Monitoring, Non-critical Infrastructure Inspection, Routine Surveying and Mapping, Environmental Monitoring, Delivery of Consumer Goods, Delivery of Groceries with Long Shelf Life, Charging of Urgent Medical Payload (Grounded only)	Unpopulated	B1
Recreational Flying, Paramotors, Hot air balloons, Sightseeing Tours, Agricultural Manned Aviation, Manned Aerial Photography and Surveying, Manned Pilot Training	Populated	B2
Delivery of Groceries with Short Shelf Life, Delivery of Non-urgent Medical Supplies, Delivery of Non-urgent Medicine, Routine Blood Supply Delivery, Critical Infrastructure Inspection	Unpopulated	C1
Business and Corporate Travel, Commercial Passenger Transport, Cargo Transport, Private and Charter Flights	Populated	C2
Search and Rescue, Firefighting Support, Law Enforcement and Surveillance, Routine / Training Military Operations, Oil Spill Response, Security Inspections	Unpopulated	D1
Search and Rescue, Firefighting Support, Law Enforcement and Surveillance, Humanitarian Aid and Relief, Routine / Training Military Operations	Populated	D2
Urgent Delivery of Medical Supplies, Urgent Delivery of Medicine, Disaster Response and Relief, Urgent Military Operations, Organ Transplant Delivery, Urgent Blood Supply Delivery	Unpopulated	E1
Emergency Medical Services, Medical Evacuation, Disaster Response and Relief, Urgent Military Operations	Populated	E2
Defibrillator (AED) Delivery, Life raft Delivery	All	F
Critical Military and Defence Operations	All	G

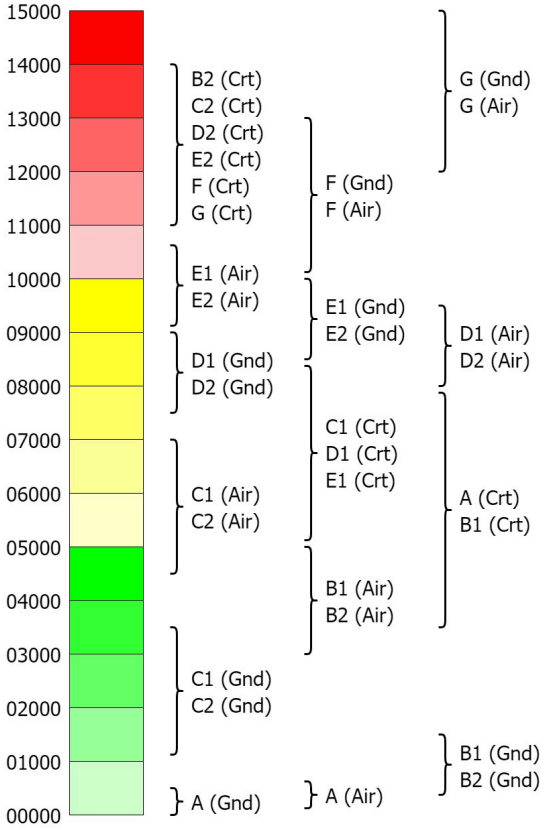


Fig. 8. Expected priority ranges for different mission types and statuses.

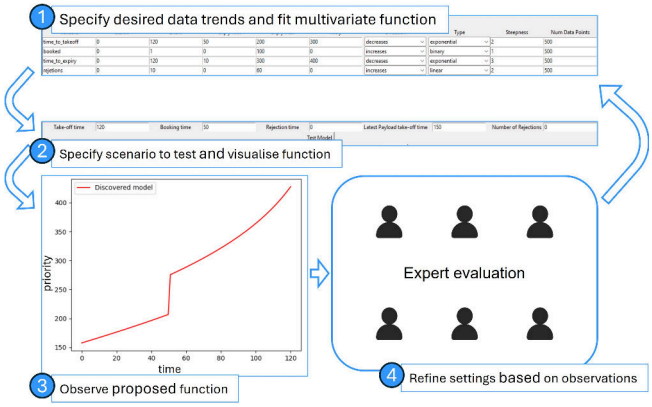


Fig. 9. Symbolic regression tool used to facilitate the definition of continuous prioritisation functions.

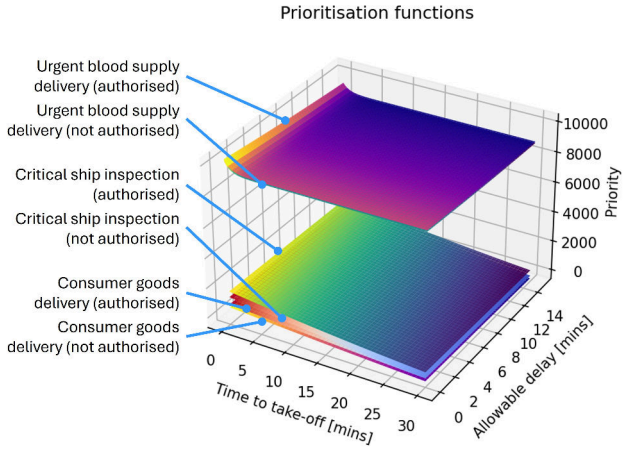


Fig. 10. Preliminary continuous prioritisation functions defined by stakeholders using the bespoke symbolic regression tool.

E. Expert-defined priority functions

Three mission types were selected to explore simple priority computation techniques, namely: a grounded UAS consumer goods delivery (B1), a grounded critical ship berthing inspection (C1), and a grounded urgent blood supply delivery (E1). Stakeholders first defined simple rules to map mission context to generic metrics. For delivery missions, the maximum allowable delay was defined as the remaining payload lifetime minus the expected takeoff time and worst-case mission execution time. For inspection missions, the maximum allowable delay was calculated as the remaining time until another ship required berthing minus the worst-case execution time.

Simple rule-based piecewise functions were first defined by stakeholders as a simple baseline for priority calculations. The bespoke tool depicted in Fig. 9 was then used to refine continuous prioritisation functions for each use case. The resulting functions are depicted in Fig. 10, confirming that urgent blood deliveries (E1) consistently held the highest priority, while the other two use cases exhibited dynamic priority relationships depending on operational context. While this approach offered valuable insights into stakeholder expectations, it is inherently limited in scalability, as manually defining multivariate prioritisation functions becomes increasingly impractical with the introduction of more mission types and parameters.

F. Supervised learning for prioritisation

A dataset of 200 expert pairwise comparisons was collected for the same three grounded use cases (B1, C1, E1), with randomly assigned times to take off (from 0 to 30 minutes) and allowable delays (from 0 to 15 minutes). Each conflicting mission request could also be booked or pending authorisation, and all four input parameters were randomly and uniformly distributed, as exemplified in Fig. 11.

A neural network was trained using the Siamese learning network described in Section III, featuring one hidden layer with 16 neurons, ReLU activation functions, and normalised input parameters. The model was trained on 70% of the collected data, with the remaining 30% reserved for testing. The accuracy of the model on this testing dataset is shown in Fig. 12 across increasing training epochs, where accuracy is defined as the percentage of relative rankings made by the algorithm that match expert decisions. Notably, the neural network outperformed expert-defined continuous and piecewise functions, random priority assignment, and a simple static prioritisation scheme that solely depends on the mission type.

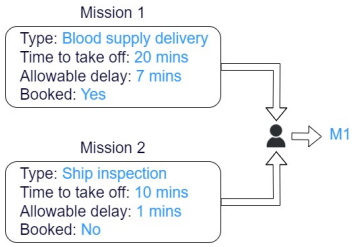


Fig. 11. Example of a pairwise expert decision on mission prioritisation.

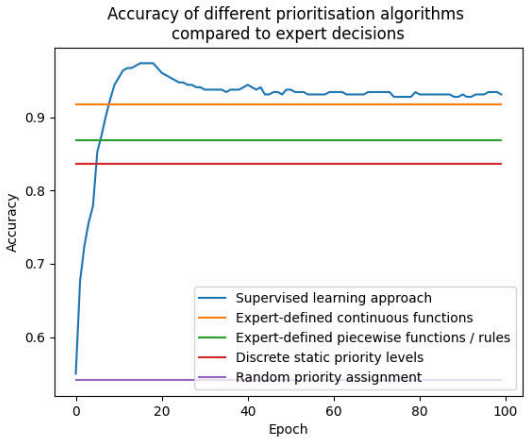


Fig. 12. Comparison of the accuracy of different priority computation techniques for simple use cases, when compared to expert decisions.

G. Discussion

Stakeholder feedback confirmed the diversity and time-sensitive nature of UAS missions, reinforcing the need for dynamic, non-binary prioritisation in UTM. Simulations of a federated UTM ecosystem further demonstrated that priority-based resource allocation is a viable approach to improving system-wide success rates of high-priority missions, even when different stakeholders follow independent decision-making processes. Additionally, a set of standardised prioritisation metrics was identified as a baseline for future prioritisation frameworks, promoting transparency and standardisation. While refining prioritisation algorithms was not the focus of this study, several preliminary computational techniques were successfully explored as a baseline for further research.

A custom symbolic regression tool successfully enabled stakeholders to define continuous prioritisation functions, which outperformed random assignment, static type-based priorities, and piecewise (rule-based) prioritisation functions, as demonstrated in Fig. 12. This highlights the need for dynamically adjusting priority levels rather than relying on fixed, category-based prioritisation models. Furthermore, the trained neural network achieved even higher accuracy, confirming that data-driven models are more effective at learning expert prioritisation decisions than expert-defined rules or functions. This trend is expected to become even more pronounced in more complex scenarios, where defining appropriate multivariate functions becomes increasingly challenging and impractical. However, learning-based methods would also require larger datasets of expert preferences and decisions. Future research should thereby focus on expanding expert datasets, exploring advanced data-driven techniques, and integrating LLMs for direct context-to-priority mapping.

This study does not explore how priority levels should be communicated among stakeholders, which remains an open topic for future research. In airspace managed by a USP, SDSP, GM, or ANSP, priority levels could be periodically communicated by operators, transmitted by the operator upon request from the airspace manager, or shared directly through an encrypted priority function spline. Conversely, in uncontrolled airspace with mandated e-conspicuity and no SPs, mission priority levels could be broadcast as part of the e-conspicuity signal. The specific method of priority dissemination, however, depends on the regulatory and technical framework in place. Moreover, this work proposes that higher priority missions should incur less operational delays and disturbances, but does not define specific right-of-way procedures.

V. Conclusion

A. Summary

This study proposed a dynamic, non-binary prioritisation scheme for UTM, designed to accommodate crewed, uncrewed, and military missions while addressing the increasing diversity and time-sensitive nature of aerial operations. The findings demonstrate that priority-based resource allocation, for both strategic and tactical conflict resolution, significantly improves success rates for higher-priority missions in a federated UTM ecosystem. To ensure alignment with operational and regulatory expectations, focus groups with key UTM stakeholders were conducted, providing valuable insights into prioritisation requirements and expectations. Preliminary expert-defined prioritisation functions were also derived using a bespoke symbolic regression tool, outperforming simpler static and rule-based approaches. Furthermore, a Siamese neural network trained on expert pairwise comparisons demonstrated superior performance compared to expert-defined functions, reinforcing the potential of data-driven approaches for UTM priority computation.

B. Future work

Future research will focus on expanding stakeholder datasets and developing more advanced computational models tailored to realistic operating scenarios with a broader range of mission characteristics and constraints. Specifically, LLMs will be explored to map mission context to standardised metrics or directly to priority levels. Priority-based allocation algorithms will also be refined, examining how optimisation and deconfliction strategies can adapt to dynamic mission priorities. New priority-related metrics may also be introduced, including the certainty of executing an authorised flight plan according to its underlying priority.

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