MULTIVARIABLE SIMULATION-BASED CAPACITY ESTIMATION FOR DECENTRALISED AIR TRAFFIC CONTROL. A CASE STUDY ON FUTURE NORTH ATLANTIC OPERATIONS

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Abstract

The transition from current centralised to future decentralised airspace concepts offers potential to increase airspace capacity. This is particularly relevant for intercontinental airspaces, such as the North Atlantic, with limited terrestrial infrastructure restricting the centralised coordination. Decentralised airspace concepts are defined by a partial transfer of the separation assurance responsibilities from a central unit to the flight deck. The capacity of centralised airspace concepts is mainly estimated based on the controller workload. Due to the transfer of the separation assurance responsibilities it is no longer possible to estimate the capacity and assess the benefits based on this parameter for decentralised airspace concepts. In order to evaluate the potential capacity benefits of decentralised concepts, new metrics are required. This paper addresses this problem in two stages. First, a simulation-based concept named Multivariable Simulation-based Capacity Estimation for Decentralised Air Traffic Control (MuSCEDA) to provide capacity estimates independent of the controller workload is described and second, an advanced Airborne Separation Assurance Systems (ASAS) algorithm to further increase airspace capacity is implemented. Both are evaluated for a simplified North Atlantic subspace in a fast-time simulation. The framework estimates the capacity by defining critical thresholds across three key categories: Safety (Intrusion Prevention Rate, Intrusion Severity), Complexity (Domino Effect Parameter) and Efficiency (Delay, Additional Fuel Consumption). Unlike conventional separation assurance algorithms, the advanced algorithm features an assigned control logic tailored to the characteristics of NAT traffic, where aircraft mostly operate in cruise-flight close to their maximum Mach number and maximum operating altitude. The simulation results demonstrate that with the framework and a conventional separation algorithm the capacity can be estimated. However, some capacity limitations remained with regard to the conventional algorithm. The advanced algorithm, especially the implemented control logic, improved the results by preventing more separation infringements and increased efficiency. With the proposed concept it is possible to make robust, simulation-based assessments regarding airspace capacity for decentralised airspace concepts. Based on these results, a full-scale simulation study should be carried out under realistic operating conditions.

Keywords

Air Traffic Management; North Atlantic; Fast-Time Simulation; Capacity Estimation

NOMENCLATURE

Abbreviations

ASAS	Airborne Separation Assurance Systems
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CD	Conflict Detection
CNS	Communication, Navigation and Surveillance
CPA	Closest Point of Approach
CR	Conflict Resolution
CW	Controller Workload
DEP	Domino Effect Parameter
FRA	Free Route Airspace
FTS	Fast-Time Simulation
IPR	Intrusion Prevention Rate
MVP	Modified Voltage Potential
NAT	North Atlantic
OCA	Oceanic Control Areas
OTS	Organized Track System
RTS	Real-Time Simulation

1. INTRODUCTION

1.1. Air Traffic Control Concepts

Airspace capacity is a central metric of the performance of an Air Traffic Management (ATM) system. It describes how many aircraft can be safely managed within a given airspace and time interval [1–3]. In conventional Air Traffic Control (ATC), capacity is closely related to controller workload and depends on factors such as traffic volume, traffic complexity, aircraft mix and the number of climb and descent manoeuvres. For new airspace concepts, the capacity is therefore often determined through Real-Time Simulation (RTS) with Air Traffic Controllers (ATCo)s [4].

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The capacity also affects the flexibility available to airspace users. A higher capacity can allow aircraft to use more direct and efficient trajectories and provides more room for adjustments to react to disruptive events such as weather hazards. The concept of Free Route Airspace (FRA) is one approach to increase airspace flexibility: Instead of following predefined routes, aircraft can select trajectories between defined entry and exit points. The implementation of FRA in European upper airspace, for example, contributed to a reduction of the average difference between flown trajectories and the great circle distances by 2 % between 2007 and 2024 [5].
A further approach is to combine FRA with a partial delegation of separation assurance to the flight deck. In such a decentralised ATM concept, aircraft would be responsible for separation assurance to aircraft in their vicinity, while centralised ATC would retain responsibility for the wider traffic flow and coordination. This approach can reduce the need for continuous coordination between a centralised controller and all aircraft in an airspace. It is therefore of particular interest for airspace where Communication, Navigation and Surveillance (CNS) capabilities limit the applicability of conventional ATC.

1.2. Capacity Estimation Problem

The North Atlantic (NAT) airspace is one example of such airspace. The limited availability of ground-based communication and surveillance infrastructure has led to the use of a procedural ATM system. Aircraft operate along predefined tracks and are subject to relatively large separation requirements. On the one hand, this provides a high level of safety with limited infrastructure, but on the other hand it also restricts the flexibility. In this particular case, a decentralised ATM concept could increase airspace capacity and therefore provide operational benefits such as an increase in efficiency.
Assessing the capacity of such a decentralised airspace concept requires a different approach than the conventional capacity assessment based on the Controller Workload (CW). In conventional ATC, CW is closely linked to the number of aircraft and complexity of the airspace that can be managed within an airspace. When separation assurance is partly delegated to the flight deck, the CW no longer serves as a sufficient capacity limiting indicator.
A capacity assessment for decentralised airspace therefore requires a new concept. Such a concept needs to provide a basis for determining the maximum traffic demand that can be accommodated while maintaining the defined operational requirements.

1.3. Paper Contribution and Structure

This study addresses this gap and investigates how the airspace capacity can be determined simulation-based without relying on the CW as a limiting factor. To address this, first the NAT airspace is described followed by a description of potential metrics in Section 2. In Section 3.1 a new concept named Multivariable Simulation-based Capacity Estimation for Decentralised Air Traffic Control (MuSCEDA) is introduced and discussed. The simulation environment used to verify the concept is described in Section 3.2, which includes an extended separation algorithm used in the simulation study. The overall simulation study design is then presented in Section 4. Results and discussion are provided in Section 5, followed by the limitations and conclusions of the study.



FIG 1. North Atlantic airspace (purple dashed line) and the six Oceanic Control Areas [6].

2. BACKGROUND

In this section the NAT airspace and its ATM system will be presented and discussed, followed by a selection of metrics to be used for the capacity estimation concept.

2.1. North Atlantic Airspace

The North Atlantic (NAT) airspace is the most heavily used oceanic airspace worldwide. It is structured into six Oceanic Control Areas (OCA)s, as shown in Figure 1. More than 500,000 flights operate in this region per year, with an estimated annual traffic growth of approximately 3 % [7]. Traffic is dominated by two directional demands: westbound and eastbound. These traffic demands are driven by factors including time zone differences, passenger demand and meteorological conditions such as the jet stream [8]. The strength and location of the jet stream can vary significantly over the year and between days, which affects the oceanic operations.
In contrast to continental airspace, ATM in the NAT is constrained by limited CNS capabilities. No ground-based surveillance infrastructure is available over large parts of the oceanic region. That is why the navigation and ATM in NAT is carried out on a procedural basis to maintain the required level of safety. To do so, the Organized Track System (OTS) is used [6]. It consists of a set of predefined tracks that support separation and routing across the NAT. Within the OTS, longitudinal separation is applied time-based while lateral separation is applied distance-based.
While the OTS ensures safe operations, it introduces constraints on routing flexibility in the NAT. Aircraft are often unable to operate at optimal flight trajectories. Since aircraft mass decreases over time due to fuel consumption, the optimal flight level changes continuously and a continuous cruise climb would generally be favourable for fuel efficiency. In addition, lateral trajectory optimisation, such as wind optimal routing, is often restricted. Both limitations mainly arise from the high separation minima and the fixed structure of the track system. As a result, operational efficiency is reduced and fuel consumption increases, motivating the need for alternative ATM concepts in the NAT in the context of increasing traffic demand.

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With the growing Low Earth Orbit (LEO) satellite constellations, space-based ADS-B became operational in the NAT airspace, which improved the communication and surveillance capabilities [9]. This is a key driver for lowering the separation standards in the NAT airspace, which can enable new ATM concepts such as decentralised airspaces.

2.2. Metrics for Capacity Estimation

Assessing the capacity of decentralised airspace concepts requires the consideration of new metrics besides the controller workload, as this metric is no longer applicable. The idea and impact of decentralised ATC has been investigated by several studies in the past, ranging from efficiency analysis [10, 11] up to stability studies [12, 13]. In [14], a simulation-based approach was employed to determine the effects of different airspace structures on the capacity. However, a combined simulation- and concept-based comparative analysis to determine a holistic capacity has not yet taken place. In this section a selection of metrics for the capacity estimation of decentralised airspace concepts are introduced and discussed. The metrics are grouped by the following three categories: safety, complexity and efficiency. The three categories reflect the legal requirements of ATC to ensure the safe, orderly and smooth flow of air traffic as laid down by, inter alia, the German Aviation Act (Luftverkehrsgesetz) in accordance with ICAO Annex 11 [15]. The adherence to legal requirements is essential for the possibility of integration into the air transportation sector.

2.2.1. Safety

For the definition of the safety parameters the differentiation between a conflict and an intrusion is essential.
In Figure 2 the difference is illustrated in the horizontal plane. A conflict is a predicted intrusion while an intrusion is the current violation of minimum separation distances. An unsolved or unsuccessfully solved conflict will always result in an intrusion.

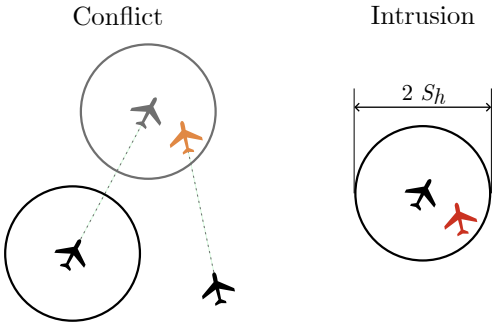


FIG 2. Conflict vs. Intrusion (based on [16]).

The occurrence and characteristic of intrusions are the significant parameters to quantify the safety of an airspace. Within the NAT, in-depth terrain related safety considerations are not necessary and will therefore not be explicitly considered as part of the safety parameters. The first metric is denoted Intrusion Prevention Rate (IPR) which quantifies how many conflicts were solved successfully without resulting in an intrusion [14]:

$$\text{IPR} = \frac{n_{cfl} - n_{int}}{n_{cfl}} \tag{1}$$

The best case is an IPR of 100 %, meaning all conflicts were solved successfully. If $n_{cfl} = 0$ the IPR is categorically set to 100 %, because no intrusions need to be prevented. However, if IPR $< 100\,\%$ it becomes necessary to provide further information on the characteristics of the intrusion. This can be achieved by including the Intrusion Severity (I_{sev}) as the second safety parameter [14]:

$$\text{I}_{\text{sev}} = \max_{t_0 \le t \le t_1} \left[\min \left(\hat{I}_h(t), \hat{I}_v(t) \right) \right] \tag{2}$$

The intrusion severity outputs the maximum of the less severe (minimum) vertical and horizontal relative penetration severity of the protection zone defined by the separation minima over the entire intrusion time frame from t_0 to t_1. An I_{sev} of 0 % implies, that the minimal distance was exactly the same as the minimum separation requirement while an I_{sev} of 100 % implies that both aircraft were at the exact same position with no separation. The horizontal and vertical intrusion severity are constructed in an analogous manner:

$$\hat{I}_{h/v}(t) = 1 - \frac{d_{h/v}(t)}{S_{h/v}} \tag{3}$$

Where the current horizontal/vertical distance $d_{h/v}(t)$ is compared to the respective minimum separation $S_{h/v}$. This concludes the introduction of the safety parameters.

2.2.2. Complexity

In addition to the safe flow of air traffic, the requirement of orderliness must be ensured. In [16], the Domino Effect Parameter (DEP) is introduced as the central part of the Capacity Assessment Method for Decentralised Air Traffic Control (CAMDA). The DEP quantifies how conflicts propagate throughout the airspace due to conflict resolution manoeuvres. It does so by comparing the number of conflicts without resolution manoeuvres to the number of conflicts with resolution manoeuvres to express the stability of the airspace and thus provides information on the orderliness of the air traffic [16]:

$$\text{DEP} = \frac{C_{total,wr} - C_{total,nr}}{C_{total,nr}} = \frac{C_{total,wr}}{C_{total,nr}} - 1 \tag{4}$$

The DEP in CAMDA is a function of the traffic density ρ (traffic volume per airspace volume). The DEP provides the following information on the (de)stabilizing effect of the conflict resolution:

- DEP $< 0 \Leftrightarrow$ stabilizing effect
- DEP $= 0 \Leftrightarrow$ no effect
- DEP $> 0 \Leftrightarrow$ destabilizing effect

2.2.3. Efficiency

The efficiency will be modelled based on relative differential time and fuel consumption of the air traffic. For both cases, the comparison is made between the case without conflict resolution (the ideal case) and the case with conflict resolution. It is therefore assumed, that the no resolution case indeed represents an optimised trajectory

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from the respective point of initialization to the destination. The additional time cost is denoted as:

$$\text{Delay} = \frac{T_{wr}}{T_{nr}} - 1 \tag{5}$$

while the additional fuel consumption is denoted as:

$$\Delta\text{FC} = \frac{FC_{wr}}{FC_{nr}} - 1 \tag{6}$$

Because different conflict resolution manoeuvres may affect these metrics in different ways, both must be taken into consideration. Aircraft may generally change their trajectory and speed to avoid intrusions. An exemplary decrease in speed would increase the Delay, but simultaneously may decrease the fuel consumption of the aircraft if it flies closer to its Maximum Range Cruise speed. This reduced fuel consumption could now lead to a negative ΔFC. A temporary speed increase may then have the opposite effect: A negative Delay and a positive ΔFC.

3. CONCEPT AND SIMULATION

In this section the MuSCEDA concept is introduced, followed by an introduction of the simulation environment developed for the verification. In this context the extended separation assurance algorithm will be outlined too.

3.1. The MuSCEDA concept

This section presents the MuSCEDA concept based on the Metrics introduced in section 2.2.

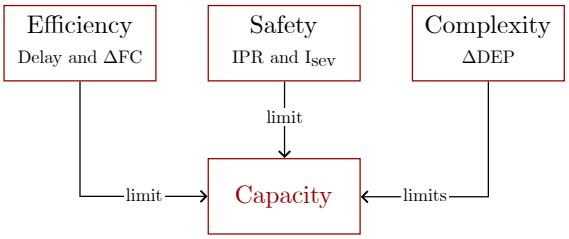


FIG 3. MuSCEDA Concept

The MuSCEDA concept - as shown in Figure 3 - employs metrics from the previously introduced categories of safety, complexity, and efficiency to quantify the capacity of decentralised airspaces. It does so by specifying capacity thresholds for each metric. The holistic capacity of the airspace is then limited by the first threshold reach with respect to the traffic volume of any of the five metrics. It is therefore essential to define thresholds for each metric to adequately estimate the capacity within the MuSCEDA concept. The thresholds are variable and dependent on the use case, ecological as well as legal requirements and stakeholder interests. The chosen limits for the conducted simulation are presented in subsection 4.2.

3.2. Simulation environment: BlueSky

For this study the BlueSky simulator is used, which is an open-source air traffic simulator [17]. It is organised in a modular architecture, including components for simulation control, traffic modelling, user interaction and tools for navigation and aircraft performance. The current version of BlueSky can be found here [18]. It supports Fast-Time Simulations (FTS)s of large traffic samples on standard computing hardware. These characteristics make it suitable for the present simulation study. For aircraft performance modelling the Base of Aircraft Data (BADA) 3 from Eurocontrol is applied during the simulation. Every aircraft is initialised with a mass of 65 % of its BADA reference mass to ensure realistic en-route performance characteristics. BlueSky originally offers a conflict resolution module based on the Modified Voltage Potential (MVP) algorithm. This module was extended for the simulation study and will be discussed in the following section.

3.2.1. Conflict Detection & Resolution (CD&R): Hybrid MVP

During the simulation the conflict detection is performed state-based. For conflict resolution BlueSky provides an MVP algorithm by default. It is a pairwise conflict resolution method based on the Eby concept [19, 20]. The objective is to compute the smallest avoidance vector needed to move the predicted Closest Point of Approach (CPA) back to the boundary of the protected zone.
First, the CPA is predicted from the current relative position and velocity. The position of the CPA is then checked against the protection zone separately for the horizontal and vertical components. If CPA is inside the protection zone an intrusion is predicted. Based on this intrusion, a minimum avoidance vector is computed. The length of the resulting avoidance vector provides insight into the intrusion severity [20]. MVP assumes that the other aircraft does not move, thus no negotiation is needed. For each aircraft, contributions from multiple conflict pairs are summed and transformed back into commanded track angle, ground speed, vertical speed and target altitude. As soon as the conflict is cleared (CPA is passed), MVP is deactivated and the control is returned to the flight management system. Generally, the module can be executed with different resolution domain settings: vertical and horizontal.
For this simulation study the MVP module has been extended by a control logic to better react to conflict characteristics emerging in NAT traffic. The NAT traffic is characterised by two main aspects: i) In the NAT airspace aircraft fly with relatively high cruising speeds. ii) The traffic picture is characterised by a bidirectional traffic demand, which generates mostly shallow and wide conflict encounter angles and usually no crossing conflicts. A simulation study was carried out to firstly define the main conflict classes appearing with flexible NAT operations and secondly to identify the most suitable resolution domain per conflict class. Each conflict pair is classified based on relative track angle, flight level separation and vertical convergence. In total, four different conflict geometric classes are defined, as shown in Table 1.

Class	Type	Geometry	Resolution
A	head-on	angle $> 150°$	vertical (lateral risks closure)
B	crossing tracks	angle 30–150°, similar FL	horizontal OR vertical
C	in-trail, same FL	angle $< 15°$, dalt < 1000 ft	speed (slow trailer) or escape via temporary FL change
D	converging climb	vertical speed > 0	vertical (delay/ accelerate climb)

TAB 1. Conflict geometry class and preferred Resolution domain based on pre-simulation study. Resolution domain depends on evaluation metrics. Main criterion is safety, followed by flight efficiency.

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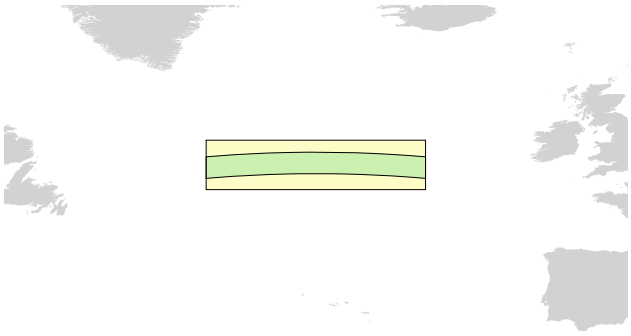
The implemented control logic creates a hybrid controller framework, referred to as hybrid MVP, which maps the conflict classes to the most appropriate control domain for each conflict. Generally, vertical manoeuvres are preferred, as they minimise lateral deviation and align with cruise operation constraints. The following conflict classes require additional treatment: The class D converging climb, where continuous vertical resolution may be insufficient to ensure separation and C in-trail, where vertical adjustments can lead to oscillatory behaviour, necessitate different treatments and fallback solutions. Based on the results the baseline domain remains vertical, but a selective heading fallback is introduced when vertical separation does not evolve sufficiently over time[1].

4. SIMULATION DESIGN

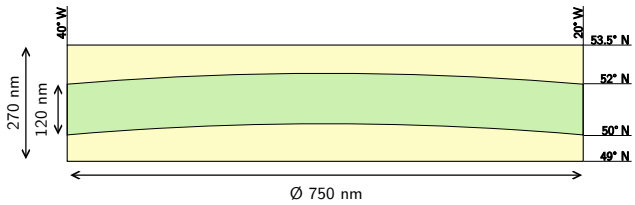
In this section the simulation design used to verify the MuSCEDA concept on a simplified NAT airspace is outlined. This includes the testing region and the independent and dependent variables. At the end a simulation matrix will summarise the simulation study setup.

4.1. Testing Region

The Testing Region is a subspace of the NAT. Figures 4a and 4b illustrate its location and horizontal dimensions respectively.



(a) Location



(b) Dimensions

FIG 4. Testing Region (visualisation with QGIS using earth data from the Natural Earth repository)

The green flight band represents the nominal area between the minimum and maximum starting and finishing latitudes spanned by its orthodromes. The width of this region is 120 nm. This represents the width necessary to accommodate two basic NAT tracks with 60 nm of lateral spacing and 30 nm half-spacing towards the nominal boundaries. The yellow area represents the Testing Region. Aircraft may fly within this region to perform necessary CR manoeuvres. Aircraft leaving this area will be discarded from the analysis. The number and implications of such "Exits" will be evaluated in section 5. The Testing Region has an average length (longitudinally) of 750 nm and a width (laterally) of 270 nm. The Testing Region is additionally limited in the vertical domain. Flights below 5000 ft will result in an Exit. The upper limit is dictated solely by the aircraft's performance capabilities.

[1] The criterion was time-based: The threshold time was set at two minutes.

4.2. Independent and Dependent Variables

In the following the independent as well as the resulting dependent global (g) and local (l) variables are summarised. The dependent variables are calculated based on the simulation log files, which are generated by a self-contained logging plug-in.

4.2.1. Independent Variables

The independent variables target, on one hand, the ASAS settings (horizontal, vertical, hybrid) and on the other hand the traffic demand. Traffic demand is varied by traffic volume and initial distribution (location).

Airborne Separation Assurance System settings

For this study, the built-in state-based CD was used. In order to evaluate the Hybrid MVP introduced in subsection 3.2.1 the identical scenarios were simulated three times using different settings of MVP CR domains:

1) Default MVP - Horizontal
2) Default MVP - Vertical
3) Hybrid MVP

In [21] the default horizontal MVP proved to be the most efficient. Based on this knowledge only the exclusive horizontal and vertical default MVP methods were employed in this study.

Traffic Volume and Distribution

For this study, the following independent variables are varied: traffic volume and traffic distribution. Firstly, the selection of the traffic volumes is based on the busiest week of European-North American air traffic in 2025 from the 23rd to 29th of June [22]. During this week, an average of 1,749 daily aircraft movements took place within the NAT. Since this study only considers the traffic flow in the eastbound direction, the stated traffic volume is halved and divided by the duration (core hours) of the eastbound night OTS (0100–0800 UTC). The resulting reference traffic volume is rounded to 120 aircraft per hour. Based on this reference 15 scenarios are generated with traffic volumes starting from 12 (10 %) aircraft per hour up to 180 (150 %) with an increment of 12 (10 %). Note that the reference value represents the entire dimensions of the NAT OTS and not only a subspace of it. The relative traffic density within the Testing Region is therefore an overestimate, as it accommodates the reference NAT traffic volume inside a smaller airspace. The scenarios initialise aircraft over a duration of two hours. Secondly, the traffic distribution (initialisation) is randomly varied ten times for each traffic scenario with respect to the following constraints:

- Time (between 0:00:00 hours and 2:00:00 hours)
- Altitude (FL300 to FL360) – this further increases density in comparison to the reference value

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- Initial Location along the 40° W meridian (50° N to 52° N)
- Destination along the 20° W meridian (50° N to 52° N)
- Aircraft Type (A339, A346, A359, A388, B763, B773, B789) – every aircraft type has an associated Mach number for this study, hence the Airspeed selection is part of the aircraft type selection

4.2.2. Dependent Variables and Thresholds

Based on the logged parameters, all dependent variables of the MuSCEDA concept can be calculated. For later analysis, thresholds have to be defined to determine the capacity of each variable/metric. The derivation of these thresholds is as follows:
Starting with the safety metrics, the IPR capacity limit will be categorically set to 100 %. A lower threshold necessitates thorough safety considerations which are not part of this study. The I_{sev} threshold however is set to 5 % to account for edge cases in the FTS regarding the minimum separation distances and safety margins. Consequently, an IPR < 100 % is acceptable as long as $I_{sev} < 5\,\%$.
For the DEP, which acts as the sole complexity metric, "CAMDA defines the maximum theoretical capacity of the airspace as the traffic density [ρ] at which the rate of change of the DEP with density approaches infinity" [16]:

$$\lim_{\rho \to \rho_{max}} \frac{dDEP(\rho)}{d\rho} = \infty, \text{ where } \rho_{max} \equiv \text{capacity} \tag{7}$$

This capacity threshold will not be adopted however, as its theoretical nature is not readily implementable in a purely simulation-based capacity estimation. Instead, the DEP threshold is defined as:

$$\delta \equiv \frac{\Delta \text{DEP}}{\Delta \rho} \geq 100\,\% \tag{8}$$

if $\delta \geq 100\,\%$ the relative increase in the DEP surpasses the relative increase in traffic density (volume), which is equivalent to progressive growth.
The determination of appropriate thresholds for the efficiency metrics, Delay and Additional Fuel Consumption, depends on ecological considerations, the interest of stakeholders, and the consideration of what is achievable in realistic operations. In this study, the Delay threshold is set to 1.5 % and the Additional Fuel Consumption threshold to 2 %. The derivation of these thresholds is done in accordance with relevant studies on the NAT [23, 24] and explained in more detail in [21]. Table 2 summarises the dependent variables and their thresholds.

4.3. Simulation Matrix

In total every traffic demand scenario (traffic volume) is simulated four times, three simulations for the varying CR algorithms/domains and one reference simulation with CR disabled.

Variable	Levels	Number
Traffic volume	10–150 %, 10 % increments	15
Aircraft number	12–180, 12-aircraft increments	–
Traffic distribution	Randomised	10
ASAS configuration	No resolution, horizontal, vertical, hybrid	4
	Total simulations: $15 \times 10 \times 4 = 600$	

TAB 3. Variables and levels of the simulation experiment.

Additionally each of these simulations is repeated ten times with a varying initial traffic distribution (realisation). The Table 3 summarises the full simulation matrix of the study. In total 600 simulation runs are conducted.

5. RESULTS

In this section the results will be described according to each metric category (safety, complexity and efficiency).
The simulation results represented by the metrics are shown in Figure 5. The first column represents the safety domain, the second column the complexity domain and the third column the efficiency domain. The complexity domain includes the DEP as the metric itself as well as the relative change in the DEP with respect to the increase in traffic volume δ as the threshold indicator. The x-axis always displays the traffic volume as the actual hourly rate of aircraft, meaning that any Exits have been removed from the initial traffic volume. The data points are plotted along the LOWESS regression as a line and the 95 % confidence interval as a semi-opaque coloured band. The CR domain is indicated as follows:

1) Blue: Default MVP – Horizontal
2) Orange: Default MVP – Vertical
3) Green: Hybrid MVP

For the relative change in the DEP the view limits of the vertical axis are set manually to the interval $[-200, 500]$ resulting in 139 results not being shown. All results are part of the regression computation regardless of the mentioned view limits. The number and content of the simulated flight plans is identical for every resolution domain apart from the CR setting.

5.1. Safety

Starting with the IPR, both the horizontal and hybrid CR perform better than the vertical CR at lower traffic volume. At traffic volume above 80, the IPR of the vertical CR appears to perform slightly better than the hybrid CR which in turn performs better than the horizontal CR. Potential interferences to the results, especially concerning the vertical resolution domain will be discussed in section 6. Note that the data points and regression of the vertical CR never reach the maximum traffic volume. This implies, that the vertical CR was not able to process high traffic volumes without a considerable amount of Exits.
For the I_{sev}, the horizontal CR has a distinctly improved performance compared to the hybrid and vertical CR. With the vertical CR performing worst throughout, the apparent flattening of the vertical CR I_{sev} curve will also be part of the discussion. The I_{sev} for the horizontal CR may be described by a linear relationship within the analysed traffic volume. The LOWESS regression of the horizontal CR stays below the threshold throughout the simulated traffic volumes. Regarding the hybrid CR, the LOWESS regression underestimates the I_{sev} at lower traffic volumes as it depicts a negative result. Subsequently, a growth of a higher than linear order is derivable in the first half of the traffic volumes. In the second half, a more linear trend is visible. The maximum I_{sev} for the hybrid CR is located at the highest traffic volume of 180 with approximately 60 %.

5.2. Complexity

Starting with the DEP, the hybrid CR performs best throughout all traffic volumes. The horizontal and vertical

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	Safety				Complexity	Efficiency	
	C_{total}	I_{total}	IPR	I_{sev}	DEP	Delay	ΔFC
Threshold	-	-	100 %	5 %	$\delta = 100\,\%$	1.5 %	2 %

TAB 2. Dependent variables and thresholds for the simulation study.

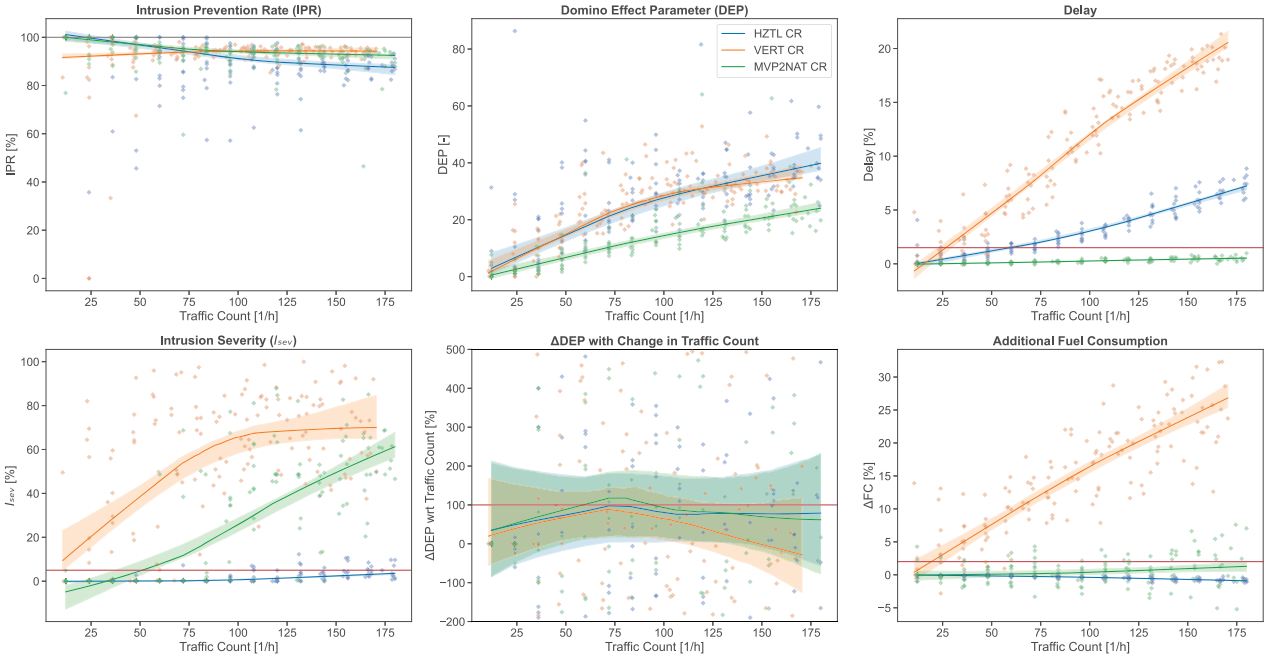


FIG 5. Simulation Results grouped in columns by category: Safety, Complexity, Efficiency from left to right. Traffic volume of 120 equals 100 % reference traffic volume.

CR perform similarly and an indentation of the vertical domain is visible again.
The analysis of the change of the DEP with respect to the traffic volume δ would result in the hybrid CR being the only domain, which reaches its DEP and thereby complexity threshold. Overall, δ increases in a first segment and tends to decrease in a second segment regardless of the CR domain. A more in-depth discussion of the complexity results can be found in section 6. The 95 % confidence interval also indicates a substantial spread of data points which could be seen as a reason to further constrain the validity of the threshold in its current mode of calculation.

5.3. Efficiency

The efficiency metrics provide the most cohesive spread of data. As mentioned in the introduction of the efficiency metrics, CR manoeuvres may affect the time and fuel domains differently. In view of the results, this asynchronous effect is most notable for the horizontal CR domain. Since heading changes deviating from the optimal trajectory must deteriorate both the time and fuel domains, the negative trend of the ΔFC must lie in the speed domain of the horizontal CR: Aircraft are slowed down closer to their most fuel efficient speed and thus burn less fuel over the course of their flight. This results in the minimal ΔFC at the highest traffic volume: ca. -1 %. Regarding the Delay, the speed decreases of the horizontal domain result in increased flight times. The Delay at the highest Traffic Volume is approximately 7 % for the horizontal CR. The vertical CR performs analogous in both metrics and worst overall. With an approximatively positive linear trend, the largest traffic volume results in a Delay of around 21 % and an Additional Fuel Consumption of around 27 %. The higher increase in the ΔFC may be a result of vertical manoeuvres, which entail a greater energy demand on the aircraft. Aircraft were observed to perform considerable climbing manoeuvres through more than one flight level, which further increases the fuel burn. The high Delay of the vertical CR is a result of the aircraft's decreased velocity and heading lock as part of their conflict resolution measures. As long as the ASAS is active, the aircraft follows a constant heading until the conflict is solved. As a result horizontal deviations compared to the planned flight trajectory occur, increasing the Delay. This is aggravated further by the fact that the vertical conflicts remain unsolved for a longer period of time compared to both the horizontal and hybrid CR as the vertical manoeuvres of the vertical CR algorithm proved to be less efficient. The return towards the destination is postponed accordingly until ASAS is deactivated.
The hybrid CR also performs similarly in both metrics and yields the best overall result as it is the only CR domain, which manages to stay below both thresholds throughout all traffic volumes. The Delay, following an approximately linear trend, has a maximum of ca. 0.5 %. The ΔFC has a lower gradient in the lower half of the traffic volumes which increases in the second half and terminates at the highest traffic volume at around 1 %. The efficiency metrics are increasingly detached from the handling of the Exit conditions. Thus, the indentation of the vertical CR domain ceases to appear.

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5.4. Additional

In addition to the metrics discussed above, the total number of Exits, conflicts and intrusions were logged and are depicted in Figure 6. These three metrics were averaged over the ten traffic realisations and summed over the 15 traffic demands.

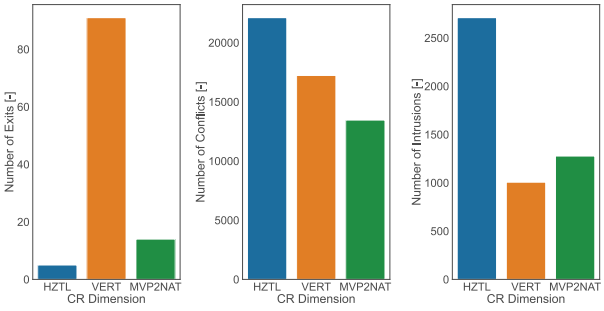


FIG 6. Averaged total Number of Exits, Conflicts and Intrusions per CR Domain. For each of the 10 initial distributions per traffic volume the numbers of Exits, Conflicts and Intrusions are averaged. The average numbers are then summed to the total Numbers.

The exact values are rounded to the nearest integer and shown in Table 4 alongside the averaged Exit Rate over all traffic realisation and demands. This provides insights into the absolute performance of the CR domains.

CR Domain	Exits	Exit Rate [%]	Conflicts	Intrusions
Horizontal	5	0.4	22,114	2,710
Vertical	91	8.6	17,230	1,006
Hybrid	14	1.1	13,460	1,277

TAB 4. Averaged total Number of Exits, Conflicts, Intrusions and average Exit Rate per CR Domain.

For a more extensive understanding of the Exit Rate progression over the traffic volumes, Figure 7 illustrates the Exit Rate in the same format as in Figure 5 displaying the data points, LOWESS regression and confidence interval.

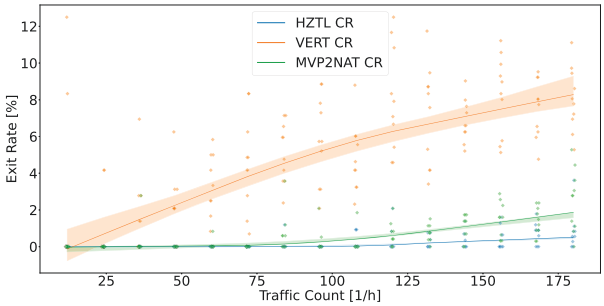


FIG 7. Exit Rates per ASAS domain setting over traffic volume [1/h]

The vertical CR results in significantly more Exits compared to the other CR domains. The hybrid CR results in the least amount of conflicts. The horizontal CR results in more conflicts as well as intrusions compared to the vertical and hybrid CR. The amount of intrusions of the horizontal CR is more than double compared to the hybrid CR, these intrusions however are - in their peaks - less severe as shown in Figure 5.

Regarding the overall capacity of the various CR domains, the results - rounded to the nearest integer - are provided in Table 5.

CR Domain	Capacity	Capacity (%)	Limiting Metric
Horizontal	59	49	Delay
Vertical	12	10	I_{sev}
Hybrid	51	43	I_{sev}

TAB 5. Absolute and relative capacity of study by CR Domain and limiting metric.

Due to the vertical CR's initial overshoot of the I_{sev} threshold, the capacity is constrained at the lowest traffic volume. The horizontal CR results in a relative capacity of 49 % which is limited by the specified Delay threshold. The hybrid CR delivers a relative capacity of 43 % limited by the I_{sev}.

6. DISCUSSION

The results demonstrated that the MuSCEDA concept is able to determine the capacity of a decentralised airspace by comparing the thresholds of every metric and defining the lowest traffic volume at which one of the metrics thresholds is reached as the overall airspace capacity. In the context of ongoing research regarding decentralised ATM, MuSCEDA provides an initial framework for quickly assessing their impact on capacity.
Based on the conducted simulation, the performance of the employed ASAS significantly affects the resulting capacity. While the horizontal and hybrid CR algorithms deliver capacities of comparable magnitude (40-50 %), the vertical CR performs worse and thereby results in a lower capacity (10 %). In this context, it is important to restate that the traffic density was overestimated in the simulation. This overestimation results from the fact that the reference values were based on the busiest week in NAT and applied to a Testing Region with smaller horizontal and vertical dimensions compared to the NAT airspace. If the following two aspects were taken into account: i) two NAT-OTS routes fit within the nominal area of the Testing Region and ii) 6–7 OTS tracks are typically published, the estimated decentralised capacity would exceed those of the reference. The introduced MuSCEDA concept, as a simulation-based empirical method, benefits from robust data. The calculation of δ was performed directly on the values of the DEP. In this study, a large data spread of δ was the result. The calculation of δ based on the values of the LOWESS regression could increase the informative value and validity of δ as a relevant threshold. Regarding the indentations of the vertical CR, visible most notably for the metric I_{sev}, the cause is suspected to lie within the handling and processing of Exits. Aircraft leaving the Testing Region are removed from the entire analyses process. This entails the removal of such aircraft from all metrics. For the vertical CR, at a traffic volume of 132, around 9 aircraft exit the Testing Region on average and are consequently deleted. The average number of Exits further increases up to 14 at a traffic volume of 180. This could significantly affect the number of resulting conflicts and intrusions which directly impact the DEP and may have an impact on the I_{sev}. Furthermore, in the vertical CR domain, aircraft were observed to descend lower as needed for resolution. The analysis pointed to some systematic issues in the level allocation when calculating the resolution vector. Since this results in aircraft

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staying well outside the Testing Region (i.e. area of interaction between aircraft), the metrics may be distorted.
This study focused on the technical verification and initial validity of the MuSCEDA concept. In further testing, the implementation of various wind and weather conditions as well as operationally viable flight plans will provide a more comprehensive basis for evaluation in the respective conditions. Additionally, the metric's thresholds play a crucial role for determining the airspace capacity. Future work could conduct a sensitivity study for the metric's thresholds.

7. CONCLUSION

This study presented a simulation-based concept for estimating the capacity of airspace under decentralised ATM. Conventional controller workload measures are not applicable when separation management is delegated to the flight deck. The proposed concept (MuSCEDA) therefore combines metrics for safety, complexity, and efficiency. Capacity can be determined by applying predefined thresholds to the individual metrics.
The concept was verified using a simplified NAT simulation setup. The results indicate that the proposed approach can be used to assess the capacity of decentralised operations. In this context, they further indicated that the capacity was mainly driven by the performance of the applied ASAS algorithm.
Future work should examine the ASAS algorithm in greater depth and identify its main limitations. The simulation study should also be extended to the full NAT airspace and multiple traffic days. The proposed concept provides a basis for such analyses and for the capacity assessment of decentralised airspace operations.

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