

Defining airspace quality

A new metric for defining air traffic situation quality in a defined airspace based on geometric traffic properties

by

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Acronyms

AC aircraft.

ADS-B automatic dependent surveillance - broadcast.

ASAS airborne separation assurance system.

ASQ airspace quality.

ATC air traffic control.

ATCo air traffic controller.

ATM air traffic management.

CAS calibrated air speed.

CD conflict detection.

CD&R conflict detection and resolution.

CFMU central flow management unit.

CPA closest point of approach.

CR conflict resolution.

dCPA distance between aircraft at CPA.

DD dynamic density.

IAS indicated air speed.

LoS loss of separation.

MAP monitor alert parameter.

MUAC Maastricht upper area control.

RNAV random navigation or area navigation.

RVSM reduces vertical separation minima.

SD static density.

SEP minimum separation distance.

SQL structured query language.

SSR secondary surveillance radar.

TAS true air speed.

TCAS traffic alert and collision avoidance system.

tCPA time to CPA.

UAV unmanned aerial vehicle.

VSM vertical separation minima.

WJHTC William J. Hughes Technical Center.

1

Introduction

The use of our airspace is rapidly increasing with an ever more varying mix of aircraft. From small drones to giant jumbo jets. Keeping these aircraft separated while allowing them to get to their destination efficiently is no small feat. Currently most commercial aircraft fly according to the structured route system. They follow a set of instructions given to them by the air traffic controller (ATCo). These ATCos will direct aircraft to fixed routes which makes traffic easy to control and separate from the perspective of the ATCo. Unfortunately, this also means that aircraft are not flying at their optimum efficiency as they are not flying a direct route at their optimal speed and altitude to their destination.

Technologies like secondary surveillance radar (SSR) mode-S and automatic dependent surveillance - broadcast (ADS-B) allowed airborne separation assurance system (ASAS) to be developed. These systems ensure separation and thus safety when air traffic management services cannot provide this. It is thus possible to safely deviate from the current principle where everything is controlled by the ATCo, at least under certain conditions. This is called random navigation or area navigation (RNAV), and allows pilots to determine their own route.

At one point in the future the current structured route system on its own will not be able to keep up with the capacity demands and RNAV will become more common. Due to this shift towards RNAV it is highly likely that the role of the ATCo will change significantly. The ATCo cannot maintain situation awareness with the current set of tools he has. On his 2D radar screen it will seem as a beehive of aircraft flying all over the place. Therefore depending on how exactly air traffic will evolve in the future it is very likely that the role of the ATCo will look totally different.

A result of assuming a different involvement of the ATCo and an increase in RNAV traffic means the design of the airspace itself will have an ever greater impact on airspace use and the way it is controlled. Therefore having the correct tools to analyze and compare traffic scenarios independent of the manner the air space is controlled is necessary.

Analyzing and comparing airspace structures currently involves simulating air traffic and is very time consuming. It can take up to weeks of simulation time to analyze a new airspace design. Each iteration on this design then again needs this extensive simulation to analyze and validate the design making the process slow and very lengthy. Imagine the time saved in this process if a method could be found able to quickly classifying the design of a certain airspace without a need for simulating traffic over long periods of time.

This research will focus on finding a metric based on the geometry of traffic patterns. The metric this project sees to develop, based on the geometric properties of traffic patterns, is closely related to the well-researched complexity metrics. However, while the complexity metrics define a metric for ATCo workload in different traffic scenarios, the envisioned metric will not approach this problem from the perspective of the ATCo. Instead, the new metric will be independent of the air traffic control (ATC) method and solely a result of air traffic properties.

Different metric concepts are proposed in chapter 4. In chapter 5 a validation method is shown to validate the metrics proposed. Promising metrics are then compared with the existing conflict rate, which does require simulation of the traffic over time. Relevant results are shown in chapter 6 and discussed in chapter 7.

2

Research context

This chapter introduces relevant concepts and some industry background in section 2.1. The chapter continues with section 2.2 where current complexity metrics are introduced and briefly touched upon.

2.1. Background: evolution of air traffic

Air traffic management (ATM) encompasses many different systems and services. These services can be divided in three main categories: air traffic flow management, air traffic service and airspace management[19]. Air traffic flow management is a central service planning air traffic according to availability of slots at airports, ATC capacity, congestion of airspace and other relevant factors. For the Netherlands this service is provided by the central flow management unit (CFMU) or central flow management unit of Eurocontrol. Air traffic services is a broad term, but it usually encompasses services like weather reporting, flight information service, alerting service and air traffic advisory service. The third category is airspace management, opening and closing airspace blocks or cells belong under this category. Blocks can also change function, they can for example switch between restricted military use or civil aviation use. The task of controlling these blocks usually falls to a national aviation authority for each country.

Changes in any of these three categories of ATM could have implications on many different systems across the different categories. It is a necessity to keep this in mind during a research project in ATM. Many research projects are ongoing in the ATM field, many fueled by the SESAR program and its US counterpart, NextGen. SESAR stands for single European sky ATM research. The program sets out ambitious goals to unify or normalize systems and services in Europe to improve efficiency and safety. The NextGen research project does the same in the United States, but with slightly different targets. This is due to differences in airspace use between Europe and the US, today and in recent history. The main differences being that general aviation is more common in the US, about five-fold in 2010[8]. In Europe, ATM services are not spread efficiently over the continent but rather follow country borders in most cases.

Use of air transportation has grown since the first plane took flight over a century ago and the industry is far from stagnating. The biggest increase in passenger air travel over the next 20 years is to be expected in Asia. The European and US markets should also expect an increase in passengers of 2.7% and 3.3% respectively every year[1]. This translates into an estimated global increase of 82% in number of commercial aircraft in service over the next 20 years[2]. Half of the increase is due to the growth in the Asia-Pacific region. But nonetheless, a significant rise in number of aircraft is also to be expected over Europe and the US. This growth rate is not sustainable with current ATM systems in place. ATCos will eventually not be able to handle the increase in traffic and the current structuring of airspace could cause congested areas over the busy European airspace.

The Metropolis[20] study deals with the future of air traffic and the ever more varying mix of aircraft that will exist. The advent of the unmanned aerial vehicle (UAV) and growing fleet of jumbo jets as supported by the annual global fleet forecast support these predictions. The study focuses on an ideal way of structuring the air space while operating at or near its capacity limits. This level of airspace use is not nearly the case right now and will probably never be the case in every airspace around the

world. So in essence the outcome of the Metropolis study is very specific and focused in the distant future. However, the Metropolis study makes similar assumptions about the evolution of air traffic as this research does. This shows the need to develop new methods to effectively operate air space in the future.

The use of our airspace is rapidly increasing. Keeping these many various aircraft separated is no small feat. Currently most commercial aircraft fly according to a structured route network[12]. This network is governed by ATCos who give a set of instructions to the pilots. These ATCos will direct aircraft to fixed routes, which gives the ATCo a good situational awareness and in turn makes traffic easy to control and separate. Unfortunately this also means that aircraft are not flying at their optimum efficiency, as they are not flying a direct route on their optimal speed and altitude to their destination. It also limits the capacity of an airspace to the amount of aircraft an ATCo can handle in a certain situation. There are many different factors influencing ATCo workload, some of them being, number of conflicts, number of hand offs, heading and speed differences, aircraft proximity to each other and sector boundary, presence of weather and number of aircraft[3][16]. Next to these factors the controller workload is a subjective attribute, for example, depending on how well an ATCo deals with stress and unpredicted situations could influence the ATCo to a lesser or larger extend.

A direct result of today's ATCo centered ATC system is that the operational capacity of an airspace is determined simply as the number of aircraft a controller is willing to accept in its sector. To estimate this sector capacity most traffic control centers use the monitor alert parameter (MAP), among them being Maastricht upper area control (MUAC) in the Netherlands. Unfortunately the way this MAP value is determined varies between operational centers and not always has a scientific basis[13]. The reason why this capacity limit still exists, while many supporting systems could lighten the workload and enlarge capacity, is that in case of a failure in the automated systems the workload should not exceed the limitations of the human controller[13].

New tools are continuously being developed and implemented to support the ATCo in their duties. Eventually automating a big part up to the complete task of the ATCo. This would result in a centralized automated ATC system, but this is not necessarily the case. There is also the trend to move ever more responsibility towards the cockpit. This is possible due to technologies like SSR mode-S and ADS-B resulting in ASAS like the traffic alert and collision avoidance system (TCAS). Bilmoria shows in his research the advantages of these novel automated systems[4], be those centralized or decentralized. Making the probability that ATM will evolve in this direction at least a decent possibility.

These ASAS ensure separation and thus safety when air traffic management services cannot provide this. It is thus possible to safely deviate from the current principle where everything is controlled by the ATCo, at least under certain conditions. The responsibility for separation thus shifts towards the cockpits. This new way of managing air traffic allows for a more flexible way of navigation called RNAV. In this case the pilots plan their own, often direct, route instead of following the structured route system. This way of navigation does not only allow for more efficient routes for aircraft, but also enlarges the capacity of the airspace. This capacity increase is due to the fact that the ATCo situational awareness is no longer the limiting factor [11].

Thus, in the future the responsibility of separating aircraft might shift from the ATCo to the cockpit[13]. This change in role of the ATCo and shift in responsibility will require new tools to analyze the use of air space. Most of the current tools are focused on or around the ATCo. Distributed ATC or heavily automated ATC will need to be evaluated before they are broadly put into use. Tools are thus needed to evaluate and classify air space and the use of them.

Overall there is a tendency to approach classification of air space or traffic situations from the perspective of the ATCo workload, as this is the current situation. Kopardekar stated that the ATCo workload is an effect of air traffic complexity[13]. This air traffic complexity is a much researched field to classify traffic situations. The next section will elaborate on the many different complexity metrics and why they are or are not suitable to the goal of this research project.

2.2. State of the art: current metrics

A frequently researched topic in the ATM field is air traffic complexity. It describes the complexity of a traffic situation from the perspective of the air traffic controller. Many different metrics have been developed over the years focusing on the ability of the air traffic controller to separate the traffic. With air traffic evolution in mind there's a high probability that ATC methods will shift to self-separation and

more RNAV will take place. This will significantly change the role of the air traffic controller. This results in a need for a metric similar to the existing air traffic complexity metrics, but instead focusing on the geometrics properties of the air traffic and thus cutting out the air traffic controller. This new metric will in effect look at the inherent features of the air traffic itself and not result in a complexity level for an ATCo to solve. It should rather be a measure describing the air traffic situation only looking at the traffic itself. Nonetheless, looking into the existing ways of determining air traffic complexity is imperative to this research project.

Air traffic complexity is mainly determined with the goal of determining the amount of aircraft the ATCo can handle in an airspace. The term complexity is defined as the collective effect of all factors, or variables, that contribute to sector level air traffic control complexity or difficulty at any given time[13]. The actual factors and variables differs quite a bit. Herein, two main factors of air traffic complexity can be identified. The first is a human factor related to the controller itself and the second being an intrinsic complexity related to traffic structure [17]. The human factor brings a lot of difficulties to the table, from the difference between local airspace structures to the level of experience and state of mind of the ATCo.

Currently ATC centers use the , which has no standard definition and has no real scientific basis. It often incorporates the number of aircraft in a sector and some subjective human factors[13]. This monitor alert parameter (MAP) is a static density (SD) metric. Static metrics only use the number of aircraft in a sector property. It is evident that the relative positions and movements of the aircraft are also important factors. The number of aircraft alone cannot describe the complexity of an air traffic situation as is evident from Figure 2.1.

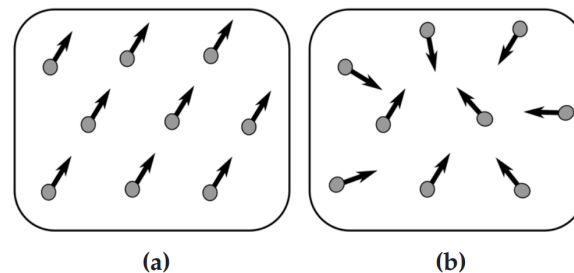


Figure 2.1: Same number of aircraft (AC) but totally different traffic situations.[18]

Attempts have been made at better metrics. Dynamic density (DD) metrics[6] are one important category. For example the William J. Hughes Technical Center (WJHTC) DD metric incorporates aircraft count per sector, sector volume, degrees of freedom in a conflict, a measure of separation distance and a task load index among some other factors. These are already big improvements over the simple number of aircraft[13] but focus mainly on the complexity from the standpoint of the ATCo[15].

Delahaye tries to provide better metrics with a topological entropy called the Kolmogorov entropy[6]. This approach looks at the overall flow of traffic but lacks the detailed coupling with individual conflicts. Later Delahaye also shows a possible metric by use of Lyapunov exponents, showing a measure of sensitivity to initial conditions of the underlying dynamical system[17]. Unfortunately calculation of this latest metric requires an enormous amount of computational power because of differential equations who require solving in this method. Michon[15] also shows the erratic behavior of this metric making it very unpredictable.

There are also some other approaches which could inspire new methods. For example Jardin shows the relation between conflict rate and air traffic density[12]. This serves as the basis for a relation between conflict rate and airspace capacity[10]. The case described though is a very specific application of the relation on the layered airspace system[20] and not yet proven to be applicable to other forms of traffic structuring. Moving on there are even more approaches to be found, Idris tries to approach the issue from the perspective of maintaining trajectory flexibility [11]. But rather than analyzing the level of complexity, this research focuses on lowering the level of complexity by implementing new methods of navigation. The complexity metric used in this research is the before mentioned Kolmogorov entropy developed by Delahaye.

Lee compiles a method where the required maneuvering to maintain a conflict free area upon entering of a new aircraft is a measure of complexity[14]. This latest method is also called the input-output

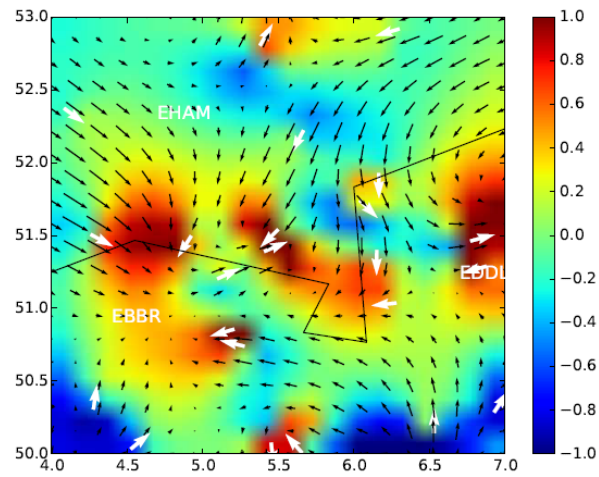


Figure 2.2: A plot of the Lyapunov exponents and vector field for a complex scenario, aircraft are indicated as white arrows.[15]

method. The method is good at identifying problem zones upon entry of an extra aircraft in the area. Unfortunately this is not always the case, this is thus not a way of analyzing a current traffic situation, but the sensitivity to an additional aircraft entering the area.

There are thus quite a few metrics analyzed already, but none provide a way to describe any traffic situation independent of the ATC method. Some of the metrics incorporate the ATC component and others do not provide a reliable method to classify any traffic situation.

3

Research objectives

From the projected growth of air traffic and the accompanied need for new ATC methods follows that a distributed or highly automated ATC system will probably be the standard in the future. This means the ATCo role will disappear or change. In order to study new air space structures or ATM systems a way of classifying and comparing traffic situations is needed. The objective of this research is to find a metric that is able to compare air traffic situations or scenarios based on the geometry of traffic patterns. Such a metric would allow comparison of different air traffic situations independent of the ATC method and without the need for extensive simulations but rather by simple calculations using properties of aircraft flying in a particular airspace structure. The outcome of this research could provide a quick way to compare traffic situations, saving valuable time for fellow researchers in the ATM field.

The primary objective for this research project thus reads:

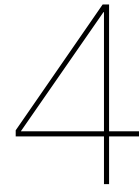
Find a metric to compare air traffic situations or scenarios in a defined airspace, based on the geometry of traffic patterns, without the need for traffic simulations over time.

From this research objective a hypothesis can be derived:

It is possible to develop a metric able to compare air traffic situations or scenarios in a defined airspace, based on the geometry of traffic patterns, eliminating the need for traffic simulations over time.

From this hypothesis a few subquestions arise: Is it possible to eliminating the need for traffic simulations over time by developing a metric able to compare air traffic situations or scenarios in a defined airspace:

- **based on direct traffic properties**
- **based on an extrapolation of traffic properties**
- **based on a combination of traffic properties**



Concept

This chapter describes a concept for possible new metrics and the reasoning behind it. All to achieve the goal stated in chapter 3.

4.1. Different approach to air traffic complexity

Current complexity metrics focus on the ATCo, his situational awareness and the ability of the air traffic controller to solve a conflict situation. The combination of these factors makes this a very complex problem. Based on the evolution of air traffic, this research project expects the responsibility for separation will move from ATC to the cockpit. This simplifies the problem in a number of ways.

First of all, the air traffic controller is taken out of the equation and with this the human factors. The result in this case is that the problem is easier to express as an equation of factors based in beta sciences and not social or behavioral sciences.

As a result of moving conflict resolution to the cockpits the conflicts are much simpler as well. Instead of one instance trying to solve a very complex problem with many aircraft and conflicts, it is split up per aircraft pair. Every aircraft pair solves its conflict, which is an easy job to do. The following sections will thus try to define a new metric based on the distribution of all the difficulty levels of each single traffic situation between two aircraft.

There are two caveats to this approach. Firstly, when the use of the airspace nears the capacity limit, the domino effect comes into play and a single conflict might result in many conflicts. Secondly, a central automated ATC system could in theory provide an overall higher efficiency in airspace use compared to a distributed system. This is because a central system can optimize for a global optimal use of airspace, while a distributed system will only optimize its own route in the case of distribution to the cockpit or slightly beyond that resulting in a very local area optimization.

Nonetheless, this new method for classifying air traffic situations should be applicable to any and all situations. This means that even though the starting point for this new metric is the assumption that ATC will change to a more cockpit based distributed system, it is not dependent on this assumption.

4.2. Defining airspace quality

The question remains what it should actually describe? In order to classify an air traffic situation one has to look at all aircraft in a defined space. This space could be represented as a 2D projection on the earths geoid for example. This would then be an area where aircraft fly with no upper or lower boundaries, other than the physical limitations of the earths surface and the maximum altitude the relevant planes can reach. But in order to investigate a traffic situation it might be better to only look at a certain layer of airspace with minimum and maximum flight levels. For example excluding general aviation or aircraft taking off or landing. The new metric must thus be applicable to this three dimensionally defined space, or simply airspace.

When looking at a traffic situation in a volume, one would like to know how good it is, in a sense a level of quality. According to the Oxford dictionary quality is defined as the standard of something as measured against other things of a similar kind. This is exactly what was intended for this new metric,

the ability to compare air traffic situations. Thus the new metric could be called the air traffic situation quality in a defined airspace or in short, airspace quality (ASQ).

Quality in the context of air traffic still has to be defined, what kind of factors will be looked at in order to compose a level of airspace quality and result in this new metric. To start off one could simply state that the design of an air traffic system has a high quality if it has a high capacity and a high safety level.

$$\text{AirSpaceQuality} = f(\text{Capacity}, \text{Safety}) \quad (4.1)$$

Unfortunately, maximizing one of those two factors compromises the other. Therefore, a set of rules are utilized to ensure a minimum level of safety. For example, the minimum separation criteria. When technology progresses these rules are also tweaked. More advanced ASAS for example allow for a lower minimum separation distance for a similar level of safety. This in turn allows the capacity of the airspace to go up, as the density of air traffic is allowed to increase.

Capacity could be quite simply expressed as the number of aircraft per square kilometer, when looking at 2D situations or cubic kilometer for 3D airspace. This capacity could also for example be extended for a unit of time. Capacity can change due to many factors. Some are due to changes in the actual air traffic, others are not, for example changing weather conditions or functional air block availability. This research project will not take into account weather conditions or other factors not originating from the air traffic itself. Therefore, the capacity in the Equation 4.1 is a theoretical maximum capacity.

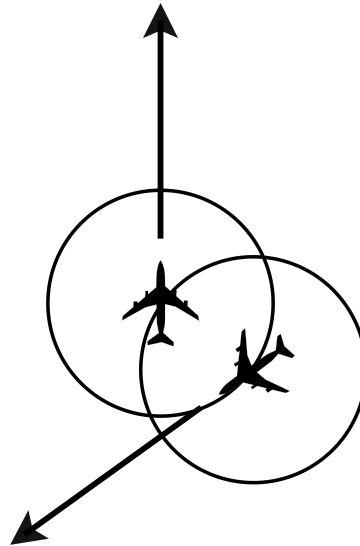


Figure 4.1: Loss of separation between two aircraft.

The safety part of the equation is still to be determined. Many different properties can be regarded to define the safety. One of them is loss of separation (LoS). LoS happens when an aircraft enters the safety bubble around another aircraft. Typically this safety zone is shaped like a disk around the aircraft with a radius of 5NM in controlled airspace. The disk has a height of 2000ft below FL290 and 4000ft above, unless the reduces vertical separation minima (RVSM) are in effect. The RVSM lower the vertical separation minima (VSM) to 1000ft between FL290 and FL410 when the airspace and aircraft equipment allow for it. Smaller disk radii are also allowed when the aircraft is close to a radar or an airport, flying in the terminal maneuvering area. The amount of LoS occurring in an airspace can thus tell something about the safety. Unfortunately it does not say anything about aircraft who do not have LoS.

More information is thus needed and can be found in the conflict detection and resolution (CD&R) corner. Systems providing information on future LoS along the current route of an aircraft pair are called conflict detection (CD). conflict resolution (CR) techniques then provide possibilities to handle this future LoS and avoid it. Conflict detection thus extrapolates air traffic geometric properties and provides a list of future LoS when no route changes occur.

When an airspace is at or near its capacity limit the domino effect comes into play[20]. This effect occurs when CR maneuvers result in an overall higher number of conflicts detected in an airspace. This

effect has been extensively researched and will not be part of this research. The goal of this research project is to determine the airspace quality from geometric traffic data. This means that the airspace is not necessarily at its capacity limits. So what is actually directly measured is not a theoretical maximum, but rather a usage level. Since the level of usage can be defined as a function of the capacity and the use factor, the airspace quality becomes a function of level of usage and level of safety.

$$\text{AirSpaceQuality} = f(\text{UseFactor}, \text{LevelOfUse}, \text{Safety}) \quad (4.2)$$

LoS detection provides a direct measure of current LoS occurrences, conflict detection provides future LoS predictions. But these measures are not able to fully describe every situation. There is, for example, a big difference between one aircraft trailing the other with a minor difference in speed or two aircraft flying straight towards each other with the relative speed being the sum of both aircraft speeds. In both situations a conflict would be detected, but it is clear that one is way more severe than the other. A possible metric to reflect the difference between such situation would be the range rate. The range rate is the change of the distance between two aircraft over time. It is effectively the sum of the projection of the speed vectors of both objects on a straight line between the two objects in question. The length of this line is the range. Range rate by itself does not encompass every aspect of the function surmounting to a level for safety. A very negative range rate can be potentially bad, meaning the aircraft are flying at each other with a high speed. But if those aircraft are far enough apart this does not matter. So a measure of time or distance to closest point of approach (CPA) is needed in this function.

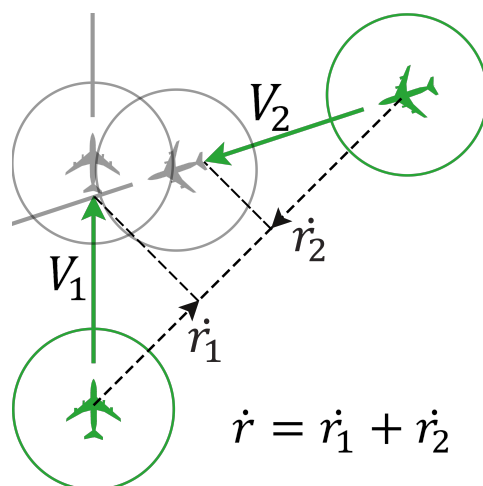


Figure 4.2: Aircraft pair in conflict, velocity and range rate vectors shown.

The same counts for distance between aircraft at CPA (dCPA), aircraft can have a very negative range rate with a short time to CPA (tCPA), but when the dCPA is just larger than the minimum separation criteria there is no actual problem. This situation will in fact be an efficient use of airspace. Although this situation is in theory efficient and safe it also has some dangers. Small course corrections or drift due to for example weather conditions could make this safe and efficient situation a very bad one.

$$\text{Safety} = f(t\text{CPA}, d\text{CPA}, \dot{r}) \quad (4.3)$$

It is clear many factors play a role in predicting the safety component of the airspace quality. But just as clear is the fact that a good measure for safety exists if the airspace is completely simulated, the number of conflicts and/or LoS occurring. This can for example be quantified using the conflict rate.

4.3. Possible metrics

The following subsections will discuss three possible kinds of metric categories followed by an overview and conclusion subsection of the different metrics.

4.3.1. Direct geometric properties

The geometric data available might already provide some information about the traffic scenario. The properties of one aircraft by itself are useless to the ends of this project but the trends in this data could

Velocity distribution
Relative velocity distribution
Relative distance distribution
Angle between tracks distribution
Range rate distribution

Table 4.1: Direct geometric properties.

Range vs tCPA
Range squared vs tCPA
Range rate vs tCPA
dCPA vs tCPA

Table 4.2: Extrapolation of properties over time.

provide useful information. Grouping the data by frequency results in a distribution. Skewness, minima or maxima and standard deviation are investigated. Direct geometric properties investigated are listed in Table 4.1.

4.3.2. Prediction of properties

The goal of this project is to develop a new method of air traffic scenario classification without the need of simulations. The direct geometric properties alone might not be enough to build a robust picture of a traffic situation. So a prediction could be made about how traffic would evolve based on these properties. An extrapolation of the direct properties can be made assuming the current course of aircraft. This method provides more information about the traffic situation. For example the range at CPA (or dCPA) and tCPA can be calculated. This, together with the range rate, might provides a comprehensive view of the traffic situation. The dCPA values lose accuracy the higher the tCPA. This is because the prediction of tCPA and dCPA are just linear extrapolations of the current geometric traffic properties. Weather conditions and course corrections will make this extrapolation inaccurate.

When discarding high tCPA values there might still be a pattern to be found between these tCPA and dCPA data which could compare to the patterns found in the conflict rate.

4.3.3. Combination of properties

Two properties, the dCPA and tCPA have a huge impact on the severity of a conflict situation between two aircraft. The lower the tCPA and dCPA are the more dangerous the situation is. Then there is also the range rate. Which adds an overall level of severity to a situation. A positive range rate means aircraft are diverging and a very negative range rate means the distance between two aircraft is diminishing rapidly. Including the sign of the range rate is enough since tCPA in essence is the range rate.

A mathematical expression of these factors could be:

$$\text{Severity of a conflict} = \text{sgn}(\dot{r}_i) \cdot tCPA_i \cdot dCPA_i \quad (4.4)$$

In the case of Equation 4.4 the severity of a converging conflict, where tCPA or dCPA are close to zero, is very low. This is not correct since this is the most dangerous situation possible. To solve this, the tCPA and dCPA factors should be inverted for the converging part of the equation. Equation 4.5 shows the converging part of the equation. Equation 4.6 shows the diverging part of the equation. However, one has to take note that the diverging conflicts don't provide much information about a traffic situation. They could have never existed. They are in a sense virtual and are foremost an indicator for a lack of converging conflicts for the particular aircraft pair.

$$\text{Severity of a converging conflict} = \text{sgn}(\dot{r}_i) \cdot \frac{1}{tCPA_i \cdot dCPA_i} \quad (4.5)$$

Even though the exact state of diverging conflicts are not of much importance to this research project, a distinction is being made between calculating the converging and diverging conflict. This to ensure both adhere to the idea behind the concept. This means that a more positive severity value should be a better diverging situation. In order to achieve this, part of the converging conflict formulation must be inverted.

$$\text{Severity of a diverging conflict} = \text{sgn}(\dot{r}_i) \cdot tCPA_i \cdot dCPA_i \quad (4.6)$$

Equation 4.5 and Equation 4.6 are set up with the following conditions:

$$\forall tCPA_i, dCPA_i > 0$$

The converging and diverging part of the equation can be combined using the sign of the range rate as an exponent. In order to be able to compare several conflicts in different scenarios tCPA and dCPA are normalized with the lookahead time and the minimum separation distance (SEP) respectively. One could first split all conflicts in a set of converging and diverging pairs and then perform the analysis. But combining the equation to give one usable result applicable to any aircraft pair would be an easier to implement method in whatever simulator or tool this concept is applied. Equation 4.7 show this new equation applicable to converging and diverging aircraft pairs.

$$\text{Severity of a conflict} = \text{sgn}(\dot{r}_i) \left(\frac{tCPA_i}{tlookahead} \frac{dCPA_i}{SEP} \right)^{\text{sgn}(\dot{r}_i)} \quad (4.7)$$

$$\forall tCPA_i, dCPA_i, tlookahead, SEP > 0; \dot{r} \neq 0$$

Investigating a severity level of a single conflict is not the ultimate goal of this research. This method has to be applied to each aircraft pair in a designated air space. Summing up or taking the average of the results of these equations would just destroy much valuable information. Analyzing the distribution of the severity of conflicts can tell much more about an airspace.

Equation 4.2 also requires a quantified level of airspace usage. A very simple way of doing this for a 2D problem is the number of aircraft per area, or in 3D per volume.

$$\text{Level of airspace usage} = \frac{\#AC}{Volume} \quad (4.8)$$

$$\forall Volume > 0$$

The unit for airspace quality usage level then becomes $\frac{\#AC}{m^3}$ and the ASQ safety level is dimensionless.

4.3.4. Summary of metric concepts

Three main categories of metrics are proposed and related to the three questions posed in chapter 3. The first category contains basic geometric property distributions which can simply be collected from radar data and represented as a distributions. The properties in question are mentioned in Table 4.1. The second category contains extrapolations of basic geometric properties, this results trajectory for an aircraft which could cross other aircraft trajectories. The CPA then tells at what point this happens. The distance at CPA between the two aircraft and the time to CPA give valuable information about a traffic scenario. Table 4.2 lists the metrics investigated in this category. The third category is a combination of properties to form a new metric called the airspace quality. The previous subsection elaborates in depth about this. The result is a metric represented by two formulas. The severity of a conflict:

$$\text{Severity of a conflict} = \text{sgn}(\dot{r}_i) \left(\frac{tCPA_i}{tlookahead} \frac{dCPA_i}{SEP} \right)^{\text{sgn}(\dot{r}_i)} \quad (4.9)$$

$$\forall tCPA_i, dCPA_i, tlookahead, SEP > 0; \dot{r} \neq 0$$

The level of airspace usage:

$$\text{Level of airspace usage} = \frac{\#AC}{Volume} \quad (4.10)$$

$$\forall Volume > 0$$

The level of airspace usage is a single value for an entire scenario while the severity of a conflict is calculated for every aircraft pair. The distribution of these severity levels in turn provide the necessary information to compare air traffic situations.

5

Validation

This chapter describes the validation methods used to check the validity of the concept and methods proposed in earlier chapters.

5.1. Scope of data

In order to fix the scope of this research project a set of boundaries to the input data has to be defined. What are the actual geometric properties of air traffic? Direct geometric properties are defined as properties which are measurable. The ones used are listed in Table 5.1. Typically technologies like SSR mode S and ADS-B or a combination of those, provide at least aircraft position, altitude, speeds and track. This data is enough to reconstruct a traffic situation and perform the required analysis.

Ground speed is used instead of other measures of speed (calibrated air speed (CAS), indicated air speed (IAS), true air speed (TAS)) because the atmospheric conditions are not taken into account in this project. Ground speed is the speed vector projected on the Earth surface and thus has the same reference for every vehicle in the simulation.

For the same reason track is used instead of heading. The track is the actual direction the aircraft moves in and not the direction the nose of the aircraft is pointed in. The track can differ from the heading due to crosswinds.

Data which might be available in some cases but is not used, is weather data. Information about the weather would allow for a more detailed prediction of traffic movements to be made, as aspects like drift are taken into account. Just as well information about flight plans is not taken into account. This would also allow for a more accurate prediction over a longer period of time. But because of the general level of inaccuracy of the position data and assumptions made in this research, the accuracy of the predictions made quickly degrades over time. The added value of flight plan data is thus assumed to be low for this particular research project.

5.2. Testing scenarios

Different types of traffic situations can occur, these are called scenarios. The scenarios can be divided in 3 main categories. First of all, uniformly distributed traffic or true random traffic. This type of scenario is very useful as a baseline to identify patterns or trends in non-uniform traffic.

The second type is the real world traffic. This can be a synthetically created approximation of a real world situation or it could be actual real world traffic data. An example is depicted in Figure 5.1.

Position	latitude, longitude [°]
Speeds	ground speed $\left[\frac{m}{s}\right]$, vertical speed $\left[\frac{m}{s}\right]$
Altitude	$[m]$
Track	In respect to true North [°]

Table 5.1: Direct geometric traffic properties.

The last type is synthetically generated traffic. It creates an extreme traffic situation not normally seen in the real world. This in turn could create extreme patterns or trends in the data making the change of properties more evident in the data. The different synthetic scenarios being investigated are all situated in the same area on Earth. This to make the mathematical errors in the calculation due to curvature of the Earth equal in every test case. The area above the Netherlands is chosen as this will also be the test area for the real-world data. An overview of possible synthetic scenarios can be found in Table 5.2.

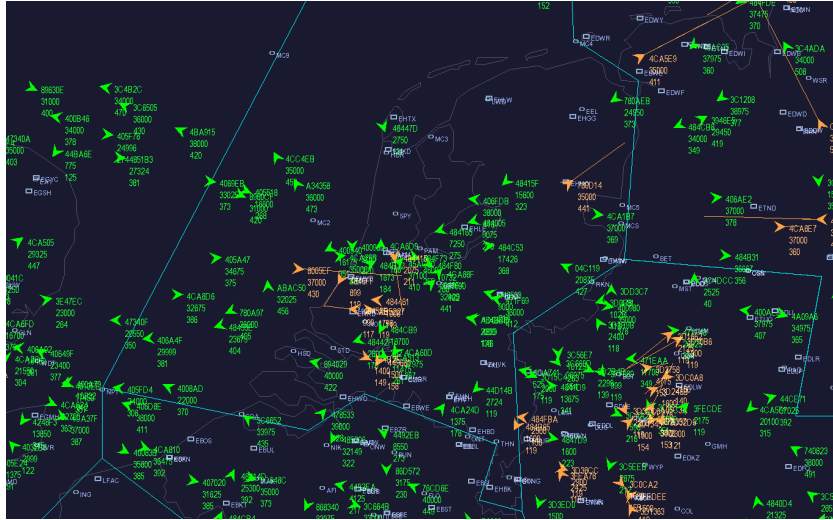


Figure 5.1: Real world scenario loaded in BlueSky.

5.3. Validity of input data and accuracy of simulation

The stability of some of the properties used can be shown by plotting the evolution of the properties over time. A list of them is shown in Table 5.3. First of all it serves as a check to see if synthetically created scenarios make sense. If a property converges to a value very different from the initial value at the start of the simulation it might mean that aircraft are created with properties outside their normal flight envelope or it could mean the simulation suite is lacking some details on certain fronts. So it functions as a check of the input data and simulator. Second, it shows the stability of a property in different scenarios. This could be very useful in order to estimate the impact a property might have on the metrics. If a property is naturally very unstable it could make the outcome of the metric in which it is included very erratic or unpredictable.

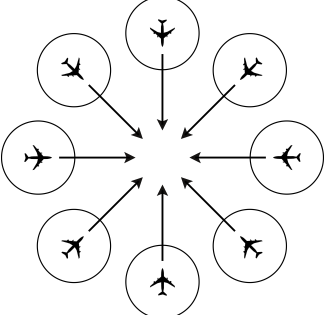
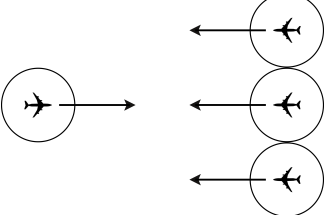

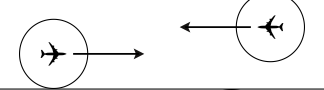
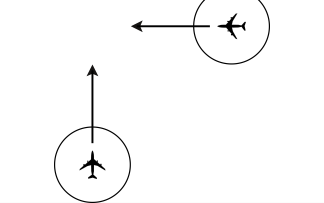
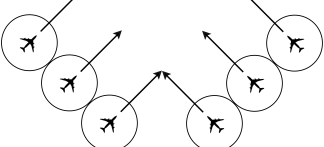
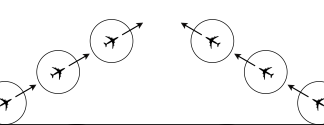
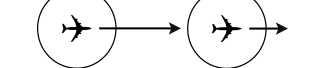
Super	A super is a set of aircraft positioned on a circle all flying towards the center of that circle with an identical speed.	
Wall	A wall scenario has one aircraft flying head on into a row of aircraft flying side by side.	
Head on	Two aircraft having opposite headings and flying towards each other at the same speed.	
Near miss	Two aircraft flying towards each other on parallel tracks. This results in a near-miss.	
Crossing	Two aircraft crossing at different angles, two main cases are important here. A perpendicular case and a non-perpendicular case, say a 60deg angle between tracks.	
Row	The same as the crossing but with two rows of aircraft.	
Column	The same as the crossing but now a string of aircraft is flying on each track, this gives a little insight in the crossing variation in time. It also slightly resembles a structured route system with very dense traffic.	
Overtake	Multiple aircraft flying on the same track but with different speeds	

Table 5.2: Synthetic scenarios.

Number of aircraft evolution
Conflicts per aircraft evolution
Average conflict rate evolution
Average velocity evolution
Average relative velocity evolution
Average relative heading evolution
Aircraft per square kilometer evolution
Average range rate evolution

Table 5.3: Evolution of properties.

5.4. Correlation of concept with known metric

This research main objective is to replace simulation by a prediction of traffic and thus quickly classify the air traffic. This means that the prediction method and therefore the classification needs to be validated by an already proven method. This can be done by simulating the scenario or looking at the entire set of air traffic data changing over time in case of a real world scenario. The metric of choice for this validation is the conflict rate. The conflict rate (Cr) is the number of conflicts occurring in an area per amount of time. This can also be extended to be the number of conflicts occurring for each aircraft in an area per amount of time.

$$Cr = \frac{Conflicts}{Time} \quad (5.1)$$

The number of conflicts detected depends on the lookahead time of the conflict detection method. Lowering this will make the detected conflicts nearer to LoS and thus a more imminent threat but when analyzing areas under control of ATC no conflicts will be detected as all of them will be solved by ATC before the tCPA equals the lookahead time. When comparing scenarios with ATC controlled areas one should raise the lookahead time accordingly. While also taking into account the added inaccuracy of the detected conflicts with a high tCPA.

From the perspective of a single aircraft pair the conflict rate can tell a lot. But when representing an entire airspace it is a bit more difficult. Averaging or summing the conflict rates for all aircraft pairs in an airspace loses most of the useful information of the traffic situation. Rather than coming to a single global conflict rate it is also possible to look at a frequency plot of the individual conflict rates. Comparisons in frequency plots could then be made in order to find similarities between two different traffic situations.

If similar comparison conclusions can be made using the newly developed metric one could say the new metric is a suitable replacement of the conflict rate without the need for simulations and can thus be used to classify airspace.

6

Results

In chapter 4 possible concepts for determining airspace design quality are listed and chapter 5 elaborated on a way to validate these concepts. This chapter shows the results of these concepts analyzed and validated by use of the BlueSky air traffic simulation suite. Elaboration on some of the programming methods and tools used can be found in Appendix C. In Appendix D the scraper is described which is used to gather some of the input data. The results are divided in three main categories, uniformly distributed traffic, synthetic scenarios and real world replays. The uniformly distributed traffic scenarios are in fact also synthetic scenarios but of such a different nature that the results are listed in their own separate section. The uniformly distributed traffic results can be seen as a baseline while the other synthetic scenarios demonstrate extreme results. The real world scenario then brings it all together and analyzes several interesting data points in a 24 hour period of aircraft flying over the Netherlands.

6.1. Uniformly distributed traffic

This section displays results for uniformly distributed, randomly generated traffic. The results are generated with the BlueSky simulator with the MCRE or multiple create command. The command creates a given number of aircraft randomly in a selected area. These aircraft use the basic B744 aircraft model implemented in BlueSky. Each aircraft is spawned on a random altitude between FL20 and FL390, a random speed between 250kn and 450kn and a random heading.

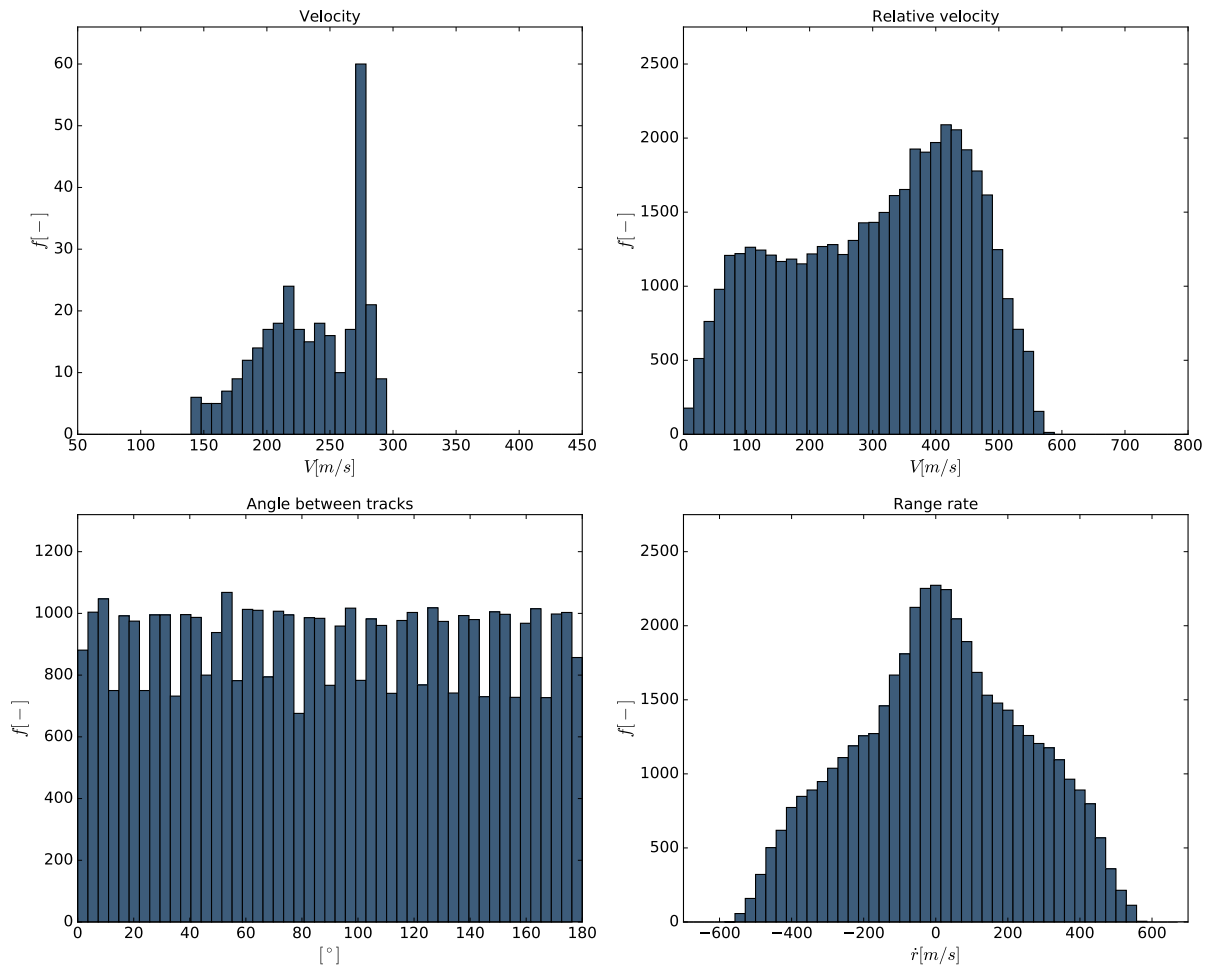


Figure 6.1: Direct geometric properties, low density uniformly distributed traffic

The aircraft are spawned in an area much larger than the research area. This is to ensure traffic enters the research area over the required test time. The research area is a defined area for which the metrics are calculated. In case of this project an area is chosen between 51° and 53.5° North and between 3° and 7° East. There is no vertical limit imposed through this method. However, aircraft are created within vertical bounds. Pop-up flights do not occur in this scenario except for the initial creation.

Two different scenarios are run, a low traffic density and a high traffic density version.

Figure 6.1 shows direct geometric properties of a set of randomly created aircraft. The distributions for velocity, relative velocity, relative distance, relative angle between tracks. Noticeable in these plots are the local maxima in the relative velocity distribution as well as the shape of the range rate distribution not being triangular as would be expected. These odd shapes of the distributions are due to the fact that the defined space where measurements are performed is a box rather than a sphere. The presence of aircraft in the corners of these boxes results in these shapes. The relative distance also tends to suffer from this effect. The relative angle between tracks is a uniform distribution and shows the random heading is truly uniformly distributed.

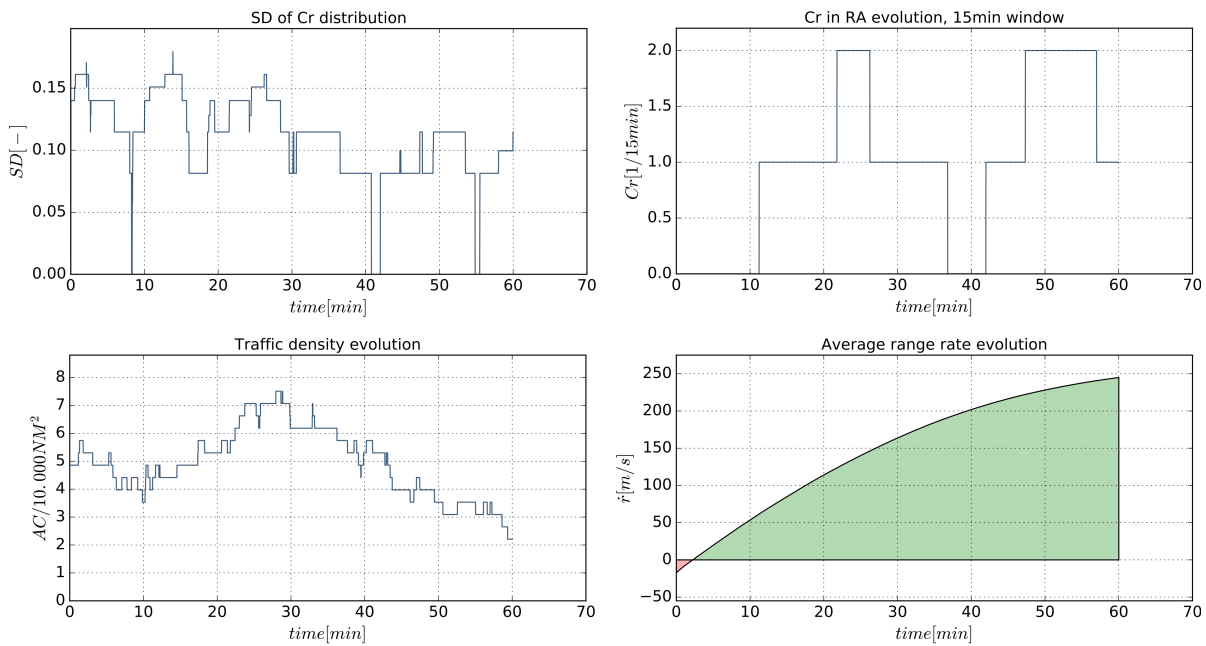


Figure 6.2: Evolution of properties, low density uniformly distributed traffic

Figure 6.2 shows the evolution of properties. Since no new aircraft are created the total scenario eventually diverges outside of the borders where the initial set was created. Therefore the traffic density in the research area and the conflicts per aircraft go down as the space between aircraft increases. Furthermore the conflict rate varies over the course of the simulation but generally stays low. The standard deviation of the conflict rate (SD of Cr) is taken globally and thus shows slightly more variation than the conflict rate in the research area (Cr in RA) does. The average range rate goes up because of diverging traffic. Furthermore the velocity and heading for all aircraft stays constant throughout the test.

Figure 6.3 is from a higher density test and shows more conflicts in the research area. After about 2800s the traffic density drops as there are no new aircraft created and the scenario only keeps diverging.

The density plots depicted in Figure 6.4 gives some insight in different metrics of range in function of tCPA. These plots are generated at the start of the scenario. The color of the points is a function of the number of other data points nearby. The color thus depicts the density of the data points in the graph. The colors shift from blue to dark red, blue points are in a very low density area and red points in a very dense area.

Due to the setup of this scenario there are more aircraft which are closer together than further apart resulting in more density towards the lower range values. There is a lower limit though which is close to zero, this limit would shift closer to zero NM when more aircraft are spawned in the same area,

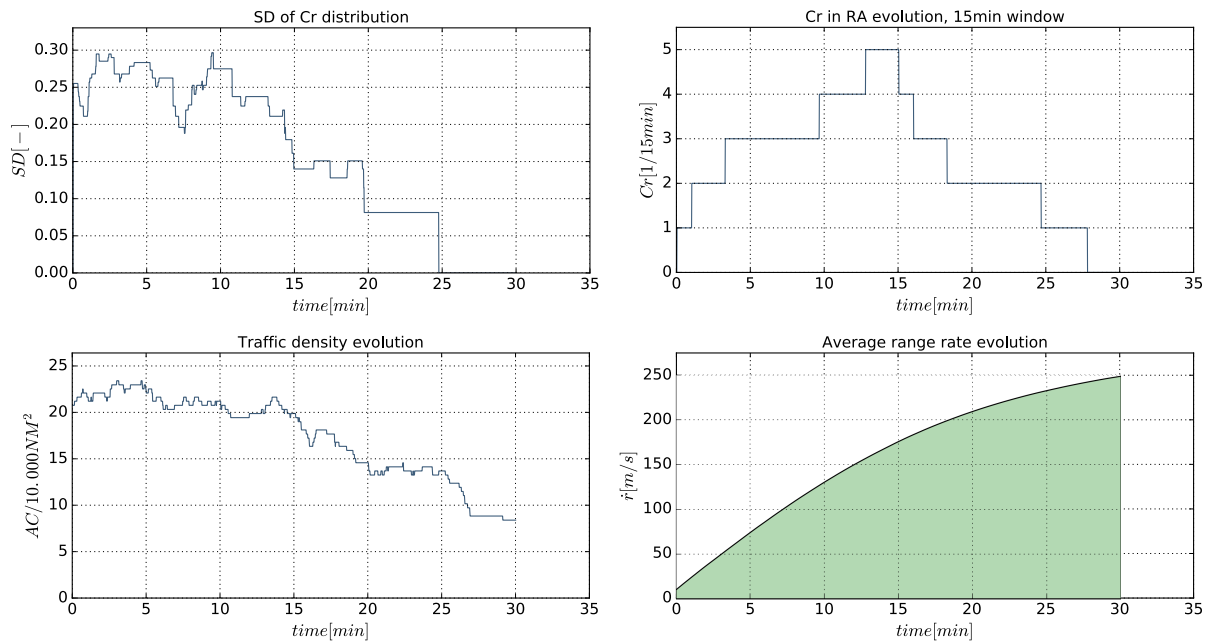


Figure 6.3: Evolution of properties, high density uniformly distributed traffic

increasing the density. The lower limit also slightly goes up for higher tCPA values. This is because aircraft who are further away from their tCPA usually have many miles to travel as well. Where this is not the case aircraft are flying on almost parallel tracks and this results in outliers on this range vs tCPA plot. The range squared vs tCPA shows the same effects but more profound due to the quadratic range. The range squared vs tCPA metric is depicted because the idea rose during the concept face that this quadratic range plot could show a distinctive pattern. The range rate vs tCPA is plotted for the converging pairs. Here most aircraft pairs have a small tCPA and small negative range rate. This plume shape would stretch towards higher tCPA values and closer to zero range rates if the traffic density would decrease. There are also some outliers with a very negative range rate of about $-500m/s$ and a tCPA below one minute. This means these aircraft are rapidly approaching opposed to the the range vs tCPA outliers which are very slowly converging aircraft pairs. The dCPA vs tCPA plot shows that the data points are clustered close to the origin and drop off as tCPA and dCPA get higher. The spread of this plot is a property of the traffic density. A higher traffic density would shift the high density area on the plot more towards the origin. A lower density traffic distribution would result in a shift of the high density data point area on the plot away from the origin, as well as a wider spread of the data points.

Mean	4.494313
Skewness	0.654773
Variation	1.856899
STD	10.221089
SEM	5.901148

Table 6.1: Distribution analysis ASQ for low density uniformly distributed traffic

Mean	6.843747
Skewness	6.373000
Variation	2.909920
STD	19.922572
SEM	0.557944

Table 6.2: Distribution analysis ASQ for high density uniformly distributed traffic

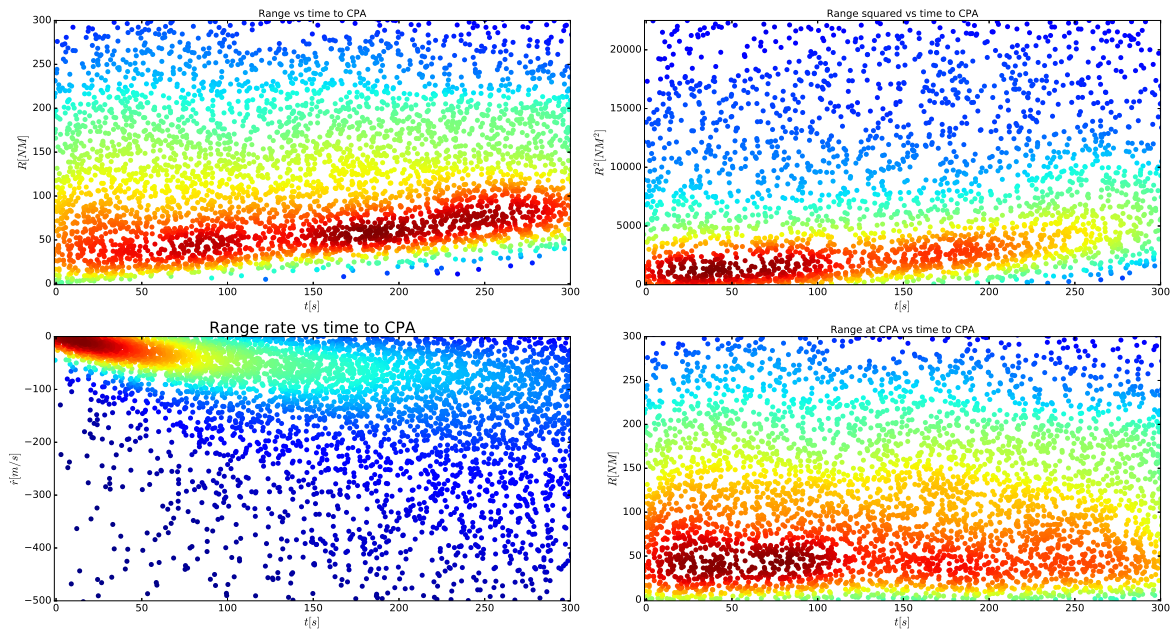


Figure 6.4: Density plot of properties, high density uniformly distributed traffic

The uniformly distributed traffic graphs for ASQ safety levels, Figure 6.5 and Figure 6.6, show a distribution similar to a normal distribution. However, for Figure 6.5 this is barely visible as there seems to be very little data available. If the aircraft density increases the distribution approximating a normal distribution becomes more visible.

Analysis of the distributions shown in Table 6.1 and Table 6.2 show that the standard deviation for the low density test is much lower than for the high density one. The high density test in return seems to be skewed towards negative values. This is not visible from Figure 6.6 since outliers are clipped in this plot.

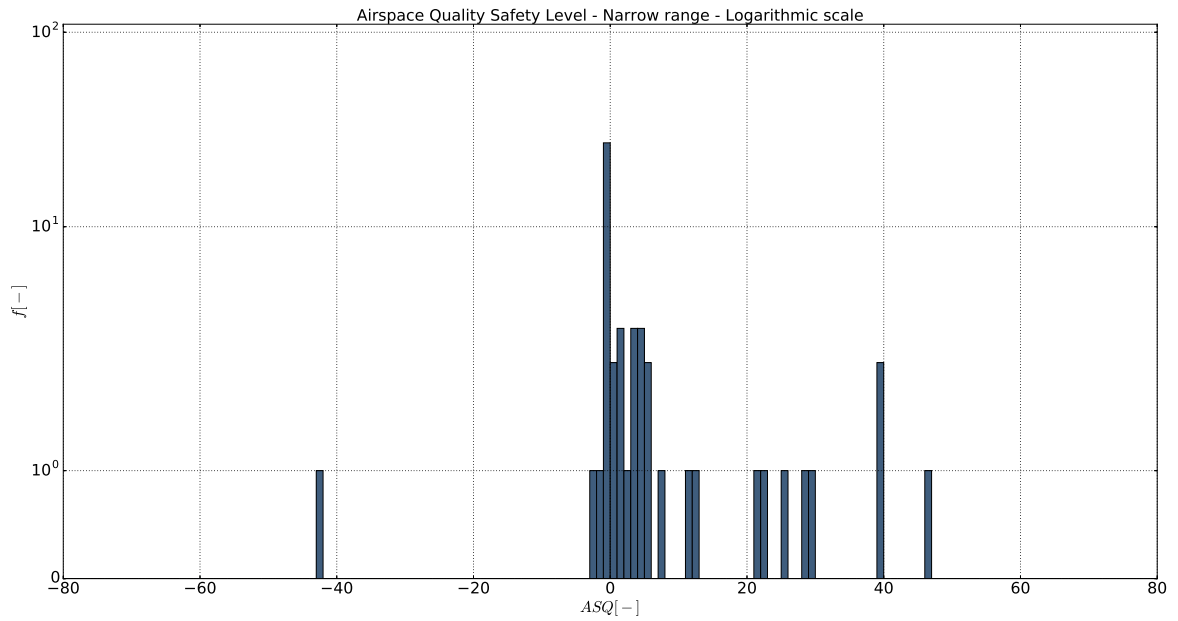


Figure 6.5: ASQ plot, low density uniformly distributed traffic

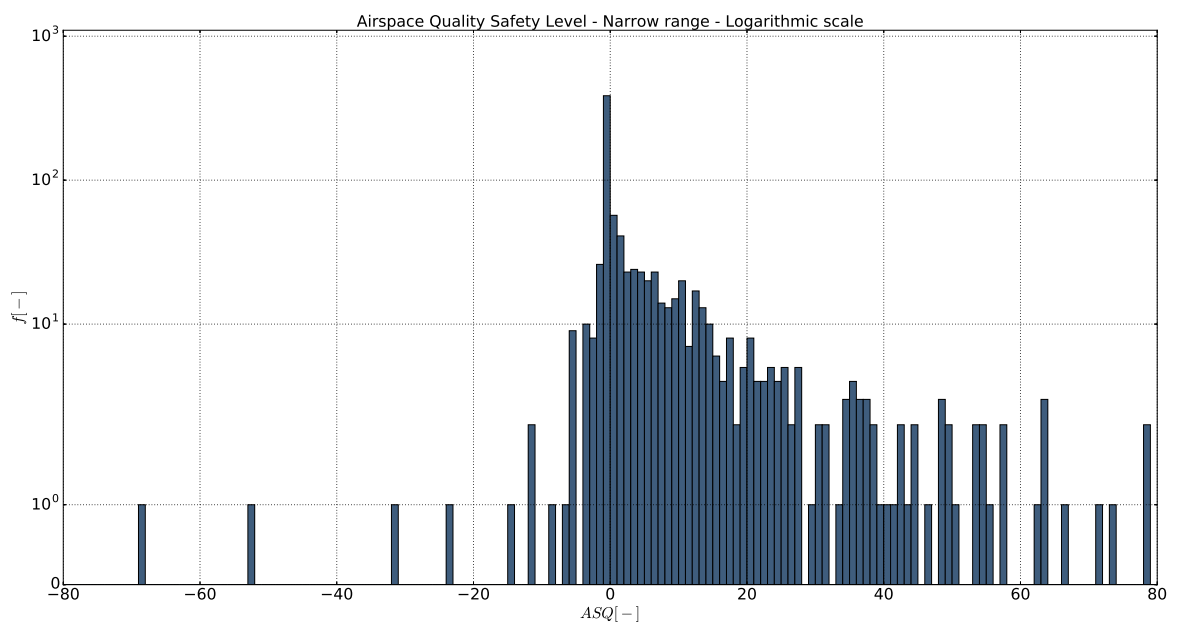


Figure 6.6: ASQ plot, high density uniformly distributed traffic

6.2. Synthetic scenarios

The synthetic scenarios in this section are explained in Table 5.2. The following synthetic scenarios are tested: Super conflict, wall conflict, near miss, overtake, crossing. The head-on collision is not performed as this situation also occurs in the super and wall scenario.

6.2.1. Super conflict

The super conflict spawns 10 aircraft according to the B744 basic model on a circle. Their heading all points them towards the center of the circle. They are all spawned at the same altitude, FL200 with a speed of 200kn. No conflict resolution method is used so the aircraft will keep flying towards the center.

Several points of measurement are chosen for the super conflict. The first point is the start of the scenario where the radius of the circle is 50NM. The second point is where the conflict is detected by the ASAS. The last measurement is taken post-conflict.

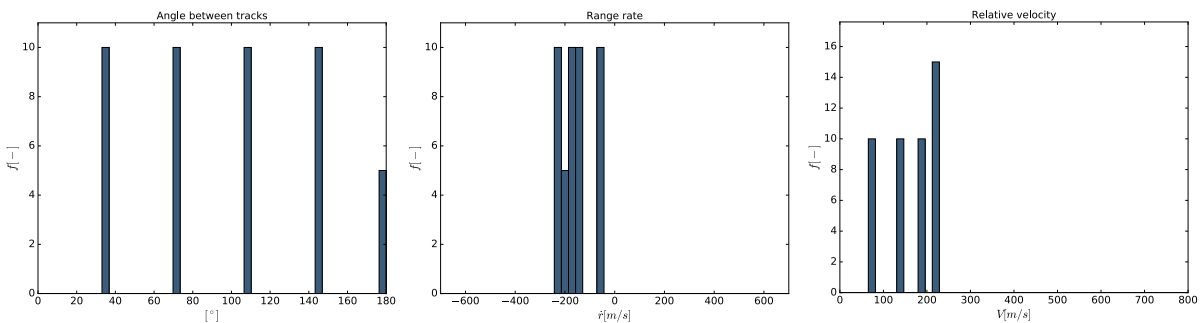


Figure 6.7: Direct geometric properties, super conflict, initial condition

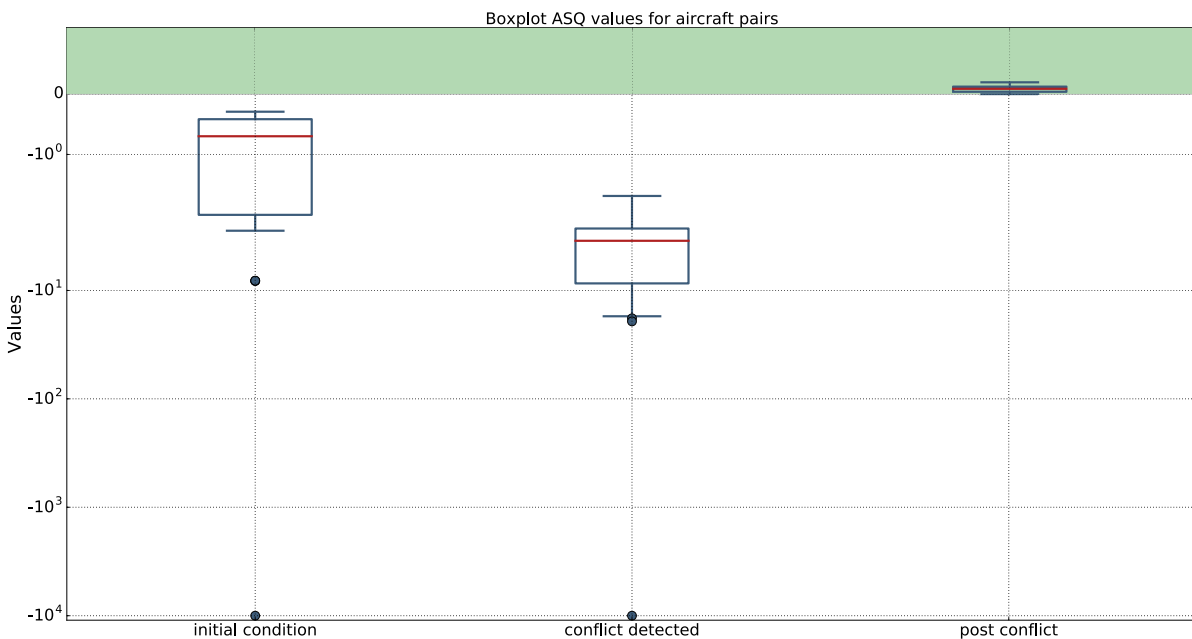


Figure 6.8: ASQ value evolution throughout the super conflict scenario

The distribution of the direct geometric properties relative bearing, range rate and relative velocity for the initial condition are shown in figure Figure 6.7. The first property, the relative bearing distribution clearly shows what is to be expected from aircraft on a circle. The second plot is the range rate, which stays about constant but flips sign once the conflict is passed. The range rate is not divided in equal bins as is visible. The variations are due to inaccuracies of the calculations used. The relative velocity shows 15 aircraft pairs in the highest speed category. This is due to the size of the bins, there are actually 5 head-on situations in the circle resulting in the top speed followed by 10 situations with a

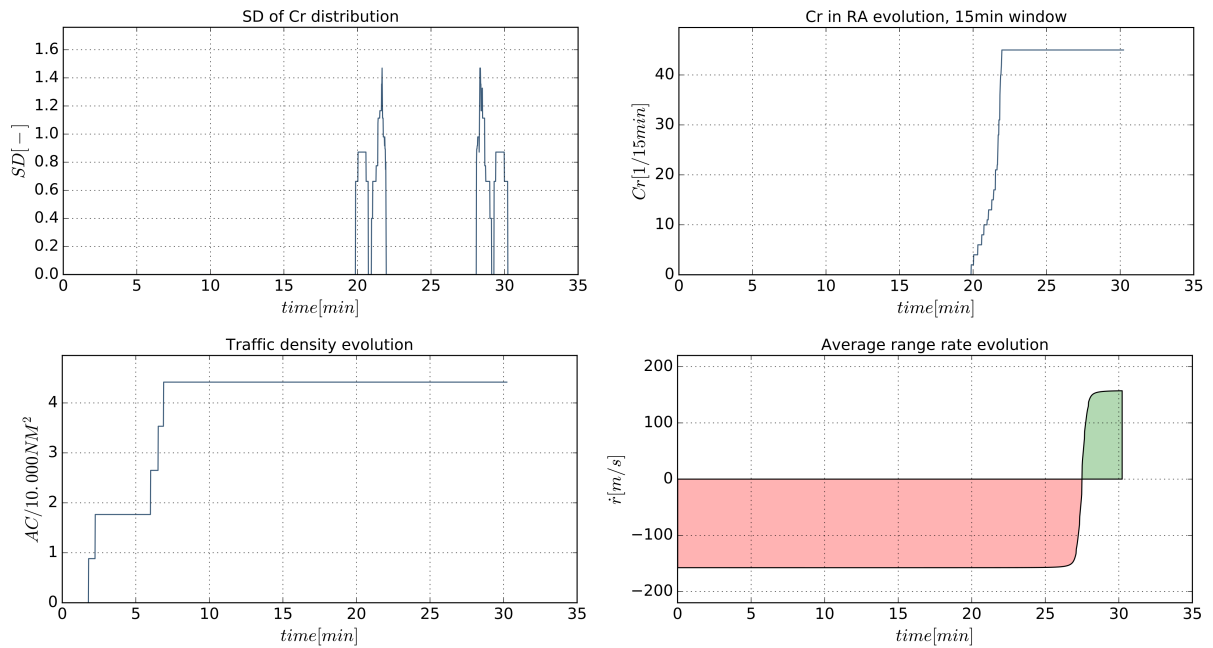


Figure 6.9: Evolution of properties, post super conflict

shallow angle of crossing.

The evolution of the ASQ metric is shown in Figure 6.8. This box plot of ASQ values represents the distribution of ASQ severity levels for all aircraft pairs investigated. The box plot clearly shows the distribution, outliers and median of the ASQ values. Multiple box plots can be shown in one figure, they show situations that can be compared. This can be across scenarios or just different points in time in one scenario. The median is shown by a red line. A positive ASQ value means there is no conflict ahead for the aircraft pair in question. The actual value is not important once it is positive as this is only a metric to a past conflict that might have never happened. The most important parts of this representation are the location of the median in respect to the zero line and the outliers which potentially represent unwanted traffic situations.

The values in this particular case shown in Figure 6.8 change from small negative values to larger negative values when the collision becomes more imminent. Eventually the metric values jumps to zero as the conflict is passed. One extreme value of -10000 is visible when the conflict is detected while the other values are way closer to zero. This is unexpected as theoretically the conflicts with the same geometry should be of equal severity. In this case there should be 5 equally bad values representing the head on conflicts in the circle. Investigating this proves the problem to be twofold. The first error happens when spawning the aircraft. They are spawned on a circle where the positions of the aircraft are calculated from the center coordinate of the circle. Because of inaccuracies in the trigonometric calculations and differences between the method of calculating the positions and the actual simulation model of the globe, the positions are not projected on the globe in an accurate circle but slightly more like an ellipse. This error is subject to the location on Earth as it depends on the latitude. Second, next to the initial inaccuracy during creation there are inaccuracies in trigonometric calculations over the course of the simulation. This results in a slight drift of the aircraft. This drift is minor but due to the setup of the ASQ metric this has a big influence on it. The main equation for ASQ, Equation 4.7, seems to be very sensitive when a tiny drift causes the CPA to move. To be precise, the dCPA term causes this to happen. In a converging situation where a dCPA of zero means very large negative values for the ASQ metric. But the slightest deviation from this dCPA of zero makes the ASQ value smaller by an order of magnitude. This is certainly to be taken into account when using the ASQ metric as proposed. Note that the effect of this error is extreme in these synthetic scenarios where dCPA values of zero are used.

The conflict rate distribution is also very trivial in this scenario. It starts of with all the aircraft having no conflicts. It moves to all the aircraft having 9 conflicts when tCPA is equal to the lookahead time and eventually, post conflict, all aircraft again have zero conflicts.

Figure 6.9 shows the overall evolution of properties during the scenario. Visible effects are for example the stepwise rise in number of aircraft in the research area visible in the traffic density metric. This means that the aircraft are created outside of the research area and fly in during the scenario. The stepwise increase also shows that the research area is not a circle, sphere or cylinder but rather a box. The average range rate flips at around 1600s when the conflict is passed. The conflict rate in the research area as well as the standard deviation in the global conflict rate don't show a step rise and fall. This means the aircraft don't enter into a conflict all at the same time, which should theoretically be the case. This is again due to approximation errors in the calculations. The error depends on the curvature of the Earth and thus the location on the globe.

6.2.2. Wall

The wall conflict scenario spawns one aircraft flying head-on into a row, or wall, of 20 aircraft flying on parallel tracks. All aircraft are spawned on FL200 using the B744 aircraft model in BlueSky. They all fly with a speed of 200kn. The head-on scenario described in Table 5.2 can be seen as a subset of this scenario and will thus not be mentioned separately.

Two points of measurement are chosen for this test. The first is when the conflict is detected, the second is post conflict.

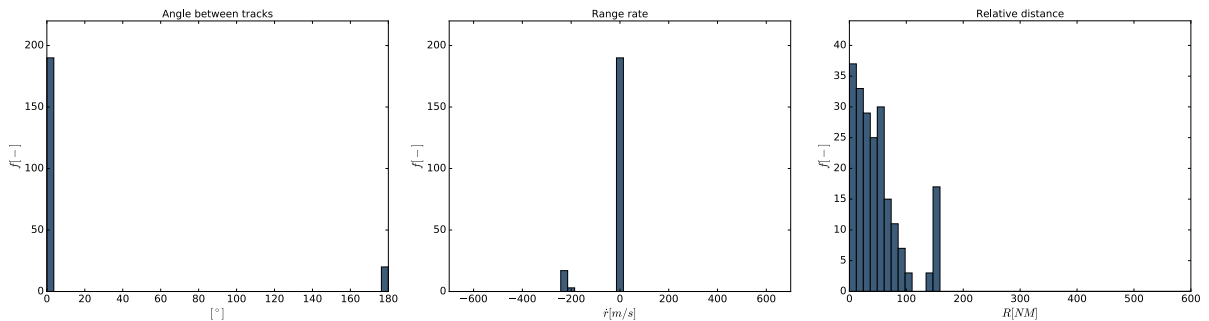


Figure 6.10: Direct geometric properties, wall conflict, conflict detected

The distribution of basic geometric properties are exactly as expected. The velocities are equal for all aircraft and constant throughout the scenario. The relative bearing depicted in Figure 6.10 shows all but one aircraft flying at the same heading. The range rate also shows this, most aircraft pairs flying at the same range rate of zero. While the pairs with the aircraft flying head-on into the wall show a range rate of around $-200m/s$. The relative distance should show half a triangle if it was just the wall, the peak around 60NM is the relative distance between the aircraft in the wall and the one flying into it.

The ASQ is expected to have a significant amount of pairs to be zero for all aircraft flying in the wall. Then there would be negative values with diminishing frequencies for more negative values. This is because the condition is highly undesirable for the one aircraft flying in the middle of the wall, and less bad for the ones flying next to the middle who will just miss the oncoming traffic. Figure 6.11 shows this behavior as expected.

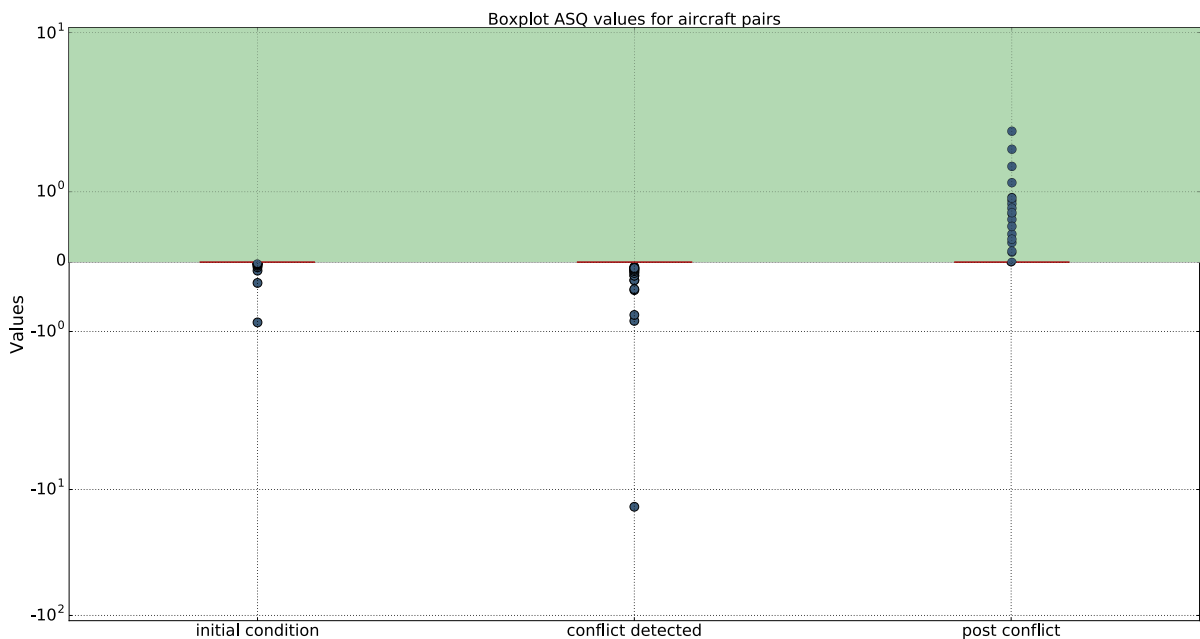


Figure 6.11: ASQ value evolution throughout the wall scenario

The conflict rate distribution starts out with one aircraft being in conflict with the aircraft in the middle of the wall. The rest of the aircraft stay conflict free. In contrast to the ASQ the conflict rate results show

a bad situation, or conflict, for only one aircraft pair. The Figure 6.11 gives a bit more detailed information in this case and shows the different levels of severity opposed to a simple conflict or not.

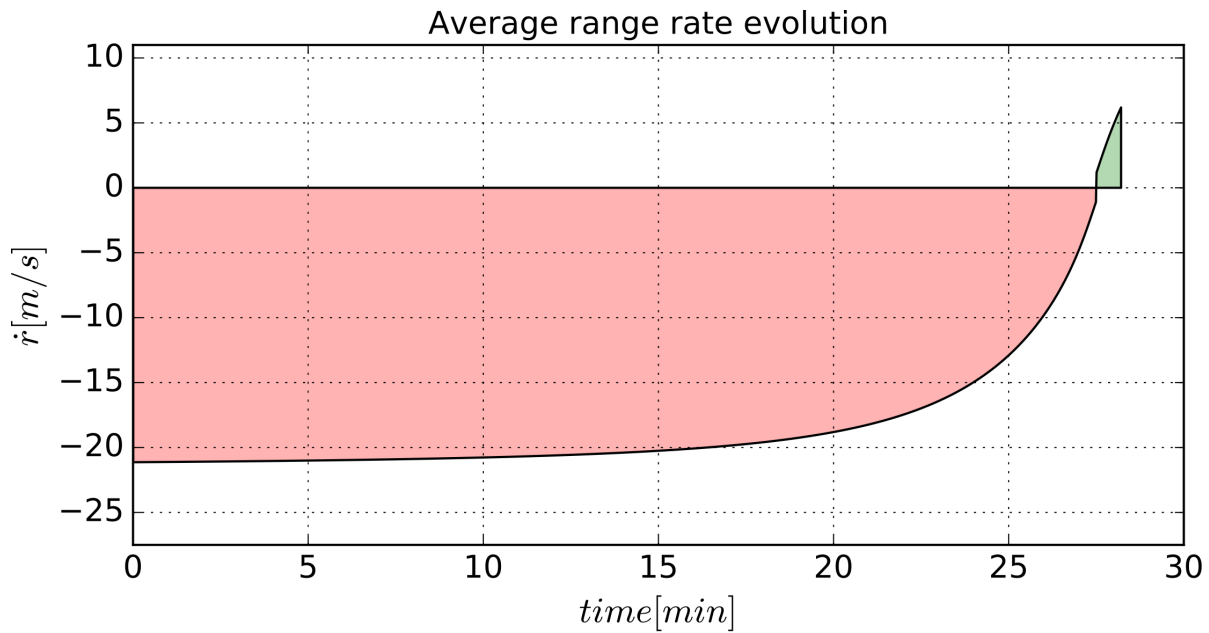


Figure 6.12: Evolution of properties throughout the wall scenario

The properties mostly stay constant. The conflict rate changes when tCPA becomes smaller than the lookahead time and then changes again when the conflict passes as seen in the standard deviation of the global conflict rate. The average range rate visible in Figure 6.12 shows a smooth path from negative values to positive values while it progresses through the scenario.

6.2.3. Near miss

In the near miss scenario two aircraft are spawned at FL200 with a speed of 200kn. They are flying on parallel tracks, one aircraft flies eastbound, one westbound. In the first test the tracks are 3NM apart so traffic will cross without conflict. In the second test the dCPA is lowered to 1NM which would result in aircraft passing through each others safety zone.

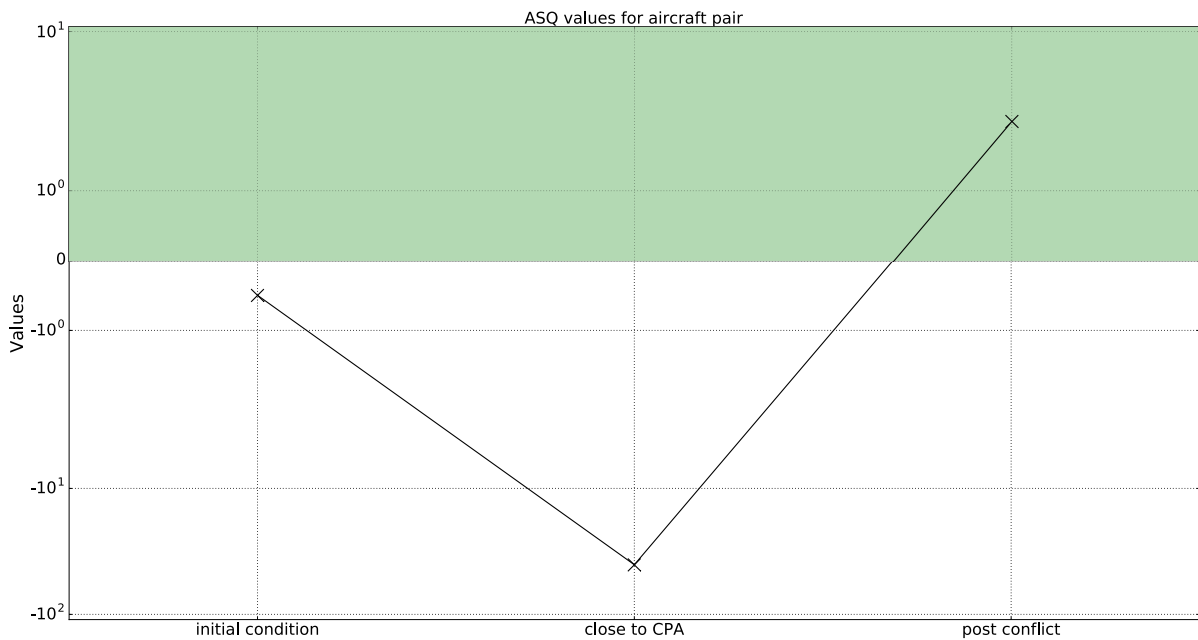


Figure 6.13: ASQ value evolution throughout the near miss scenario at 3NM

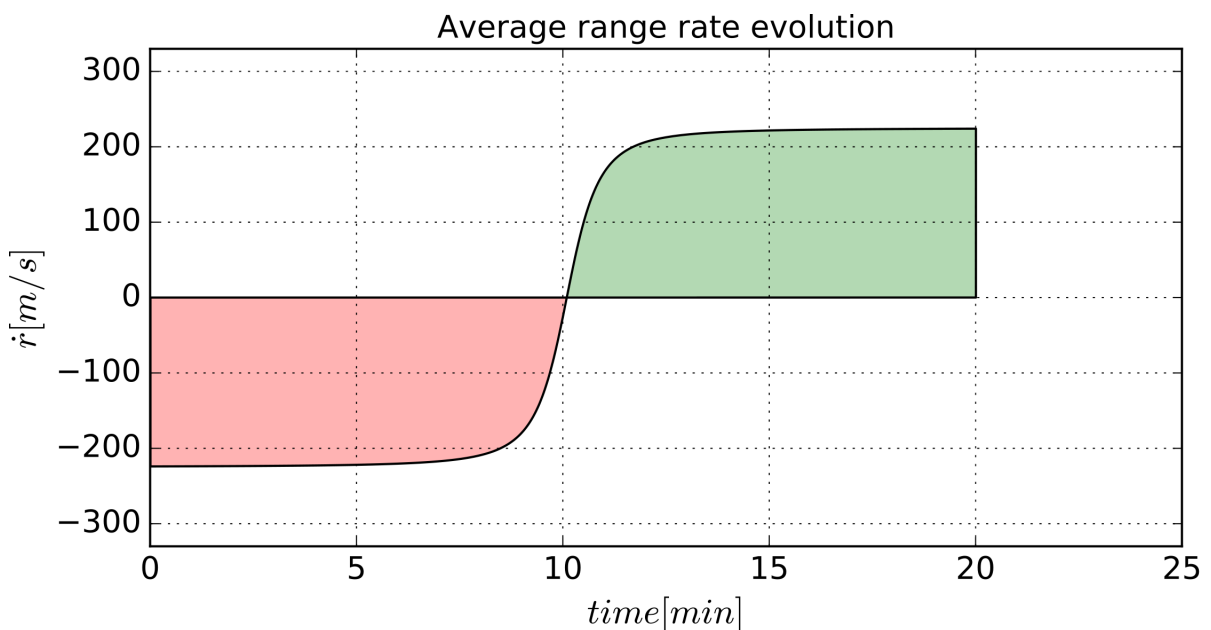


Figure 6.14: Evolution of properties, post 3NM near miss situation

The direct geometric property distribution shows 2 aircraft at the same speed and just one data point for the single aircraft pair for relative velocity, relative distance, relative bearing and range rate. The range rate evolves from negative to a positive values while the relative distance diminishes till the dCPA of 3NM and then increases again. The other properties stay constant.

The ASQ should be slightly negative and become more negative as both aircraft approach CPA.

This is shown in Figure 6.13. The post conflict state shows the ASQ has jumped to zero again as both aircraft are diverging again.

Since there is no conflict in this test case the conflict rate stays at zero throughout the test.

Figure 6.14 shows the evolution of the average range rate. All other properties stay constant throughout this test.

The following results are from a similar test but with a dCPA of 1NM instead of 3NM. This should result in a conflict between the two aircraft.

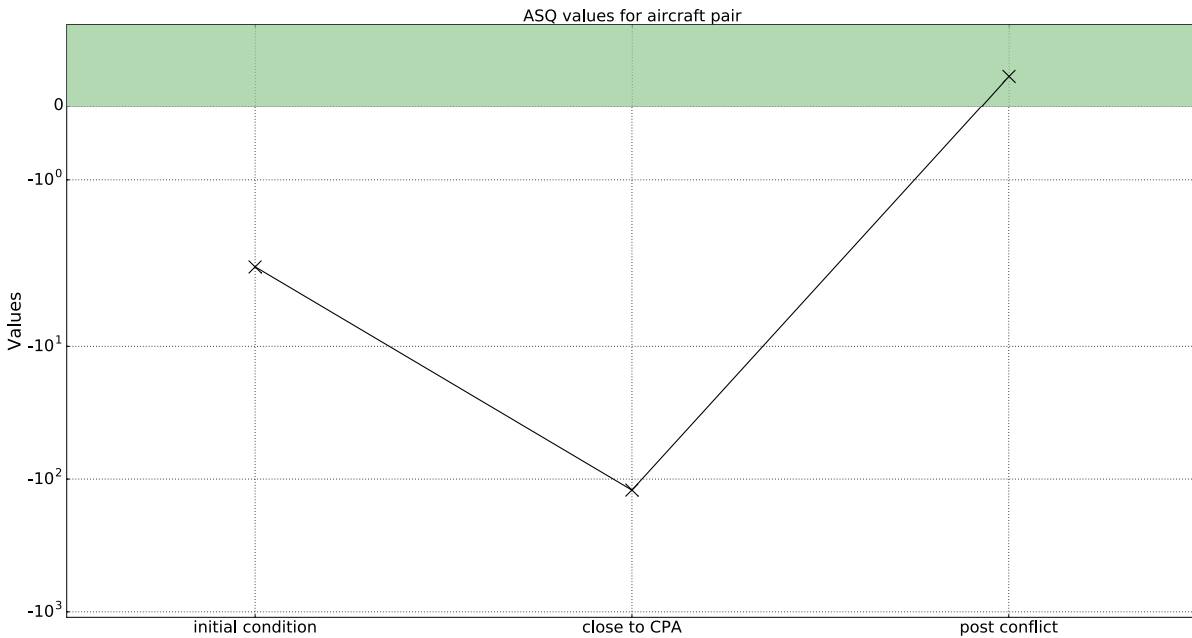


Figure 6.15: ASQ value evolution throughout the near miss scenario at 1NM

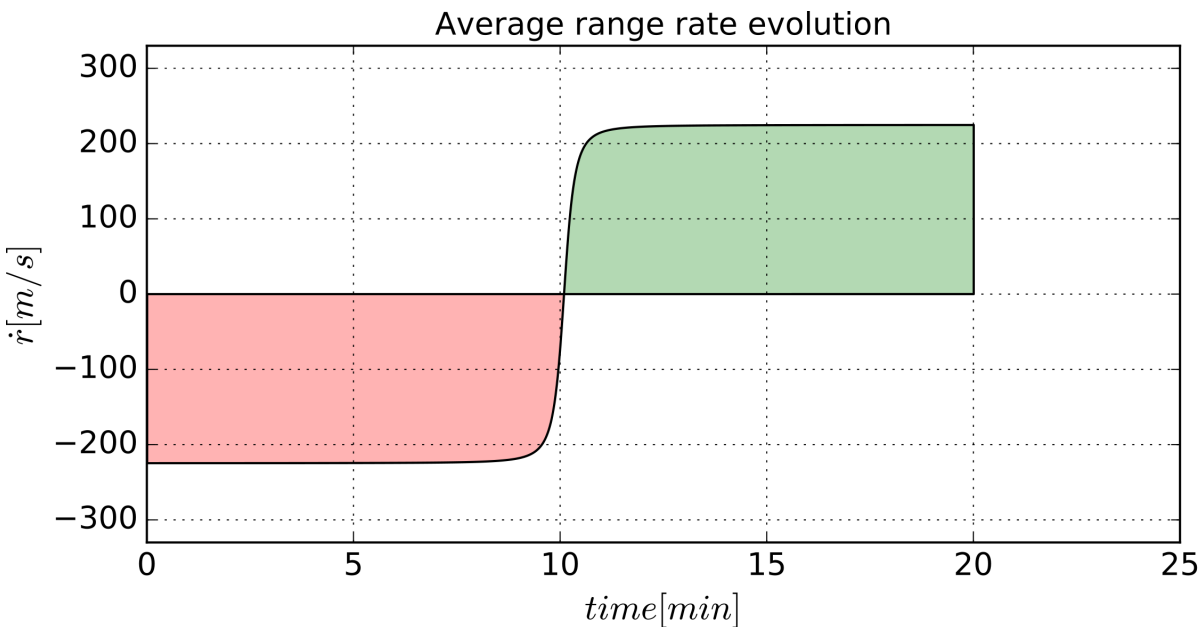


Figure 6.16: Evolution of properties, post 1NM near miss situation

The direct geometric property distributions are almost the same as for the 3NM test. The relative distance goes lower to the new dCPA of 1NM and the range which now has slightly larger values. The larger range rate values are due to the smaller dCPA which results in a narrower angle between the

aircraft speed vector and the relative bearing vector. The conflict rate evolves as expected from no conflict to one and then to zero again.

The ASQ in Figure 6.15 is fairly negative due to the severity of the situation. The values are more negative than for the 3NM test shown in Figure 6.13. This is due to the dCPA being significantly closer.

Most properties stay constant throughout the test as is obvious due to the setup. The range rate in Figure 6.16 again shows a fluent profile from negative values of the converging situation to similar positive values when the conflict is passed. The conflict rate does become one in this case opposed to the 3NM near miss in the previous test.

6.2.4. Overtake

In the overtake scenario two aircraft are flying on the same track with a heading of 90deg. The situation occurs at FL200, the front aircraft flies 150kn and the perusing aircraft 200kn. Both aircraft are created within the B744 aircraft model in BlueSky. This should result in a conflict situation over a long period of time. In theory the dCPA is zero. Equation 4.7 cannot handle a dCPA of zero. This means the result would become zero which would be a safe traffic situation while the reality is very different. Therefore dCPA values which are zero will be set to a very small value, 10^{-4} in this case.

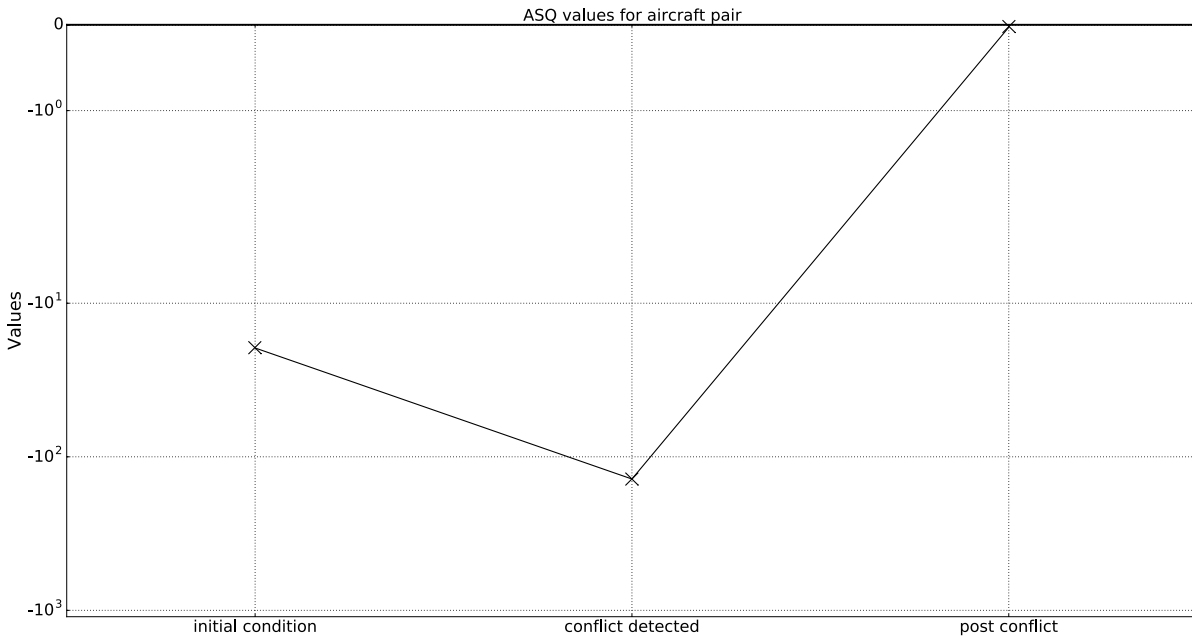


Figure 6.17: ASQ value evolution throughout the overtake scenario

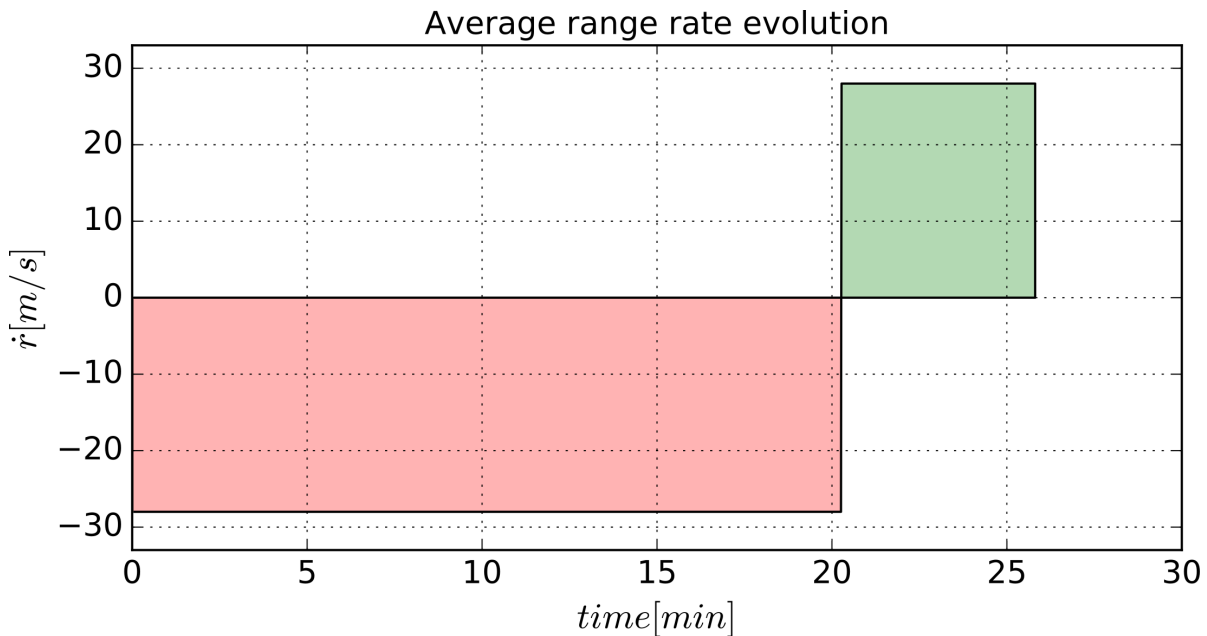


Figure 6.18: Evolution of properties, overtaking traffic, post conflict

Due to the setup of this scenario the direct geometrics properties are trivial. The velocities are 2 constant but different values, the relative velocity stays constant, the relative distance diminishes to zero and then increases again, the relative heading stays constant at zero and the range rate jumps

from slightly negative to slightly positive when the overtake aircraft passes the slower one.

The ASQ in Figure 6.17 shows one value being fairly negative, becoming even more negative when tCPA comes closer. Eventually it jumps to zero when the conflict is over.

The conflict rate in this situation moves from zero to one conflict. It stays at one for a while until the overtaking aircraft has sped past and outside the safety zone of the initially leading aircraft. At this point the conflict rate drops back to zero.

Figure 6.18 shows normal evolution of the range rate similar to other synthetic scenarios previously discussed. Other properties show similar behavior, they stay constant due to the setup of the test and the conflict rate jumps to one during the period the conflict takes place.

6.2.5. Crossing

In the crossing scenario two aircraft fly on two crossing tracks with a heading difference. Two tests are performed. One with a heading difference of 90° and one with 30°. Both aircraft fly at FL200 with a speed of 200kn and are created within the B744 aircraft model in BlueSky. They are spawned 50NM from the crossing of the tracks flying towards it.

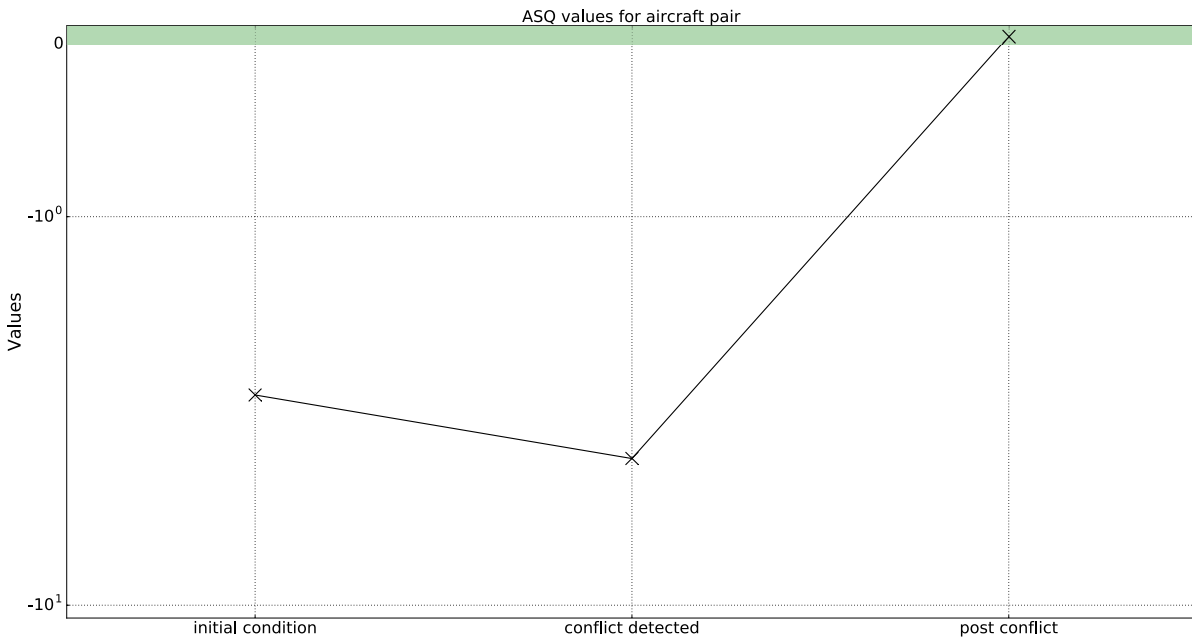


Figure 6.19: ASQ value evolution throughout the perpendicular crossing scenario

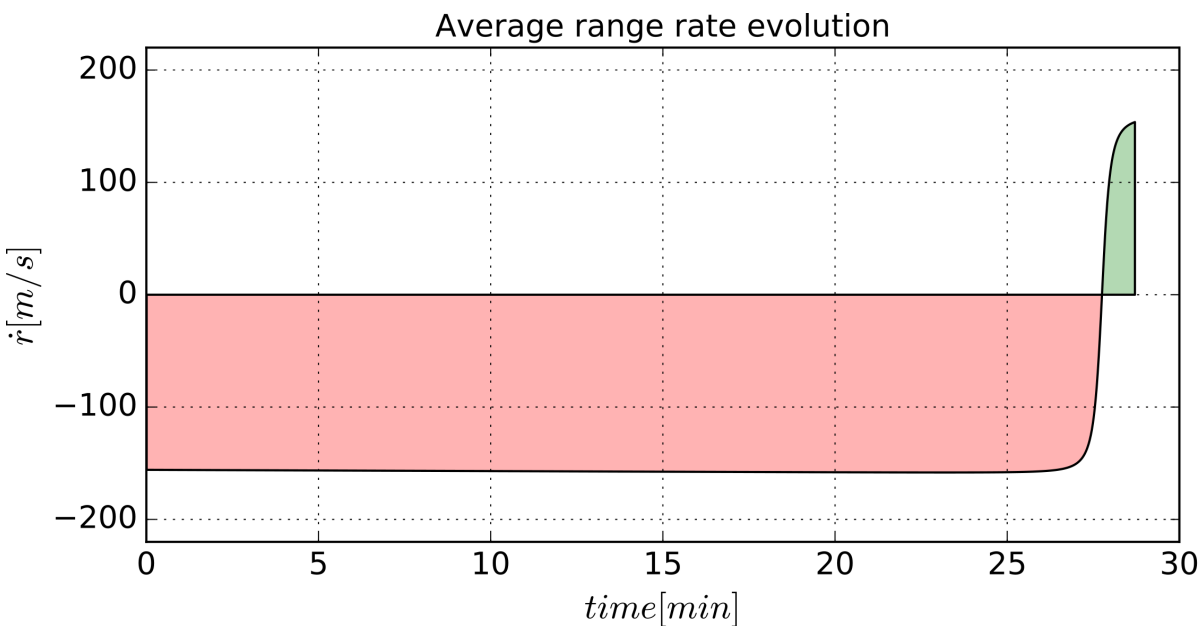


Figure 6.20: Evolution of properties, perpendicular crossing traffic, post conflict

Distribution of direct geometric properties and conflict rates are straight forward for this scenario. They are very comparable to previous synthetic tests with two aircraft involved. Conflict rates jump from zero to one and back to zero during the test. The constant speed, relative velocity and relative bearing are equal and constant for both aircraft. The range rate and relative distance obviously change over the span of the test as the aircraft move. The relative distance changes gradually, while the range

rate flips when the aircraft have crossed as is visible in Figure 6.20. However, the ASQ plot might not be as expected at first glance. The severity drops from a very negative value to a less negative value while the tCPA lowered significantly between those two graphs. In theory the ASQ value should become more negative. The reason behind this unexpected change is due to the sensitivity to dCPA changes around zero. The effect is also explained in more detail in subsection 6.2.1. The effect means the ASQ values are not as expected but are reflecting the actual situation in the simulator. Due to the drift the dCPA has become larger meaning the situation has in fact become more safer, hence the rise in safety level values.

The following ASQ level plot is from a test where the difference between the tracks is only 30° .

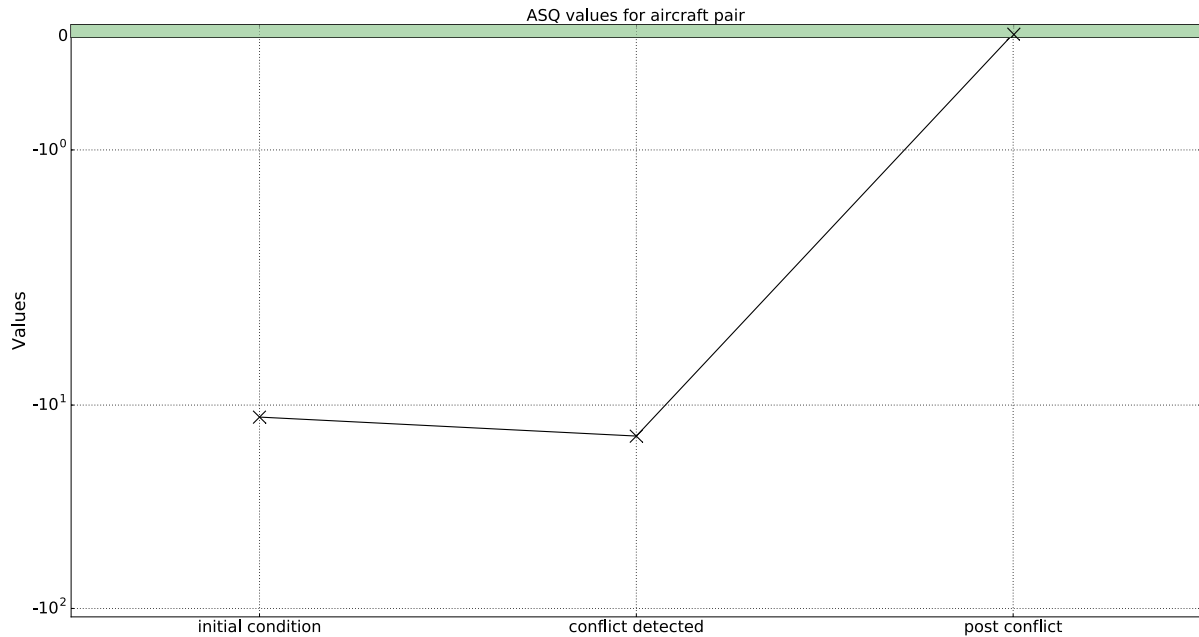


Figure 6.21: ASQ value evolution throughout the 30° crossing scenario

The same is visible as for the perpendicular crossing. A very large initial severity followed by a lower than expected level. The effect of the CPA drift is thus also visible in this case. Note that the values are slightly more negative. This is caused by the fact that the angle of the crossing tracks is only 30° . As a result a drift of the CPA due to trigonometric calculations will be smaller and thus have a smaller effect on the ASQ values.

6.3. Real world replays

The metrics also need to be tested on more realistic scenarios. For this purpose a scraper, described in Appendix D gathers real world traffic data from Flightradar24.com. This data can then be played back in the simulator. The real world scenarios analyzed are from January 10th 2017 starting at 1AM UTC. The research area is a box slightly larger than the Dutch airspace, the same as for the synthetic scenarios. Aircraft between 51° and 53.5°N latitude, 3°E and 7°N longitude and above FL30 are included in the analysis. The vertical limit excludes aircraft landing and in initial climb. The actual aircraft spawned in the simulation can also exist just outside the borders of this airspace to allow for conflicts just inside the borders of the research area.

The choice to analyze January 10th is not completely at random. It's a regular Tuesday day and a work day outside of holiday periods. This is chosen to get a day as normal as possible. To get a first general sense of the scenario throughout the day the data is loaded in the simulator and the evolution of basic metrics has been plotted for the period of 24 hours as can be seen in Figure 6.23. Plots in this section show UTC times, the local time in the area analyzed at that particular date was CET or UTC+1.

Figure 6.23 shows a couple of interesting trends throughout the day. First and foremost the daytime cycle is clearly visible. Traffic goes up around 8AM and drops around 11PM. During this daytime period the traffic doubles in respect to the night hours, from about 20 AC to 40 AC, with peaks around 80 AC in the research area. This goes hand in hand with the conflict rate as seen in the averaged CR and standard deviation of CR plots. The average speed and relative speeds are pretty constant in the scenario but show a more erratic behavior during off-peak hours. This is obviously due to the higher influence of a single aircraft with a diverging speed. The same is noticeable for the average relative heading which shows an extreme peak around 2:30AM. This coincides with the minimal amount of aircraft present in the airspace. So it jumped to the value of this one aircraft pair, where the aircraft are apparently flying in almost opposite directions. The range rate is discussed in more detail in the next paragraph.



Figure 6.22: Jan 10th 2017, 8AM traffic bunching

The research area is heavily dominated by the Schiphol airport. Big airports often have inbound and outbound peaks scheduled to make optimal use of their facilities and passenger needs. This translates in converging traffic for inbound peaks and diverging traffic for outbound peaks. This is clearly visible in Figure 6.24. Two trends are visible, first of all the overall inbound and outbound periods. There is for example a dominance of incoming traffic between 5:30AM and 9:30AM which then flips into an outbound period until 11:30AM. In between these period there is a second method of operation visible, this is bunching. Aircraft are grouped together in batches and landed or sent off. This results in tiny peaks within the inbound or outbound periods. The peak in the relative heading at 2:30AM is here also visible as negative range rate spike. This confirms the assumption that two aircraft are flying in about opposite direction.

A couple of interesting points are chosen to further analyze the behavior of the ASQ metrics. The points are highlighted with dashed red lines in Figure 6.24 and Figure 6.23. The first point is at 2:30AM where a minimal number of aircraft exists. The second point is at 5:30AM, just before the number of aircraft soars to daytime levels, the range rate shows a negative range rate here. The third point is to

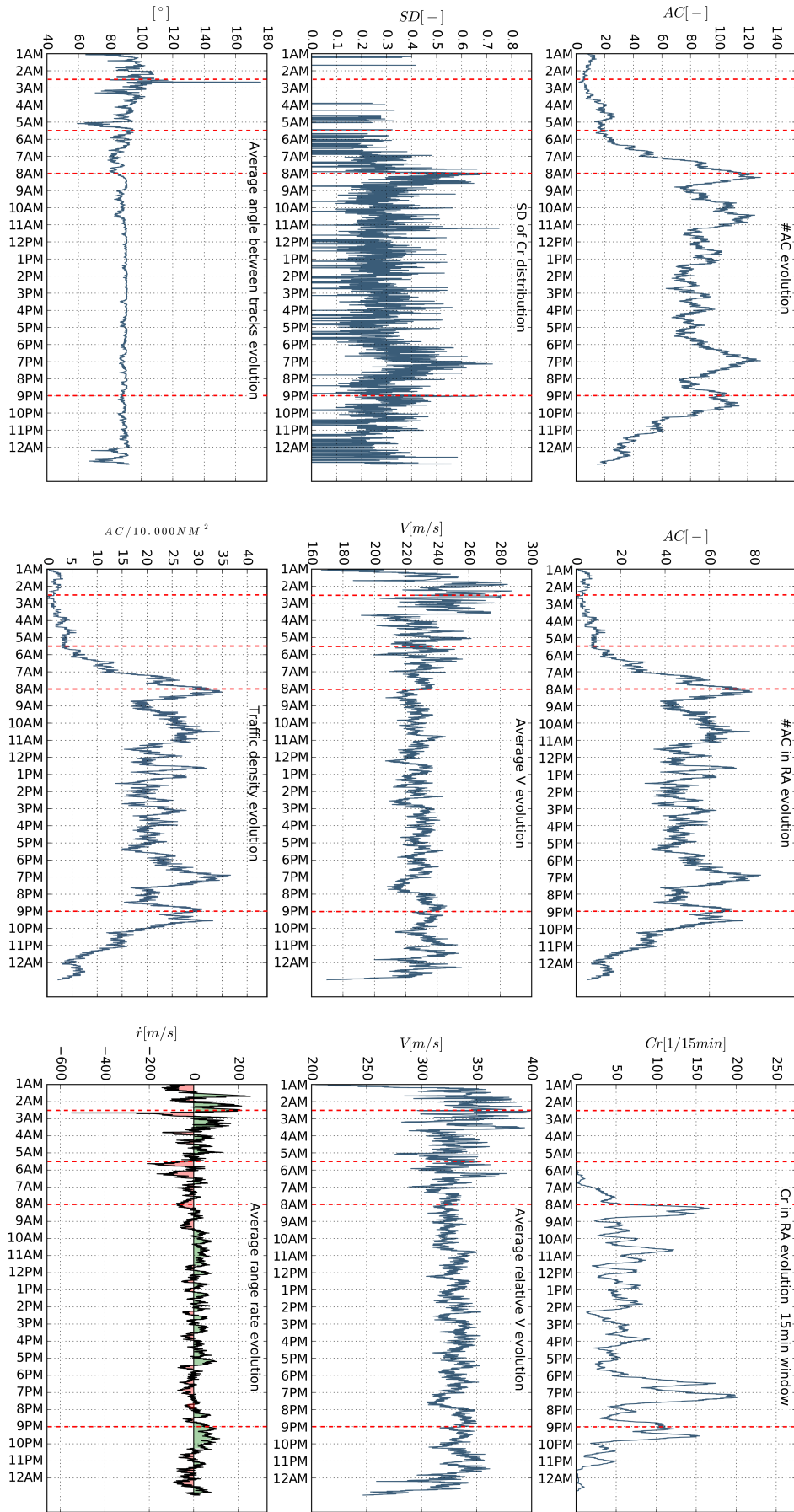


Figure 6.23: Jan 10th 2017, evolution of properties

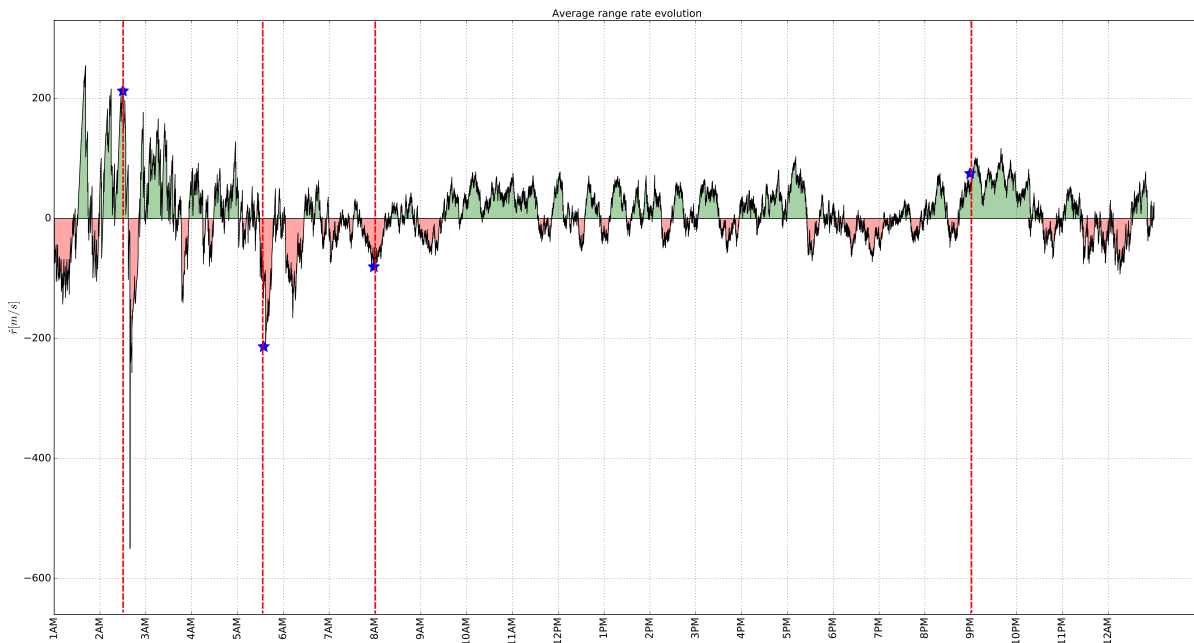


Figure 6.24: Jan 10th 2017, evolution of range rate

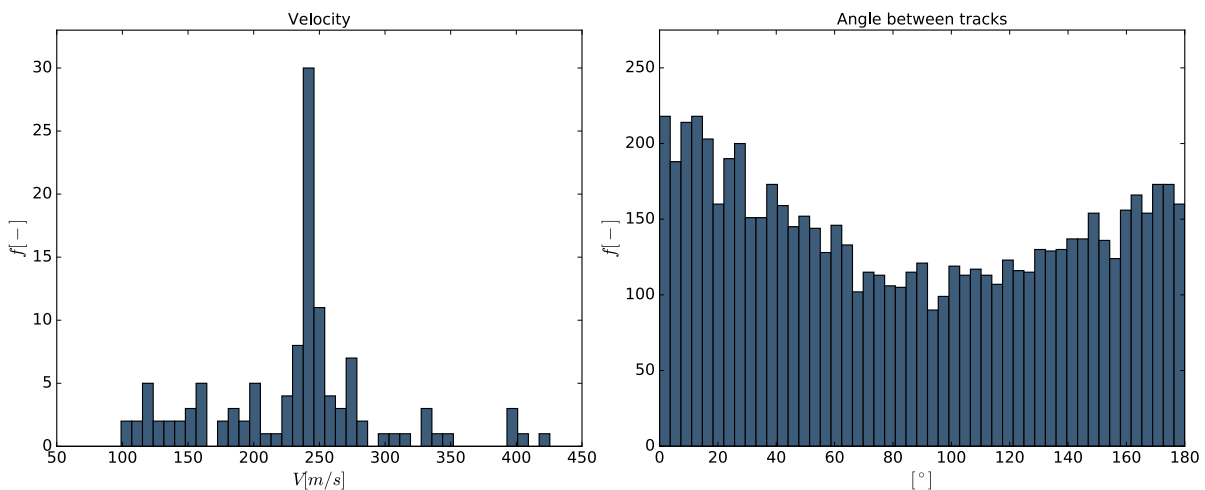


Figure 6.25: Jan 10th 2017, direct geometric properties at 8AM

be found at 8AM when the number of aircraft reaches nears the maximum of the day. The last point is at 9PM when there is again a peak in number of aircraft but now the peak is outbound so the range rate is positive.

Figure 6.26 shows ASQ values for these selected points of interest. The first point at 2:30AM shows a minimal number of aircraft, the number of aircraft is not directly readable from the ASQ plot but there are no outliers so that at least limits the amount of aircraft involved. The situation is quite good according to the ASQ plot, with very little negative values. At 5:30AM the range rate is mostly into the negative values, a high amount of aircraft pairs do have small ASQ values which is good, meaning the traffic situations are not too severe. There are only a few outliers which show more serious situations. At 8AM traffic has increased a lot, most of the aircraft pairs show positive values but there are a good amount of negative ASQ values and a mean below zero. This can be linked to the negative range rate of this inbound peak. The 9PM ASQ box plot shows a mean shifted way more towards positive values which is due to the fact that this point is in an outbound peak with converging traffic.

The distribution of the conflict rate shown in Figure 6.27 gives us little additional information. It is clear that when the traffic density is low, before 8AM the conflict rate is zero for all pairs but when the

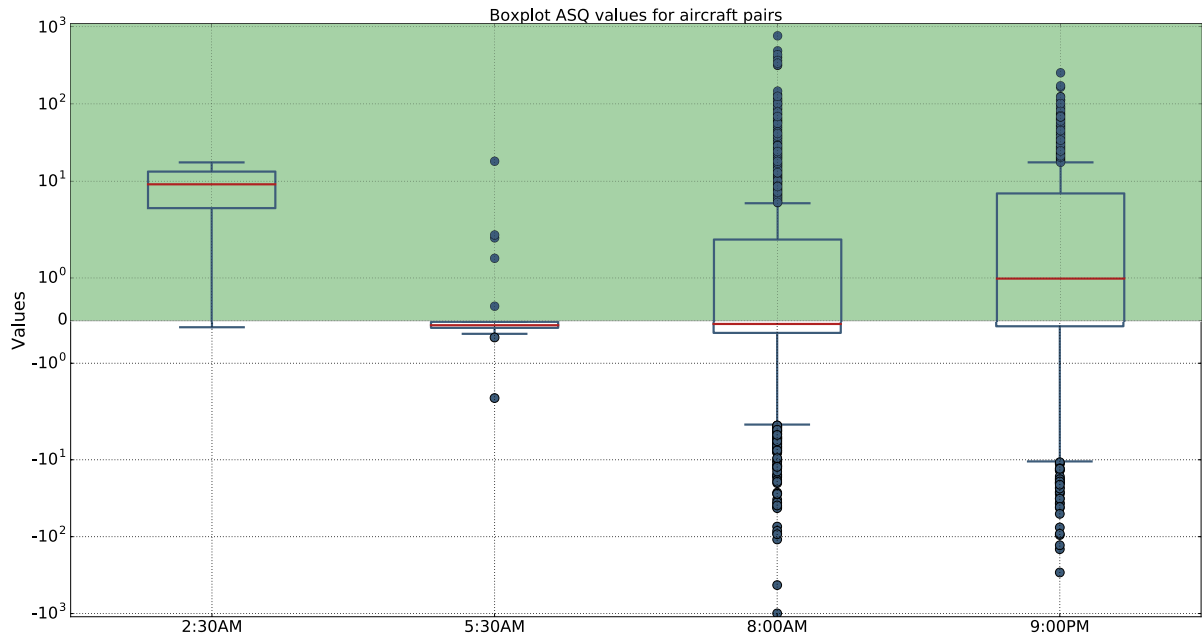


Figure 6.26: Jan 10th 2017, ASQ

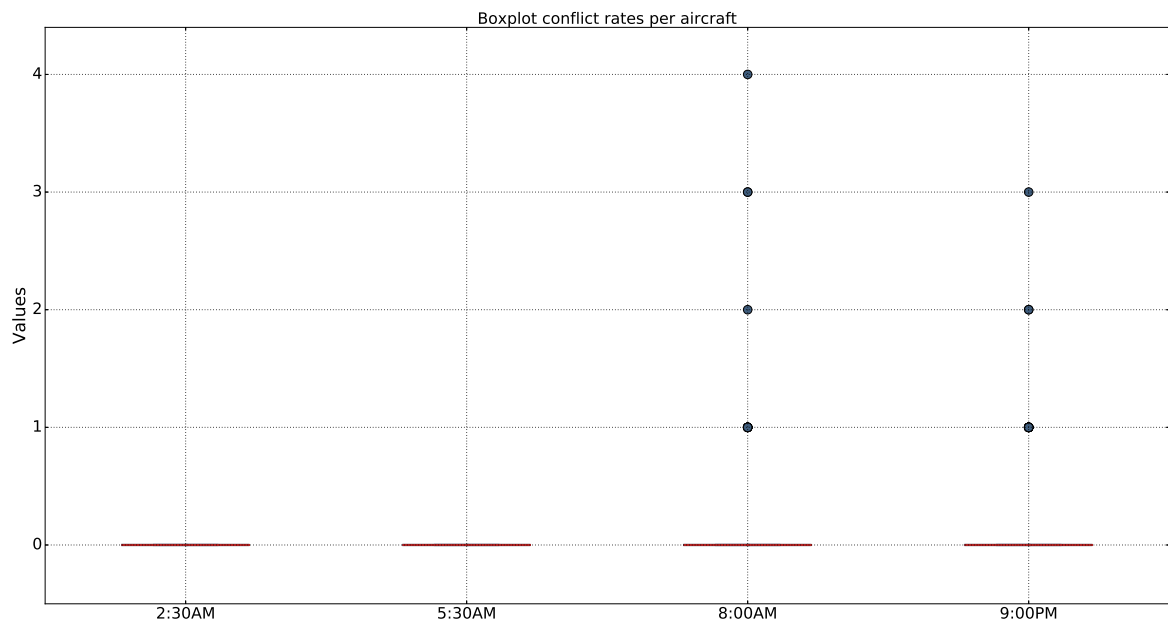


Figure 6.27: Jan 10th 2017, Conflict rate

traffic density goes up conflicts do start to occur, at 8AM there are even aircraft who are in 4 conflicts at the same time. These are a group of aircraft landing in close succession. Guided by an ATCo the pilots do not need to resolve these conflicts. This bunching of aircraft can also be seen in the simulator screen capture in Figure 6.22

The direct geometric properties shown in Figure 6.25 show the involvement of an ATCo. The relative bearing is clearly grouped, meaning aircraft are flying along predefined routes. This is a clear difference with the random generated traffic properties shown in Figure 6.1. There is also a peak of aircraft flying at about 240m/s this is most probably the cruise speed for a large portion of these airplanes.

7

Discussion

This chapter discusses the overall results from chapter 6 and how well the actual concepts brought forward in chapter 4 stood up to the validation discussed in chapter 5. The research objective and hypothesis stated in chapter 3 are checked. The research objective stated: Find a metric to compare air traffic situations or scenarios in a defined airspace, based on the geometry of traffic patterns, without the need for traffic simulations over time.

7.1. Geometric property distribution as a metric

The first category is the distribution of direct geometric properties as described in subsection 4.3.1. These properties are the distributions for the velocity, relative velocity, relative distance, relative track angle and range rate. These results showed no real surprises. This is evident from for example Figure 6.7 where for the super conflict a trivial distribution of the relative track angles, relative velocity and range rate is visible. They only show the setup of a scenario or a simple concentration of data points as seen in Figure 6.25 where a much used cruise speed is visible as well as a grouping of the relative track angles indicating a structured route system. Although this might be considered interesting information about traffic in an airspace, it is not usable as a tool to compare traffic situations. The amount of information carried by the shape of these property distributions is just too low in most cases. Information is missing on convergence of traffic or CPA. The exceptions are a few synthetic scenarios where patterns in these distributions are so extreme that it could still be used to compare to other similar synthetic scenarios. The goal is thus only partially achieved in a few extreme cases, therefore this concept is discarded as a valid method.

7.2. Extrapolation of traffic properties as a metric

In the second metric category an extrapolation of geometric traffic properties is made. This results in a known CPA for each aircraft pair accompanied with a tCPA and dCPA. The metrics investigated in this category are the range vs tCPA, range squared vs tCPA, range rate vs tCPA and dCPA vs tCPA. As discussed in section 6.1 the density plots only convey little information about the actual traffic situation. This is visible in the density plot in Figure 6.4. Variations in the plots are mainly visible when the number of aircraft in the area changes by a large amount. The outliers in the different plots do give some meaningful insight. Both types of outliers are made visible here. Aircraft moving very slowly towards each other are visible on the range vs tCPA plot while aircraft rapidly approaching their CPA are clearly visible in the range rate vs tCPA plot. This metric category is far more usable as a tool to compare situations than the distributions of geometric properties. Unfortunately this representation is not easy to use and it needs quite a bit of knowledge on the underlying systems to correctly interpret the metrics. For example the dCPA vs tCPA metric could indicate problems in the airspace if a lot of points are close to the origin. However this could also be the case in a highly efficient and safe airspace like a structured route and layered airspace design. These metrics alone are thus not enough to paint a robust picture of the traffic situation. This is in part because different elements which are important to each individual conflict, like the dCPA and range rate, are represented separately and not linked in the data.

7.3. Combination of traffic properties metric

The previous section was on the right track by using the dCPA, tCPA and range rate to represent a traffic situation but the presentation in different plots gives no simple metric but a just a large amount of data to be interpreted by the user. This third category attempts to combine these metrics in a single easy to use metric, the airspace quality. The setup of the equations is described at length in subsection 4.3.3. This results two main equations to calculate the metric. The first calculates the severity of a traffic situation between two aircraft using the dCPA, tCPA and range rate. The second is a simple level of airspace use, in this case represented as the number of aircraft per area or volume. The combination of the properties results in a simple representation of the overall quality of the airspace. This is shown by a distribution of the severity level of traffic situations for each aircraft pair. The severity level can be represented by a frequency plot or a box plot. In most cases the box plot gives the best overview of the situation. The second part of the metric, the usage level, is represented by a single value.

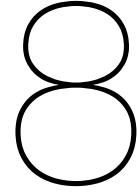
Because of the manner the ASQ severity level equation is set up there are some limitations to this method. First of all there are positive and negative severity levels, negative values mean the aircraft in the pair are converging which is unwanted. The positive values mean they are diverging, thus a safe situation. The actual value of the positive ASQ values is of no importance as this concerns a CPA which has passed. That's why the mean is never calculated for the ASQ only the median is of importance. The median in this case represents the amount of aircraft pairs diverging opposed to the ones converging. If for example in a scenario of 10 aircraft one pair has a very positive ASQ value the mean of this scenario would be influenced towards a more positive value. This has however no meaning at all since the actual value of positive ASQ values is useless.

Secondly the ASQ box plot on its own does allow two traffic situations to be compared. Looking at the ASQ values of 24 hours of real traffic in Figure 6.26 one might assume the 5:30AM situation is worse than the 8:00AM situation since it has a lower ASQ severity level median and a bigger percentage of the values are negative. However, if one looks at the evolution of properties in Figure 6.23 the usage level is a factor ten higher at 8AM. This tells us that while the percentage of aircraft being in unwanted situations is lower at 8AM, it is probably a worse situation as the maneuverability would be diminished at higher traffic density levels. This is also supported by the conflict rate being much higher at 8AM as is seen in the evolution of properties in Figure 6.23. The third limitation to the ASQ metric is the sensitivity to tCPA and dCPA values around zero. This is described in subsection 6.2.1.

$$\text{Severity of a conflict} = \text{sgn}(\dot{r}_i) \left(\frac{tCPA_i}{tlookahead} \frac{dCPA_i}{SEP} \right)^{\text{sgn}(\dot{r}_i)} \quad (7.1)$$

$$\forall tCPA_i, dCPA_i, tlookahead, SEP > 0; \dot{r} \neq 0$$

Looking at Equation 7.1 it is clear that when the range rate becomes negative the dCPA and tCPA factors move to the denominator. So for very small dCPA and tCPA variations around zero the changes in the ASQ value become very large. This is no problem when comparing one aircraft pair at the same tCPA but this sensitivity potentially influences the results in other traffic situations. Depending on the simulator used, the update interval and the accuracy of the time steps the sensitivity to the tCPA could vary.



Conclusion

This research project set out to find a metric to compare air traffic situations or scenarios, based on the geometry of traffic patterns, eliminating the need for traffic simulations over time. Three categories of metrics have been investigated.

First of all the direct geometric properties. Distributions of aircraft velocities as well as relative velocity, relative distance, angles between tracks and range rate between aircrafts have been investigated. The most telling of them all appeared to be the angle between tracks distribution, this metric clearly showed if traffic was routed along predefined routes. Unfortunately this is not enough to compare two traffic situations. The velocity distribution added some information in certain cases that could point to a certain type of aircraft or cruise speed being common or not. The second category used extrapolation of the geometric properties over time to arrive at the tCPA, dCPA and range rate. Plotting these metrics against each other already gives a better insight in the overall traffic situation in an airspace. It provides information about the density and clearly shows outliers being aircraft moving towards each other slowly on almost parallel tracks, or the opposite, aircraft flying towards their CPA at incredible rates. Although a lot of information is to be found in these plots, it is also up to the reader to interpret these different plots and combine the information. This requires in-depth knowledge about air traffic systems and even then it is easy to overlook certain aspects when interpreting this amount of information. Therefore a third category of metrics is tested where these promising second category metrics could be combined to an easy to use new metric. In the third category one concept is put forward and tested. The ASQ or airspace quality is defined. It exists out of two parts. The first part is an airspace usage level which is simply the number of aircraft per volume. And the second part is the severity level of an individual traffic situation between two aircraft. This severity level can be calculated for all aircraft pairs and the distribution of these levels is what is of importance for this metric. The severity level for an aircraft pair is calculated by:

$$\text{Severity of a conflict} = \text{sgn}(\dot{r}_i) \left(\frac{tCPA_i}{tlookahead} \frac{dCPA_i}{SEP} \right)^{\text{sgn}(\dot{r}_i)} \quad (8.1)$$

$$\forall tCPA_i, dCPA_i, tlookahead, SEP > 0; \dot{r} \neq 0$$

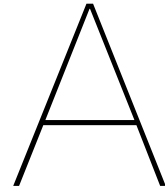
The outcome is plotted in a box plot to easily represent the spread and mean of the ASQ values as well as the mean. Multiple box plots can be shown in one figure to be able to compare different traffic situations. The values of positive ASQ levels can be discarded as they represent a CPA in the past that might never have happened. The amount of positive values compared to negative ones is important and is shown by the mean. This shows if a traffic scenario is diverging or converging. There is one pitfall to this metric and this is the sensitivity towards tCPA and dCPA values around zero. Small changes very close to zero make the ASQ value change significantly. This could change the perception of the traffic situation in the box plot. Small changes for dCPA do have a large impact in real life as well, they can be the difference between a collision or a near miss. But this is not the case for small tCPA values. They will exist for every converging aircraft pair at some point. Luckily this is easily fixed by lowering the accuracy of the tCPA values and simply not allowing very small values near zero to

exist. To recap, the ASQ metric shows promise but more refinement is needed to make it a usable and robust tool. At the very least, one could say that the extrapolation of properties, the tCPA, the dCPA and range rate, are instrumental in finding a metric to compare air traffic scenarios without the need of running through a traffic simulation.

9

Recommendations

This research project attempts to find a method to compare traffic situations in an airspace based on geometric air traffic properties. The ASQ metric concept is a step in this direction although it has some shortcomings. What is clear from the entire research is that the tCPA, dCPA and range rate are metrics that convey much information about a situation. It is a matter of finding the right combination of these factors to come to a robust method. Solving the sensitivity issue of tCPA and dCPA values around zero would go a long way towards a robust method. Dealing with positive ASQ values in a better way would make the presentation of ASQ much clearer. This is all work that could be done to improve the current concept. But there might be totally different possibilities using the tCPA, dCPA, range rate and maybe other factors that haven't been considered. During this research it became clear that only using the geometrics properties listed in Table 4.1 will not be enough to make a robust classification method. The tCPA, dCPA and range rate are properties derived from the geometric properties. They carry more information while making acceptable assumptions about geometric traffic properties in the near future. They are not computational intensive and therefore the prime candidates in the search for a better tool to classify and compare air traffic situations.



Project proposal

Project proposal and plan

By Pieter J.S. Danneels

Control and Operations: Air traffic management and airports - 1397230

A.1. Executive summary

This project proposal and plan outlines the necessary facets to try and answer the following research question: Can a metric for airspace design quality be found based on the geometry of traffic patterns. The literature survey in this report describes the already performed research in this field that could be relevant over the course of the project. The focus of the relevant research is on the current complexity metric which has some similarity to the metric and property this research tries to find. This research project is a theory developing project and this type of research has some implications on the method and planning. A theory that pans out to be viable might quickly lead to a validation phase and an answer to the hypothesis, but it might just as well turn out not to be a valid theory or method pushing the project back to square one. This results in several iterations or rounds being incorporated in the planning. The project will make use of the BlueSky software to simulate air traffic[9], perform the necessary tests and generate the results. This tool is written in Python and actively maintained by the department. New methods will have to be programmed to generate the required data.

A.2. Introduction

The use of our airspace is rapidly increasing with an ever more varying mix of aircraft. From small drones to giant jumbo jets. To maintain a safe and efficient flow of air traffic new methods of air traffic structuring are and will be developed. Developing such a new structuring of airspace usually involves massive simulations of air traffic consuming many hours up to even weeks. Each iteration of such an airspace design then again needs the extensive simulations significantly slowing down the design process. Finding a property based on the geometry of traffic patterns could change this. Such property could provide the designer with a simple and fast method to test his airspace design and iterate much faster.

Currently most commercial aircraft fly according to the structured route principle. They follow pre-defined routes making traffic easy to control for air traffic controllers. Unfortunately, this also means that aircraft are not flying a direct route to their destination. If aircraft do fly a self-determined and more direct route they are applying random navigation techniques. In the case of random navigation the pilots have to rely more on self-separation technologies like the airborne separation assurance system instead of separation by the air traffic controller. Depending on how exactly air traffic evolves into the future the role of the air traffic controller will change significantly or not exist at all.

The metrics and property this project sees to develop or uncover are based on the geometric properties of traffic patterns and are closely related to the well-researched complexity metrics. But while the complexity metrics try and define a metric for air traffic controller workload in different traffic scenarios the newly to be developed metric will not approach this problem from the perspective of the air traffic

controller. It is therefore necessary to find this new metric to be able to classify new airspace designs according to their ability to support self-separation of aircraft instead of ATCo supported separation.

A.3. State-of-the-art/Literature Review

This particular research project aims to develop a new theory. So the first part of the literature survey will be to actually test if this is indeed a new concept and this research or a very similar research has not been performed before. After an extensive search the author of this proposal could not find any published research which has the same goal as this project. Although there is some mention of a need for this kind of research when a paper mentions that a geometric approach to air traffic complexity is important because it cuts out the ATCo and provides a measure of complexity regardless of the human factor. This is exactly the basis of this proposal, since this research anticipates the change of the ATCo roll and the shift of responsibility from ATC to the cockpit[13]. Thus the necessity of this research project is confirmed.

Next a survey is held into similar subjects that might help in understanding current ways of measuring air traffic scenarios and their difficulty to navigate or control them. The main area where research has been done and which might be relevant is air traffic complexity. Air traffic complexity is a measure of how difficult an air traffic scenario is to control. There is no one definition for air traffic complexity but in most cases it's broken down in two major facets[17]. The first being the human factor and the second being an intrinsic property of the traffic geometry or air space design. Many papers have tried to determine a measure for air traffic complexity and several are well known throughout the research field. These well-known metrics are the static and dynamic density[13]. These metrics are better than the simple number of airplanes in a sector used by many operations centers today[13]. Next to these basic metrics some other attempts have been made to determine complexity based on geometric features. For example, by use of the Kolmogorov entropy[6] or Lyapunov exponents[17]. Unfortunately, these methods also have some shortcomings as has been pointed out[15].

More important sources which could be an inspiration are investigated in this literature survey[10][11][14][20]. The geometric properties already investigated, their downsides and upsides and which areas lack prior research all came to light.

A.4. Research Question, Aim/Objectives and Sub-goals

The main research question for this project is:

Can a metric for airspace design quality be found based on the geometry of traffic patterns? This has to be subdivided in sub questions, since this is a fairly theoretical research more sub questions will arise or some of them might change but to start the research off these will do:

- Can a metric for airspace design quality be found based on the geometry of traffic patterns using a combination of the number of conflicts and relative velocity properties.
- Can a metric for airspace design quality be found based on the geometry of traffic patterns taking into account range rate between aircraft.
- How does the metric perform on layered airspace design.
- How does the metric perform on the current airspace structure above the Netherlands.

The objective of this research is to find a metric for airspace design quality based on the geometry of traffic patterns. Such a metric would enable one to test the quality of a certain airspace structure without the need for extensive simulations but rather by simple calculations using properties of aircraft flying in that particular type of airspace structure. The outcome of this research could provide a quick way to test an airspace design saving much time in the airspace design process.

A.5. Theoretical Content/Methodology

While a lot of research exists on airspace complexity there is none trying to answer the above research question. Nonetheless air traffic complexity research has lots of similarities with this project and can be used as a theoretical basis and inspiration for the metric developed.

Several papers [11][12][10][20][17][13][14] state complexity methods which could potentially be used to find the metric we are using. However, the most promising of these methods is mathematically quite complex[6] and the author of this research hopes to come up with a simpler and more elegant method.

The research will be a combination of a theory-developing research and a theory-testing research. Different theories will be developed as to what the metric should be composed out of. Each of these methods will be tested as described in the next chapter to see how well it performs in synthetic and real scenarios as described in the sub research questions in the previous chapter.

It is assumed that each round of method testing will give rise to new questions or allow for improvements to the method to be made. Therefore 3 major rounds are scheduled to iterate the methods.

A.6. Experimental Set-up

As described in the previous section, the experiment will be to test the developed theories. Since it is obviously not possible to implement a new airspace structure as an experiment the only possibility is to perform simulations. The BlueSky simulator is an open source tool developed at the faculty used for air traffic simulations. It is comprised of different modules adding different levels of functionality or realism to the simulator. The modular structure makes it fairly easy to build your own module performing tests on the simulation. In the case of this project the module will perform the calculations for the metric being developed. As described before in this document there is a need to test the metric against synthetic traffic scenarios and real world scenarios. The BlueSky simulator allows for this. Synthetic traffic patterns can be created to quickly figure out what happens to the metric in specific situations for example: Two aircraft flying towards each other on the same track and flight level. Performing these simulations does require a good understanding of Python since this is the programming language used for BlueSky. As well as the Python Numpy library needed to perform the calculations in a timely fashion. Of course an in depth knowledge of the simulation tool is also necessary, so at the start of this project object based programming, Python, Numpy and BlueSky have to be studied in order to be able to perform the necessary simulations.

A.7. Results, Outcome and Relevance

At one hand the theory developing research will produce theories or methods on how to calculate the required metric. This theory will be tested in the simulations. The simulation will result in the metric on a single point in time in a traffic scenario or changing over time as the traffic moves through the test sector. Not only different types of traffics will have to be tested but a statistical test will have to be done to determine how significant the results are if at all. Ideally we would like to find a theory that determines the quality of the airspace design regardless of the type of traffic scenario unfolding in the airspace. So the results will have to be interpreted very carefully in order to say something meaningful about the airspace quality design while only looking at a particular traffic pattern in that airspace.

A.8. Project Planning and Gantt Chart

In this section the reasoning behind the planning will be elaborated on. Please see the attached Gantt chart for an overview.

The project is started off with a 24-day orientation phase. In this phase 4 days are reserved for reading into the assignment and some very shallow literature survey just to see what this project might entail. The other 20 days are reserved for learning Python as this is not a programming language I used before and learning to work with the BlueSky simulator.

After that an initial first test phase is performed. This phase both continues on the previous phase by diving deeper into BlueSky while also testing some initial simple theories. This phase is crucial to be able to make a realistic planning for the rest of the project. 24 Days are reserved for this because a first real programming experience with a new programming language and program tend to take up quite some time.

In order to then continue the research, we first need to do an extensive literature survey and make a project plan on how to attack this project. 28 Days are reserved for this.

Some theoretical work has to be done after the literature study to actually develop the methods to be tested later. 10 Days are reserved for the first round of theory development.

Two iterations have been planned each taking up 23 working days. Each round can comprise of more than one theory; a round is more like a batch of theories to be developed. This can be one main theory and several variations upon that. Note that the programming of methods for the two iteration rounds are a little shorter than the first simulation round. It is anticipated that programming tests in the simulator will take less time with every iteration. Nonetheless the needed time does not decrease by a lot because it is entirely possible that extensive new modules have to be programmed for new tests.

At the end about 20 days is reserved to write the actual thesis, this includes generating extra results from previously performed methods.

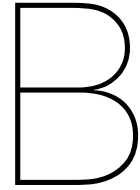
The current planning sets the total number of working days for this project at 184 days. This is about 37 weeks and about the proposed project length of 38 weeks.

The author of this proposal believes this planning to be fairly realistic although he is aware of the fact that while dealing with programming and debugging delays quickly arise and tried to incorporate this as much as possible in the planning. Since the proposed project time is not exceeding the 38-week mark in the planning there is some room for unforeseen delays or an extra round of tests.

A.9. Conclusions

This research project aims to find a geometric property to an air traffic situation able to put a value to a severity of a traffic situation. This closely relates to the already investigated air traffic complexity metrics but does not account the human factor of the air traffic controller. It is thus more tuned towards developing a theory applicable in the development of tools to aid or automate decision making, centralized or in the cockpit. A method able of providing a good objective measure of the air space quality is still non-existent and will be ever more desired by the ATM community in the future. Thus making this and similar research certainly relevant.

The tools used for this research will be the Python programming language used in extending the BlueSky simulator. With this programming some caution has to be taken to constrain the development of the tests and not get caught up in the active development of the BlueSky simulator. As well as the fact that often much time is spend programming and debugging, so this has to be carefully considered in the planning and during the project. The planning of this project tries to account for the fact that this is a theory developing research project. This results in the project being divided in several rounds allowing for multiple theory developing and testing opportunities.



Literature Review

Literature Review
By Pieter J.S. Danneels
Control and Operations: Air traffic management and airports – 1397230

B.1. Abstract

This paper presents an overview of the available research in air traffic management and more particular in the field of air traffic complexity. It focuses on the intrinsic properties of air traffic rather than the human factors. Other factors are also considered in an attempt to provide an broad basis to answer the following question: Can a metric for airspace design quality be found based on the geometry of traffic patterns?

The ever changing composition of air traffic as well as the growing number of aircraft contribute to the need for new air traffic control methods. These new methods and systems will require tools to measure the severity of an air traffic situation and thus the quality of air space design. This paper shows the need for this research and the possible basis for it.

B.2. Introduction

Unlike literature surveys supporting the design of a system this survey should support the development of a theory. A design supporting survey might try to compile as much relevant technical information as possible to set design parameters for the new system. Theory developing surveys are alike in some aspects but still a bit different. Since there is no actual technical system to be developed the focus of the survey turns from finding relevant technical data and system descriptions to finding similar research. The survey will in this case shape a general picture of the research field. It will help provide context for the research question posed and it will try and find similar work with relevant parts that might be usable for this project. Next to providing context in the field of ATM research this survey will look for relevant work in two main fields. First of all it will try to find as much methods and ideas for complexity metrics as possible. Although complexity metrics are not the same as airspace design quality metrics what we are trying to find it is somewhat comparable. The approach is very different though, complexity metrics research tries to find a measure of complexity for the ATCo. While the metric sought by this research is independent of the ATCo and a property of the airspace itself. Nonetheless, this complexity research does provide valuable constructs, methods and ideas usable in this project. The second type of literature to be studied is to be found in the field of statistical analysis. Finding the right statistical tests to analyze the simulation data is critical in order to come to a conclusion. This part however will be rather small at the start of the project but might expand if new tests are required during the course of this project.

B.3. State of the art/Literature review

First of all, a need for this research has to be proven. Kopardekar[13] states that complexity metrics exist out of two facets: An intrinsic complexity related to traffic structure and a human factor aspect

related to the controller itself. The authors continue to state that the intrinsic complexity related to traffic structure is the most relevant for a highly automated ATC system. From [20] we can conclude that an ever more varying mix of aircraft will exist, ranging from UAVs to jumbo jets. This would put an enormous strain on the current ATC system. Luckily Bilmoria[4] show the advantages of new automated systems, be those centralized or decentralized. The combination of these factors provide an opening for this research.

In order to measure the quality of an airspace a metric has to exist in order to classify airspace, and determine capacity limits. Currently ATC centers use the Monitor Alert Parameter (MAP) which has no standard definition and has no real scientific basis. It often incorporates the number of aircraft in a sector and some subjective human factors[13]. So attempts have been made at better metrics, for example the static density (SD) and dynamic density (DD)[6]. These are already big improvements over the simple number of aircraft[13] but still are not able to encompass the entirety of air-traffic complexity[15]. Delahaye tries to extend these metrics with a topological entropy called the Kolmogorov entropy[6] and later extends this even further with the Lyapunov exponents[17]. Although Michon[15] states that there are still problems with these new theories and how they describe the air space quality. Fortunately there are also some other approaches which could inspire new methods. For example Jardin shows the relation between conflict rate and air traffic density[12]. This serves as the basis for a relation between conflict rate and air space capacity[10]. The case described though is a very specific application of the relation on the layered airspace system[20]. Moving on there are even more approaches to be found, Idris tries to approach the issue from the perspective of maintaining trajectory flexibility and does provide some valuable insights[11]. Lee compiles a method where an area is defined and aircraft entering or leaving this area are considered. With this method Lee is able to plot interesting complexity maps[14].

The previous material provides a basis for the start of new research but to actually perform this research tools are also needed. The BlueSky simulator is the tool of choice, it is an open-source tool developed at the faculty of aerospace engineering of the Delft university of technology[9]. The academic backing of this tool and the open-source nature makes this the perfect tool to simulate and test methods and theories on air traffic complexity or airspace design quality.

B.4. Analysis

While complexity metrics can provide valuable insight[13] they also have their shortcomings[15]. The ever more varying mix of aircraft[20] and the assumed shift of responsibility from the ATCo to the cockpit[17] or the automatization of ATC[4] requires new metrics to be developed independent of human factors[17] or control entity. This thus creates an opening for this research project to exist.

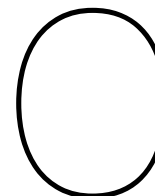
Many papers exist trying to define air traffic complexity but not one good metric is found. This is in part due to the fact that air traffic complexity generally incorporates the human factor of the air traffic controller. With the future of air traffic control in mind it would be prudent to try and find a single metric which only takes into account the geometric properties of traffic in order to measure its level of severity. This could then be used in design of airborne separation assurance systems or centralized automated air traffic control systems. Even though previous research did not reach this goal it does provide the needed tools for a new research project which might be capable of succeeding at this task.

B.5. Discussions and Conclusions

The need for the research presented in this paper is based on the fact that air traffic will grow significantly and that in turn air traffic control systems will have to change drastically. It also assumes that air traffic control systems will change according to the research presented. Meaning, the responsibility will shift from air traffic control centers to the cockpit by use of airborne separation assurance systems or the air traffic control will be centralized and highly automated. But since many different regions in the world develop their air traffic at different rates and with different focuses one might argue that the proposed research might at least be relevant in some part of the world at some point in time. Even though the assumptions prove to be incorrect for the European and/or US airspace which dominate this research field.

With the future in mind the role of air traffic control will change. Thus the tools required to design the new systems will differ from the current. In that light this paper showed a need for new research into a new and human independent form of air traffic complexity, it could be called air space design quality since the quality arises from its intrinsic properties. The paper shows the evolution of air traffic

complexity and its problems. But while this research might not be directly applicable to future concepts and systems it is a very valuable basis to a new method able of supporting this future needs. The author of this paper also argues that the BlueSky simulator is the preferred tool to use in this particular research field.



BlueSky modules

BlueSky is an open source air traffic simulator developed mainly at the control and operations department at the faculty of aerospace engineering at the Delft University of Technology. Most of the project is coded in Python 2.7 with the exception of a few libraries doing calculations using faster C++ code. The project has a general simulation core and a choice of two GUI versions. One using Qt and one using pygame. The pygame version exists to support older non OpenGL 3.3 supporting hardware. This also results in a limitation in resources used as the pygame is only available for 32 bit Python. The software is set up in a modular fashion allowing the users or developers to add new modules expanding the functionality of the simulation suite.

C.1. Coding standards

In any software project worked on by multiple people a variety of rules have to be set in order to code in a uniform matter and be able to merge code easily and efficiently. The main code repository is maintained on Github by Prof. Hoekstra and Dr. Ellerbroek. The PEP8 style guide is to be adhered to whenever possible. Working with Git also requires some getting used to. Git is a distributed version control system where a set of commits is merged between branches or forks, a fork is a branch maintained by another user. Several types of work flows are possible but a relatively easy and good one is shown in Figure C.1. The general idea is to keep deviations from the master branch of the main repository as small and contained as possible, so when a merge is performed this is done quickly and easily. In case a merge is done of big adaptations to the master branch one could temporarily first do this merge in a different branch than the master to test the adaptations and ensure no functionality is broken. This effectively becomes a testing branch.

The branches depicted in the proposed work flow in Figure C.1 can also be in a forked repository and do not necessarily need to all be within the same repository.

C.2. Overview of modules

BlueSky is a modular simulation suite allowing to easily add functionality by enabling or disabling modules. New modules can off course also be build in order to add previous non existing functionality. In order to perform all tests required by this research project a few modules are created. In the tools section the metrics, MongoDB connector and research area modules are created from scratch. In addition the synthetics module in the stack section is expanded in order to create different types of synthetics scenarios.

As also described in section C.1, the newly created code should adhere to the PEP8 style guide. Compliance with this style guide is checked with the PyLint static code analyzer. In order to make use of system resources in an efficient way classes are used with inheritance wherever is possible. Additionally nested for loops are avoided and processes able to hold the simulator are spawned in a different thread.

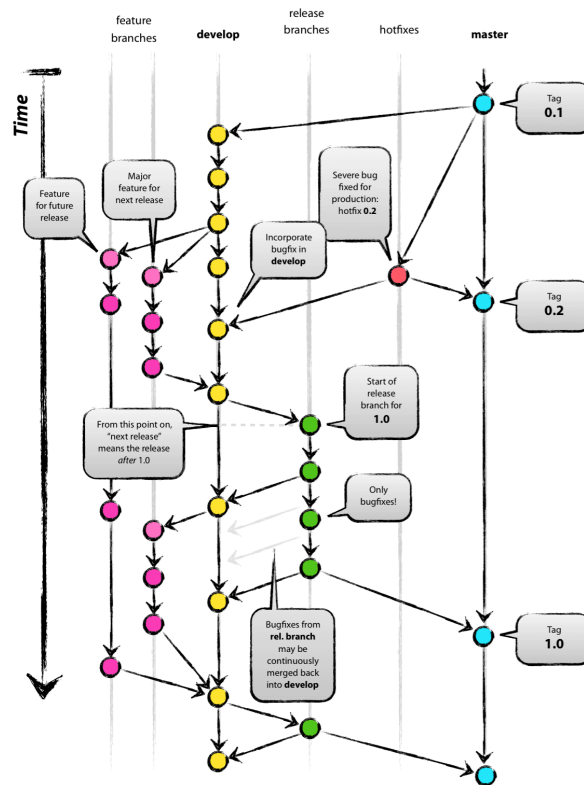


Figure C.1: A Git work flow.[7]

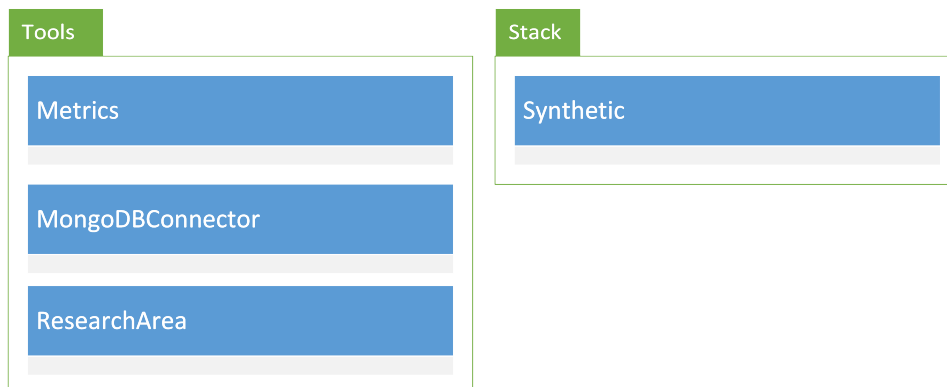


Figure C.2: Overview of modules.

C.3. Synthetics module

The synthetics module is expanded and meanwhile heavily adapted to adhere to the new dictionary style command definition.

The new commands are:

- ROW: Two angled rows of aircraft flying towards one point.
- COLUMN: Two angled columns of aircraft flying towards one point.
- HELP: Display information on usage of synthetics module.

C.4. MongoDB Connector

In order to analyze real world scenarios they have to be imported into BlueSky. The scraper described in Appendix D makes sure the aircraft motions are logged into a MongoDB database. In order to get a

set of data from the MongoDB database into the simulator a connector has to be developed. A library exists capable of talking with the MongoDB service in Python. This library is called pymongo.

Connecting to another service over IP takes time depending on the speed of the machine running the database service and the connection to the service. This would block the process and lose valuable CPU time for the simulation. To circumvent this a thread is spawned to retrieve the required data. The thread is started and a minimum and maximum time are set and passed to the thread. This minimum and maximum time define the minimum and maximum time stamp used to filter the data. When retrieving live data for example the maximum time stamp will always be the current time. When historic data is played the maximum time stamp will be the simulation runtime added to the replay start time. The retrieved datasets are then stored in a queue where they can be retrieved by the simulator thread. When the simulator thread retrieves the latest packet from the queue it empties the entire queue. Depending on the simulation update time with the database and the data retrieval time the precision of played data can be tweaked. What happens is the real traffic data is retrieved every 10 seconds as a default and in between the simulator simply extrapolates the current speed and course of each aircraft. When a new packet of real traffic data is read the geometric properties of the traffic are updated to match the real world data. On every update interval there is thus a small jump in geometric properties correcting the inaccuracies of the simulator.

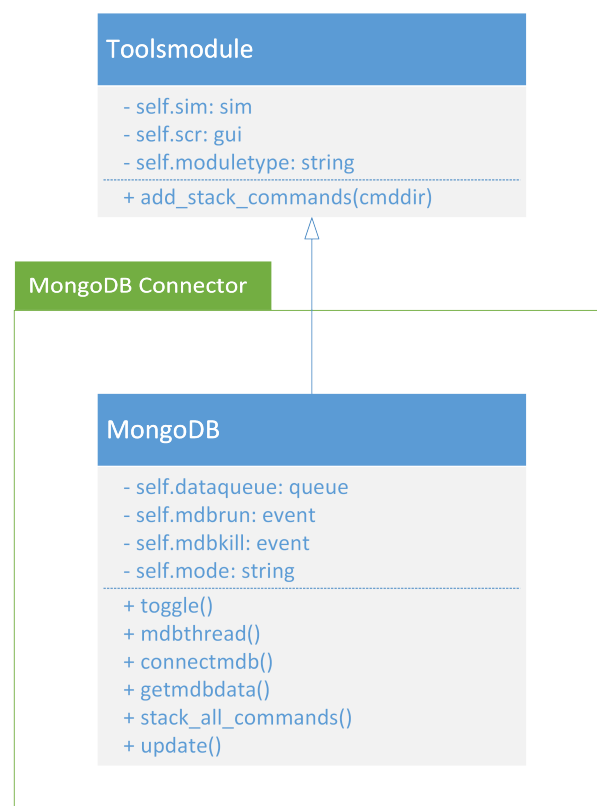


Figure C.3: MongoDB connector module overview.

C.5. Metrics module

The metrics module can be found in the tools section and is made to perform calculations on traffic data. The module is divided in several parts each having their own function which can be enabled and disabled when required. The module is set up this way because some calculations can be very resource intensive and might not be needed for certain tests.

The first big part of the metrics module is the main module file. It has one class which inherits from the toolsmodule class. The main part adds the required commands to the stack, has the update routine where the simulator lands and centralizes all configurable variables for the user.

The update routine updates all metrics data which can be found in the metrics part. One class exists

containing the standard set of geographic data which is updated first on every update cycle. Then every specific metric being a subclass of the metrics class can use this geometric data to calculate the specific metric. Since every specific metric class has the same structure the basic get and set functions are inherited from the general metric class. When all enabled metrics are updated the program then continues to the different output parts. One of the possible output parts of the metrics module is the statistics section. This can print statistical data tot the screen. The second output method is the plot method, this section provides functions to plot the metrics. Lastly there is also the log section where data can be written to a file on disk.

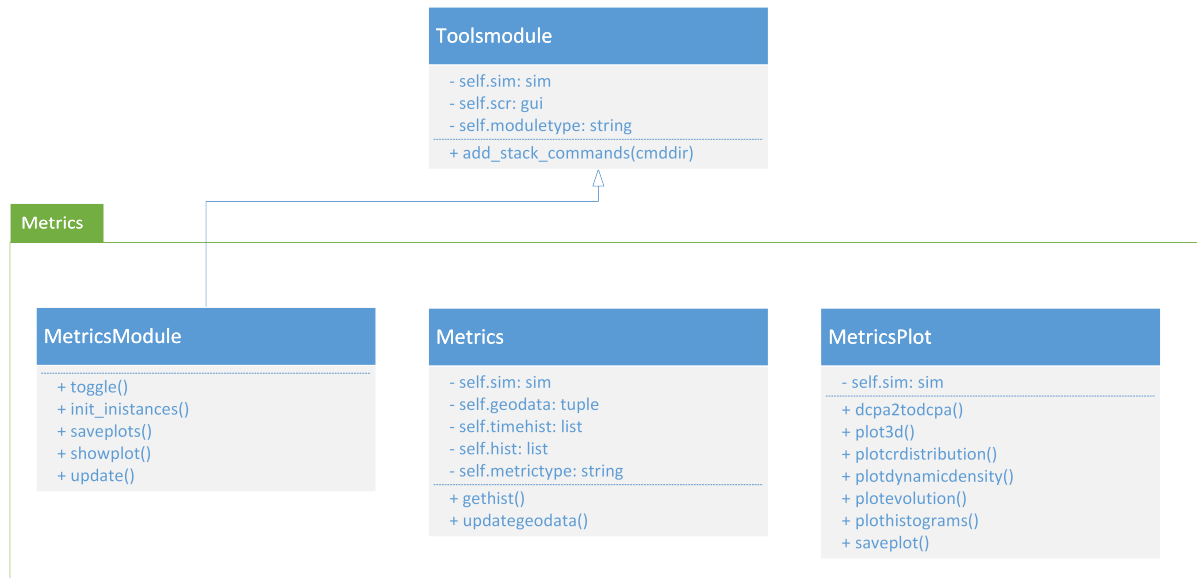
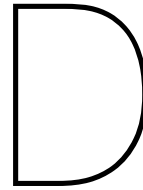


Figure C.4: Some important classes in the metrics module.

C.6. Computational restrictions

When calculating metrics it is important to realize the use of resources, especially when using a 32bit python distribution. Calculating relative data where N^2 amount of data points are created, with N being the number of AC, can consume vast amounts of memory quickly. One should therefore try to reuse such data as much as possible, store it efficiently and iterate over it as efficient as possible. This usually means the use of Numpy arrays instead of lists and the using Numpy methods instead of for loops.

When processing large amounts of aircraft it might be beneficial use a data structure which by itself says something about the object inside. For example with octrees the location of the aircraft in the data structure already contains information about the sector where the aircraft is located. This could make processing of aircraft in each others area more efficient. For example when looking for aircraft with LoS one could for example exclude parts of the database which are far apart in the structure.



Radar data scraper

In order to test the new metrics on real world scenarios, data points of real world scenarios have to be collected. The choice was made to build a scraper for flightradar24.com (FR24). Building a scraper maximizes flexibility of data collected for an acceptable amount of time spend on the development. It is also useful for future research and colleagues who wish to collect live aircraft data. The code is written in Python which is easily executable on many platforms and is made available on Github[5].

D.1. Requirements

There will be many data points logged every day, one for every aircraft movement. An suitable storage method has to be selected for this data collection. The collection needs to be able to handle millions of data points on a daily basis, it must also be possible to query the data collection pretty fast in order to show a filtered set of this data in the simulator. These queries need to be fast enough in order to not delay the simulation on simple data retrieval. The sheer amount of data and the query requirements exclude structured query language (SQL). A non-tabular database system would be better in this situation. A powerful open source NoSQL implementation is MongoDB. The document and collection structuring in MongoDB is also compatible with Python dictionary structure which will eliminate extensive data parsing while developing the connector.

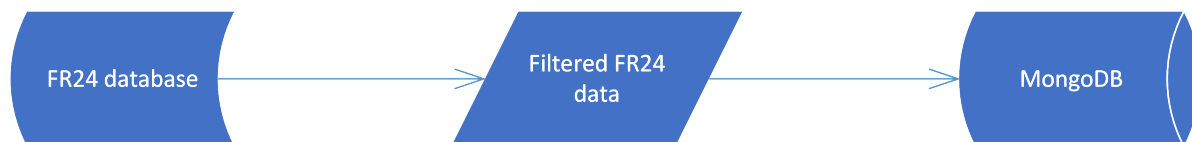


Figure D.1: Flow of data through different databases.

D.2. Software structure

Figure D.2 shows the overall process of the program. The scraper retrieves a JSON format set of aircraft movements from FR24 followed by doing some quick filtering on the data to only have valid data points. Then each data point is checked against the database if it already exists. If not it is added. Here the advantages of NoSQL come into play, the query to filter and find the latest data point for the aircraft in question is very fast and efficient in comparison with tabular databases. Both the connections with the FR24 and MongoDB database can drop because data is send to other machines over the network or simply because a process is busy. If this happens the scraper will attempt to perform the operation again. If too many failures occur an email is send to the administrator and the scraper exits. Sleep timers are added in the process to not over query the FR24 or MongoDB services. The sleep timers combined with the maximum number of retries effectively ensure the amount of request send to the FR24 service are limited. To avoid having too much overhead operations on the MongoDB server, data points are stored in a queue and executed as a bulk write operation.

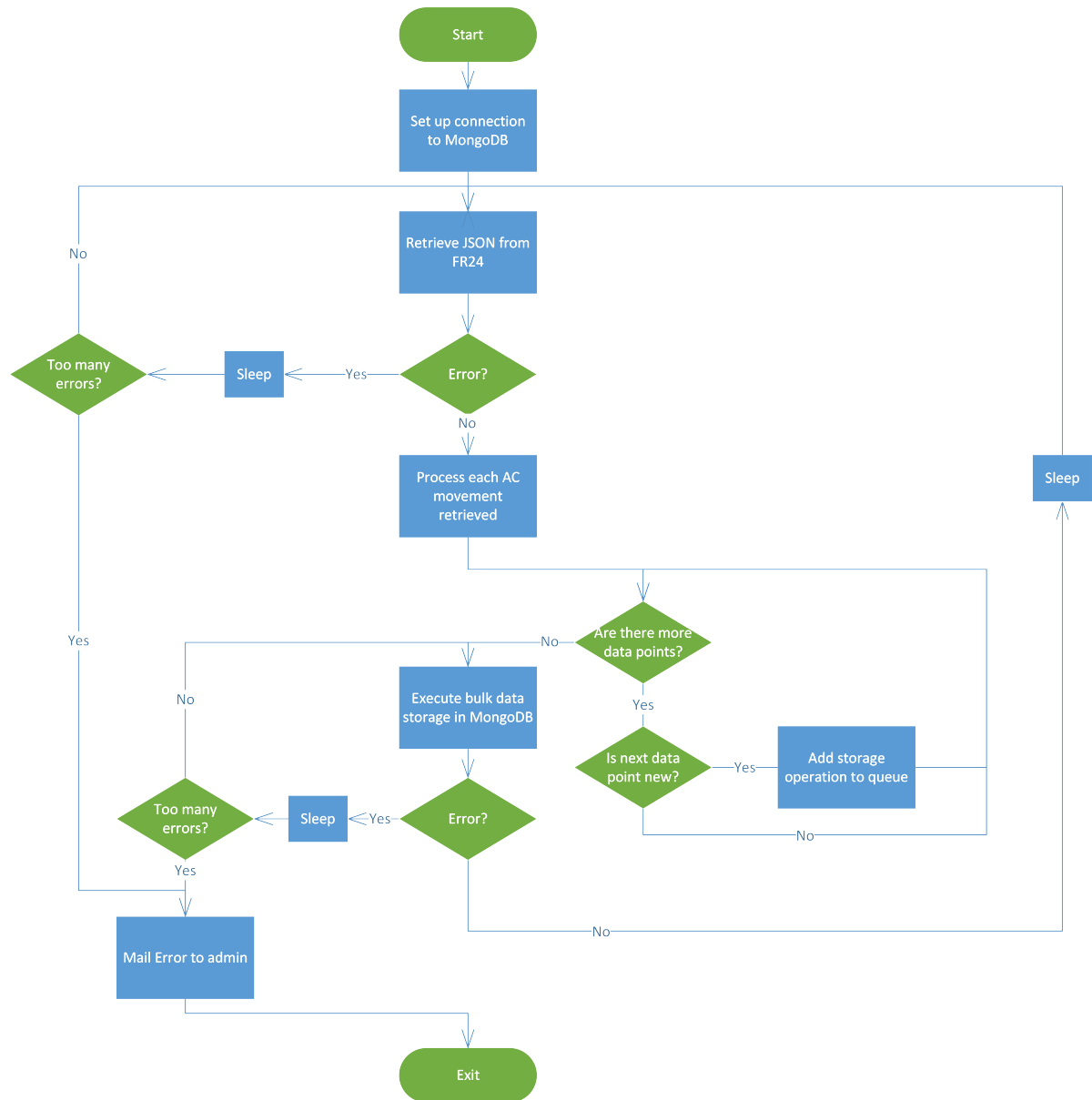


Figure D.2: Flow chart for scraper.

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