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Chapter 2

Measuring Sector Complexity: Solution Space-Based Method

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1. Introduction

In Air Traffic Control (ATC), controller workload has been an important topic of research. Many studies have been conducted in the past to uncover the art of evaluating workload. Many of which have been centered on the sector complexity or task demand based studies [1,2,3,4]. Moreover, all have the aim to understand the workload that was imposed on the controller and the extent to which the workload can be measured.

With the growth in world passenger traffic of 4.8% annually, the volume of air traffic is expected to double in no more than 15 years [5]. Although more and more aspects of air transportation are being automated, the task of supervising air traffic is still performed by human controllers with limited assistance from automated tools and is therefore limited by human performance constraints [6]. The rise in air traffic leads to a rise in the Air Traffic Controller (ATCO) task load and in the end the ATCO's workload itself.

The 2010 Annual Safety Review report by European Aviation Safety Agency (EASA) [7] indicates that since 2006, the number of air traffic incidents with direct or indirect Air Traffic Management (ATM) contribution has decreased. However, the total number of major and serious incidents is increasing, with incidents related to separation minima infringements bearing the largest proportion. This category refers to occurrences in which the defined minimum separation between aircraft has been lost. With the growth of air traffic, combined with the increase of incidents relating to separation minima infringements, a serious thought have to be put into investigating the causes of the incidents and plans on how to solve them.

Initiatives to design future ATM concepts have been addressed in both Europe and the United States, within the framework of Single European Sky ATM Research (SESAR) [8] and Next Generation Air Transportation System (NextGen) [9]. An increased reliance on airborne and

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ground-based automated support tools is anticipated in the future ATM concept by SESAR and NEXTGEN. It is also anticipated that in both SESAR and NEXTGEN concepts a better management of human workload will be achieved. However, to enable that, a more comprehensive understanding of human workload is required, especially that of controllers.

This chapter wil start with a discussion on sector complexity and workload and is followed by a deliberation of previous and current sector complexity and workload measures. Next, a method called the Solution Space Diagram (SSD) is proposed as a sector complexity measure. Using the SSD, the possibility of measuring different sector design parameters are elaborated and future implications will be discussed.

2. Sector complexity and workload

ATCO workload is cited as one of the factors that limit the growth of air traffic worldwide [10,11,12]. Thus, in order to maintain a safe and expeditious flow of traffic, it is important that the taskload and workload that is imposed on the ATCO is optimal. In the effort to distinguish between taskload and workload, Hilburn and Jorna [1] have defined that system factors such as airspace demands, interface demands and other task demands contribute to task load, while operator factors like skill, strategy, experience and so on determine workload. This can be observed from Figure 1.

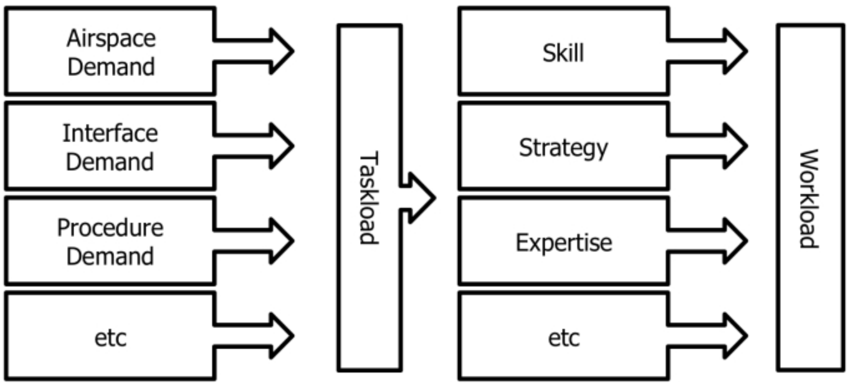


Figure 1. Taskload and Workload Relation [1].

ATCOs are subject to multiple task demand loads or taskloads over time. Their performance is influenced by the intensity of the task or demands they have to handle. Higher demands in a task will relate to a better performance. However, a demand that is too high or too low will lead to performance degradation. Thus, it is important that the demand is acceptable to achieve optimal performance.

The workload or mental workload can be assessed using a few methods such as using performance-based workload assessment through primary and secondary task performance, or using subjective workload assessment through continuous and discrete workload ratings, and lastly using physiological measures. However, because physiological measures are less convenient to use than performance and subjective measures, and it is generally difficult to distinguish between workload, stress and general arousal, these are not widely used in assessing workload [13].

Previous studies have also indicated that incidents where separation violations occurred can happen even when the ATCO's workload is described as moderate [14,15]. These incidents can be induced by other factors such as inappropriate sector design. Sector design is one of the key components in the airspace complexity. Airspace complexity depends on both structural and flow characteristics of the airspace. The structural characteristics are fixed for a sector, and depend on the spatial and physical attributes of the sector such as terrain, number of airways, airway crossings and navigation aids. The flow characteristics vary as a function of time and depend on features like number of aircraft, mix of aircraft, weather, separation between aircraft, closing rates, aircraft speeds and flow restrictions. A combination of these structural and flow parameters influences the controller workload [16].

A good airspace design improves safety by avoiding high workload for the controller and at the same time promotes an efficient flow of traffic within the airspace. In order to have a good airspace design, the ATC impact of complexity variables on controller workload has to be assessed. Much effort has been made to understand airspace complexity in order to measure or predict the controller's workload. In this chapter the solution space approach is adopted, to analyze in a systematic fashion how sector designs may have an impact on airspace complexity, and ultimately the controller workload.

2.1. Previous research on complexity factors

The Air Traffic Management (ATM) system provides services for safe and efficient aircraft operations. A fundamental function of ATM is monitoring and mitigating mismatches between air traffic demand and airspace capacity. In order to better assess airspace complexity, methods such as 'complexity maps' and the 'solution space' have been proposed in Lee et. al [17] and Hermes et al. [18]. Both solutions act as an airspace complexity measure method, where a complexity map details the control activity as a function of the parameters describing the disturbances, and the solution space details the two-dimensional speed and heading possibilities of one controlled aircraft that will not induce separation violations.

Much effort has been made to understand airspace complexity in order to measure the controllers' workload. Before introducing the solution space approach, first some more common techniques are briefly discussed.

2.1.1. Static density

One of the methods to measure complexity is the measurement of aircraft density and it is one of the measures that are commonly used to have instant indication of the sector complexity. It is defined as the number of aircraft per unit of sector volume. Experiments indicated that, of all the individual sector characteristics, aircraft density showed the largest correlation with ATCO subjective workload ratings [19,20]. However, aircraft density has significant shortcomings in its ability to accurately measure and predict sector level complexity [19,21]. This method is unable to illustrate sufficiently the dynamics of the behavior of aircraft in the sector. Figure 2 shows an example where eight aircraft flying in the same direction do not exhibit the same complexity rating when compared to the same number of aircraft flying with various directions [18].

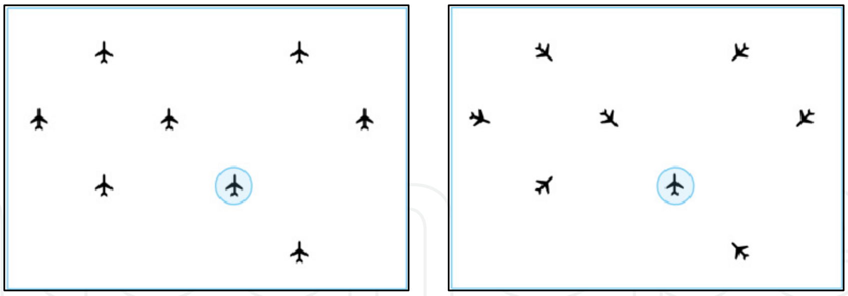


Figure 2. Example of Different Air Traffic Orientation.

2.1.2. Dynamic density

Another measurement of sector complexity is dynamic density. This is defined as "the collective effort of all factors or variables that contribute to sector-level ATC complexity or difficulty at any point of time" [19]. Research on dynamic density by Laudeman et al. [22] and Sridhar et al. [16] has indicated few variables for dynamic density and each factor is given a subjective weight. Characteristics that are considered include, but not limited to the number of aircraft, the number of aircraft with heading change greater than 15° or speed change greater than 10 knots, the sector size, and etc. The calculation to measure dynamic density can be seen in Equation (1).

$$\text{Dynamic Density}=\sum_{i=1}^{n} W_i DV_i \tag{1}$$

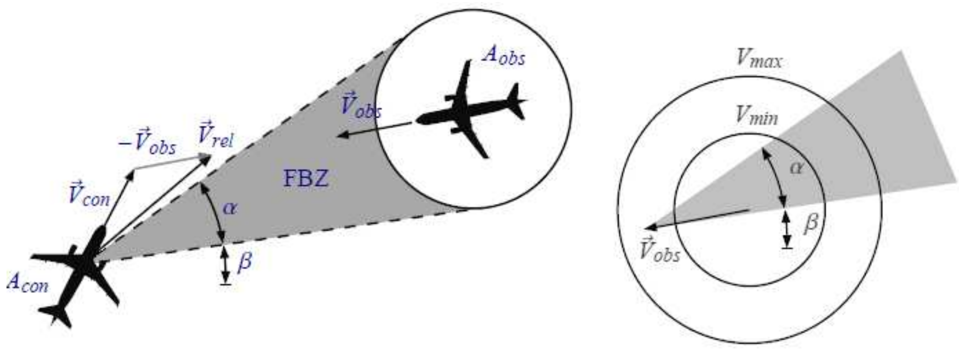
where dynamic density is a summation of the Dynamic Variable (DV) and its corresponding subjective weight (W). The calculation of the dynamic density is basically based on the weights gathered from regression methods on samples of traffic data and comparing them to subjective workload ratings. Essentially, the assignment of weights based on regression methods means that the complexity analysis based on dynamic density could only be performed on scenarios that differ slightly from the baseline scenario. Therefore the metric is not generally applicable to just any situation [18].

2.1.3. Solution space-based approach

Previous work has shown that the SSD is a promising indicator of sector complexity, in which the Solution Space-based metric was proven to be a more objective and scenario-independent metric than the number of aircraft [18,23,24]. The Forbidden Beam Zone (FBZ) of Van Dam et al. [25] has been the basis for representing the SSD. It is based on analyzing conflicts between aircraft in the relative velocity plane. Figure 3 (a) shows two aircraft, the controlled aircraft (A_{con}) and the observed aircraft (A_{obs}). In this diagram, the protected zone (PZ) of the observed aircraft is shown as a circle with radius of 5NM (the common separation distance) centered on the observed aircraft. Intrusion of this zone is called a 'conflict', or, 'loss of separation'. Two tangent lines to the left and right sides of the PZ of the observed aircraft are drawn towards the controlled aircraft. The area inside these tangent lines is called the FBZ.

This potential conflict can be presented on a SSD. Figure 3 (b) shows the FBZ in the SSD of the controlled aircraft. The inner and outer circles represent the velocity limits of the controlled aircraft. Now, if the controlled aircraft velocity lies inside the triangular-shaped area, it means that the aircraft is headed toward the PZ of the observed aircraft, will eventually enter it, and separation will be lost.

The exploration of sector complexity effects on the Solution Space parameters and, moreover, workload is important in order to truly understand how workload was imposed on controllers based on the criteria of the sector. Having the hypotheses that sector parameters will have a direct effect on the SSD geometrical properties, the possibility of using the SSD in sector planning seems promising. Figure 4 shows the relationship between taskload and workload as described by Hilburn and Jorna [1], where we adapted the position of sector complexity within the diagram. The function of the SSD is included as a workload measure [18,23,24] and alleviator [26] and also the possibility of aiding sector planning through SSD being a sector complexity measure [24].



(a) (b)

Figure 3. Two Aircraft Condition (a) Plan View of Conflict and the FBZ Definition. (b) Basic SSD for the Controlled Aircraft. (Adapted from Mercado-Velasco et al., [26])

Initial work by Van Dam et al. [25] has introduced the application of the Solution Space in aircraft separation problems from a pilot's perspective. Hermes et al. [18], d'Engelbronner et al. [23], Mercado-Velasco et al. [26] and Abdul Rahman et al. [24] have transferred the idea of using the Solution Space in aircraft separation problems for ATC. Based on previous research conducted, a high correlation was found to exist between the Solution Space and ATCO's workload [18,23,24]. Abdul Rahman et al. [24] also investigated the possibility of measuring the effect of aircraft proximity and the number of streams on controller workload using the SSD and have discovered identical trends in subjective workload and the SSD area properties. Mercado-Velasco et al. [26] study the workload from a different perspective, looking at the possibility of using the SSD as an interface to reduce the controller's workload. Based on his studies, he indicated that the diagram could indeed reduce the controller's workload in a situation of increased traffic level [26].

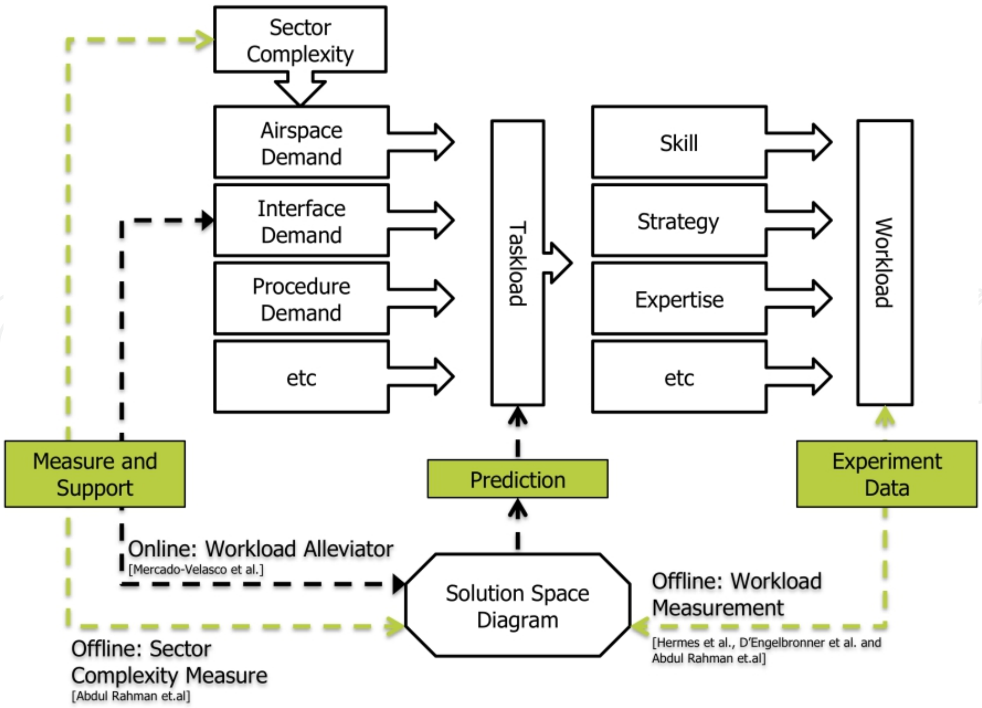


Figure 4. Solution Space Diagram in Measuring and Alleviating Workload (adapted from Hilburn and Jorna [1])

3. Complexity measure using the solution space diagram

The results gathered here are based on offline simulations of more than 100 case studies with various situations as detailed in this chapter. The affected SSD area has been investigated to understand the effects of sector complexities on the available solution space. Conclusions from previous work by Hermes et al. [18] and d'Engelbronner et al. [23] stated that the available area in the Solution Space that offers solutions has a strong (inverse) correlation with ATCO workload. In this case study, two area properties were investigated in order to measure the complexity construct of the situation, which are the total area affected (A_{total}) and the mean area affected (A_{mean}) for the whole sector. The A_{total} percentage is the area covered by the FBZs as a percentage of the total area between the minimum and the maximum velocity circles in the SSD, based on the currently controlled aircraft. The A_{mean} percentage affected is the A_{total} affected for all aircraft in the sector divided by the number of aircraft. This will give an overview of the complexity metric for the whole sector.

$$A_{total} = \sum A_{affected} \tag{2}$$

$$A_{mean} = \frac{\sum_{t=1}^{n} A_{total_t}}{n} \tag{3}$$

Both measures were used as a complexity measure rating, based on the findings in earlier studies where the A_{total} and A_{mean} showed to have a higher correlation with the controller's workload than the static density [24].

4. Sector complexity variables

Previous research on sector complexity showed that the aircraft intercept angle [27,28,29], speed [27] and horizontal proximity [3,16] are some of the variables that are responsible for the sector complexity. The goal of the present study is to systematically analyze the properties of the SSD due to changes in the sector design. It is hypothesized that using these properties we can obtain a more meaningful prediction of the sector's complexity (or task demand load) than existing methods.

In a first attempt, we studied the effects of aircraft streams' (that is, the airways or routes) intercept angles, the speed differences and horizontal proximity between aircraft, and also the effect of number of aircraft and their orientation on the SSD. For this purpose, several cases were studied. The cases that were being investigated involved two intercepting aircraft at variable intercept angles, route lengths, and speed vectors. Quantitative analysis was conducted on the SSD area properties for the mentioned sector variables. In the study of quantitative measurement of sector complexity, it was assumed that a denser conflict space results in a higher rating for the complexity factor. IIn later stage, a human-in-the-loop experiment will be conducted to verify the hypotheses gathered from the quantitative study and will provide a better understanding on the relationship between the SSD area properties and the workload as indicated by the subject. Figure 5 shows an example of one of the case studies with the speed vectors, route length, horizontal proximity, initial position, corresponding angle between the aircraft and the intercept angle properties. One sector complexity factor was changed at the time in order to investigate the effects of that factor on the SSD. Changes in these factors will be translated into differences in the geometry of the FBZ and area affected on the SSD.

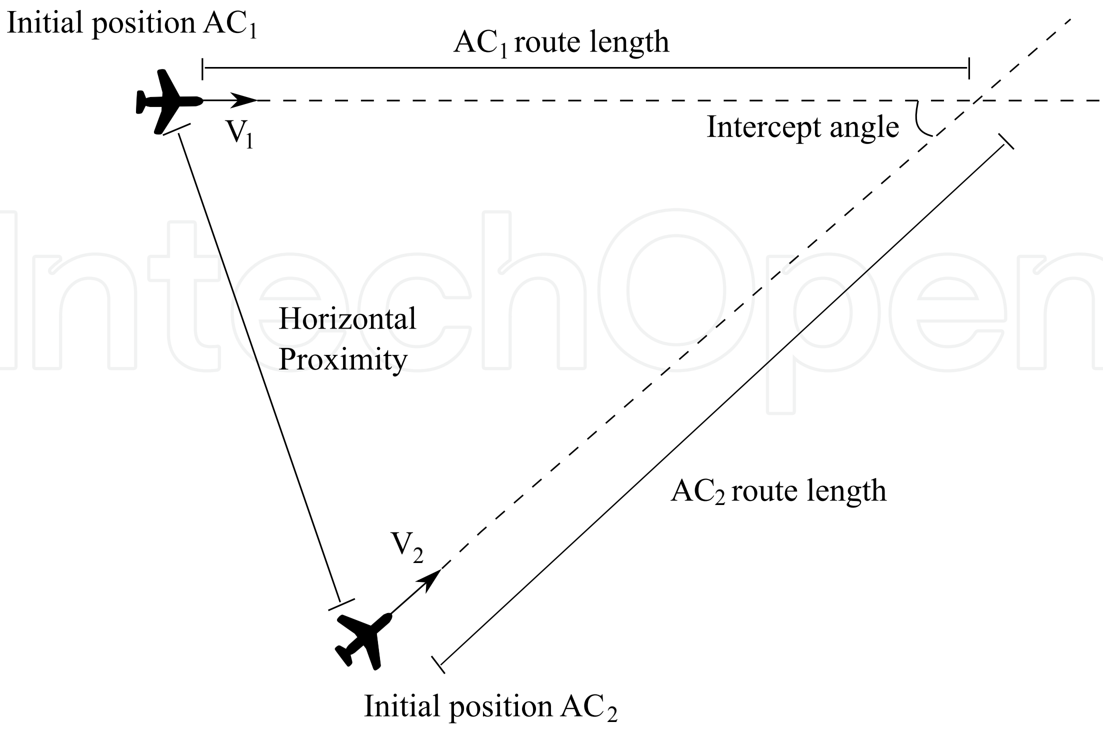


Figure 5. Example of Case Study Properties

The diagram we hereby elaborate is based on three important assumptions. First, both aircraft are on the same flight level and are not ascending or descending during the flight. Secondly, it is assumed that both aircraft have the same weight classes and will have the same minimum and maximum velocities. Lastly, the minimum separation distance, represented by a PZ with radius of 5 NM around each aircraft, is to be maintained at the same size at all time. Different complexity factors are compared using a quantitative analysis.

4.1. Horizontal proximity

Previous research on sector complexity has shown that the aircraft horizontal proximity [3,16] is one of the variables that is responsible in the sector complexity construct. There are several relationships that can be gathered from the FBZ. In order to analyze the relationship between FBZ and time to conflict and the position of aircraft, some parameters have to be determined. These parameters can be found in Figure 6 where the absolute and relative space of the FBZ was illustrated in Figure 6 (a) and (b), respectively. In the absolute space (Figure 6 (a)), two aircraft situation with distance between aircraft (d) and minimum separation distance (R) were illustrate. The FBZ is then translated into the relative space (Figure 6 (b)) where the same situation was projected with the assumption that the controlled aircraft will be in direct collision with the observed aircraft in the future. Based on the figures, it is observed that the FBZ and the corresponding Solution Space share similar geometric characteristics. These, as shown in Figure 6, make it clear that:

$$\frac{|V_{rel}|}{r} \sim \frac{|d|}{R} \tag{4}$$

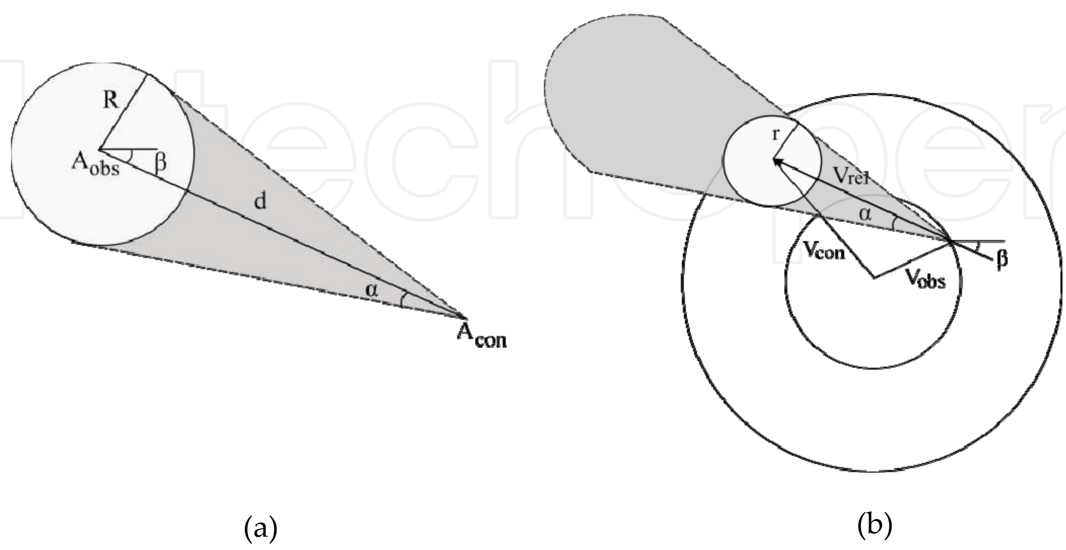


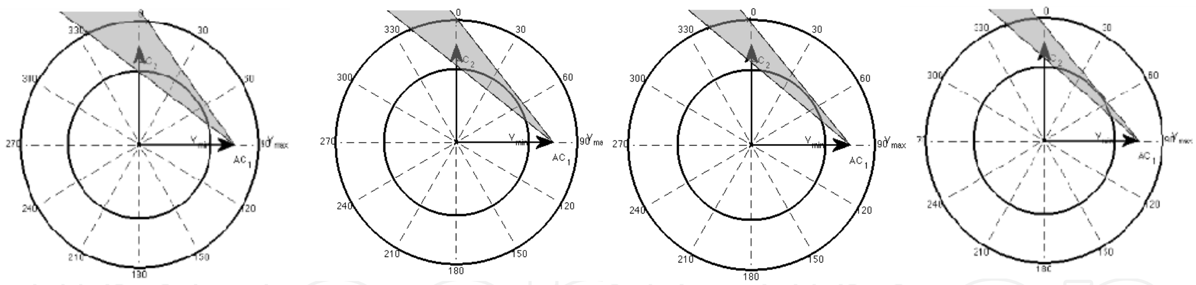
Figure 6. Projected Protected Airspace. (a) Absolute Space. (b) Relative Space.

The separation between aircraft in terms of time and horizontal proximity can be directly observed on the SSD through the width of the FBZ. A narrow FBZ translates to a longer time until loss of separation and also a larger separation distance between both aircraft. The relation can be seen in Equation (5) [34] and Equation (6), where the time (t) and distance between aircraft (d) is inversely proportional to the width (w) of the FBZ.

$$w = \frac{2R}{t\cos\alpha} \tag{5}$$

$$w = \frac{2RV_{rel}}{d\cos\alpha} \tag{6}$$

The importance of horizontal proximity has also been stressed in other research where it is indicated that aircraft that fly closer to each other have a larger weight on the Dynamic Density [3,16]. In order to see the effect of horizontal proximities on the SSD and to confirm the previous study, more than 50 position conditions with intercept angle of either 45°, 90° or 135°, were studied. To simulate horizontal proximity, aircraft were assigned with a different route length at a different time instance. It is important to ensure that only one property is changed at a time. During this study, the velocity of both aircraft was maintained at same speed at all times. The effect of the horizontal proximity on the SSD is shown in Figure 7. The situation in Figure 7 is based on aircraft flying with a fixed heading angle of 90°, while both aircraft having the same speed vector of 200 knots, but having a different route length.



(a) (b) (c) (d)

Figure 7. SSD for AC2 Observing Horizontal Proximity Changes.

From the analysis, it was found that aircraft that are further apart from each other have a narrower FBZ width than the ones being closer to each other. This can be seen in Figure 7 with aircraft progressing from being nearest (Figure 7 (a)) to furthest (Figure 7 (d)) apart from one another. The same pattern also applies to other intercept angles studied. The area affected is less dense for aircraft with a larger horizontal proximity where the area affected within the SSD decreases from 11% for the case in Figure 7 (a) to 6% for case in Figure 7 (d). This also shows that a large horizontal separation between aircraft result in a less dense SSD, thus a lower complexity metric. A narrower width also implicate that there are more options to solve a conflict. This can be seen in Figure 7, where in Figure 7 (a) and (b), there is no room for AC2 to resolve the conflict using a speed-only correction, whereas in Figure 7 (c) and (d) the conflict can be resolve by either increasing or decreasing the AC2 speed.

Similar patterns were observed with different speed settings and speed boundaries in conjunction with different intercept angles. Figure 8 illustrates the percentage area covered as a function of the horizontal distance and the intercept angle while having the same velocity vector. It can be seen from this figure that the area properties decrease with larger distances between both aircraft at any intercept angle. The regression rate of the SSD area properties against the horizontal distance is also similar with any other intercept angle as indicated by Equation (6) regarding the width of the FBZ.

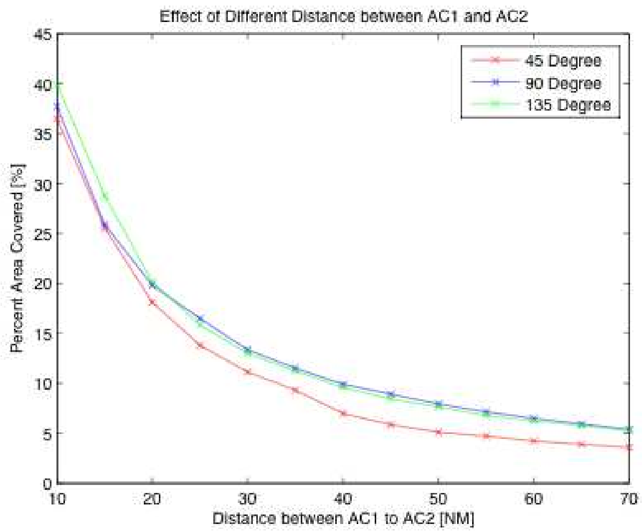
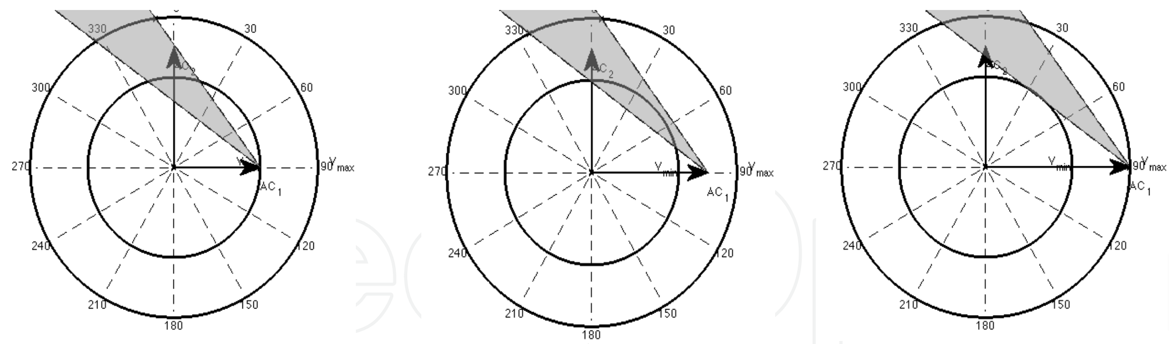


Figure 8. Percent Area Covered with Distance for Different Intercept Angle

4.2. Speed variations

A previous study by Rantenan and Nunes [27] has suggested speed as a confounding factor to conflict or intercept angles and the ability to detect a conflict. It was indicated in their research that increasing the speed differential between converging objects increased the temporal error, resulting in a lower accuracy. This is due to the fact that the controller now has to integrate two (rather than one) pieces of speed information and project their implications. This shows the importance of studying the effect of speed variations to the sector complexity, especially when coupled with the intercept angle.

A number of cases of aircraft pairs at the same distance between each other were investigated in this preliminary study. The first observation is illustrated in Figure 9 where the speed and the heading of the observed aircraft can be seen on the SSD mapping of the controlled aircraft through the position of the tip of the FBZ. This is because the FBZ is obtained by transposing the triangular-shaped conflict zone with the observed aircraft velocity vector. In a case such as seen in Figure 9 (a) to (c), an aircraft with the same horizontal separation at an intercept angle of 90° between each other will result in a different SSD as a function of the 150, 200 and 250 knots speed settings.



(a) (b) (c)

Figure 9. SSD of AC2 observing speed changes for the same aircraft position. (a) AC1 at 150 knots. (b) AC1 at 200 knots. (c) AC1 at 250 knots.

In Figure 9, AC1 will encounter a separation violation problem in the future with AC2 when the aircraft maintains its current heading and speed. However, giving speed or heading instructions to one or both aircraft can resolve the future separation issue. In this case, an increase (Figure 9 (a)) or decrease (Figure 9 (c)) in speed for AC2 will solve the future separation issue. It is not desired for on-course aircraft to change the heading angle in order to fulfill efficiency constraints, however, if required to maintain safety, it may be the proper way to resolve a conflict, such in Figure 9 (b). It is found that the higher the speed of the observed aircraft, the more the FBZ in the SSD is shifted outwards. The changes in the speed only affect the currently controlled aircraft's SSD. Because there is no change of speed for the controlled aircraft, AC2, the corresponding diagram for AC1 observing AC2 remains the same during the change of speed vector in AC1.

The total area affected on the SSD depends on the relative positions and the intercept angle of both aircraft, where a shift outwards will be translated as more or less SSD area percentage affected. This can be seen by comparing Figure 9 (a) to (c) where a shift outwards results in more area affected within the SSD, which gives the value of 8%, 11% and 15% area affected for cases (a), (b), (c), respectively. Hence it can be hypothesized that larger relative speeds can result in a higher or lower complexity metric, depending on the position and intercept angle of the aircraft.

The effect of speed differences was also investigated further for aircraft intercepting at 45°, 90° and 135° with more possible cases, and the results are illustrated in Figure 10. Differences in intercept angle, speed limit band (which may represent differences in aircraft performance limits or aircraft types) and the size of the speed limit were investigated. Figure 10 shows the effect of speed differences on a 180 - 250 knots speed band, with both AC1 and AC2 at either 30 NM or 40 NM distance from the interception point at different intercept angles. Both aircraft's initial speeds were 250 knots and to illustrate the effect of speed variations, one of the aircraft was given a gradual speed reduction toward 180 knots.

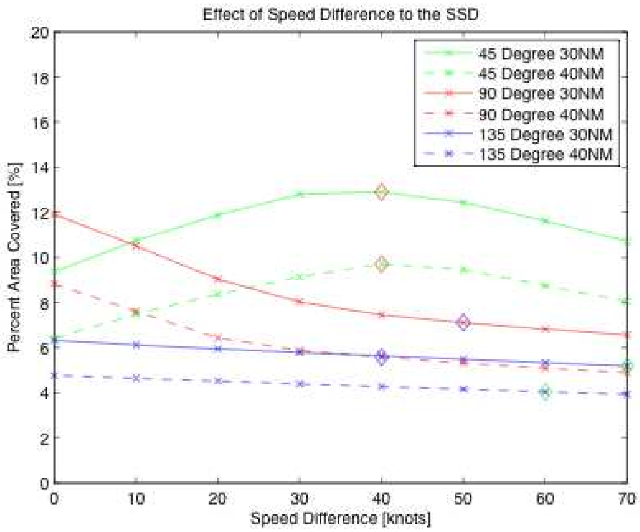


Figure 10. The SSD area values as a function of different speed settings for same aircraft position with different intercept angles.

The diamond shapes in Figure 10 indicate the minimum difference needed for aircraft not to be in a future separation violation. Based on Figure 10, the effect of speed and distance is evident with 45°, 90° and 135° intercept angles showing a decrease in the SSD area properties with a larger relative distance while maintaining the trends of the graph. In 90° and 135° cases, larger distances also indicated that a smaller speed difference (marked with diamond) was needed in order for both aircraft not to be in a future separation violation. Figure 10 also shows that aircraft flying at a smaller intercept angle needed less speed difference than aircraft flying larger intercept angle to avoid future separation violation caused by having the same flight path length to the intercept point.

The effect of the intercept angle on the other hand shows different patterns in SSD area properties in regards to the speed variations. A 45° intercept angle showed an increase of SSD area properties up until the intermediate speed limit followed by a decrease of SSD area properties with increased speed differences. However, for 90° and 135° intercept angle cases, the reduction of speed is followed by a continuing decrease in SSD area properties.

Differences in the pattern also indicated a difference in sector complexity behavior toward distinctive intercept angle. The effects of speed limit bands for 45° intercept angle cases are illustrated in Figure 11 and 12. Figure 11 (a) shows the effect of different speed band values while maintaining the same size of the controlled aircraft speed performance and Figure 12 (b) shows the effect of different sizes of the speed band. Based on both figures, irrespective of the speed band ranges (aircraft speed performance limit) or speed band size, the same pattern in area properties were found, in all eight scenarios. The only difference was the peak value of the SSD area properties (Figure 11 (a)) is greater for speed bands with higher speed limits. This is due to the fact that with the same position between both aircraft, higher speed (for AC1 in this case) indicates a higher possible relative speed (Vrel) for the maximum speed band, thus implicating a broader FBZ (can be seen in Equation (6) and Figure 11 (b)). The same pattern was illustrated with different speed band sizes (Figure 12) with higher peaks of the SSD area values for higher AC1 speeds.

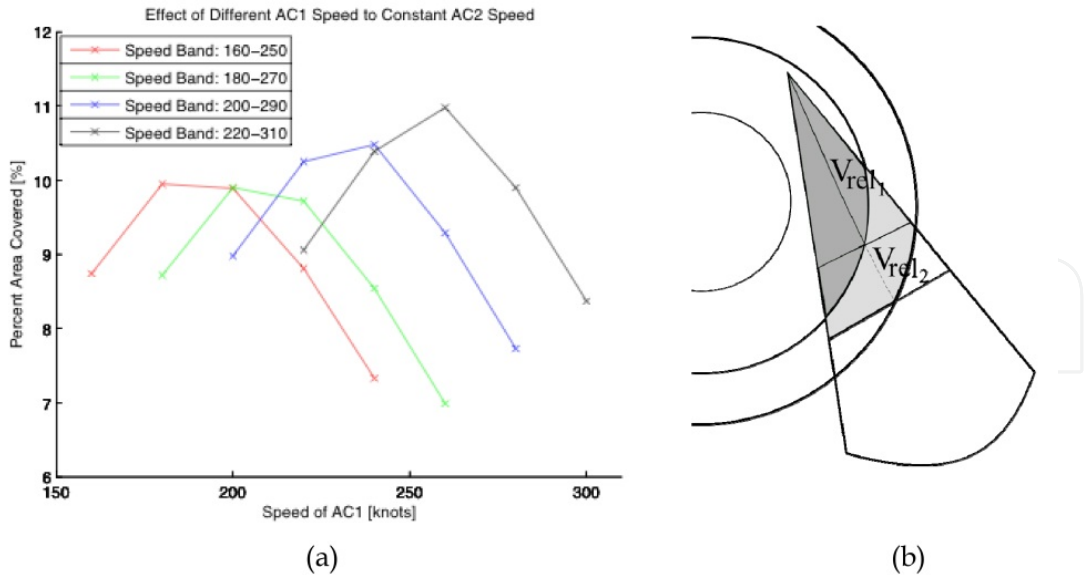


Figure 11. (a) Various speed settings for the same 45 Degree Intercept Angle with different speed limit boundaries (b) Different speed band maximum limit of the controlled aircraft

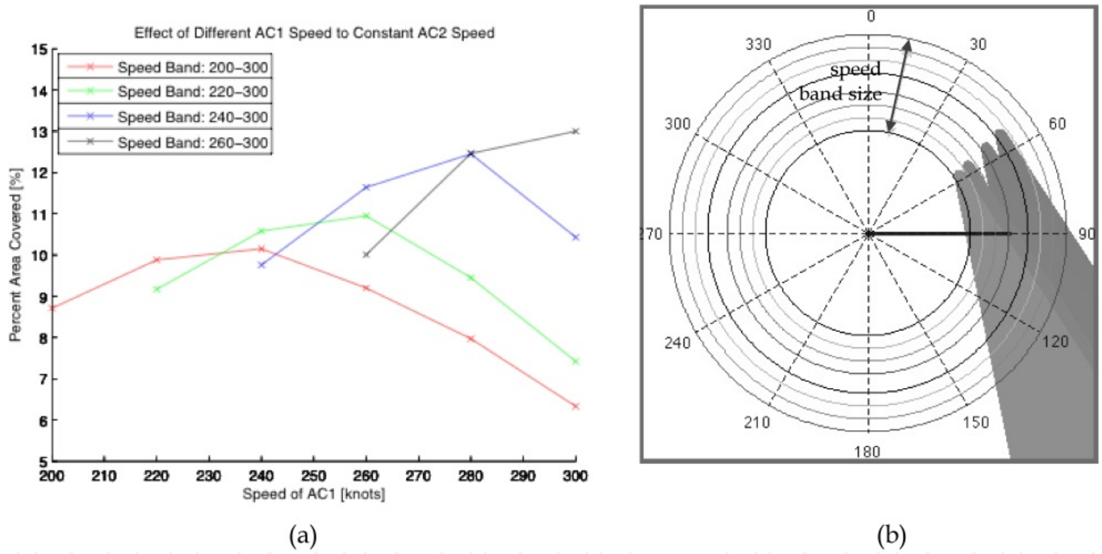


Figure 12. (a) Various speed settings for the same 45 Degree Intercept Angle with different speed band size (b) SSD of Different speed band sizes.

4.3. Intercept angle

Based on previous researches, the ability of the controller to ascertain whether or not an aircraft pair will lose separation (more commonly known as conflict detection) is affected by a variety of variables that include, but are not limited to, the convergence angle [27,28,29]. However, previous research also found that conflict angle as a factor affecting conflict detection ability, is often confounded with speed [27]. Nonetheless, in order to understand the intercept angle as part of the sector complexity measure, the effect of intercept angle on the SSD area property is important.

There are several types of crossing angles that are being studied. The main goal of the study was to investigate the effect of crossing angle towards sector complexity through the SSD. The effect of different intersection angles on the SSD is shown here for the case where the route length between AC1 and AC2 remains constant and equal at all time. Both aircraft were flying the same speed vector of 200 knots, but with different heading angles for AC2, which are 45°, 90° and 135°. The negative intercept angles were assigned for aircraft coming from the left, while positive intercept angles were assigned for aircraft coming from right. As seen here, only the changes in the heading angle were investigated, while other variables were fixed to a certain value.

From the analysis, it is found that the larger the heading angles of intersecting aircraft, the less dense the area within the SSD. Figure 13 shows the resulting SSD for different intercept angles. Figure 13 also shows the effect of aircraft coming from right (Figure 13 (a) to (c)) or from the left (Figure 13 (d) to (e)) side of the controlled aircraft. It is concluded here that aircraft coming from any direction with the same intercept angle and route length will demonstrate the same complexity measure due to the symmetrical nature of the conflict For aircraft with 45°, 90° and 135° intercept angles, the SSD area properties are 14%, 11% and 8%, respectively. The same area properties hold for the opposite angle. This also shows that a larger intercept angle results in a lower complexity metric based on the properties of the SSD, because the solution area covered with the conflict zone is smaller. However, this condition only applies if the observed aircraft has a route length larger or equal to the controlled aircraft. This also means that the condition where the effects of intercept angles on the complexity metric is only valid when the observed aircraft is approaching from a certain direction.

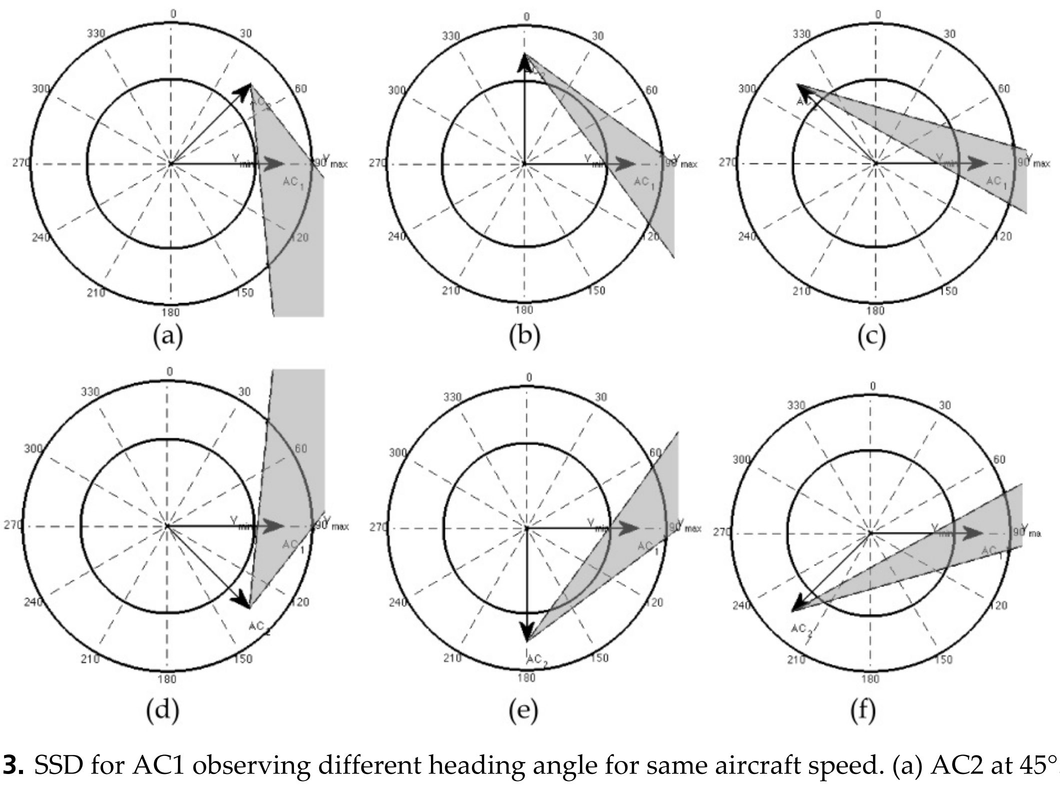
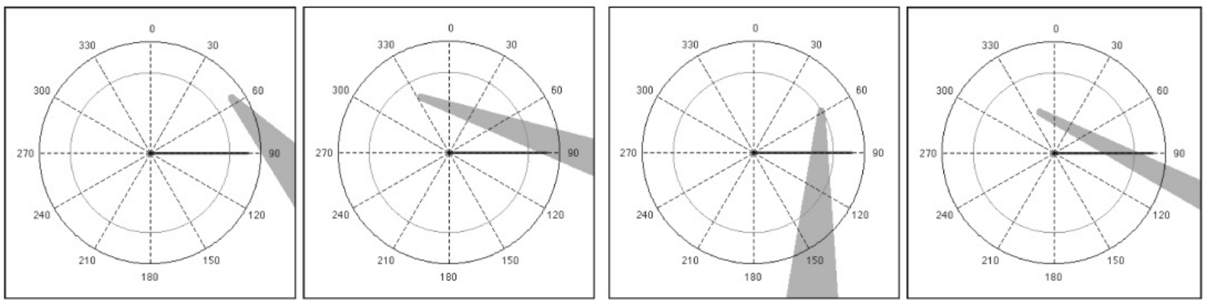


Figure 13. SSD for AC1 observing different heading angle for same aircraft speed. (a) AC2 at 45°. (b) AC2 at 90° (c) AC2 at 135° (d) AC2 at -45°. (e) AC2 at -90° (f) AC2 at -135°.

4.3.1. Front side and backside crossings

It was found that there are differences between observing an aircraft crossing in front or from the backside of the controlled aircraft with an increasing intercept angle. A case study was conducted where an aircraft observed front side and backside crossings at an angle of 45° and 135°. Both aircraft had the same speed of 220 knots and intercepted at the same point of the route, giving the same flight length for each case observed (see Figure 5). In a case where the controlled aircraft, which was farther away, was observing an intercept of an observed aircraft crossing in front at a certain angle, the area affected was increasing with an increasing intercept angle. The area affected measured in this case was 3% for 45° intercept angle (Figure 14 (a)) compared to 5% area affected for the 135° intercept angle (Figure 14 (b)). On the other hand, in a case where the controlled aircraft was observing an aircraft crossing from the backside, the area affected was decreasing with increasing intercept angle. The area affected measured in this case is 8% for 45° intercept angle (Figure 14 (c)) compared to 3% for 135° intercept angle (Figure 14 (d)). These area-affected values concluded that a slightly higher complexity metric was found with an increasing intercept angle when the observed aircraft was already present in the sector and passing the controlled aircraft from the front side. The opposite situation appeared when the observed aircraft was approaching a sector and crossed the observed aircraft from the backside.



(a) (b) (c) (d)

Figure 14. (a) Observed Aircraft Crossing from the front side at 45° (b) Observed Aircraft Crossing from the front side at 135° (c) Observed Aircraft Crossing from the backside at 45° (d) Observed Aircraft Crossing from the backside at 135°.

To extensively study the effect of intercept angle and the relative aircraft distance on the SSD area properties, several other cases were looked into and the results are illustrated in Figure 15. Figure 15 showed static aircraft at 35 NM distance from the intercept point, observing an incoming or a present aircraft in the sector at a variable intercept angle. Based on the initial study, it can be seen that observing present aircraft in the sector (with a distance from the intercept point less than 35 NM) will lead to an increase of SSD area properties with an increasing intercept angle. Despite this result, it was observed that a larger intercept angle for incoming aircraft (aircraft with distance more than 35 NM) results in a less dense area inside the SSD with an increasing intercept angle. The results gained here, matches the initial observations discussed earlier.

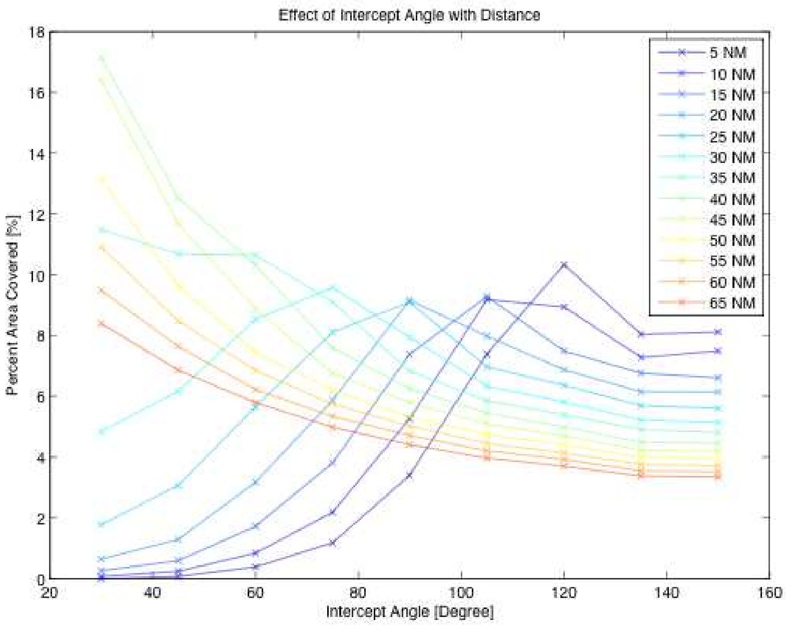


Figure 15. Plots of SSD Behavior showing the Differences in Intercept Angle and Distance to Intercept Point

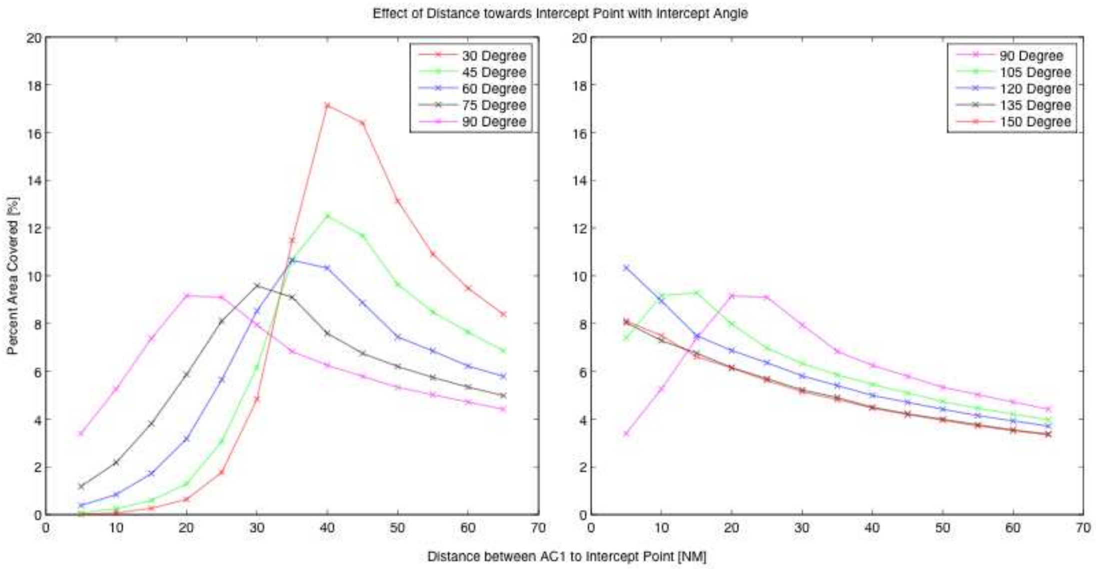
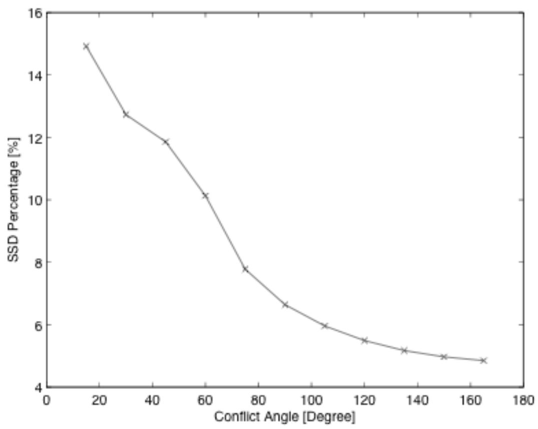


Figure 16. Plots of SSD Behavior showing the Differences in Intercept Angle and Distance to Intercept Point

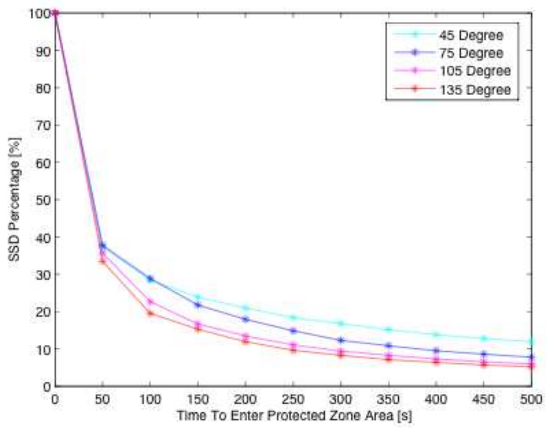
Figure 16 shows the effect of intercept angle and the relative aircraft distance to the intercept point from a different perspective, where the effect of different intercept angle on the distance towards the intercept point was focused. From the figure it is observed that a larger distance for larger intercept angles (120°, 135° and 150°) results in a continuing decrease of SSD area properties, thus relating to a lower complexity metric, whereas a larger distance for smaller intercept angles (30° to 90°) result in an initial increase of SSD area properties, thus relating to a larger complexity metric and followed by decreasing SSD area properties after a certain distance (more than 35 NM). This also suggested that for a bigger intercept angle, the increase in distance always relates to a less complex situation whereas for a smaller intercept angle, the increase of distance up to a point where the length path is equal relates to a more complex situation.

4.3.2. Time to conflict

The effect of intercept angle on the sector complexity construct was also investigated from a different perspective, namely the Time to Conflict (TTC). As illustrated in Figure 17 (a), with a fixed TTC at 500 seconds, a larger conflict angle will result in lower SSD area properties, thus a lower sector complexity construct. However, this can be due to the larger distance between the aircraft for larger conflict angles, even with the same TTC value. Having said that, this also indicates that with a larger intercept angle, a later conflict detection and lower initial situation awareness are predicted. An example of the progression of a future conflict that will occur at an equal time in the future with different conflict angles is shown in Figure 17 (b). Based on Figure 17 (b), a larger conflict angle results in lower SSD area properties, and also has a faster rate of SSD progress toward total SSD occupation.



(a)



(b)

Figure 17. (a) SSD Area Properties for Different Conflict Angle Properties of Aircraft with the Same TTC. (b) SSD Area Progression with TTC for Different Conflict Angle

4.4. Number of aircraft and aircraft orientation

One of the methods to measure sector complexity is through the measurement of aircraft density. Aircraft density is one of the measures that is commonly used to have instant indication of the sector complexity. It is defined as the number of aircraft per unit of sector volume. This section discusses the effects of the number of aircraft within a sector on the SSD area properties together with the aircraft heading orientations. Figures 18 and 19 show the number of aircraft and the traffic orientation that was investigated here. An example SSD for two aircraft, AC1 and AC2 as indicated in Figure 18 and 19 were illustrated for all cases. For all four situations, all aircraft are free of conflicts. In a four-aircraft situation, illustrated in Figures 18 (a) and (d), an A_{mean} of 9% and 16%, respectively, were gathered whereas in a six-aircraft situation, illustrated in Figure 19 (a) and (d), an A_{mean} of 15% and 20%, respectively were gathered. Based on the SSD area properties, it was clear that more aircraft relates to a higher SSD area properties comparing cases in Figure 18 (a) to Figure 19 (a). The corresponding SSD also illustrates the effect of adding two aircraft to AC1 and AC2 where additional two FBZ were present in Figure 19 (b) and (c) if compared to Figure 18 (b) and (c).

This case study also agrees with the notion that aircraft orientation also influences the complexity construct of a sector through cases illustrated in Figure 18 and Figure 19. Here it can be seen that cases with converging aircraft ((Figure 18 (d) and Figure 19 (d)) result in higher SSD area properties than cases where all aircraft have an equal heading (Figure 18 (a) and Figure 19 (a)). The SSD also showed the effect of heading with Figure 18 (b) and (c) showing the FBZ of aircraft with one heading and Figure 18 (e) and (f) showing the FBZ of aircraft with several headings. The same four- aircraft situation in Figure 18 and six-aircraft situation in Figure 19 showed to be more complicated with several aircraft headings. The area properties of the situation in Figure 18 (d) (A_{mean} of 16%) and Figure 19 (a) (A_{mean} of 15%) also showed that the SSD has the potential to be a good sector complexity measure that is, it has the capability to illustrate that more aircraft does not necessarily mean higher complexity, but that the orientation of aircraft within the sector matters more.

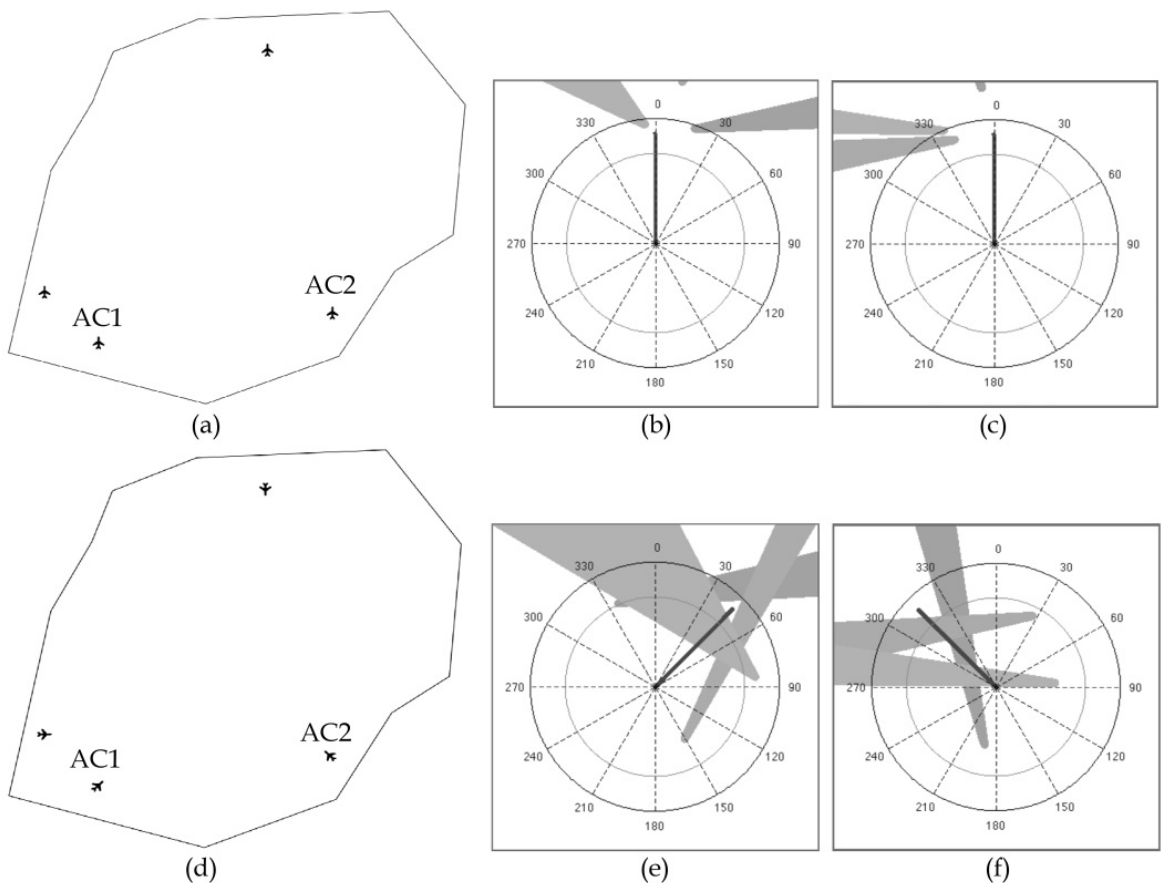


Figure 18. Different heading for same aircraft position. (a) Four Aircraft in One Heading. (b) SSD AC1. (c) SSD AC2. (d) Four Aircraft in Several Heading. (e) SSD AC1. (f) SSD AC2.

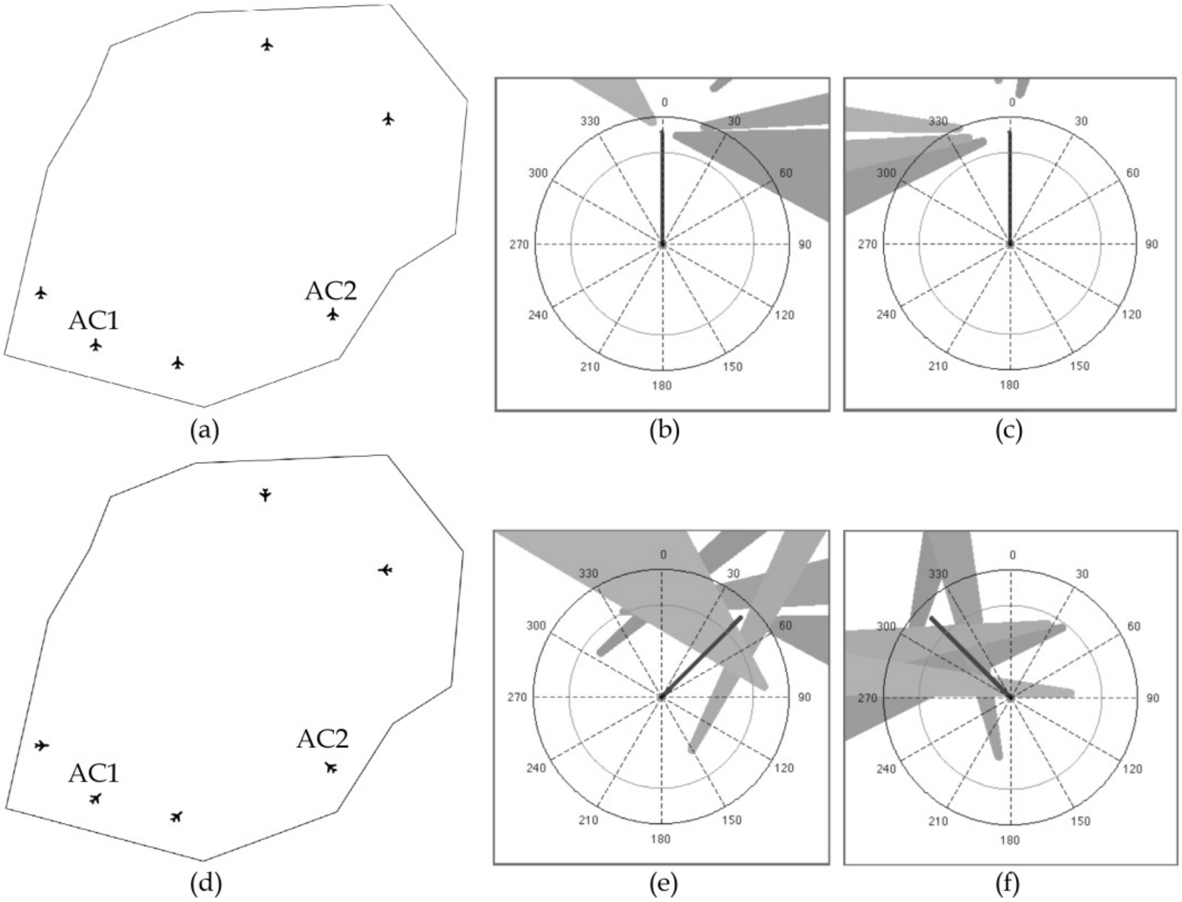


Figure 19. Different heading for same aircraft position. (a) Six Aircraft in One Heading. (b) SSD AC 2. (c) SSD AC 4. (c) Six Aircraft in Several Heading. (e) SSD AC 2. (f) SSD AC 4.

5. Solution space diagram in measuring workload

The complexity construct is an intricate topic. It is interrelated between multiple complexity variables, and altering one variable in a single scenario may result in changing other aspects of complexity. In order to measure complexity, it is hypothesized that sector complexity can be measured through the controller's workload based on the notion that the controller workload is a subjective attribute and is an effect of air traffic complexity [30]. The controller's workload can be measured based on a subjective ratings in varying scenario settings. From the many different measurement techniques for subjective workload, the Instantaneous Self Assessment (ISA) method is one of the simplest tools with which an estimate of the perceived workload can be obtained during real-time simulations or actual tasks [33]. This method requires the operator to give a rating between 1 (very low) and 5 (very high), either verbally or by means of a keyboard, of the workload he/she perceives.

While the problems encountered in Air Traffic Control have a dynamic character and workload is likely to vary over time because of the changes in the traffic situation that an ATCO is dealing with, the measurement of workload through ISA should also be made at several moments in time. To enable the SSD to become an objective sector complexity and workload measure, the correlation between the subjective ratings given by participant and the SSD area properties should be studied at several moments in time. Figure 20 shows examples of correlation study between SSD area properties and workload [24]. The plots show the subjective workload ratings in conjunction with the SSD area properties taken every minute in six different scenarios per subject. A total of 120 subjective ratings were gathered together with 120 SSD instants where SSD area assessments were conducted. With these practice, the correlation between SSD area properties and workload as indicated by controller can be evaluated.

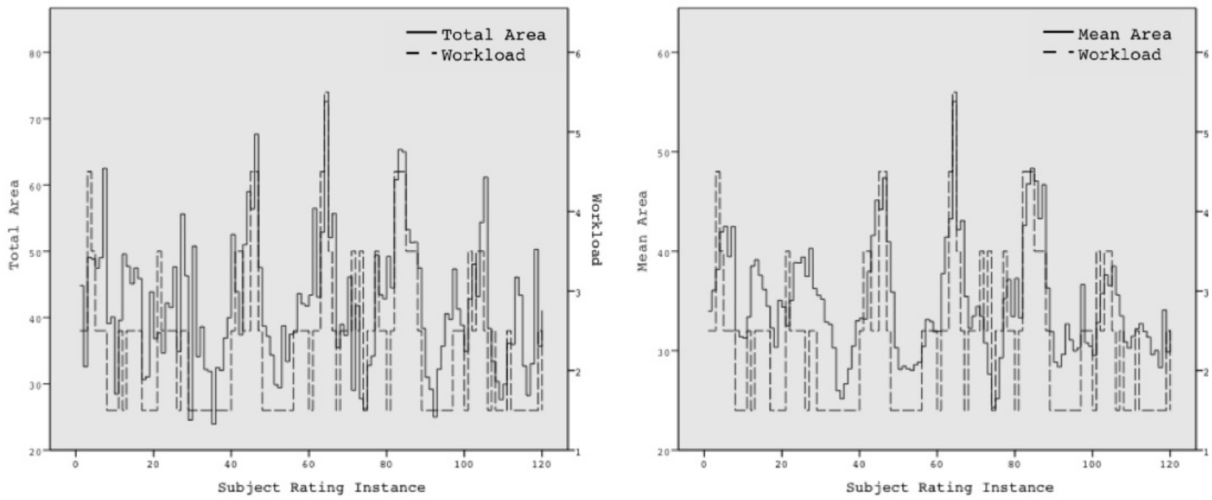


Figure 20. A_{total} and A_{mean} Plots Together with the Subjective Workload Rating as Indicated by Subject [24].

Previous experiments have shown that using the SSD area properties, a higher correlation than the static density was found [23,24]. The possibility of using the SSD in measuring workload as a function of different sector design parameters were also explored with the SSD area properties and showed to be capable of illustrating the same trend in the complexity measure with the ISA ratings [24]. However, to understand more on the complexity construct, a more focused study is needed to study different sector complexity effects on the SSD such as the number of streams, the orientation of the streams, the position of in-point and out-point of a route within the sector and etc. This preliminary study will then serve as the driver of a more elaborated research in the future.

6. Future research

The exploration of sector complexities on the Solution Space parameters and moreover workload is important in order to truly understand how workload is imposed on controllers. Because this preliminary investigation showed that various sector parameters and traffic properties are reflected by the geometry of conflict and solution spaces geometry in the SSD, the possibility of using the SSD in sector planning seems promising. This has also opened up a possibility of quantifying workload objectively using the SSD as a sector complexity and workload measure. Apart from using the SSD for offline planning purposes, having the capability to quantify sector complexity and/or workload has also a potential role in dynamic airspace assessment. This enables a more dynamic airspace sectorization or staff-planning than using the conventional maximum-number-of-aircraft limit that is primarily driven by the air traffic controller's ability to monitor and provide separation, communication and flow-control services to the aircraft in the sector.

Other than using the SSD as a sector planning aid, it is also envisioned that in the future, the SSD can be used as an operation tool. It is anticipated that by using the SSD as a display, controllers will have an additional visual assistance to navigate aircraft within the airspace. The SSD can serve as a collision avoidance tool or also a support tool for ATCOs, to indicate sector bottlenecks and hotspots.

Finally, the possibility of implementing the SSD in a three-dimensional problem is not far to reach. Initial studies have been conducted on an analytical 3D SSD [31] and an interface-based 3D SSD [32]. In the analytical solution, the 3D SSD area for the observed aircraft (A_{obs}) were comprised of two intersecting circles (both from the top and the bottom of the protected area) and the flight envelope of the controlled aircraft (A_{con}) comprising the rotation of the performance envelope around its vertical axis with 360 degrees, resulting in a donut-shaped solution space. A simplified diagram of the solution space constructed by the protected area of the observed aircraft and the flight envelope of the controlled aircraft is illustrated in Figure 21. Further studies need to be conducted to verify the capability of the 3D SSD in efficiently measuring workload or sector complexity.

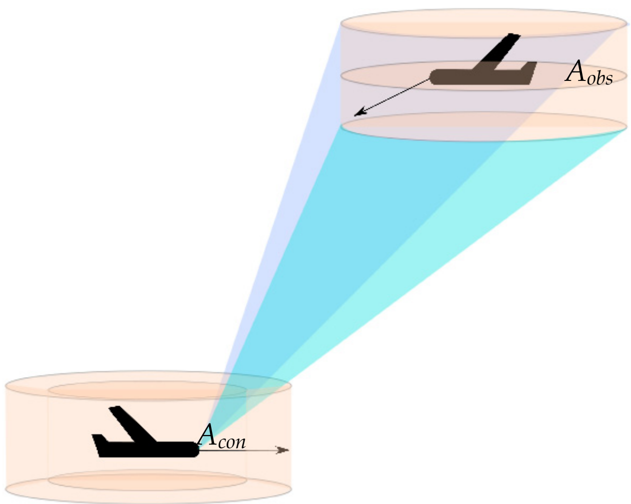


Figure 21. Two Aircraft in 3 Dimensional Conditions.

In a different study, the altitude dimensional was integrated into a 2D-based SSD ATCO display [32]. The altitude extended SSD was calculated by filtering the aircraft in accordance to their Altitude Relevance Bands and cut off the SSD conflict zones by the slowest and fastest possible climb and descent profiles. In this way, the algorithm can discard conflict zones that can never lead to a conflict. Based on this algorithm, a display prototype has been developed that is able to show the effect of altitude changes to the controller. This display will be used in the future to perform a human-in-the-loop experiment to assess the benefits of including altitude information in the 2D SSD ATCO displays.

7. Discussion

The SSD represents the spaces of velocity vectors that are conflict free. The remaining conflict areas were used as an indication of the level of difficulty that a controller has to handle. When conflict zones in the SSD occupy more area, fewer possible solutions are available to resolve future separation violations. The capability of SSD area properties in measuring the dynamic behavior of the sector was proven in previous studies [23,24]. The ongoing research is aimed at understanding the possibility of using the SSD in investigating the effects of various sector design properties on complexity and controller workload.

Based on the results gathered from the simulations, the complexity measure of intercept angle, aircraft speed, horizontal proximity, the number of aircraft, and the effect of aircraft orientation can be illustrated through the covered area percentage of the SSD. Each sector complexity factor is portrayed differently on the SSD. It is assumed that a denser area is related to a higher complexity measure. From the initial study conducted, it is concluded that a higher intercept angle, results in a smaller complexity metric, but also that this condition only applies if the observed aircraft has a route length larger or equal than the controlled aircraft. For horizontal proximity properties, it was found that further apart aircraft have a lower complexity metric. The effect of speed on the other hand depends on the position and intercept angle of the observed aircraft where a larger speed may result in higher or lower complexity metric. The number of aircraft within a sector also has a high implication on sector complexity and this was also portrayed in the SSD. However, the importance of the aircraft orientation was also an important characteristic that has an effect on the SSD area properties and thus, sector complexity.

However, it should be noted that these sector complexity parameters did not change individually at each instant, because of the dynamic behavior of the aircraft within the sector. As an initial stage of an investigation, this case study will provide the basis for hypotheses that will be tested systematically in subsequent studies. To further understand the behavior of the SSD it is important to investigate other and more combinations of sector complexity metrics. In future studies, the findings regarding the relationship between sector complexity factors and SSD metrics should be validated by means of human-in-the-loop experiments to also get the ATCO's insight on the perceived workload and how this can be related to the sector complexity mapped on the SSD.

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