

SECTOR COMPLEXITY MEASURES: A COMPARISON

Article history

Received

13 February 2015

Received in revised form

31 May 2015

Accepted

30 June 2015

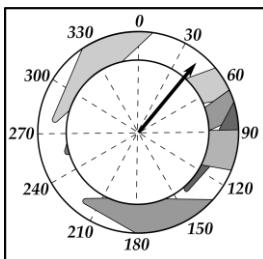
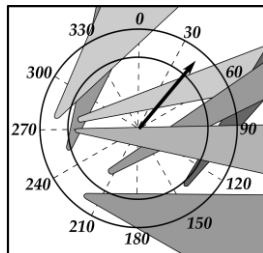
Siti Mariam Abdul Rahman^{a*}, Clark Borst^b, Max Mulder^b,
Rene van Paassen^b

^aFaculty of Mechanical Engineering, University Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

^bControl and Operation Division, Delft University of Technology, Delft, The Netherlands.

*Corresponding author
mariam4528@salam.uitm.edu.my

Graphical abstract



Abstract

In developing a more advanced human-machine systems for future Air Traffic Management (ATM) concepts requires a deep understanding of what constitutes operator workload and how taskload and sector complexity can affect it. Many efforts have been done in the past to measure and/or predict operator workload using sector complexity. However, most sector complexity metrics that include sector design are calculated according to a set of rules and subjective weightings, rendering them to be dependent of sector. This research focuses on comparing the Solution Space Diagram (SSD) method with a widely accepted complexity metric: Dynamic Density (DD). In essence, the SSD method used in this research, observed aircraft restrictions and opportunities to resolve traffic conflicts in both the speed and heading dimensions. It is hypothesized that the more area covered on the solution space, that is, the fewer options the controller has to resolve conflicts, the more difficult the task and the higher the workload experienced by the controller. To compare sector complexity measures in terms of their transferability in capturing dynamic complexity across different sectors, a human-in-the-loop experiment using two distinct sectors has been designed and conducted. Based on the experiments, it is revealed that the SSD metric has a higher correlation with the controllers' workload ratings than the number of aircraft and the un-weighted NASA DD metric. Although linear regression analysis improved the correlation between the workload ratings and the weighted DD metric as compared to the SSD metric, the DD metric proved to be more sensitive to changes in sector layout than the SSD metric. This result would indicate that the SSD metric is better able to capture controller workload than the DD metric, when tuning for a specific sector layout is not feasible.

Keywords: Air traffic control, sector complexity, solution space diagram

© 2015 Penerbit UTM Press. All rights reserved

1.0 INTRODUCTION

Air Traffic Controllers (ATCOs) are responsible for the supervision of a safety, efficiency and orderly flow of air traffic. Current Air Traffic Control (ATC) uses conventional technology (e.g., radar and Radio Telephony (RT) communication) and little automation support exists in supervising air traffic. Although more aspects of air transportation are being automated over time, the task of supervising air traffic is still performed by human controllers and is therefore limited by human performance constraints [1].

Without counter-measures, the rise in projected air traffic [2] would inevitably result in a further increase in the workload of Air Traffic Controllers (ATCOs). The latter is often cited as one of the main impediments to the growth of air transport [3,4,5].

Consequently, a more objective measure of sector complexity is needed in order to determine the level of task demand load imposed on the controller. In order to successfully construct an objective measure, a more comprehensive understanding of controller's task demand load, is required. A long and ongoing research in this area suggests the importance of

exploring ATC sector complexity in understanding its relation to workload [6-10].

1.1 Taskload-Workload Relation

In normal ATC practice, there is a maximum number of aircraft that can be contained simultaneously in each particular sector. Whenever traffic demand exceeds sector capacity, two solutions are available, either more controllers can be assigned to the sector, or a single sector can be divided into two or more sectors, each of which is assigned to its own team of controllers. These concepts of manageable number of aircraft per sector will be less relevant with more complex air-traffic situations. Thus, a need to forecast complexity and a method to reduce complexity by enabling varying degree of automation or assistance provided to controller when an air-traffic situation becomes more complex is foreseen.

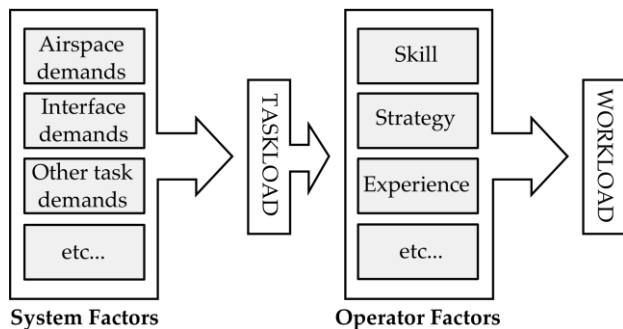


Figure 1 Taskload and workload relation Hilburn and Jorna [11]

A number of factors affect controller's workload including but not limited to airspace complexity, traffic complexity, interface complexity and controller's level of skills and experience. To enable air traffic growth while ensuring the safety of air traffic, we need a better understanding of where the workload comes from. There is one main distinction generally made between task demand load (in this paper referred to as 'taskload') and mental workload (in this paper referred to as 'workload'). Taskload refers to the objective demands of a task, whereas workload addresses the subjective demand experienced by the operator in the performance of a task. In the effort to distinguish between taskload and workload, Hilburn and Jorna [11] defined that system-related factors such as airspace demands, interface demands and other task demands contribute to taskload, while operator-centered factors like skill, strategy, experience and so on determine workload. This is illustrated in Figure 1.

Also, perceived operator workload is highly dynamic, thereby, it is not only dependent on contextual factors (such as traffic state, weather conditions, sector layout and etc.), but also dependent on the operator's own actions. That is, an operator can influence his own workload by the decisions he makes and be totally unaware of how

he actually influenced his own future workload (or task complexity). This conform to a study on occurrences of Short Term Conflict Alert (STCA) warnings, which highlighted that a large number of these alerts do not occur in isolation, but were linked to earlier alerts [12].

2.0 SECTOR COMPLEXITY MEASURES

In the effort to balance air traffic growth demand and airspace capacity, describing airspace sector complexity is indeed important. Many efforts have been done in the past to measure and/or predict operator workload using sector complexity [4,7,9, 13,14]. Measures such as counting the number of aircraft, or Static Density (SD), which uses the number of aircraft per-sector basis [4,7], in many experiments, present the highest correlation with ATCO subjective taskload ratings [9,10]. However, it has significant shortcomings in its ability to accurately measure and predict sector complexity [8,9] due to its inability to illustrate sufficiently the dynamics of the behavior of aircraft in the sector. Thus, the SD method alone is unable to represent the maximum number of aircraft that is manageable by a controller.

Another sector complexity measure such as the Dynamic Density (DD) incorporates the dynamic behavior of aircraft in the sector. The DD metric takes into account "the collective effort of all factors or variables that contribute to sector-level ATC complexity or difficulty at any point of time" [9]. However, the calculation of the DD is based on the weights gathered from regression methods on samples of traffic data and comparing them to subjective taskload ratings. As a result, the DD metric represents a complexity measure that incorporates both subjective and objective workload measurements. The method is therefore both sector-dependent and controller-dependent. However, most sector complexity metrics that include sector design are calculated according to a set of rules and subjective weightings, rendering them to be dependent of both sector and individual controllers.

Other notions of sector complexity measure using visualization techniques have also been proposed through complexity maps such as the Input-Output (IO) approach by Lee et al. [13], the Lyapunov Exponents (LE) approach by Puechmorel and Delahaye [14] and a medium-term multi-sector planning tool called the Tactical Load Smoother (TLS), which was realized during the Programme for Harmonised Air-Traffic Management Research in Eurocontrol (PHARE) project [15]. However, these complexity maps all have the shortcomings of either being controller dependent (IO approach) or both controller and sector dependent (TLS tool approach) or having a computational challenge (LE approach), which is critical for application to high density airspace.

The long and still ongoing research attempts in this

area confirm the importance of exploring ATC sector complexity metrics in understanding its relation to ATCO workload. Clearly, there is a need for an objective metric that can be used to predict taskload in a controller-independent fashion, and also that can be used to compare the complexity of sectors in a quantitative way.

3.0 SOLUTION SPACE DIAGRAM APPROACH

In this paper, approach based on the investigations of problems using the solution space based analysis was incorporated. Initial work by Van Dam et al. [16] has introduced the application of a Solution Space Display in aircraft separation problems from the pilots' perspective. Hermes et al. [17], d'Engelbronner et al. [18] and Mercado Velasco et al. [19] then continued the idea of using the Solution Space in aircraft separation from the perspective of the ATCO. A high correlation was shown to exist between derived metrics from the Solution Space, and the subjective workload reported by ATCOs [17,18]. This research will continue expanding the Solution Space by utilizing the solution space method in sector complexity exploration and also relating workload to sector complexity.

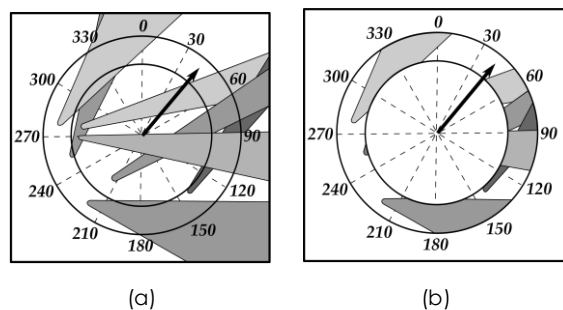


Figure 2 The example of SSD unsafe area. (a) SSD with multiple no-go beams. (b) The unsafe area (A_{whole}).

This paper investigates whether the solution space area of a two-dimensional ATC separation problem can be used to assess the inherent difficulty of ATC situation more accurately and objectively than current metrics. The metrics based on the SSD method consider the SSD area percentage measures (both individual and/ or average SSD area properties) in order to quantify the level of sector complexity. Figure 2 (a) illustrates an example of the SSD of an aircraft, with seven other aircraft within the area. The unsafe area within minimum and maximum velocity-heading band of the respective aircraft (such as in Figure 2 (b)) is referred in this paper as A_{whole} . It defines all possible velocity vectors for the controlled aircraft that could lead to future separation violation. Another area property investigated is the mean area affected (A_{mean}). 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.

4.0 EXPERIMENT

To more thoroughly investigate the applicability and potential advantages of the SSD metric, it is crucial to compare it with a widely accepted complexity metric: DD. In this paper, the number of aircraft and the DD metric are compared to the SSD metric in terms of their correlations to controller workload.

As the study described in this paper relies on correlation analysis between the controller's workload ratings with the complexity metrics, the first step includes collecting subjective workload ratings throughout the experiment at regular time intervals to capture a workload profile for each controller. Secondly, based on the recorded aircraft parameters, such as such as position, speed, and heading, the SSD and un-weighted DD metrics can be computed after a run. Linear regression analysis will then be performed to gather weighting coefficients corresponding to a number of Dynamic Variables (DV) to produce the weighted NASA DD metric that improves the correlations per individual. With all the information gathered, the comparison study between the number of aircraft and also both the un-weighted and weighted NASA DD with the SSD can be facilitated.

4.1 Subjects And Tasks

In the experiment, the participating eight male subjects with age between 29 and 51 ($\mu = 35.63$, $\sigma = 8.18$), have all received an extensive ATC introductory course. As such, all subjects have a similar basic experience level in ATM. The subjects were instructed to clear aircraft to their designated sector exit points and keep aircraft separated by at least 5 NM.

All traffic was situated at FL290 and the function to change the altitude of aircraft was not enabled. Thus, the participants could only use heading and/or speed clearances to control aircraft. To support the controllers in their task, aircraft were color coded to indicate their course deviations and when they were in conflict. The unselected aircraft, which were headed towards their assigned exit point, were colored in green, whereas unselected and deviating aircraft were colored in gray. Further, a selected aircraft was colored in white and would display an inner circle, indicating the 5 NM protected zone, and a green circle that indicated the current speed and a magenta circle and line, indicating the intended speed and heading clearance (Figure 3 (b)). In safely separating aircraft, a predicted loss of separation within 3 minutes (simulated-time) would trigger an aural alert and the involved aircraft in the conflict would be colored in red. Figure 3 shows an example of the simulator presented to the subjects.

Only aircraft, which were inside the controlled

sector, could be given a speed and/or heading command. To control an aircraft, subjects first had to select an aircraft. Then, by dragging the heading line with the mouse to a new heading and/or scrolling with the mouse to a new heading and/or scrolling

the mouse scroll wheel up or down for speed change, the state of the aircraft could be changed. To confirm and implement a speed and/or heading change, the enter key had to be pressed.

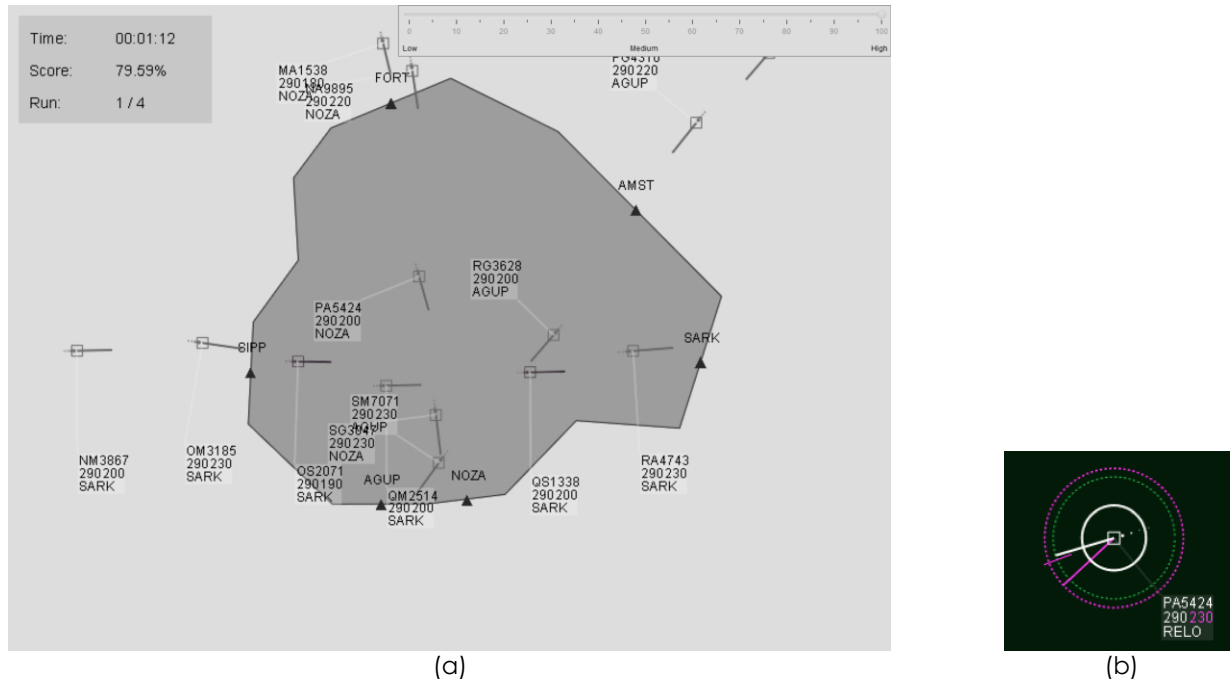


Figure 3 (a) Experiment Simulator. (b) Aircraft control area.

During the experiment, the participants were asked to rate their perceived workload every 60 seconds. An automated stimulus provided a scale on the display that triggered the participants to rate their workload by means of clicking between 0 (low workload) and 100 (high workload). A mouse click on a scale that appeared on the same display (Figure 3) is presumed to provide subjects with a more direct and less intrusive workload rating measure than typing a number on a keyboard. The scale is also much finer grained, allowing the slightest change in workload to be captured.

4.2 Complexity Measures

The complexity measures consisted of two DD metrics and the SSD area metric. Both DD metrics were measured every 60 seconds to match with the workload rating instances. The first DD metric, NASA DD Metric 1 (NASA1) is based on research conducted by Chatterji and Sridhar [8]. For further details on the Dynamic Variables (DV) and calculation methods, readers are encouraged to refer to Chatterji and Sridhar [8]. The metric consisted of 16 DV and it is calculated as follows:

$$DD = \sum W_i DV_i$$

The second DD metric, NASA DD Metric 2 (NASA2) calculation based on research by Laudeman et al.

[6] and Sridhar et al. [7]. For further details on the DV and calculation methods, readers are encouraged to refer to Laudeman et al. [6] and Sridhar et al. [7]. The metric consisted of 8 DV, excluding traffic density (TD) and it is calculated as follows:

$$DD = \sum W_i DV_i + TD$$

The original NASA DD metrics represented in previous researches [6,7,8] were constructed based on a 3-Dimensional (3D) airspace model. In gathering airspace and traffic factor to produce NASA DD metrics from a 2-Dimensional (2D) airspace model as used in this research, several DV were canceled out from both NASA1 and NASA2 metric. These DV are relevant to changes in altitude measures (DV 2 and DV 4 for NASA1 metric and DV 3 for NASA2 metric) and also related to vertical proximities (DV 8, DV 9 and DV 10 for NASA1 metric).

The SSD area properties were calculated using the mean of SSD area (A_{mean}) of all aircraft within the sector (referred in this paper as SSD). It is gathered using the following equation with A_{whole} representing the total area within minimum and maximum velocity-heading band of each individual aircraft within the sector and n being the number of aircraft within the sector. The SSD area properties were measured every 60 seconds to match with the workload rating instances.

$$A_{mean} = \frac{1}{n} \sum_{i=1}^n A_{whole_i}$$

4.3 Sector Layout

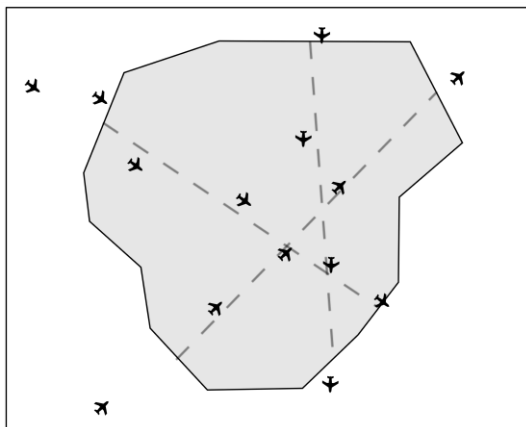
The experiment scenarios were constructed based on the 'clearance to exit point task' with one type of aircraft on one flight level. There were three streams of incoming aircraft entering the sector. Apart from these three main similarities in sector designs, a number of differences were designed in both sectors in order to produce two different sectors. This is crucial in order to be able to test the metrics sensitivity to sector design. Figure 4 shows an example of the two sector designs used in this experiment.

The sector design variables can be observed from Figure 4 and the settings are detailed as follows:

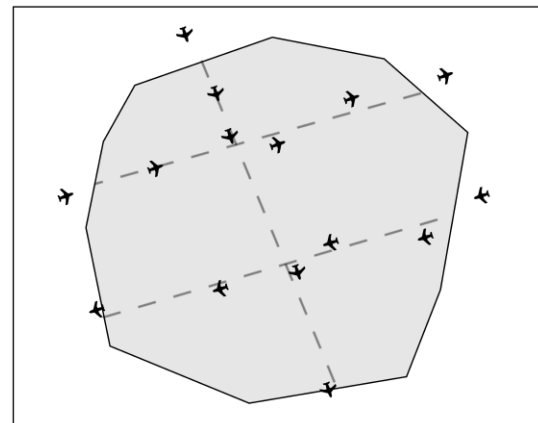
1. Sector 1 has three crossing points, while Sector 2 has two crossing points.
2. Sector 1 has mixed combinations of the intercept angle of traffic routes of approximately 45°, 90°

and 120°. Whereas Sector 2 has two approximately 90° crossing angles.

3. The two sectors had a different pattern in crossing point clusters. That is, Sector 1 had more clustered crossing points near the sector border, whereas Sector 2 had a less clustered intersection points with the two crossing points having ample spacing between them.
4. Both sector also had a different pattern in the clustering of entry and exit points. Sector 1 has all exit points on the right hand side of the sector, whereas Sector 2 has entry and exit points at both sides of the sector.
5. Different sector shapes were designed for both sectors. Sector 1 has a more odd polygon shape, whereas Sector 2 has a more regular polygon shape.
6. The two sectors had different sector area properties. Sector 1 has an area of approximately 30% less than Sector 2. Sector 1 has a total area of 7000nm², whereas Sector 2 has a total area of 10400nm².



(a) Sector 1



(b) Sector 2

Figure 4 Sector design and the traffic flow assignment

5.0 RESULTS AND DISCUSSION

5.1 Un-weighted Correlation Analysis

The analysis of un-weighted NASA DD metrics was made based on the assumption that all DV weighting coefficient are equal and were all assigned as 1. The un-weighted NASA DD metrics in this section were calculated using Equation (1) and (2).

Based on the results of the correlation analysis between workload rating and sector complexity measures, SSD showed the highest correlation with workload rating. Average number of aircraft is second in line as a good sector complexity measure which demonstrates that indeed the number of aircraft is one of the most important sector complexity variable that in influences controller's workload.

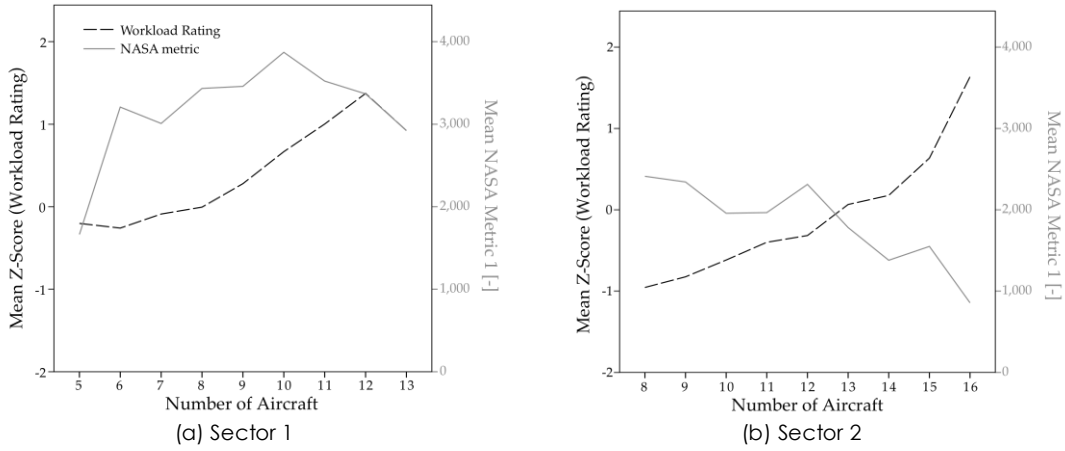


Figure 5 Un-weighted NASA1 based on different sectors

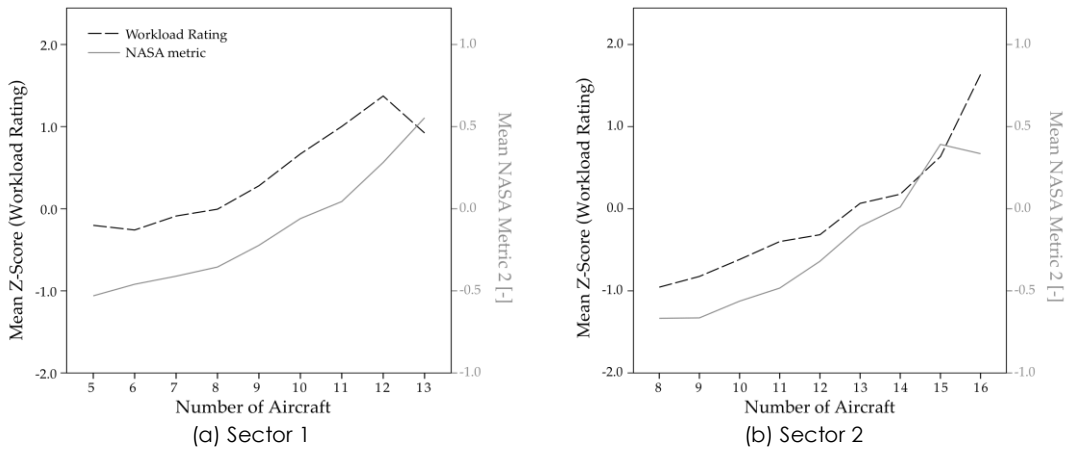


Figure 6 Un-weighted NASA2 based on different sectors

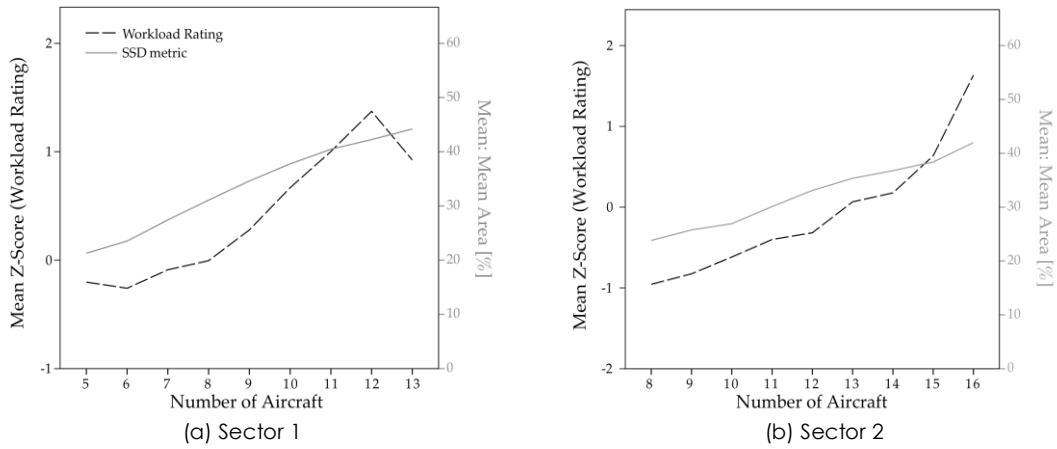


Figure 7 SSD area properties based on different sectors

Figure 5, 6 and 7 showed plots of un-weighted NASA DD and SSD metric compared to workload rating based on number of aircraft, respectively. The plots were intended to illustrate how workload ratings behave towards number of aircraft and also how un-weighted NASA DD and SSD metric behave in responds to the same number of aircraft.

Based on Figure 5, NASA1 plots did not show a pattern that is closely related to workload rating. Other sector complexity measures such as NASA2

(Figure 6) and SSD (Figure 7) showed a more resembling pattern that of the workload rating.

5.2 Weighted Correlation Analysis

In this section, the un-weighted NASA DD metric were fixed to the workload rating data, using the linear regression method, resulting in a fitted weighted NASA DD metric. In principle, the weighted NASA DD metric should correlate better than the un-weighted

ones. The regression analysis was conducted based on different sector. This is done in order to investigate whether the weighted NASA DD metric is consistently better than the SSD regardless of different sector. Also, in the subsequent section, analysis on the transferability of the weighted NASA DD metric across different sector design.

First, linear regression analysis were conducted on the basis of different sectors. Based on the analysis, a number of significant variables were identified.

1) Sector 1:

$$NASA1 = 1.134 + 1.191 * DV1 - 0.738 * DV3 + 7.301 * DV6 + 0.534 * DV11 + 0.0003 * DV14 - 1.189 * DV15 - 0.0003 * DV16$$

$$NASA2 = -0.466 + 0.111 * DV1 + 0.111 * DV2 + 0.023 * DV5 + TD$$

2) Sector 2:

$$NASA1 = -0.761 * DV3 + 9.902 * DV5 + 3.043 * DV6 + 1.750 * DV7$$

$$NASA2 = -0.844 + 0.098 * DV1 + 0.036 * DV5 + 0.012 * DV6 + TD$$

For both sectors, the NASA1 DD metric are defined as having different significant DV, which are included in the end DD equation. In Sector 1, the significant DV are focused more to the variables related to aircraft horizontal proximity (DV 6), speed (DV 14 and DV 15) and intercept angle (DV 16), whereas in Sector 2, only variable concerning horizontal proximity (DV 5 to DV 7) are found to be significant. It is also concluded that the number of aircraft has shown a significant effect for Sector 1, but not in Sector 2.

For the NASA2 DD metric, the speed change variable (DV 2) showed to be significant in Sector 1, but not in Sector 2. However, in both sectors, variable concerning heading change (DV 1) and horizontal

Variables that computed regression weights were small and non significant were removed from the equation that was used to compute the end DD. The weighted NASA DD metrics were constructed based on the coefficient individual contribution (b-value), representing the weighting factor for each DV. By replacing the significant b-value into equation (1) and (2), the NASA DD model can be defined as follows with the corresponding DV detailed in earlier sections:

proximity (DV 5) were found to be significant. Differences in variables that influence the NASA DD model for both sector showed that different sector design demand for different weighted NASA DD metric.

The correlation between the resulting weighted DD and workload rating were gathered again using Kendall's tau correlation coefficient. Based on the result, NASA1 for Sector 1 and NASA2 for Sector 2 have higher correlation than SSD. It is observed that weighted NASA1 showed an increase in correlation on both sector if compared to un-weighted NASA1. However weighted NASA2 showed a lower correlation in Sector 1 and a higher correlation in Sector 2 compared to un-weighted NASA2.

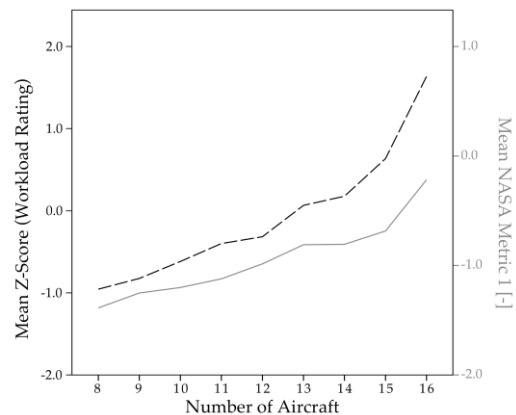
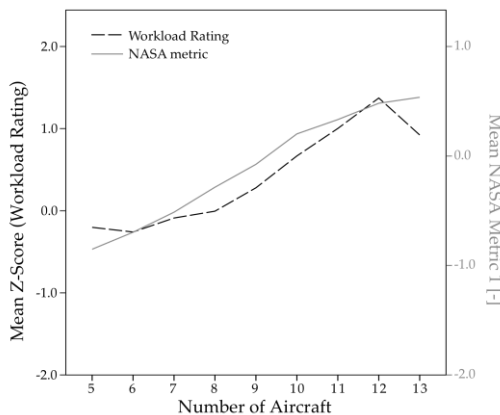


Figure 8 Weighted NASA1 based on different sectors.

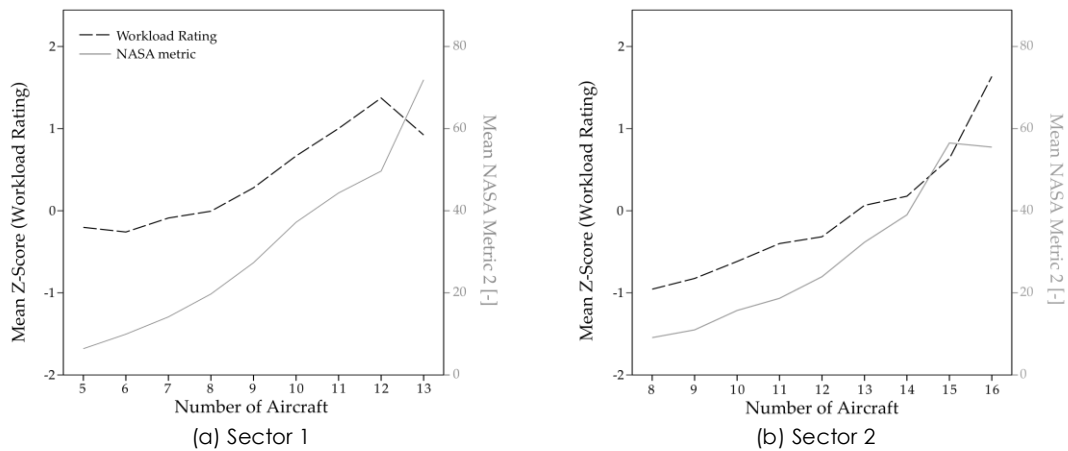


Figure 9 Weighted NASA2 based on different sectors.

Figure 8 and 9 showed weighted NASA DD with workload rating also against the number of aircraft. This can be compared with the initial un-weighted NASA DD from Figure 5 and 6 where the plots of weighted NASA1 and NASA2 have improved to a plot that better matches the workload rating in Figure 8 and 9.

5.3 Cross-Sector Transferability

In addition to the weighted NASA DD analysis, to demonstrate that the weighting coefficient only serves a certain sector, a cross analysis of NASA DD metric between different sectors was carried out. Cross-sector analysis was conducted by applying the weighting coefficient gathered in Sector 1 to Sector 2 and vice versa. Based on the analysis, only NASA2 for Sector 1 showed a higher correlation level than the original correlation value. Others showed lower correlation level. However, both NASA1 and NASA2 showed lower correlation than SSD metric sector complexity measure.

6.0 DISCUSSION

This paper compares the proposed metric, SSD with known metrics such as the number of aircraft and NASA DD metric gathered from research by Laudeman et al. [6], Sridhar et al. [7] and Chatterji and Sridhar [8]. Multiple scenarios from two different sectors were presented to the subjects with varying incoming traffic sequences. This is to avoid scenario recognition during the course of the experiment.

Analysis with regards to subject's behavior and workload rating were initially conducted to observe whether both sectors represent two sectors of different complexity, which would enable cross-sector transferability investigation on sector complexity measures. It is gathered that both sector indeed represent different levels of complexity, based on significant differences gathered from both subject's behavior and workload rating. It is also

gathered that the number of aircraft present in a sector does not need to constitute the main factor that determines controller workload. Other sector complexity influencing variables, such as sector volume, route design and also geographical location of intercept points also contribute to the effect on how much effort was needed to control the sector. This is consistent with the concept of having different maximum number of aircraft per sector basis.

Initial correlation analysis were conducted to compare the SSD metric and un-weighted NASA DD metric towards workload rating. The analysis is aimed at having a neutral comparison between both un-weighted NASA DD and the SSD metric without the influence of any post-processing procedures. It is observed that based on initial correlation analysis, SSD is shown to have a higher level of correlation than un-weighted NASA DD metric and number of aircraft. This is found in analysis based on different sector.

Weighted NASA DD metrics from a collection of significant DV coupled together with weighting coefficient were gathered through regression analysis. Different sets of DV used to construct NASA DD metric for different sector, were an indication of differences in controller's strategy in handling traffic within a sector. Thus, controller's individual differences would highly influence the construction of the DD metric. An improved correlation between weighted NASA DD and workload rating were gathered compared to un-weighted NASA DD. However, when compared to SSD metric, only some weighted NASA DD metric showed a better correlation than SSD metric with workload rating.

It has been observed that when transferring a certain NASA DD model to a different sector, it has resulted in the metric not delivering the same level of correlation as previously found. The cross-sector analyses also reveal that both NASA DD metrics is sensitive towards different sector.

The original NASA DD metric was constructed based on a 3D airspace model with traffic samples from 36 high and low sectors, respectively. Due to the extent of data used in producing the metric, it is

assumed that the NASA DD metric should be robust enough to be used on other traffic samples. However, the fact that the linear regression analysis to produce the weighted NASA DD metric in this experiment was gathered based on 2D airspace model using limited number of participants over a large number of variables, there could always be a possibility of the model being overfitted and in the end produce a poorer predictive performance. Exaggeration of minor fluctuations in the data could have deteriorated the method's performance. Nevertheless, the NASA DD metric should not be too sensitive to a specific sample size and should perform well on any sector design.

7.0 CONCLUSION

This paper presents the result of the investigation of whether the SSD indeed presents a more reliable and objective sector complexity measure as it managed to show the same level of correlation under various sector designs settings. Comparisons between proposed SSD metrics and other known sector complexity measures, namely the number of aircraft and DD were conducted. From the experiment, it is concluded that the proposed method indeed represents a reliable and objective sector complexity measure, which could function better than number of aircraft, un-weighted NASA DD metric and in certain conditions, than the weighted NASA DD metric. The SSD metric, which can be use in real-time situation without any post-processing procedures also, appeared to be less sensitive than the NASA DD metric, towards controller differences as to sector design.

References

- [1] Costa, G. 1993. Evaluation of Workload in Air Traffic Controllers. *Ergonomics*. 36(9): 1111-20.
- [2] Airbus, S. A. S. 2013. Global Market Forecast 2013-2032. Technical report. *Airbus*.
- [3] Janic, M. 1997. A Model of Air Traffic Control Sector Capacity Based on Air Traffic Controller Workload. *Transportation Planning and Technology*. 20: 311-335.
- [4] Hilburn, B. G. 2004. Cognitive Complexity in Air Traffic Control - A Literature Review. *Technical Report EEC Note 04/04*. EUROCONTROL, Bretigny-sur-Orge, France.
- [5] Koros, A., Della Rocco, P. S., Panjwani, G., Ingurgio, V. and D'Arcy, J.-F. 2004. Complexity in Air Traffic Control Towers: A Field Study. Technical note (DOT/FAA/TC-06/22). Atlantic City International Airport, NJ: Federal Aviation Administration William J. Hughes Technical Center.
- [6] Laudeman, V., Sheldon, S. G., Branstron, R. and Brasil, C. L. 1998. Dynamic Density: An Air Traffic Management Metric. *Technical Report NASA-TM-1998-112226*. NASA Center for Aerospace Information.
- [7] Sridhar, B., Sheth, K. S. and Grabbe, S. 1998. Airspace Complexity and its Application in Air Traffic Management. *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL. 1-9.
- [8] Chatterji, G. B. and Sridhar, B. 2001. Measures for Air Traffic Controller Workload Prediction. *1st AIAA Aircraft Technology, Integration, and Operations Forum*, Los Angeles, CA.
- [9] Kopardekar, P and Magyarits, S. 2002. Dynamic Density: Measuring and Predicting Sector Complexity. *21st Digital Avionics System Conference*, Piscataway, NJ. 1-9.
- [10] Masalonis, A. J., Callahan, M. B. and Wanke, C. R. 2003. Dynamic Density and Complexity Metrics for Realtime Traffic Flow Management. *Technical report, Center for Advanced Aviation System Development (CAASD)*, The MITRE Corporation.
- [11] Hilburn, B. G. and Jorna, P. G. A. M. 2001. Workload and Air Traffic Control. P. A. Hancock and P. A. Desmond, editor. *Stress, Workload and Fatigue: Theory, Research and Practice*. Erlbaum, Hillsdale, New Jersey, USA. 384.
- [12] Lillo, F., Pozzi, S., Ferrara, G. and Lieutaud, F. 2009. Coupling and Complexity of Interaction of STCA Networks. *8th Inovative Research Workload Exhibition*, Bretigny-sur-Orge, France.
- [13] Lee, Feron, E. and Pritchett, A. R. 2009. Describing Airspace Complexity: Airspace Response to Disturbances. *Journal of Guidance, Control and Dynamics*. 32(1): 210-222.
- [14] Puechmorel S. and Delahaye, D. 2009. New Trends in Air Traffic Complexity. *Proceedings EIWAC*, Tokyo, Japan.
- [15] Whiteley, M. 1999. PHARE Advanced Tools Tactical Load Smoother. *Technical report*, European Organisation for the Safety of Air Navigation (EUROCONTROL).
- [16] Van Dam, S. B. J., Abeloos, A. L. M., Mulder, M. and van Paassen, M. M. 2004. Functional Presentation of Travel Opportunities in Flexible Use Airspace: an EID of an Airborne Conflict Support Tool. *IEEE International Conference on Systems, Man and Cybernetics*. 1: 802-808.
- [17] Hermes, P., Mulder, M., van Paassen, M. M., Beoring, J. H. L. and Huisman, H. 2009. Solution Space-Based Analysis of Difficulty of Aircraft Merging Tasks. *Journal of Aircraft*. 46(6): 1-21.
- [18] d'Engelbronner, J., Mulder, M., van Paassen, M. M. de Stigter, S. and Huisman, H. 2010. The Use of the Dynamic Solution Space to Assess Air Traffic Controller Workload. *AIAA Guidance, Navigation, and Control Conference*, Toronto, CA. 21.
- [19] Mercado Velasco, G. A., Mulder, M. and van Paassen, M. M. 2010. Analysis of Air Traffic Controller Workload Reduction Based on the Solution Space for the Merging Task. *AIAA Guidance, Navigation, and Control Conference*, Toronto, CA. 18.