Annales Mathematicae et Informaticae
48 (2018) pp. 65–73
http://ami.uni-eszterhazy.hu

Functional model of a decision support tool for Air Traffic Control supervisors

Bence Számel, Géza Szabó

Budapest University of Technology and Economics
szamel.bence@mail.bme.hu
szabo.geza@mail.bme.hu

Submitted March 5, 2018 — Accepted September 13, 2018

Abstract

The optimization of operator workload in Air Traffic Control systems is of high importance regarding both safety and efficiency of air transportation. The default means of optimizing workload in practice is division of traffic among controllers by splitting the airspace into sectors. Decisions about opening or closing sectors are made by a human supervisor who can sometimes encounter difficulties during decision making, especially when facing uncommon traffic situations.

This makes it advisable to create a decision support tool designed to automate decision making by suggesting a sector configuration based on traffic complexity to the supervisor. The main modules of this tool are centered on a model of cognitive functions that have to be executed by the supervisor throughout the decision making process. The functions include prediction of future traffic, calculation of complexity and determining optimal sector states to finally produce the optimal configuration. In this paper, we outline the formal description of the functionality of the tool's modules, focusing on the algorithms they should implement.

Keywords: Air Traffic Control, decision support, neural network

MSC: 68T99

1. Introduction

The Air Traffic Control (ATC) system is responsible for ensuring the safe and efficient movement of aircraft in controlled airspace. Controlled airspace is the section of the atmosphere in which all air vehicles are compulsively required to comply with the instructions of Air Traffic Control Officers (ATCOs). ATCOs observe traffic in the airspace in real time and issue clearances in order to separate aircraft on conflicting routes or help them evade thunderstorm areas or restricted airspace. As ATCOs can pay attention to a limited number of aircraft at the same time, when traffic increases, the airspace is divided into sectors with different responsible ATCOs.

Nowadays the division of airspaces is done by using deterministic geographical and/or altitudinal borders. If such a border is actually in use for dividing the airspace, it will be referred to as an active border, otherwise it will be referred to as an inactive border. If a sector does not contain any inactive borders, it will be called an elementary sector. A certain combination of active borders will be referred to as a sector configuration. A theoretical combination of one or more elementary sectors will be simply referred to as a sector, while sectors that are present in a specifed sector confguration will be referred to as active sectors. In general, sectors can assume the “split” (contains more than one active sector), “armed” (used on its own) or “merged” (part of an active sector) state.

Making and executing decisions related to sector configuration change is done by a designated person, known as the supervisor. The supervisor is responsible for assigning ATCOs to newly activated sectors, replacing personnel in already active sectors and above all for making decisions about when to change sector configuration and which should be the new configuration to use.

In a general airspace, a great amount of possible sector configurations may exist and different sector configurations usually mean a different distribution of traffic among ATCOs. The basic aim of sectorization is to keep the workload of ATCOs near the optimum level which means that they should neither be assigned too difficult nor too simple traffic situations as both can lead to higher error rates [1, 2]. Since workload is not only influenced by traffic volume (i.e. the number of aircraft) but also by traffic complexity (and other complexity factors related to airspace, equipment, operators etc.)[3], finding the optimal sector configuration for a certain traffic situation can not be done via a simple algorithm based on the number of aircraft in sectors. Instead, the optimal sector configuration can be interpreted as a product of a complex function based on the above mentioned complexity factors. Note that many Air Navigation Service Providers use the number of aircraft to determine a suitable basic sector configuration. Supervisors can then change this basic configuration taking into account other factors based on their experience.

In ATC centers, the above function is realized by the supervisor. Due to the complexity of this decision and the fact that supervisors may differ in experience, skills and/or decision-making preferences, the actual sector configuration produced depends on the supervisor. Therefore, it is prone to human error, especially in case of uncommon traffic situations. In order to increase the probability of using safe and efficient sector configurations, it is advisable to provide an automated advisory tool that can suggest sector configuration solutions to the supervisor who can decide to approve or reject them. In this paper, we provide an overview of the functional requirements of a tool that fulfils the mentioned purpose by presenting a model to formally describe the decision making process (Section 2), providing a more detailed description about the tool's modules which are based on this model (Sections 3 and 4) and drawing conclusions (Section 5).

2. Model of the decision making process

As it was adumbrated in the previous section, the tool needs to use the same data that is available to supervisors and produce a sector configuration as an output. In other words, it should mimic the decision making mechanism of a human supervisor.

The first step in the decision making process is the collection and evaluation of different data that can be relevant to ATCO workload and thus sector configuration. The data used by supervisors as input for their decisions can originate from any of the following sources:

- Radar data (real time position, flight level and speed vector of aircraft)
- Flight plan data (scheduled route of aircraft)
- Airspace restriction data (due to thunderstorm or scheduled restrictions)

In order to create an appropriate model of the data evaluation process, it is important to consider the timely nature of the supervisor's decision. When making their decisions, supervisors are aware that performing a sector configuration change requires a certain amount of time, because ATCOs have to get familiar with the traffic situation before assuming control and newly assigned ATCOs even have to man their workstations first. In real life situations, this procedure requires 10-20 minutes to complete. Such an amount of time is enough for considerable changes to happen in the characteristics of air traffic. This means that the supervisor can not simply rely on the data that is valid at the time of the decision but should make projections and create a mental picture of traffic expected in 10-20 minutes and then use this for actual decision making.

Formalizing the above, let D_R, D_{FP} and D_{TRA} be sets of radar data, flight plan data and temporary airspace restriction data respectively, which are available at the moment of the decision, although D_{FP} and D_{TRA} contain information about the future. In the model of the decision making process, D_R and D_{FP} are used first by a projection function (F_P) that creates a set of projected radar data (D_R^P) whith a structure similar to D_R but it is valid at the time of configuration change.

$$F_P : D_R \times D_{FP} \to D_R^P \tag{2.1}$$

After projecting future traffic based on actual aircraft movement and flight plans, the supervisor has to update the mental picture by considering areas of the airspace that are restricted to flight by thunderstorm or scheduled restrictions by other parties using the airspace. This correction is modelled by the corrected projection function (F_{CP}) which transforms the set of projected radar data into corrected projected radar data (D_R^{PC}) by using a set of data about temporary airspace restrictions (D_{TRA}).

$$F_{CP} : D_R^P \times D_{TRA} \rightarrow D_R^{PC} \tag{2.2}$$

Once the mental picture of the (corrected) projected situation is available, the supervisor analyzes it by evaluating the characteristics of air traffic and the airspace. In the model, these characteristics are represented by so called complexity factors. Complexity factors each describe a certain attribute of traffic (or airspace structure) by a numeric value. The set of complexity factors (C) can contain different parameters such as the number of descending aircraft or the number of aircraft pairs on conflicting routes (further examples can be found in [3, 6, 7]). Set C turns out as the product of the complexity calculation function (F_C) which transforms corrected projected radar data into complexity factors.

$$F_C : D_R^{PC} \rightarrow C \tag{2.3}$$

When the supervisor has successfully evaluated the projected traffic situation, the most complex (and thus the most difficult to model) stage of the decision making process takes place. In this stage, the supervisor tries to figure out which would be the optimal sector configuration by taking all the complexity factors into consideration simultaneously with different "weights" depending on their significance. In the model, this process is represented by two successively executed functions. The first function is called the sector state function (F_{SS}) and it is responsible for assigning a set of sector states (S) to the sectors based on the set of complexity factors. S contains the state (i.e. "split", "armed" or "merged") that is considered optimal for each sector under the given circumstances.

$$F_{SS} : C \rightarrow S \tag{2.4}$$

The second function is the sector configuration function (F_{SC}) which transforms the sector state set produced by F_{SS} into a sector configuration which can be interpreted as a corrected set of sector states (S^C).

$$F_{SC} : S \rightarrow S^C \tag{2.5}$$

Including F_{SC} in the model is necessary because F_{SS} models a highly complex function and thereby it is likely to produce some erroneous states in S. Errors in S can mean that there is no applicable sector configuration in which every sector would have the state considered optimal. This can happen for example if two partially overlapping sectors are both assigned "armed" as their optimal state. These errors can be corrected by F_{SC} if it applies certain restrictions about possible sector configurations and rules to handle inconsistent sector states.

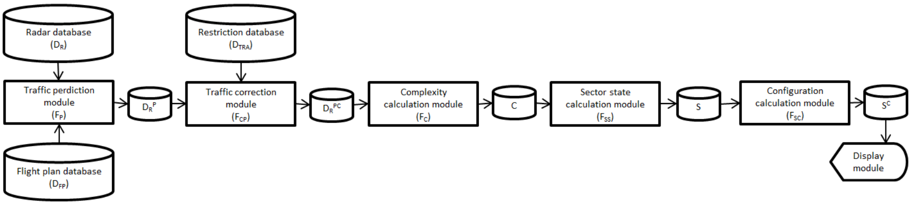

Figure 1: Modules of the decision support tool

3. Creating and correcting projected radar data

Projected radar data is created by using actual radar data and flight plan data in a similar manner as supervisors would use such data types. Therefore, it has to be understood how supervisors create their mental picture about future traffic in reality. When it comes to predicting future position, flight level and speed, aircraft can be classified into the following three categories:

1. Approaching aircraft outside the airspace with radar data only
2. Approaching aircraft outside the airspace with radar data and flight plan data synchronized
3. Aircraft already in the airspace

The future parameter values of aircraft in the first category can only be calculated by using actual radar data, because there is no information about the expected changes in direction, flight level or speed. A radar data record for a particular aircraft in a specified point in time contains information about the geographic distance from a specified point in two perpendicular directions (integer x and y), the speed vector's coordinates in the same directions (integer v_x and v_y) and flight level (integer l). These data can be used by the tool for the simple projection of the aircraft's position by implementing a function that uses the following equation (with t_0 representing the time belonging to the data record and t_P representing the time of the predicted situation 15 minutes after t_0):

$$x_{t_P} = x_{t_0} + v_x(t_P - t_0), y_{t_P} = y_{t_0} + v_y(t_P - t_0) \tag{3.1}$$

In case of aircraft in the second and third category, data prediction is primly based on flight plan data, because it provides more information about an aircraft's expected future characteristics. The flight plan of a particular aircraft contains the identifiers of the next n waypoints to cross ($W_1..W_n$) along with the expected speeds ($v_{W_1}..v_{W_n}$) and expected flight levels ($l_{W_1}..l_{W_n}$) upon crossing each waypoint. Besides these data, we can also assume that the tool has access to the geographic coordinates of the waypoints ($x_{W_1}..x_{W_n}$; $y_{W_1}..y_{W_n}$).

Based on the cruising speeds and the distance between subsequent waypoints, the tool can calculate the expected time of crossing each waypoint ($t_{W_1}..t_{W_n}$) and thus determine which will be the last (W_i) and next (W_j) waypoint of the aircraft at t_P. If this information is available, the aircraft's expected position at t_P can be obtained from the following equations where $\hat{v}(t_P)$ is the average speed between t_{W_i} and t_P supposing that the aircraft changes speed from v_{W_i} to v_{W_j} by constant acceleration:

$$\alpha = \arctan \frac{y_{W_j} - y_{W_i}}{x_{W_j} - x_{W_i}} \tag{3.2}$$

$$\hat{v}(t_P) = v_{W_i} + \frac{\frac{v_{W_j} - v_{W_i}}{t_{W_j} - t_{W_i}}(t_P - t_{W_i})}{2} \tag{3.3}$$

$$x(t_P) = x_{W_i} + \hat{v}(t_P)\cos\alpha(t_P - t_{W_i}), y(t_P) = y_{W_i} + \hat{v}(t_P)\sin\alpha(t_P - t_{W_i}) \tag{3.4}$$

Once the radar data is produced for t_P, it also has to be produced for time $t_P^{'}$ which represents a moment in time 10 seconds after t_P. This is necessary because some of the complexity factors' values can only be produced by functions that require information about the vertical dynamics of traffic which can only be obtained from the comparison of flight levels for the same aircraft at two different points in time.

The correction of projected radar data is required if certain sections of the airspace are restricted to the aircraft controlled by the ATC center in scope. The restriction can be planned if airspace is in use by other parties (e.g. military) in a predefined time and manner or unplanned if thunderstorm activity is present making the section unsafe to fly through. In this phase of designing the advisory tool, the two types of restriction will be handled by using the same algorithm.

In a real life air traffic situation, aircraft avoid entering restricted airspace sections by flying a modified route planned by the ATCO. When the supervisor makes a prediction about the future traffic situation, he or she has to take such modified routes into consideration and so does the tool. In order to achieve this, the tool has to implement an algorithm that simulates avoidance of restricted airspaces by modifying flight plan data. This algorithm would first decide whether a given aircraft is expected to cross a restricted section if it flies according to its initial flight plan data. This can be decided by analyzing whether any of the expected route's upcoming sections intersects with the restricted airspace section (modelled as a polygon). If an intersecting section is found, the given aircraft's flight plan data set has to be extended by replacing the intersecting section with multiple sections that do not intersect with the polygon. Calculating coordinates of the replacment sections can either be done by using an off-the-shelf model (like the geometric recourse model in [4] or the dynamic rerouting model in [5]) or by developing a purpose-made algorithm which is outside the scope of this paper. Once the additional sections are added, the aircraft's projected radar data has to be calculated by using the newly modified flight plan data.

4. Calculating sector states and –configuration

When projected radar data is available for a future situation, it is used by the tool's complexity calculation module for producing the actual values of complexity parameters. Complexity parameter values are calculated by applying simple geometric functions which are described in [6] along with the set of complexity factors planned to be used by the tool. Complexity calculations have to be performed for the whole airspace as well as each sector inside it given that they can be used as active sectors in a practical sector configuration.

Complexity values of each sector are then passed on to the tool's central logic module as real numbers. The central logic module's main function uses neural network based estimation to produce the optimal state for each sector. To make this function applicable, training of the neural network has to be performed before starting to use the tool in order to obtain the values of the network's weight parameters. These weight parameters have to be made accessible to the tool in a database and they should be continuously modified in accordance with the user's feedback. A more detailed description about applying neural network logic for sector state estimation – including the training process of the networks – can be seen in [7].

The trained neural network's function (F_{SS}) transforms a vector of complexity factors ($\mathbf{c}$) into a sector state matrix (S). The rows of S each represent a sector while the columns represent possible sector states (split, armed and merged). As an example, in case of the Hungarian airspace where there are 31 usable sectors, S is a 31x3 matrix. S consists of real numbers between 0 and 1 with each number providing information about how close the given state is to the optimal one in case of the given sector.

$$F_{SS} : c \to S \tag{4.1}$$

Getting the optimal sector configuration requires turning the sector state matrix (S) into a sector border matrix (B) via function $F_S S$ which is responsible for eliminating errors from the state matrix.

$$F_{SC} : S \to B \tag{4.2}$$

In case of the Hungarian airspace, B is a 2x4 matrix with the two lines representing the east ('E') and west ('W') sectors of the airspace while the columns represent the altitudinal borders in E and W. Elements of the matrix assume the value 1 if the represented border is active in the configuration and 0 otherwise. F_{SC} is only executed by the tool if the airspace has to be split according to S, otherwise the airspace itself will be the optimal configuration. F_{SC} is represented in the tool's logic as a function that iterates through the lines of S and compares the split, armed and merged values in each line. Based on the comparison results, it modifies the elements of B from 0 to 1 in accordance with the following algorithm:

1. If the 'E' (or 'W') sector's state with the highest value is not the split state, 'E' (or 'W') should be used as an armed sector.

2. If an elementary sector's armed state has a higher value than its merged state, it should be armed, so the values representing its lower and upper border in B should be set to 1.
3. If a non-elementary sector's split value is higher than the armed and merged value, it has to be split. Sectors that have to be split are evaluated in the following steps, which are repeated until none of the conditions are fulfilled and no additional split operations are necessary.
4. If a sector contains 4 borders, it has to be split at the border with the highest average split value (i.e. the average split value of all sectors that contain the given border), so the given border's value in B should be set to 1.
5. If a sector contains 2 or 3 borders, it has to be split at the border with the highest average split value but only if it exceeds 0,5.
6. If a sector contains exactly 1 border, it has to be split if the border's average split value exceeds 0,8.

When B has been created with the above algorithm, the configuration has to be displayed visually to the supervisor as graphical and/or textual information.

5. Conclusion

A decision support tool that can suggest sector configurations to supervisors would be useful for enhancing ATC safety. Developing such a tool requires creating a functional model of the real decision making process and implementing the functions of this model. The latter can not be done without solving such problems as the lack of flight plan data for certain aircraft, the presence of restricted airspace sections or the errors in sector states calculated by neural networks. Thes can be solved via different algorithms presented (or referred) in this paper.

Due to the simplifications and ommitances in the design of the model and its functions, the dependability of the tool's suggestions can not be guaranteed in the first phase of usage. In order to subdue this issue and continuously improve dependability, the tool should contain a feedback function (by requesting direct feedback from the supervisor or simply monitoring the actual configurations used) through which it can modify its own parameters (e.g. weights of the neural network). Details of the feedback function are expected to be presented in later works.

References

[1] Rodgers, M.D., Mogford, R.H., Mogford, L.S., The relationship of sector characteristics to operational errors, *FAA Aviation Medicine Report* Vol. 98/14 (1998)

[2] Stager, P., Hameluck, D., Ergonomics in air traffic control, *Ergonomics* Vol. 33(4) (1990), 493–499.

[3] Gianazza, D., Guittet, K., Evaluation of air traffic complexity metrics using neural networks and sector status, *Proceedings of the 2nd International Conference on Research in Air Transportation, ICRAT 2006*

[4] Yoon, Y., Hansen, M., Ball, M. O., Optimal route decision with a geometric ground-airborne hybrid model under weather uncertainty, *Transportation Research Part E* Vol. 48 (2012), 34–49.

[5] Mukherjee, A., Hansen, M., A dynamic rerouting model for air traffic flow management, *Transportation Research Part B* Vol. 43 (2009), 159–171.

[6] Számel, B., Szabó, G., Towards safer air traffic: Optimizing ATC controller workload by simulation with reduced set of parameters,, *Safety and Reliability: Methodology and Applications: ESREL2014* (2014), 979–987.

[7] Számel, B., Mudra, I., Szabó, G., Applying Airspace Capacity Estimation Models to the Airspace of Hungary, *Periodica Polytechnica: Transportation Engineering* Vol. 43(3) (2015), 120–128.