A Complex Network Approach to Analyze the Effect of Intermediate Waypoints on Collision Risk Assessment

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This paper investigates how estimated collision risk in upper airspace varies with changes in underlying airspace network complexity. Direct Route model (which assumes great circle route between entry and exit waypoints) and Intermediate Waypoint model (which uses airway-waypoint routes between entry and exit waypoints) were used. One month of traffic data (more than 200,000 flights) from 12 countries in the Middle East was analyzed for collision risk estimates, and the airspace network was characterized for several complex network indicators. Results show that intermediate waypoint leads to a significant increase in collision risk estimates. Results also show the correlation between estimated collision risk and specific network complexity measures. From an operational perspective this means that in airspaces with a highly structured airspace, collision risk may be underestimated when using the widely accepted direct route model.
INTRODUCTION

One of the key challenges faced by the Air Navigation Service Providers (ANSPs) is how to accommodate continued growth in air traffic while meeting the safety targets. ANSPs are exploring new paradigms (e.g., SESAR [EUROCONTROL, 2008] and NextGen [2007]) and procedures (for e.g., Reduced Vertical Separation Minima [ICAO-Doc-9574, 2001]) for managing airspace efficiently and safely.

Although a mid-air collision is a rare event, its impact is significant because of the large number of fatalities involved. International Civil Aviation Organization (ICAO) standards separating aircraft in time and space have well served the purpose until the surge in air traffic during the last decade. ANSPs are now compelled to relax these standards and adopt new procedures to accommodate increasing traffic [Netjasov et al., 2008]. A compelling need exists for a safety risk assessment of these new procedures [Stroeve et al., 2009].

One of the vital indicators for estimating air traffic safety is the Airspace Collision Risk Assessment [ESARR-4, 2001]. Most of the collision risk models are based on the Reich Model [Reich, 1966a, c, b], which was developed in the early 1960s to estimate the collision risk for flights over the North Atlantic and to specify appropriate separation rules for the flight trajectories. No one universal model for collision risk assessment exists, however, because of different communications, navigation, and surveillance capabilities of ANSPs in different regions of the world.

EUROCONTROL uses a sophisticated collision risk model developed by the Mathematical Drafting Group that uses precision 4D radar data/ADS-B data to account for flights vectoring frequently in European airspace [EUROCONTROL, 1997]. The African region (ARMA) and Middle East region (MIDRMA) use the ICAO Collision Risk Model [Circ-319-an/181, 2008], based on entry and exit flight plan data because of the presence of large volumes of procedural airspace and limited Communication, Navigation and Surveillance (CNS) capabilities. The focus of this study is the MIDRMA region, which consists of 13 countries: Bahrain, Egypt, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, UAE, and Yemen.

In particular when an airway network structure is more complex, this complexity may lead to significant variations in collision risk estimates between different flight information regions of the world. One of the motivations of this paper is to improve the collision risk estimates given the limited amount of flight data available in regions with limited CNS capabilities. Another research question that we attempt to address is how the collision risk estimates vary with network measures for airspace network complexity. This situation also raises the question as to which airspace network measures are most significant in identifying the need for collecting more traffic data.
The characterization of airspace network features given the changes and impact on collision risk estimates may provide a motivation on better data collection practices and may identify the airspace network features where such data collection may influence the collision risk estimates significantly.

The airspace in consideration for this paper is reduced vertical separation minimum (RVSM) airspace. Within RVSM airspace air traffic control (ATC) separates aircraft by a minimum of 1,000 feet vertically between flight level (FL) 290 and FL 410 inclusive [ICAO-Doc-9574, 2001].

AIRSPACE NETWORK CHARACTERISTICS

Network analysis to characterize complex systems has become widespread during the last few decades where complex network frameworks have been applied in a growing range of disciplines including air traffic [Hossain et al., 2013].

Airspace Network

In any air traffic management system airspace network features, such as number of airways, crossing angle, and number of crossings, have significant impact on collision risk [Alam et al., 2013].

Figure 1. Airspace network modelled as a graph (network), comprising the waypoint as vertices or nodes linked by airways (links) connecting them.
As illustrated in Figure 1, an airspace network can be modelled as a graph (network), comprising the waypoint as vertices or nodes linked by airways connecting them. Interestingly, many real networks, including airspace networks, share a certain number of topological properties; for example, most are small worlds [Guimerà et al., 2005], that is, the average topological distances between nodes increase very slowly (logarithmically or even more slowly) with increases in the number of nodes. Additionally, “hubs” (nodes with very large degrees \(k\)) compared with the mean of the degree distribution \(\langle k \rangle\) are often encountered. More precisely, in many cases, the degree distributions exhibit heavy tails which are often well approximated for a significant range of values of \(k\) by a power-law behavior [Albert et al., 2002].

A graph \(G(V, E)\) is used to describe the airspace network, where the node set \(V\) represents all waypoints and the crossing points of two line segments. As illustrated in Figure 1, all the entry/exit points A, B, C, D, G, F and the crossing of two line segments at Y also consider as node in the network. To model the airspace network we have consider two different network model (i) Direct route network (DRN) and (ii) Intermediate waypoints network (IWN). In the direct route approach only the entry/exit points are considered as node, and the crossings of the straights lines route from entry to exit points. A flight route, however, consists of a collection of waypoints. A waypoint is a navigation marker whose longitude and latitude coordinate is determined by the ground navaids and keeps the pilots informed about the aircraft’s desired track and heading direction. To quantify the effect of waypoints to the topology and the collision of an airspace network, we model the network considering all the waypoints. Figure 2 illustrates the difference in calculating the crossing points between the DRN and IWN model. In figure 2 the intermediate waypoints air route is denoted by the solid line and the direct route is shown by the dotted straight line.
The edge set $E$ represents all line segments of air routes between nodes (waypoints, crossing, and entry/exit points). After generating the initial network, however, a crossing node can be very close to an existing waypoint, in such a case the crossing node is merged to the closest node if the distance between them is less than 1 nautical mile. Finally, the network is represented by an adjacency matrix $A_{n \times n}$ such that $a_{ij} = 1$ if a link exists between the city-pair $i$ and $j$ otherwise $a_{ij} = 0$. From the resulting network we have found the networks always remain connected and the IWN is highly structured than of the DRN. Figure 3 shows the DRN and IWN of air space networks of Oman.

**Network Characteristics**

Different networks have different topological features that characterize their connectivity, interaction, and the dynamical processes executed by the network [Barrat et al., 2004].

The analysis, discrimination, and synthesis of airspace networks, therefore, rely on using measurements capable of expressing the most relevant topological features, which enable us to characterize the airspace properties. Several indices are used in this paper to measure the topological configuration of the airspace network:

- **Average Degree**

  \[
  \langle k \rangle = \frac{1}{n} \sum_{i=1}^{n} k_i
  \]  

  (1)

  The average degree of a network refers to the average number of neighbors a node has in the network. A major crossing point will have higher average degree.

**Figure 3.** The DRN (left) and IWN (right) of Oman, one of the countries in the Middle East (MIDRMA) region.
• Clustering Coefficient

\[ C_i = \frac{1}{k_i(k_i - 1)} \sum_j k_j a_{ij} a_{jk} a_{ik} \]  \hspace{1cm} (2)

This captures the local cohesiveness of the node and also represents the network transitivity [Albert et al., 2002]. This value ranges between 0 and 1.

• Closeness Centrality

\[ C_c(i) = \frac{n - 1}{\sum_{v_j \neq i} d_{ij}} \]  \hspace{1cm} (3)

The centrality measures the relative importance of a node within a network [Borgatti, 2005]. Closeness centrality measures the extent to which nodes are closer to all other nodes along the shortest path and reflects their accessibility in a given network. This value ranges between 0 - 1.

• Betweenness Centrality

\[ C_b(i) = \frac{\sigma_{kj}(i)}{\sum_{k \neq i \neq j} \sigma_{kj}} \]  \hspace{1cm} (4)

where \( \sigma_{kj} \) is the total number of shortest paths from node \( k \) to node \( j \), and \( \sigma_{kj}(i) \) is the number of those paths that pass through node \( i \) [Freeman, 1977].

Betweenness centrality is a useful measure of the load placed on a given node in the network. It measures the extent to which a particular node lies between other nodes in a network.

• Characteristic Path Length

\[ L = \frac{1}{n(n - 1)} \sum_{i \neq j} d_{ij} \]  \hspace{1cm} (5)

The smaller the \( L \), the more compact is the network. Thus, \( L \) could be used as an indicator of the highly dense airspace network leading to large number of crossings.
Degree correlation demonstrates the extent of a node’s degree related to the average degree of its neighbors. Degree correlation index $k_{nn}(k)$ is given by:

$$k_{nn}(k) = \sum_{k'} k'P(k' | k)$$

(6)

where $P(k' | k)$ is the conditional probability that a node with degree $k$ is connected to a node of degree $k'$. This index $k_{nn}(k)$ reflects the node’s connection tendency of the network. If high-degree nodes tend to link with each other, this tendency is referred to as assortativity and the tendency of high-degree and low-degree connectivity referred to disassortativity [Newman, 2003].

To better understand the relationship between these network characteristics and collision risk, both will be evaluated for a selected airspace area. Prior to doing so, we first outline collision risk analysis.

**COLLISION RISK ANALYSIS**

Collision risk is defined by ICAO [Circ-319-an/181, 2008] as “the expected number of mid-air aircraft accidents in a prescribed volume of airspace for a specific number of flight hours due to loss of planned separation.” The collision risk assessment methodology consists of two elements: first, risk estimation, which concerns the development and use of methods and techniques with which the actual level of risk of an activity can be estimated; second, risk evaluation, which concerns the level of risk considered to be the maximum tolerable value for a safe system. The level of risk that is deemed acceptable was termed the target level of safety (TLS) [Doc-9859, 2013]. The risk evaluation process consists of comparing the estimated risk against a TLS to provide a quantitative basis for judging the safety of air traffic operations in a given volume of airspace.

**Collision Risk in Vertical Dimension**

A mid-air collision between two aircraft nominally separated by 1,000ft could occur only if either or both aircraft were to deviate vertically from their assigned flight level such that the vertical separation between the aircraft is lost. There are two main reasons why an aircraft may not be at its assigned flight level – normal height deviations and large height deviations.

Normal height deviations arise because of typical assigned altitude deviation (AAD) and altimetry system errors (ASE), whereas large height deviations occur because of operational issues such as a level burst or TCAS alert. The focus of this paper is on normal height deviations.
deviations, which are also termed as technical vertical risk (TVR) as they happen for purely technical reasons.

Technical vertical risk is computed using historic flight data and takes into account, among several factors, the accuracy of navigation, the airway structure, the aircraft population, and the total flying time within the region. The assessment of the technical vertical risk requires the risk estimate to be less than the technical TLS of $2.5 \times 10^{-9}$ fatal accidents, per flight hour (noting that a mid-air collision counts as two fatal accidents). Appendix A provides the collision risk equations to be used for this risk calculation.

**ICAO’s Form 4 Data**

One of the key elements in TVR estimation is flight data collection. ICAO has stipulated the use of Form 4 Air Traffic Flow data [2006] for collecting RVSM traffic data from ANSPs. The ICAO Form 4 data provides sufficient detail, but often to quite low resolution for collision risk models to give an estimate of TVR. ICAO Form 4 records the following flight data:

- Flight date, aircraft call sign, aircraft type, departure aerodrome, arrival aerodrome, entry waypoint, entry level, entry time, exit waypoint, exit level, and exit time

  The ICAO Form 4 data is then processed to compute:

  - Total flight time for each region
  - Average ground speed for each region
  - Number of flight crossings in each region
  - Flight time proportions for each aircraft which is used to calculate:
    - Average aircraft dimensions
    - Altimetry system error (ASE) probability

**Limitations of Direct-Route-Model**

The direct route model assumes that there is a great circle route between entry and exit waypoints for estimating the crossing frequency. In any given airspace/sector, however, a flight may go through several intermediate waypoints before it reaches the exit point. As a result, the actual flight path may not be a straight line between entry and exit waypoints but, instead, a segment of chords that join the intermediate waypoints.

Assumption of a great circle route between entry and exit waypoints results in a simplified airspace network structure and, therefore, an incorrect number of crossings computed as well as an incorrect crossing frequency, which in turn affects the collision risk estimates.
Intermediate Waypoints Model

In the intermediate waypoint model the intermediate waypoint for a given entry-and exit-point in the airspace is considered. This may lead to fairly complex routes. The introduction of an intermediate waypoint model has several effects. The most immediate one is the increased likelihood for an aircraft crossing to occur. This is because it is not uncommon for two flight paths, if represented by the naive flight path (Figure 4, left) not to have any possible intersection. Often the airway structure, however, is such that these two flights will meet along a common path and then split and deviate, as seen in Figure 4 (right).

Another introduced effect of an intermediate waypoint model is an increased average ground speed. This occurs because of the additional distance covered by each flight in the ICAO Form 4 data. While this has no effect on the crossing frequency, while calculating the expected number of fatal accidents, the increased ground speed will drive a minor decrease in the expected number of fatal accidents (often balancing the increase in crossing frequency).

METHODOLOGY

This section explains the methodology used for comparing the collision risk and network characteristics of direct route model (great circle route between airspace entry and exit point) and intermediate waypoint model (waypoints between entry and exit points). We use one month of traffic data from 12 countries in the MIDRMA region. The airspace network features for both the models were characterized for each country and analyzed given collision risk estimates.

As illustrated in Figure 5, ICAO Form 4 data is the basis for the flight data input to the two models. Both models use the same collision risk model and databases for aircraft positional error distribution and kinematic factors (speed and dimension).

Collision Risk with Direct Route Model

In the direct route model, technical vertical risk is computed using the direct route approach. In this stage an airspace network is
generated using the entry and exit point data extracted from the Form 4 data. Network analysis is performed, and network characteristics are identified.

Collision Risk with Intermediate Waypoint Model

In the intermediate waypoint model technical vertical risk is computed, using the Intermediate Waypoint approach. Again, the airspace network is generated incorporating the intermediate waypoints between entry and exit points using ICAO Form 4 data.

Processing ICAO Form 4 Data

The two pieces of required information for calculating the number of crossings for a FIR/UIR is the complete ICAO Form 4 data for the time period and a list of waypoints and their coordinates corresponding to the names used in the ICAO Form 4 data.

The first step in the process is to read in the list of waypoints and their coordinates. These data are stored for use in the later calculations.

The second step in the process is to read in the ICAO Form 4 data, filtering out any data that is either incomplete or suspected to be
incorrect. From the first pass of the data, the number of flights \((N)\), total flying time \((T, \text{in hours})\) and average ground speed \((V \text{ in knots})\) can be calculated. Additionally taken is a list of entry-exit point pairs flown within the FIR/UIR.

The third step is to determine the crossing pairs within the data. This determination is made by taking the list of entry-exit points from the ICAO Form 4 data scan and computing whether the great circle arc formed by that flight path intersects with any of the other entry-exit great circle arcs.

Finally, each flight in the ICAO Form 4 data is processed to count the number of flights that they intersect with. This calculation is done by picking a flight and checking it against all the other flights. For each adjacent flight \(t\) their entry and exit points are compared; if they are both the same then the flights are checked to determine if they intersect in either the same or opposite directions. If the flight has a different entry and exit pair, then it is checked to determine if the two entry-exit pairs intersect; if they do, then we check to learn whether the two flights intersect in a crossing path.

**Estimating Crossing Frequency**

The crossing frequencies are the frequency with which two aircraft at adjacent flight levels pass each other. They can be in the same direction \((n_z(\text{same}))\), opposite directions \((n_z(\text{opp}))\), or pass each other on crossing tracks \(n_z(\theta))\).

The same and opposite direction crossing frequencies can be calculated by taking the number of plane crossings, dividing by the total hours of flight, and multiplying by the probability of lateral overlap as shown in equations (7) and (8):

\[
\begin{align*}
n_z(\text{same}) &= \frac{\text{number of crossing} \times P_y(0)}{\text{total flight - time in FIR/UIR}} \\
n_z(\text{opp}) &= \frac{\text{number of crossing} \times P_y(0)}{\text{total flight - time in FIR/UIR}}
\end{align*}
\]

The crossing traffic frequency is calculated in a similar manner as the same and opposite directions (with a value calculated for each crossing angle). However, it is not multiplied by the probability of lateral overlap and a larger crossing diameter is taken when the crossings are counted. This is because if the crossings were counted on the average aircraft diameter \((\lambda_{xy})\), this would result in a very small number of crossings. Therefore, a larger, proximity, distance \((S_x)\) is taken in order to better estimate the frequency. The number of
crossings is then scaled down by a factor of the aircraft diameter on the proximity distance as shown in equation (9).

\[
n_z(\theta) = \frac{\text{number of crossing}}{\text{total flight - time in FIR/UIR}} \times \frac{\dot{z}_{xy}}{S_t} \tag{9}
\]

**Region and Traffic Data**

ICAO’s MIDRMA is the administrator of the RVSM airspace in the Middle East region.

Figure 6 illustrates the 13 member states of MIDRMA. MIDRMA provided air traffic, waypoint, and aeronautical information data for 12 member states. Qatar data is not available. Data were collected for the month of October 2011 for all the member countries using ICAO Form 4. In total there were 203,764 flights flying in the RVSM airspace (FL 290 to FL 420 inclusive) in the region.

Table 1 summarizes the number of flights and the total number of flight hours flown in each region for the month of October 2012.

**Intermediate Waypoints**

To collect information about intermediate waypoints for given entry and exit points in an FIR/UIR, MIDRMA issued a circular to all member states to develop a database for all the entry and exit points and the most commonly flown route on them in their respective
regions. The data collection and verification exercise last more than two months. Twelve member states (Qatar data unavailable) collected and reported data on intermediate waypoints for all the entry exit points in their respective FIR/UIRs.

**Experimental Parameters and Supplementary Data**

Table 2 shows the various collision risk model parameters used in the experiments.

Aircraft dimension parameters (representing the average dimension of aircraft that fly in the region) are calculated and weighted as per the flight time proportion of each aircraft group.

Based on member state provided navigation data, the proportion of flights flying with satellite navigation in MIDRMA region was set to 75%. Airspeed parameters were used as recommended by ICAO [ICAO-Doc-9574, 2001]. Aircraft performance was modeled using EUROCONTROL’s Base of Aircraft Data (BADA). For computing

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V$ Relative along-track airspeed</td>
<td>15 kn/s</td>
</tr>
<tr>
<td>$</td>
<td>y</td>
</tr>
<tr>
<td>$</td>
<td>z</td>
</tr>
<tr>
<td>$\sigma_{GNSS}$ standard deviations for satellite navigation</td>
<td>0.0612 nmi</td>
</tr>
<tr>
<td>$\sigma_{VOR/ DME}$ standard deviations for radio navigation</td>
<td>0.3 nmi</td>
</tr>
<tr>
<td>$x$ proportion of flights flying with satellite navigation</td>
<td>75%</td>
</tr>
<tr>
<td>Length ($\lambda_x$)</td>
<td>173.51 ft</td>
</tr>
<tr>
<td>Wingspan ($\lambda_y$)</td>
<td>163.35 ft</td>
</tr>
<tr>
<td>Diameter ($\lambda_{xy}$)</td>
<td>159.91 ft</td>
</tr>
<tr>
<td>Height ($\lambda_z$)</td>
<td>45.451 ft</td>
</tr>
</tbody>
</table>

**Table 1. Flight Data from MDRMA Member States**

<table>
<thead>
<tr>
<th>Countries</th>
<th>Number of Flights</th>
<th>Flight Duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahrain</td>
<td>39206</td>
<td>23624</td>
</tr>
<tr>
<td>Egypt</td>
<td>26322</td>
<td>18160</td>
</tr>
<tr>
<td>Iran</td>
<td>17030</td>
<td>20165</td>
</tr>
<tr>
<td>Iraq</td>
<td>2810</td>
<td>2795</td>
</tr>
<tr>
<td>Jordan</td>
<td>6277</td>
<td>1513</td>
</tr>
<tr>
<td>Kuwait</td>
<td>12122</td>
<td>3395</td>
</tr>
<tr>
<td>Lebanon</td>
<td>1151</td>
<td>190</td>
</tr>
<tr>
<td>Oman</td>
<td>30000</td>
<td>18846</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>7716</td>
<td>2049</td>
</tr>
<tr>
<td>Syria</td>
<td>7716</td>
<td>5398</td>
</tr>
<tr>
<td>UAE</td>
<td>20725</td>
<td>3445</td>
</tr>
<tr>
<td>Yemen</td>
<td>5025</td>
<td>23624</td>
</tr>
</tbody>
</table>

**Table 2. Collision Risk Model Parameters**
probability of vertical overlap the EUROCONTROL's ASE parameter database and AAD flight sample lists were used.

The collision risk computation process is illustrated in Figure 7. First, the countries for which the collision risk is to be done are selected. Various supplementary data files such as waypoint/airport names and coordinates, BADA database, ASE, and AAD parameter, aircraft dimension files are then read and processed. After that the flight data for the selected countries is read and processed to compute flight time proportion and crossing frequencies. Probability of lateral overlap and probability of vertical overlap are then computed. These intermediate results are then inputted into equation (10) and technical vertical risk is computed.

RESULTS

We first present the results of crossing frequency per flight hour and the technical vertical risk with direct route model and intermediate waypoint model.

Collision Risk and Passing frequency

As can be seen from Table 3 and Figure 8, with the intermediate waypoint model, Egypt, Iraq, Lebanon, and Oman had shown a significant increase in crossing frequency as well as technical vertical risk.
Bahrain, Iran, and Saudi Arabia did not have any significant change in their crossing frequency and technical vertical risk. Most surprisingly, UAE showed a decrease in its crossing frequency as well as technical vertical risk.

The highest variability can be seen in Iraq and Oman where the collision risk increase significantly with the intermediate waypoint model.

In both models the collision risk for Saudi Arabia and Iran remains the same. This occurs because of the large airspaces where

**Table 3. Vertical Collision Risk Assessment (Passing Frequency and Technical Vertical Risk) for MIDRMA Region**

<table>
<thead>
<tr>
<th>Nation</th>
<th>Direct Route</th>
<th>Intermediate Waypoint</th>
<th>Direct Route</th>
<th>Intermediate Waypoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahrain</td>
<td>0.020211</td>
<td>0.02019</td>
<td>3.63E-11</td>
<td>3.62E-11</td>
</tr>
<tr>
<td>Egypt</td>
<td>0.019650</td>
<td>0.02843</td>
<td>3.53E-11</td>
<td>5.10E-11</td>
</tr>
<tr>
<td>Iran</td>
<td>0.023403</td>
<td>0.02348</td>
<td>4.20E-11</td>
<td>4.21E-11</td>
</tr>
<tr>
<td>Iraq</td>
<td><strong>0.009957</strong></td>
<td><strong>0.05476</strong></td>
<td><strong>1.79E-11</strong></td>
<td><strong>9.82E-11</strong></td>
</tr>
<tr>
<td>Jordan</td>
<td>0.012597</td>
<td>0.01288</td>
<td>2.26E-11</td>
<td>2.31E-11</td>
</tr>
<tr>
<td>Kuwait</td>
<td>0.000297</td>
<td>0.00117</td>
<td>5.34E-13</td>
<td>2.10E-12</td>
</tr>
<tr>
<td>Lebanon</td>
<td>0.003515</td>
<td>0.00872</td>
<td>6.31E-12</td>
<td>1.56E-11</td>
</tr>
<tr>
<td>Oman</td>
<td><strong>0.027840</strong></td>
<td><strong>0.04504</strong></td>
<td><strong>5.00E-11</strong></td>
<td><strong>8.07E-11</strong></td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>0.020981</td>
<td>0.02096</td>
<td>3.77E-11</td>
<td>3.76E-11</td>
</tr>
<tr>
<td>Syria</td>
<td>0.028031</td>
<td>0.02904</td>
<td>5.03E-11</td>
<td>5.21E-11</td>
</tr>
<tr>
<td>UAE</td>
<td><strong>0.009877</strong></td>
<td><strong>0.00640</strong></td>
<td><strong>1.77E-11</strong></td>
<td><strong>1.15E-11</strong></td>
</tr>
<tr>
<td>Yemen</td>
<td>0.006218</td>
<td>0.00720</td>
<td>1.12E-11</td>
<td>1.29E-11</td>
</tr>
</tbody>
</table>

**Figure 8.** Technical vertical risk with direct route and intermediate waypoint for MIDRMA countries.
the intermediate route has less variability and is more or less similar to direct route model. As illustrated in Figure 9, Bahrain and UAE have highly structured airways; however, UAE airspace is smaller and more structured when compared to Bahrain’s airspace. The southern airspace of Bahrain, which adjoins Saudi Arabia, has an unstructured pattern. This patterning might have led to the decrease in collision risk for UAE in the intermediate waypoint model.

Similarly, the increase in the collision risk estimate of Iraq for the intermediate waypoint model can be attributed to the significant increase in crossings (5-fold increase) because of crossing traffic from Iran and Saudi Arabia.

**Topological Properties of Airspace Network**

Figure 10 shows some key topological metric of Oman’s DRN and IWN. First, we focus on the degree distribution of the networks. In figure 10(a) and 10(b) notice that the degree distribution of DRN follows normal distribution, giving strong evidence that the DRN is a kind of random network, whereas that of IWN is right skewed. In the case of centrality based measures, both of the networks betweenness and
closeness centrality follow exponential function. That is to say, the centrality value declines exponentially with the node’s ranking.

The steep curve of betweenness indicates that a few hub nodes account for most of the traffic transfer capacity. Next, we investigated the clustering coefficient that captures the local cohesiveness of a node. It measures how the neighbors of a node are connected themselves. Network with high clustering coefficient is always beneficial to find alternative if some of its nodes (waypoints) failed due to bad weather.

The distribution of the clustering coefficient of DRN and IWN are found to be significantly different. For DRN clustering coefficient exhibit a linear decay while IWN it is an exponential decay. Beside the centrality measures, we also investigated the degree-degree correlation of the networks. Figure 10(i) and figure 10(j) shows the degree-degree correlation.
correlation of DRN and IWN respectively. For DRN there is no significant correlation among the nodes in the network. Whereas, IWN the apparent positive degree-degree correlation. That is, the high degree nodes tend to be connected with high degree nodes.

Thus the topological properties of Oman’s airspace network conforms that the IWN is highly structured than the DRN. The similar behavior is also observed for the other countries’ airspace network (DRN and IWN). The topological properties of the rest of the countries are presented in Appendix B.

Apart from the detailed topological parameters of an individual country, we also compare each of the metrics among MIDRMA countries.

Average degree (Figure 11): For the intermediate waypoint model the average degree for almost all the countries (except Lebanon) increased significantly. This mainly occurred because of the presences of major crossings (especially in large airspaces) that were not captured in

![Average degree of direct route and intermediate waypoint network for MIDRMA countries.](image1)

**Figure 11.** Average degree of direct route and intermediate waypoint network for MIDRMA countries.

![Clustering coefficient measure of direct route and intermediate waypoint network for MIDRMA countries.](image2)

**Figure 12.** Clustering coefficient measure of direct route and intermediate waypoint network for MIDRMA countries.
direct route model affecting the collision risk computation. Lebanon is a small FIR with a semi-circular design. The airspace structure is simple with all airways from the boundary of FIR merging at the Beirut VOR.

Clustering Coefficient (Figure 12): The nodes in the Bahrain, Lebanon, and Syria airspace network appear to have higher tendency to form clusters in intermediate waypoint model. In Egypt, Iran, and Saudi Arabia a lower clustering coefficient indicates low collision risk.

Closeness Centrality (Figure 13): For Iran and Saudi Arabia, given their large airspaces, the closeness centrality is very low. For Lebanon this measure is high (in both the models) because of small airspace and few airways merging at VOR. In Bahrain and Syria the Closeness Centrality is reduced for intermediate waypoint model because of their structured airspace leading to minimal or no change in collision risk estimates.

Betweenness Centrality (Figure 14): As expected, this measure has gone down for all the FIRs in MIDRMA except Lebanon. The
intermediate waypoint model reduces the possibility of a particular node lying between other nodes, as opposed to the direct route model in a network. This finding indicates that the more unstructured a network is, the the higher a collision risk.

**Characteristic Path Length (Figure 15):** The airspace network of Iran and Saudi Arabia appears to be denser (lower characteristic path length) with the intermediate waypoint network. This finding is possibly because of the presence of large areas of procedural airspace. A denser network results in higher collision risk estimates.

**DISCUSSIONS**

Collision risk was estimated using one month’s data from 12 countries in the Middle East region. Two models were used: one uses direct routes and other uses intermediate waypoints for aircraft flying at RVSM altitude. Complex network measures were used to analyze the resulting two networks to gain an insight into how the collision risk estimates vary with network measures for airspace network complexity.

The proposed methodology, despite being simple to implement, relies heavily on air traffic data collection and post-processing. This process might be challenging for ANSPs who do not have such processes in place. This methodology also requires a significant knowledge-base in identifying the intermediate waypoints given entry and exit points for an airspace. The data about when aircraft climb or descend during airspace transit is difficult to estimate from given data. This difficulty might be a source of error in estimating the crossing frequencies. The authors are hopeful that with the gradual adoption of ICAO’s Future Air Navigation System (FANS) and advances in air traffic services data link applications this process will be automated.

In the proposed methodology, only five complex network properties were identified based on the nature of insight sought for air traffic
network. Other complex network measures can be equally important in offering new insight on collision risk dynamics given the underlying network. Further, many casual factors, such as traffic flow, might affect the collision risk estimates that are not captured by the collision risk model.

As many European countries have made a gradual shift towards Radar/ADS-B based 4D data for collision risk estimates (given the large number of vectoring) a similar approach will be useful in the Middle East airspace. We recommend that Flight Data Management Systems (FDMS) of ANSPs should collect the complete flight track data, i.e. 4D trajectory to facilitate through investigations of airspace structures, thus leading to an airspace design that results in lower collision risk by design. Such a design would be challenging given that each airspace is adjacent to some other airspace and is not an individual ANSP’s exercise. ICAO regional monitoring agencies (RMAs) can play a central role in encouraging its member states to undertake better data collection measures but also in and to create a collective airspace restructuring process.

**SUMMARY AND CONCLUSIONS**

Results indicate that the intermediate waypoints lead to a significant increase in collision risk estimates, specifically for airspace networks with higher average degree and higher closeness centrality measures. Results also indicate that collision risk decreases in networks with lower betweenness centrality. We also found that a denser network results in higher collision risk estimates. From an operational point of view, results indicate that countries that have highly structured airspace are actually overestimating the collision risk with a direct route model.

This paper also demonstrated that it is possible to improve the collision risk estimates given the limited amount of flight data available in regions with limited CNS capabilities by using intermediate waypoint data available with ANSPs. The process, however, requires extensive data collection and verification.

In the future we will extend this work by developing new clustering algorithms to identify the presence of clusters in the airspace network and assessing their impact on collision risk.

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APPENDIX A. VERTICAL COLLISION RISK EQUATIONS

Technical vertical risk represents the risk of a collision between aircraft on adjacent flight levels because of normal or typical height deviations of RVSM approved aircraft. The technical vertical collision risk is assessed against a technical TLS of \(2.5 \times 10^{-9}\) fatal accidents per flight hour using a suitable collision risk model.

Following [EUROCONTROL, 2008] the vertical collision risk model for aircraft on adjacent flight levels of the same route, flying in either the same or the opposite direction satisfies:

\[
N_{az} = 2P_z(S_z)P_y(0)n_z(\text{equiv}) \left[ 1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}|\dot{z}|}{\dot{z}} \right] \quad (10)
\]

where

\[
n_z(\text{equiv}) = n_z(\text{opp}) + n_z(\text{same}) \frac{|\dot{y}| + \lambda_{xy}|\dot{z}|}{\Delta V} \frac{\dot{z}}{\Delta V} \left[ 1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}|\dot{z}|}{\dot{z}} \right] + \frac{1}{P_y(0)} \frac{1}{1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}|\dot{z}|}{\dot{z}}} \sum_{i=1}^{n} n_z(\theta_i) \left[ 1 + \frac{\pi \lambda_{xy}}{V_{\text{rel}}(\theta_i)2\dot{z}} \right]
\]

with the various symbols in (1)-(2) explained below.

The left-hand side variable \(N_{az}\) represents the expected number of aircraft accidents because of normal technical height deviations of RVSM approved aircraft for the given traffic geometry. The longitudinal overlap frequency parameters \(n_z(\text{same})\) and \(n_z(\text{opp})\) together with the kinematics factors in brackets (as functions of the relative speeds and aircraft dimensions) represent a major part of the different levels of exposure to the risk of the loss of vertical separation for the two traffic geometries covered by the collision risk model of equation (10). (The subscript \(z\) in \(n_z(\text{same})\) and \(n_z(\text{opp})\) refers to aircraft on adjacent flight levels.

There are two aircraft dimensions used by the technical vertical risk, being the average diameter \((\lambda_{xy})\) and the average height \((\dot{z})\). The probability of vertical overlap \(P_z(S_z)\) is the probability that two aircraft will overlap vertically, separated by 1000ft \((S_z)\). This indicates the probability that they will overlap while correctly flying at adjacent flight levels. The probability of lateral overlap \((p_y(0))\) is the probability of two aircraft being in lateral overlap, if they are both correctly flying at adjacent flight levels. This is calculated by taking the proportion of time that an aircraft in the region are flying using satellite navigation (GNSS) versus radio navigation (VOR/DME).
There are five relative speed parameters that appear in the technical vertical risk:

- $\Delta V$ is the relative along-track airspeed between two aircraft flying at adjacent flight levels and flying in the same direction.
- $\bar{V}$ is the average ground speed of the aircraft.
- $\bar{\dot{y}}$ is the average relative cross-track speed between two aircraft flying at adjacent flight levels.
- $\bar{\dot{z}}$ is the average relative cross-track vertical speed between two aircraft that have lost $S_z$ feet of vertical separation.
- $V_{rel}(\theta)$ is the average relative horizontal speed between aircraft flying at adjacent flight levels and intersecting at an angle given by the equation (12):

$$V_{rel}(\theta) = \bar{V} \sqrt{2(1 - \cos(\theta))}$$ (12)

APPENDIX B. TOPOLOGICAL PROPERTIES OF MIDRMA COUNTRIES
ACRONYMS

AAD assigned altitude deviation
ANSP air navigation service providers
ARMA African region
ASE altimetry system error
ATC air traffic control
BADA base of aircraft data
CNS communications, navigation and surveillance
DRN direct route network
FANS Future Air Navigation System
FIR/UIR flight information region/upper information region
FL flight level
ICAO International Civil Aviation Organization
IWN intermediate waypoints network
MIDRMA Middle East region
RVSM reduced vertical separation minimum
SESAR Single European Sky ATM Research
TCAS traffic collision avoidance system
TLS target level of safety
TVR technical vertical risk

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