On node criticality of the Northeast Asian air route network

Seyun Kim, Yoonjin Yoon*

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, 34141, Republic of Korea

ARTICLE INFO

Keywords:
Air transport network
Air route segment
Network robustness
Complex network
Weighted network

ABSTRACT

In this paper, air route network robustness of the rapidly growing Northeast Asian region is assessed based on the node criticality. Air transport network is modeled and constructed as network of Air Route Segment (ARS), which is the minimum unit constituting air routes. Three variations of networks – unweighted, distance-weighted and demand-weighted Air Route Segment Networks (ARSN) are considered. Although not scale-free, the network is more vulnerable to targeted attacks than random failure, with a set of critical nodes identified as ‘pseudo-hubs’. When loss in flight operation is measured in the disrupted network, rerouting improved flight operability significantly. Findings on the set of critical nodes provide key insights for vulnerability of the network, especially in the context of regional coordination against various natural and manmade risks.

1. Introduction

Air passengers and cargo carried by three major countries in Northeast Asia, i.e. China, Japan, and South Korea, have significantly increased in the past decade, accounting for nearly 20% of the passenger and 38% of the cargo traffic worldwide as of 2017 (ICAO, 2018). In contrast to the growing importance, there exist few regional studies on the characteristics of the Air Transport Network (ATN). Existing studies that have dealt with the ATN in this region mainly focused on the national airspace of China. Wang et al. (2011) analyzed the topological characteristics of the Chinese airport network. The study found that the Chinese airport network as of 2007 showed the small-world property, but is not scale-free. Cai et al. (2012) conducted a comparative study on the Chinese network by comparing airport versus air route network. The study found that two networks significantly differ in their topological nature; airport network follows the power-law degree distribution, and has high clustering coefficient and short characteristic path length. On the other hand, air route network follows the exponential degree distribution, and has low clustering coefficient and long characteristic path length.

One of the novelties of Cai et al. (2012) is considering not only the airport but also the air route in modeling ATN. ATN as network of airports has been widely employed in abundant literatures, both in the global (Lordan et al., 2014, 2015; Song and Yeo, 2017; Sun et al., 2017) and the regional (Dai et al., 2018; Wilkinson et al., 2012) context. Although airport network exhibits the desirable scale-free and small-world properties in general, virtual networks of directly connected airport pairs essentially model airline service network to exclude the airspace, where most of the operational resources are consumed. To address such shortcoming, several studies adopted enhanced approaches in constructing airport network. Pien et al. (2015) modeled the European ATN as network of airports and ACCs (Area Control Center). Ren and Li (2018) applied clustering techniques to aircraft trajectory data, and used the cluster size as the edge weight of the airport networks of China and the United States.

There have been notable efforts to model ATN more directly from the airspace perspective. Sun et al. (2014) studied topological properties of national air route networks of 15 countries, which included China and Japan. Five network metrics of degree, closeness, betweenness, distance strength, and edge length distribution were considered, and the authors argued the degree distributions were closer to tetration than exponential. In the follow-up study, Sun and Wandelt (2014) expanded the scope to include 58 countries, and investigated the topological similarities of air route networks based on 15 network metrics. The study concluded that there exist few commonalities among the 58 national air route networks, and noted that robust assessment on the air route networks needs to incorporate such heterogeneity.

In this study, the Northeast Asian regional airspace is modeled as network of the Air Route Segment (ARS). ARS is the minimum unit to constitute an air route, and the international standard used in the Aeronautical Information Service (AIS). The regional Air Route Segment Network (ARSN) is constructed from the individual ARSN of...
China, Japan, and South Korea in a collective manner. Three variations of ARSN – unweighted, weighted by link distance, and weighted by link-wise air traffic volume, are considered to evaluate the robustness of the Northeast Asian ARSN based on node criticality. Although ATN robustness has been well explored and researched, there exist few literatures that have studied the Northeast Asian region. In addition to the geographical limitation, the majority of existing literatures focused on airport network robustness (Lordan et al., 2014, 2015; Sun et al., 2017; Wandelt et al., 2015). In the aforementioned study on 15 national air route networks, Sun et al. (2014) concluded that the United States is the most robust among 15 countries against random or targeted node failures, mainly due to relatively small betweenness values. In this paper, two measures of robustness – the relative size of the largest component and the number of operable flights – are evaluated and discussed. If the former represents network cohesiveness in terms of connectivity, the latter represents the sustainability of flight operations in disrupted airspace. For a quick overview and comparison, related literatures are summarized in Table 1.

The rest of paper is organized as follows. In Section 2, Northeast Asian ARSN is modeled and the properties of three variations of the regional ARSN are presented. In Section 3, network robustness is discussed with respect to network cohesiveness as well as the air transport serviceability. Discussions and conclusions are included in Section 4.

2. Northeast Asian air route segment network (ARSN)

2.1. Modeling Northeast Asian air transport network (ATN) as air route segment network (ARSN)

In this paper, Air Transport Network (ATN) is modeled as network of Air Route Segment (ARS). An ARS is a \(K_2\) complete graph connecting two waypoints. It is a simple graph with no parallel edges or loops, and is the minimum unit in flight planning (ICAO, 1984). In Fig. 1, typical flight plan from Incheon International Airport, South Korea (ICN) to Fukuoka International Airport, Japan (FUK) on air route AS82 consisting of 10 consecutive ARSs is illustrated.

ARS network is represented as an undirected and connected graph \(G=(V,E)\), defined by an adjacency matrix \(A=(a_{ij})\in R^{n\times n}\), where \(a_{ij}=1\) if there exists an ARS containing adjacent waypoints \(i\) and \(j\), and zero otherwise. Data used to construct the regional and three national Air Route Segment Networks (ARSN) were extracted from the Aeronautical Information Service (AIS) of three states of interest –

![Fig. 1. Typical flight plan from Incheon International Airport, South Korea (ICN) to Fukuoka International Airport, Japan (FUK) on air route AS82. Air Route Segments (ARS) included in this route are highlighted in blue. (data source: Aeronautical Information Service (AIS) of China, Japan, and South Korea, retrieved October 15, 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image)

Table 1
Summary of literatures on Air Transport Network (ATN).

<table>
<thead>
<tr>
<th>Literature</th>
<th>Year</th>
<th>Geographical area</th>
<th>Network element</th>
<th>Robustness metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td></td>
<td></td>
<td>airport waypoint others (name)</td>
<td>size of largest component, survived links, unaffected passengers</td>
</tr>
<tr>
<td>Sun et al.</td>
<td>2017</td>
<td>World</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Lordan et al.</td>
<td>2015</td>
<td>World</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Lordan et al.</td>
<td>2014</td>
<td>World</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Song and Yeo</td>
<td>2017</td>
<td>World</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Wandelt et al.</td>
<td>2015</td>
<td>144 countries</td>
<td>– – ● (country)</td>
<td>– – ● (country)</td>
</tr>
<tr>
<td>Regional</td>
<td></td>
<td></td>
<td></td>
<td>relative area index</td>
</tr>
<tr>
<td>Pien et al.</td>
<td>2015</td>
<td>Europe</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Wilkinson et al.</td>
<td>2012</td>
<td>Europe</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Dai et al.</td>
<td>2018</td>
<td>Southeast Asia</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>National</td>
<td></td>
<td></td>
<td></td>
<td>size of largest component, canceled airline service routes</td>
</tr>
<tr>
<td>Sun and Wandelt</td>
<td>2014</td>
<td>58 countries</td>
<td>– – ●</td>
<td>– – ●</td>
</tr>
<tr>
<td>Sun et al.</td>
<td>2014</td>
<td>15 countries</td>
<td>– – ●</td>
<td>– – ●</td>
</tr>
<tr>
<td>Wandelt et al.</td>
<td>2015</td>
<td>4 countries</td>
<td>– – ●</td>
<td>– – ●</td>
</tr>
<tr>
<td>Ren and Li</td>
<td>2018</td>
<td>USA, China</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Cai et al.</td>
<td>2012</td>
<td>China</td>
<td>● – –</td>
<td>● – –</td>
</tr>
<tr>
<td>Wang et al.</td>
<td>2011</td>
<td>China</td>
<td>● – –</td>
<td>● – –</td>
</tr>
</tbody>
</table>

* ACC. Area Control Center.

China, Japan, and South Korea published in October 2018. The regional ARSN contains 1,985 individual ARSs connecting 1,459 waypoints as shown in Fig. 2. In the figure, one can immediately observe that each national airspace is unique in their air route topology, as Sun and Wandelt (2014) previously found. China is sparsely populated with waypoints across its vast airspace except for the airspace surrounding major airports. Japan is another unique network designed with abundant parallel routes. South Korea has the smallest set of ARSs, mostly

\(^{2}\)Nodes located at the sovereign limits were included in each neighboring national networks, but treated as a single node in the regional network. Any small orphan networks with total node count less than 12 were discarded.
constituting direct routes between domestic airports, and a few channeling routes for international traffic. Due to the geopolitical environment surrounding the Korean Peninsula, air routes are designed to utilize the scarce civil airspace to the maximum.

### 2.2. Topological features of Northeast Asian Air Route Segment Network (ARSN)

Topological properties of the regional and national Air Route Segment Networks (ARSN) are evaluated based on (a) the average degree, (b) characteristic path length, and (c) clustering coefficient. Degree of node \( i \) is the number of links connected to node \( i \), which is defined as \( k_i = \sum a_{ij} \) (Freeman, 1978). Characteristic path length \( L \) is given by \( L = \frac{1}{n(n-1)} \sum_{i \neq j} d_{ij} \), which is the average number of links along the shortest paths \( (d_{ij}) \) for all possible node pairs in the network. Clustering coefficient \( C \) is the fraction between the total triangles and the total connected triples (Wasserman and Faust, 1994). Short characteristic path length \( L \) and large clustering coefficient \( C \) are considered as the common properties of small-world network, which is between regular lattice and random graph (Watts and Strogatz, 1998).

In Table 2, number of nodes \(|V|\), number of edges \(|E|\), average degree \((k)\), characteristic path length \( L \), and clustering coefficient \( C \) are listed for the regional and three national ARSNs. Among the 1,985 Air Route Segments (ARS), 48% belong to Japan, 45% to China, and the remaining 7% to South Korea. Note that the average degree \((k)\) is nearly identical in all four networks even with dissimilar \(|V|\) and \(|E|\). Combinations of large characteristic path length \( L \) and small clustering coefficient \( C \) in all four networks indicate that they do not exhibit the small-world property.

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Regional</th>
<th>China</th>
<th>Japan</th>
<th>South Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes (</td>
<td>V</td>
<td>)</td>
<td>1,459</td>
<td>661</td>
</tr>
<tr>
<td>Edges (</td>
<td>E</td>
<td>)</td>
<td>1,985</td>
<td>974</td>
</tr>
<tr>
<td>Average degree ((k))</td>
<td>2.721</td>
<td>2.714</td>
<td>2.720</td>
<td>2.500</td>
</tr>
<tr>
<td>Characteristic path length (L)</td>
<td>22.00</td>
<td>16.45</td>
<td>9.91</td>
<td>8.23</td>
</tr>
<tr>
<td>Clustering coefficient (C)</td>
<td>0.065</td>
<td>0.098</td>
<td>0.038</td>
<td>0.069</td>
</tr>
</tbody>
</table>

In Fig. 3, cumulative degree distribution and degree-degree correlation plots are shown. The cumulative degree distribution \( P(\geq k) = \sum_{k=1}^{\infty} P(k) \) is the cumulative sum of degrees of \( k \) or higher given the degree distribution \( P(k) \). It follows the power-law distribution \( P(\geq k) \propto k^{-\gamma} \) in scale-free network (Albert et al., 2000). Although the air transport network has been widely recognized scale-free when modeled as airport network (Cai et al., 2012; Dai et al., 2018; Lordan et al., 2014), several studies found that national air route networks do not exhibit such a property (Cai et al., 2012; Gurtner et al., 2014; Sun et al., 2014). In our case, the regional and three national ARSNs are closer to exponential (Fig. 3(a)), which is well expected since ARSNs do not satisfy a necessary condition of scale-free network – preferential attachment (Albert et al., 2000).

In Fig. 3(b), degree-degree correlation, which measures degree correlation among neighboring nodes, is shown. The regional and national ARSNs of China and Japan exhibit neutral network characteristics, whereas South Korea shows a disassortative pattern. In other words, South Korean ARSN is closer to hub-and-spoke than the others, since the disassortative pattern implies the degree of a node is inversely related with those of its neighbors.

Despite numerous previous studies on the topological properties of Air Transport Networks (ATN) over the past decade, several recent studies have presented opinions that differ from common understanding. Broido and Clauset (2019) argued that real-world network with perfect scale-free property is a rare find, as well as in various types of transportation network. In addition, Zanin et al. (2018) claimed that there have been common errors in assessing scale-freeness and interpreting topological metrics from transportation networks in several previous studies, i.e., too small number of degrees for assuming scale-free. Reflecting on our findings as well as those earlier studies, we conclude that it is difficult to generalize the topological properties of air route networks. Although one can generally agree that air route networks rarely exhibit the scale-free property, there are numerous possibilities to define its exact probabilistic nature. Unlike airport networks established as hub-and-spoke by design, the focus of the air route network research should extend beyond discussions on the scale-free, small-world properties. Moreover, considering certain variations of the network such as air traffic demand weighted network may provide valuable insights on the robustness of the air transport network.
2.3. Weighted Northeast Asian Air Route Segment Network (ARSN)

Since the construction of Air Route Segment Network (ARSN) is dependent on the geospatial proximity by nature, studying the topological properties strictly based on the node adjacency may not suffice to fully describe the network as the air transportation network. While the ARSN as unweighted network is defined with the binary adjacency matrix, weighted ARSN is defined with the weighted adjacency matrix \( A^w = (a^w_{ij}) \in \mathbb{R}^{nxn} \), where \( a^w_{ij} \) is a continuous value to represent various weights (Newman, 2004). In this paper, two types of weights – link distance and link-wise air traffic demand were considered. In the distance-based ARSN, geographical distance of each Air Route Segments (ARS) was used as link weight \( a^w_{ij} \). The distance-based network mainly captures the critical nodes measured by geographical proximity. In the demand-based ARSN, link-wise air traffic volume was used as weight. The air traffic volume was estimated based on the actual flight trajectory data sourced from the online flight-tracking service ‘FlightAware’, which provides ADS-b surveillance data. In total, 16,734 flights between 114 busiest airports in China (50), Japan (50), and South Korea (14) on July 1, 2018 (retrieved on July 4, 2018) were included, which address 93.5% of total traffic in the region. The demand-based network identifies the set of critical nodes in terms of flight demand.

Network properties of the weighted regional and national ARSNs are evaluated based on (a) the average weight, (b) average strength, (c) weighted characteristic path length, and (d) weighted clustering coefficient. Strength of node \( i \) is the sum of weights of connected links to node \( i \), which is defined as \( s_i = \sum_j a^w_{ij} \) (Barrat et al., 2004; Newman, 2004). Weighted characteristic path length \( L^w \) given by \( L^w = \frac{1}{n(n-1)} \sum_{i \neq j} d^w_{ij} \) is the mean sum of weights on the links included in the shortest paths for all possible node pairs. Weighted clustering coefficient \( C^w \) comes in various definitions (Barrat et al., 2004; Onnela et al., 2005; Opsahl and Panzarasa, 2009), and we adopted the definition of Opsahl and Panzarasa (2009) to consider the weights of links in each triplet. The difference between \( C^w \) and the topological clustering coefficient \( C \) shows the effect of weights on clustering components in the network.

In Table 3, summary statistics of two types of weighted networks are presented. Average weight in the distance-based network shows similar values in all four ARSNs except for South Korean network, whose average weight is much smaller at 54.19. Such findings indicate that South Korean airspace relies on much shorter ARSs than the other ARSNs on average, and the regional network is dominated by those of Japan and China as mentioned in Section 2.2. In the demand-weighted networks, however, the average demand varies by geographical boundary. With the largest average link-wise demand of 259.37, Chinese ARSNs are found utilizing three times more than the ones in Japanese airspace on average. Note that the effect of weights becomes more evident when assessing the average strength, which is essentially the average degree multiplied by average weight. Since average degree values are nearly identical in all four ARSNs (Table 2), the average strength shows the proportional variations in the average weight.

The characteristics path length \( L^w \) is relevant in the distance-based weighted network since it is based on the shortest path. Comparison between unweighted versus distance-weighted characteristic path length reveals that the ratio \( L^{uw}/L^{w} \) is the largest in Chinese ARSN (108.8) and smallest in Japanese ARSN (88.3). Such observations indicate that waypoints in Chinese airspace are more dispersed than Japan, although both have similar number of nodes (Table 2). Considering the clustering coefficient \( C \) captures the proportion of triangles among triplets containing node \( i \), and composition of triplets is invariant to weight, weighted clustering coefficient \( C^w \) provides added insight on the effect of a specific weight. In the distance-weighted ARSNs, Japan shows the unique result with \( C^w (0.040) \) larger than \( C (0.038) \), suggesting that triangles in its network are more likely formed by longer ARSs. In the demand-weighted ARSNs, South Korea is the only nation with \( C^w (0.090) \) larger than \( C (0.069) \), which implies that highly utilized adjoining ARSs in its ARSN are more likely to form a triangle.

3. Network robustness

In this section, we present and discuss the robustness of the Northeast Asian Air Route Segment Network (ARSN) based on node failure analysis, in which a set of nodes is assumed to be either targeted or randomly failed. In random failure analysis, a randomly selected node is removed from the network recursively. In targeted attack analysis, nodes are first ranked by importance, and the node of the highest importance is removed sequentially. To rank the nodes by importance, six node centralities were employed including degree, closeness, betweenness, strength, weighted closeness and weighted betweenness. Note that the adaptive strategy (Lordan et al., 2014) was
also considered but not applied, since re-assigned node importance in disconnected network is limited in providing meaningful insights on the node criticality of the Northeast Asian ARSN. Network robustness was assessed by (a) the relative size of the largest component and (b) the number of operable flights with optional rerouting. The relative size of the largest component is the size of the largest surviving subgraph in proportion to the size of the original network after node removal. It represents the network cohesiveness (Callaway et al., 2000) in terms of connectivity. In addition to the structural connectivity, the number of operable flights in damaged network was evaluated with or without rerouting possibility.

### 3.1. Critical node identification using node centralities

Identifying a set of critical nodes based on node importance is widely adopted in various transport network studies (Guo et al., 2017; Hussain and Alam, 2017; Song and Yeo, 2017; Wang et al., 2011). In particular, one can assess the network robustness based on node failure analysis by removing critical nodes from the original network (Cheung and Gunes, 2012; Lordan et al., 2014, 2015; Sun et al., 2017; Xing et al., 2017).

In the unweighted Air Route Segment Network (ARSN), node importance was measured by three node centralities including degree, closeness, and betweenness. Closeness of node \(i\) is defined as \(c_i = \frac{1}{\sum d_{ij}}\), where \(d_{ij}\) is the distance of the shortest path connecting the node \(i\) and all other node \(j\) \((i \neq j)\) (Freeman, 1978). Betweenness is the frequency of a node included in the shortest path between all possible connected pairs of nodes, and defined as \(b_i = \sum_{j \neq k} \frac{n_{jk}(i)}{n_{jk}}\). Here, \(n_{jk}\) is the number of shortest paths connecting the node \(j\) and \(k\), and \(n_{jk}(i)\) is the number of shortest paths between node \(j\) and \(k\) that include node \(i\) (Freeman, 1978). If degree represents the local node connectivity, closeness and betweenness are measured in the global network structure (Zareie and Sheikhamadi, 2018).

### Table 3

Summary statistics of the weighted Northeast Asian Air Route Segment Networks (ARSN).

<table>
<thead>
<tr>
<th></th>
<th>Regional</th>
<th>China</th>
<th>Japan</th>
<th>South Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance-based weighted network</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight ((w^\text{avg}))</td>
<td>91.05</td>
<td>94.93</td>
<td>92.92</td>
<td>54.19</td>
</tr>
<tr>
<td>Average strength ((w))</td>
<td>247.75</td>
<td>257.66</td>
<td>252.80</td>
<td>135.47</td>
</tr>
<tr>
<td>Weighted characteristic path length ((w^\text{char}))</td>
<td>2008.1</td>
<td>1790.1</td>
<td>875.2</td>
<td>428.5</td>
</tr>
<tr>
<td>Weighted clustering coefficient ((w^\text{clu}))</td>
<td>0.055</td>
<td>0.076</td>
<td>0.040</td>
<td>0.062</td>
</tr>
<tr>
<td><strong>Demand-based weighted network</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight ((w^\text{avg}))</td>
<td>166.18</td>
<td>259.37</td>
<td>75.80</td>
<td>178.83</td>
</tr>
<tr>
<td>Average strength ((w))</td>
<td>452.19</td>
<td>703.94</td>
<td>206.22</td>
<td>447.09</td>
</tr>
<tr>
<td>Weighted clustering coefficient ((w^\text{clu}))</td>
<td>0.076</td>
<td>0.090</td>
<td>0.034</td>
<td>0.090</td>
</tr>
</tbody>
</table>

In Fig. 4, degree, closeness, and betweenness of the regional ARSN are shown in scale. One can observe that higher degree nodes are sporadically located inside the national airspace of China and Japan. On the other hand, nodes of higher closeness are concentrated around the East China Sea, since closeness is the largest in the centrally located nodes to radially decrease outwards. Nodes with higher betweenness are located along the air routes connecting three national airspace, identifying a limited number of nodes, or the ‘pseudo-hubs’, connecting three individual national ARSNs.

In the weighted network, node importance was measured with three centralities including strength, weighted closeness, and weighted betweenness. Weighted closeness of node \(i\) is given by \(c_i^w = \frac{1}{\sum n_{ji}^w}\), where \(n_{ji}^w\) is the weighted distance of the shortest path between node \(i\) and all other node \(j\) \((i \neq j)\) according to the given weight (Opsahl and Panzarasa, 2009). Similar to the closeness in the unweighted network, it represents how close a node is located to the center of the network under the imposed weight. Weighted betweenness of node \(i\) is defined as \(b_i^w = \sum_{j \neq k} \frac{n_{jk}^w(i)}{n_{jk}^w}\), where \(n_{jk}^w\) is the number of shortest paths connecting the node \(j\) and \(k\) in weighted network, and \(n_{jk}^w(i)\) is the number of shortest paths between \(j\) and \(k\) that include node \(i\) (Opsahl and Panzarasa, 2009). It incorporates link weight in counting the node frequency in shortest paths. Note that strength is most relevant in the demand-based weighted network since it is the sum of link weight a node. Likewise, both the weighted closeness and weighted betweenness are most relevant in the distance-based weighted network, since shortest path extraction is based on link distance.

In Fig. 5, strength, weighted closeness, and weighted betweenness of the regional ARSN are shown in scale. One can observe that top strength nodes are located on the domestic routes connecting major cities in China, such as Beijing and Guangzhou, exhibiting the evidence of air travel demand concentration among the major cities domestically. Top nodes of weighted closeness are located around South Korean airspace to radially decrease outward, in a similar fashion in the

(a) Degree  
(b) Closeness  
(c) Betweenness

**Fig. 4.** Three node centrality plots of the Northeast Asian Air Route Segment Network (ARSN).
unweighted network. Nodes of higher weighted betweenness are found in the East China Sea and the Yellow Sea.

3.2. Relative size of the largest component

The largest component in the damaged network represents the largest connected subgraph that survived the node failure. In Fig. 6, the relative size of the largest component is plotted with respect to the fraction of nodes removed. Random failure result is shown in grey, and targeted attacks are color-coded with respect to six centrality measures. Compared to random failure, targeted attacks according to node importance separated the network into a set of isolated subgraphs by removing fewer nodes in general. For instance, the largest connected subgraph maintains 80% of the initial connectivity on average with random removal of 10% of total nodes, while targeted attacks on less than 7% of total nodes reduce connectivity to the same 80%. In other words, the regional Air Route Segment Network (ARSN) is more vulnerable to targeted attacks on critical nodes.

Among the six node centralities, four measures – weighted betweenness (pink), betweenness (blue), weighted closeness (cyan), closeness (green) resulted in the significant step-down patterns for the relative size of the largest component to reach around 50% as shown in Fig. 6. For example, when top 12 nodes (0.8% of total nodes) of highest weighted betweenness are sequentially removed, the relative size of the largest component decreases from 99% to 54% (A, B in Fig. 6). Such common outcomes from four measures are the result of the Chinese network separated from the rest of the region when disconnection of two routes – G597 and A593, occurs. Both routes are channeling routes connecting three countries in the region, where G597 spans between Northern China and Western Japan, and A593 channels the international traffic through Southern China and Western Japan. The disconnection of two routes from the weighted betweenness case is illustrated in Fig. 7(a) as an example. As shown in the figure, all critical nodes belong to the channeling routes, and the regional ARSN is divided into two when those nodes become unavailable.

On the other hand, removal of the same number of top betweenness nodes affects little in the network connectivity since it requires more nodes (29 nodes; 2% of total nodes) removed to show a similar result – decreasing from 97% (C) to 53% (D).
As the Northeast Asian ARSN relies on two channeling air routes (G597, A593), it is well expected that two critical node sets from weighted betweenness and betweenness share waypoints on those routes since betweenness essentially captures the frequency for a node to appear in the shortest path. In this case, both node sets shown in Fig. 7 contain 9 common nodes out of 12. However, as weighted betweenness incorporates geographical proximity in calculating shortest paths between nodes, it captures critical nodes of the Northeast Asian ARSN more accurately than unweighted betweenness which assumes all links have distance of 1 when calculating shortest paths. In case of unweighted betweenness in Fig. 7(b), one of the channeling routes (A593) is disrupted by removed waypoints, while G597 is not completely disrupted and sustains connection between two giant subgraphs.

In case of closeness-based attack, removing several top nodes could only disconnect one channeling route (A593) as nodes with high centrality are located around the East China Sea (Fig. 4 mass), which resulted in significant step-down pattern appearing when 7% of total nodes are removed. Although weighted closeness-based attack went through a similar process, the step-down pattern appeared by removing relatively smaller number of nodes since centrality values radially decrease from around the Southeast region of South Korea and rank of nodes on two channeling routes are similar (Fig. 5(b)). Such difference between closeness and weighted closeness mainly stems from the unique design of South Korean airspace, which is populated with much shorter Air Route Segments (ARS) (Table 3). Without considering link distance, closeness identifies the channeling nodes between China and Japan the most critical, which seems more relevant in the regional context since South Korean ARSs address less than 7% of the regional ARSN. In summary, the regional network, as network of networks, relies on a small number of channeling nodes, which act as ‘pseudo-hubs’ of the regional airspace. Those ‘pseudo-hubs’ are the most critical nodes in the regional network cohesiveness both in the unweighted and distance-weighted networks.

Degree and strength in demand-weighted network show rather gradual reduction trend in Fig. 6 compared to the four node centralities discussed above. For better understanding of such results, the sets of nodes of top degree and of top strength are mutually exclusive. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 7. Top 12 nodes of highest (a) weighted betweenness and (b) betweenness shown in red triangles with corresponding air routes shown in blue lines. Removal of highest weighted betweenness nodes separates the Chinese network from the rest of the region, resulting in two giant subgraphs while removal of the same number of nodes with highest betweenness does not completely disconnect one of the channeling routes (G597). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 8. Top 12 nodes of highest degree and strength highlighted in red. The sets of nodes of top degree and of top strength are mutually exclusive. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
the domestic routes connecting major cities in China affects the connectivity of Southern China to result in some of the early small step-down. On the other hand, removal of top degree nodes mainly affects Japanese ARSN, and Japanese ARSN does not suffer from a drastic reduction in connectivity. Considering the Japanese ARSN is populated with abundant parallel routes, one can draw another interpretation of the same findings; Japanese ARSN is populated with waypoints of higher redundancy than China, and more resilient in connectivity.

Four node importance measures which showed the significant step-downs in the relative size of the largest components are related with shortest paths between nodes. While they showed similar results of separating Chinese ARSN from the rest of the region, the results of degree and strength, which depend on the local connection of nodes, were different. For evaluating damage on air traffic from node deletion and the network separation, the number of operable flights was measured.

3.3. Number of operable flights with optional rerouting

Considering the main purpose of the air transport network is to serve air traffic, understanding the robustness with respect to flight operations is essential. Flight operability, or flyability, is dependent on the availability of Air Route Segments (ARS) in its initial flight plan. When none of the planned ARSs is interrupted, the flight can retain its initial flight plan to operate as planned. When some of the waypoints in the initial flight plan become unavailable due to node failures, there are two possibilities - either canceling or rerouting the flight. Flight cancelation without rerouting is not uncommon as observed in the history of the major natural disasters such as the Eyjafjallajökull eruption in Iceland in 2010 (EUROCONTROL, 2010). Rerouting not only incurs additional operational cost, but also increases the air traffic controllers’ workload. In addition, it often requires a predefined set of alternative routes readily available. However, rerouting is recognized as one of the most effective mitigation techniques of airspace disruption, and has been increasingly incorporated into risk-based flow management (ICAO, 2016a). In this paper, flight operability in the damaged network is assessed based on the trajectories\(^4\) of 10,151 flights using 114 busiest airports in China (50), Japan (50), and South Korea (14).

Flight operations are categorized into three categories – ‘planned’, ‘rerouted’ and ‘disrupted’. While flights in ‘planned’ categories are able to retain its initial flight plan, ‘rerouted’ flights are able to operate on alternative routes. Flights no longer able to operate due to the network damage are categorized as ‘disrupted’. When rerouting is considered, a flight is classified as ‘rerouted’ as long as there exists a surviving path between its origin and destination. Note that flights in ‘rerouted’ category provides many useful insights to understand the robustness of the air transport service network. In essence, the number of flights in ‘planned’ category represents the minimum possible air transport serviceability (or the maximum possible loss), whereas the number of flights in ‘planned’ and ‘rerouted’ categories represent the maximum possible serviceability (or the minimum possible loss).

In Fig. 9, change in flight operability from sequential node removal in Northeast Asian Air Route Segment Network (ARSN) is presented when rerouting is not considered (solid lines), and considered (dotted lines). Overall, added consideration of rerouting greatly improves the overall serviceability of the network. Without rerouting, strength-based attack shows the most severe reduction of nearly 50% with the removal of just top 7 nodes (A in Fig. 9). In fact, the removal of the top single strength node of ‘Pionghzhou VOR’ disrupted 1,456 flights, which accounts for 14.4% of all flight operations. When rerouting is possible, the absence of the same top 7 nodes did not reduce flight operability at all. Similar observations can be made for other node centralities, and the large gap between the minimum possible and the maximum possible serviceability strongly suggest that active consideration to incorporate alternative routes in air traffic management can provide effective mitigation measures during airspace disruptions. It is also evident that there exist the sets of critical nodes affecting the network serviceability greatly, which require the foremost attention to consider alternative routes.

It is also notable that while removal of top 12 (0.8%) weighted betweenness nodes reduced the relative size of the largest component to 54%, loss in flight operations is much less at 7% (B in Fig. 9) when rerouting is considered. In other words, the impact of ‘pseudo-hubs’ is relatively less severe on the actual flight operations than in the topological context. However, the importance of ‘pseudo-hubs’ should not be underrated, as there is no alternative trans-national ground transport in the region. Loss of ‘pseudo-hubs’ would affect the majority of international traffic using the regional airspace.

4. Discussions and conclusions

Air Transport Network (ATN) forms one of the most efficient and safe backbones to transport goods and people. Existing studies on its properties often relied on the hypothetical network of airports, excluding the airspace. In this paper, ATN of the rapidly growing Northeast Asian region – China, Japan, and South Korea, was modeled and analyzed based on the Air Route Segment Networks (ARSN). In regard to the network properties, three national ARSNs showed little commonalities, which coincides with the findings from an earlier study (Sun and Wandelt, 2014). Unlike airport network, which incorporates the hub-and-spoke structure by design, none of the regional and three national ARSNs exhibited small-world, scale-free property.

To evaluate the regional ARSN robustness, node failure analyses based on random failure and targeted attack scenarios are employed. Critical node identification and robustness assessment were carried out both in the unweighted and weighted network by incorporating link distance and the link-wise air traffic volume as weight. In targeted attack, three node centralities - degree, closeness, betweenness are used in unweighted ARSN, and three weighted node centralities - strength, weighted closeness, weighted betweenness are used in the weighted ARSN. Overall, the regional ARSN was much more vulnerable to targeted attacks than random failure. In particular, targeted attacks on top-ranked nodes of weighted betweenness showed the most severe outcome, by decomposing the regional network into China and the rest of the region. Such findings are strong evidence of reliance on the small set of ‘pseudo-hubs’ of the regional ARSN, which serves to channel flights across the region.

Even in the disrupted ARSN, flight operations might still be possible by considering rerouting on an alternative path. Comparison between with and without consideration of rerouting showed significant gaps, especially on the removal of the top strength nodes. Our finding shed a new light on recent activities on risk-based airspace safety assessment, spurred by the 2010 Eyjafjallajökull volcanic eruption (EUROCONTROL, 2010). The epic volcanic event led to establish the International Volcanic Ash Task Force (IVATF) by International Civil Aviation Organization (ICAO), to publish the second edition of EUR Doc 019/NAT Doc 006 Part II in 2016. In the publication, one of the key paradigm shifts was the application of Safety Risk Assessment (SRA) approach. In SRA, the airspace risk is assessed in much more detail beyond the single lines connecting airport pairs (ICAO, 2016b). Such approach requires further understanding of airspace network itself, which is not readily extractable from the network of airports and airline routes. Moreover, existing academic studies employing the SRA approach to airspace disruption are limited to European airports or airspace (Biais et al., 2014; Luchkova et al., 2015; Scaini et al., 2014).

The Northeast Asian region encompassing China, Japan, and South Korea is not only rapidly growing in air traffic, but also exposed to

---

\(^4\)Trajectories were reconstructed based on the actual ADS-b surveillance data sourced from the online flight tracking service ‘FlightAware’ (retrieved on July 4, 2018).

---
various natural and geopolitical risks (Kim et al., 2019). As found in the study, Air Route Segments (ARS) belonging to two air routes (G597 and AS93 in Fig. 7) can affect the connectivity of the regional network greatly, and regional coordination is critical to achieving the coherent airspace safety. Large gaps between with and without rerouting also manifest that designing alternative routes is a key element in the regional contingency plan. One of the limitations of this study is that robustness analysis is based on hypothetic situations - sequential removal of high-centrality nodes. In the regional coordination, in-depth studies on specific disruption scenarios such as Mt. Paektu explosion (Kim et al., 2019) will be necessary to prepare for various spatial and geopolitical hazards.

As the threat of natural and man-made disasters to the air transportation system is hardly limited to airports, evaluating the airspace network robustness is critical for effective disaster preparedness. The main contribution of this paper is to analyze vulnerability embedded in the regional ARSN with respect to network cohesiveness as well as flight operability. The novel approach to construct the airspace network with ARS has the advantage of using the minimum unit of constituting flights (B) are still operable with consideration of rerouting (dotted lines) and without (solid lines). With the removal of top 7 strength nodes, about 5,100 flights (A) are operable when rerouting is not considered. Although the Chinese Air Route Segment Network (ARSN) is separated from the regional ARSN by removal of top 0.8% weighted betweenness nodes, more than 9,400 flights (B) are still operable with consideration of rerouting.

Fig. 9. The number of operable flights with consideration of rerouting (dotted lines) and without (solid lines). With the removal of top 7 strength nodes, about 5,100 flights (A) are operable when rerouting is not considered. Although the Chinese Air Route Segment Network (ARSN) is separated from the regional ARSN by removal of top 0.8% weighted betweenness nodes, more than 9,400 flights (B) are still operable with consideration of rerouting.

Declarations of interest

None.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (NRF-2017R1E1A1A01076315).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jairtraman.2019.101693.

References