Impact Analysis of Weather Factors on Aircraft Cancellation using Multilayer Complex Network

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Abstract

Aircraft is one of the most popular and important transportation services for passengers. However, its increased importance has become proportional to the increased aircraft cancellations, especially, by abnormal weather factors such as rainfall and wind speed. The previous studies have concentrated on ripple effects and individual factors of the cancellations rather than combined analysis of the factors. That is to say, we have studied aircraft cancellation using network analysis for only aircraft elements such as seat number and aircraft operation. Therefore, this study applied a multilayer complex network with three different factors of aircraft, rainfall, and wind speed for aircraft cancellation to 14 airports in South Korea. The multilayer complex network is useful for analyzing network which has various different factors. The results showed that rainfall had greater impact on aircraft cancellations than wind speed. Jeju airport was the greatest influence node by vital node identification analysis, because it had high demand of aircraft and was frequently affected by rainfall and wind speed. Through overall results, we have known that the multilayer complex network methodology can consider the relationship between the factors as well as the characteristics of each factor in analyzing the complex phenomenon.

1 Introduction

Aircraft has become an important means of transportation. From 2010 to 2018, before being affected by COVID-19, the number of customers and amount of cargo weight using aircraft have increased annually by 6.3% and 4.4% respectively. According to OECD (Organization for Economic Co-operation and Development) statistic from 2010 to 2018, total number of international departures for tourism showed annually 5% increase. One of the most important factors in aircraft operations is weather (Oliveira et al. 2021). The intensity and frequency of weather phenomena such as heavy rainfall and typhoon are increasing trend due to climate change, with a corresponding adverse effect on the aviation industry. According to statistics from the Department of Transportation, USA, there were 78,214 aircraft cancellations in the period of 2010 to 2018 due to weather factors. It also showed that half of the total cancellations were caused by weather in each year. This phenomenon has also occurred in other regions such as Europe and Asia. In South Korea, the number of cancellations is increasing annually with the climate factor accounting for more than 80% of the total cancellations (Korea Airport Corporation 2019). Many experts have projected that these will be further exacerbated by the ongoing climate change.

Many studies have analyzed aircraft cancellation. Some studies analyzed aircraft cancellation cases according to weather factors, and had estimated the direct and indirect economic damage caused by the cancellations (Sasse and Hauf 2003; Park et al. 2007; Von Grueigen et al. 2014). Other studies had attempted to identify the important weather factors in aircraft operations or estimated the impacts of the theses factors (Lee et al. 2011; Schultz et al. 2018; Goodman et al. 2019; Mcwillian et al. 2020). Studies had also developed weather models for estimating the number of cancellations (Klein et al. 2011; Zanin et al. 2020) and projected cancellations based on climate change scenarios (Mark et al. 2009; Jane et al. 2021; Lee et al. 2022). Other studies have investigated the impacts of accurate weather predictions on aircraft operation (Klein et al. 2009; Zhu et al. 2017) and resilience evaluations of airports (Zhou and
Chen. 2020). However, previous studies have concentrated on the ripple effects and causes of cancellations, rather than characteristics of the cancellation phenomenon and relationship between elements of the cancellation. Therefore, this study attempted to apply a multilayer complex network methodology, which exhibits high applicability for analyzing phenomena composed of different factors, to analyze the characteristics of aircraft cancellation by weather.

Complex network theory is first proposed by Leonard Eüler in 1735 and analyzes a target by expressing it as a graph or network. Various researchers have applied the method to various data in different fields and developed it into a new field called “network science”. The complex network can simplify complex phenomena visually into a graph (or a network) and derive useful information such as features of the target and an understanding of the physical behaviors, roles and interactions of components and their relationships (Joo et al. 2021). Aircraft studies have considered this in elucidating the characteristics of airline networks, airports and air routes (Bagler 2008; Xiaozhou et al. 2011; Lordan et al. 2014; Dan-Okoro et al. 2018; Zheng, 2020). However, as an object or phenomenon gradually becomes more complex, limitations begin to appear when it is analyzed as a single network. To solve the problems, researchers have begun to define the phenomena through a multilayer network, also called a “multilayer complex network”. In this approach, several single layer networks are built for each component, and connections are then defined between the networks through the relationships of the elements to construct a multilayer network. The multilayer complex network has the advantages of complex networks, as well as other benefits, such as being able to analyze an object in more detail including more diverse factors (Mikko et al. 2014). To analyze the characteristics of airline and air routes, studies have transformed single layer aircraft networks into multilayer aircraft networks according to airline companies or destinations of aircraft (Cardillo et al. 2013; Cozzo et al. 2013; Cardillo et al. 2013;). However, no study has considered the different types of elements (such as weather factors) in the aircraft field. Therefore, this study has attempted to apply a multilayer complex network methodology to an aircraft cancellation comprising various weather factors.

This study analyzed the aircraft cancellation phenomenon in South Korea due to weather factors using a multilayer complex network methodology. Although previous studies have created multilayer aircraft networks based on aircraft information alone, this study used both weather and aircraft data. We built three different single networks (rainfall, wind speed, and aircraft), and then defined the relationships between them to construct a multilayer network. When defining the single networks, we used event-synchronization and aircraft schedules for the two weather networks and aircraft network respectively. For the connections between the networks, we used the number of aircraft cancellations due to each weather factor. Because we defined aircraft cancellation by weather factors as interaction between aircraft and weather. After constructing the multilayer network, we applied several network analysis methods (global degree distribution and strength distribution, rich-club coefficient, clustering coefficient, shortest path and efficiency, network assortativity coefficient) to analyzing the structure and characteristics of the multilayer network. Vital node identification was used to check the importance (or impact) of each airport.
The remainder of this paper is organized as follows. Section 2 introduces the study area and research data. Section 3 presents the research methodologies used in the study. The analysis results and discussions are in Section 4. Finally, conclusions are set in Section 5.

2 Methodology

2.1 Aircraft cancellation criterion

The Korea Aviation Meteorological Office (AMO) manages aircraft safety by issuing aeronautical meteorological warnings when a weather phenomenon, which may adversely affect aircraft on the ground, (including parked aircraft, aerodrome facilities and services) is observed or predicted (AMO 2020). The warnings reflect specific weather situations, as shown in the table below:

<table>
<thead>
<tr>
<th>Type</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical cyclone</td>
<td>Strong wind or heavy rainfall due to tropical cyclones is expected to reach warning levels</td>
</tr>
<tr>
<td>Thunder and lightning</td>
<td>Thunder and lightning occur or are expected at the airport</td>
</tr>
<tr>
<td>Heavy snowfall</td>
<td>Snowfall occurs or is expected more than 3cm/24hr</td>
</tr>
<tr>
<td>Gust</td>
<td>Gale (10 min mean surface wind speed with 25kt or more, or gust with 35kt or more) occurs or is expected</td>
</tr>
<tr>
<td>Ceiling</td>
<td>A ceiling occurs or is expected a level below a criterion according to the agreement among the local meteorological authority, air traffic services authority and aircraft operation at the aerodrome</td>
</tr>
<tr>
<td>Heavy rainfall</td>
<td>Rainfall occurs or is expected at 30mm/hr or more, 50mm/3hrs or more</td>
</tr>
<tr>
<td>Yellow dust</td>
<td>Yellow dust (1 h mean concentration of fine dust($PM_{10}$) with more than 400$\mu g/m^3$ or visibility less than 5,000m) occurs or is expected</td>
</tr>
</tbody>
</table>

When the following phenomena are observed or predicted

1. Hoar frost or rime
2. Freezing precipitation
3. Frost
4. Blowing sand or dust
5. Dust or sand storm
6. Squall
7. Volcanic ash
8. Hail
9. Volcanic ash deposit
10. Toxic chemical
In the case of aircraft cancellation, the condition of the cancellation depends on the flight route and warnings. Aircraft for medium- and long-distance routes are cancelled when the phenomena included in the aeronautical meteorological warnings are predicted as difficult to fly over one to two days. On the other hand, the weather conditions at the time of takeoff determine the cancellations in the case of short-distance or domestic routes. This study defined an aircraft cancellation as an event in which weather factors affect aircraft operation, and used it to define the multilayer complex network.

2.2 Complex network analysis

A complex network analysis is a method based on a basic network analysis, and the word “complex” was added as the amounts and forms of data became more complex than before (Latora et al. 2017). The complex network method converts an object into a network and then analyzes to identify characteristics of the target and its factors, the relationships between the components and so on. It can express a complicated event as a simple graph (or network) and is used in various fields, due to its high applicability (Joo et al. 2021). The first step in applying a complex network analysis is to define “nodes” and “links”, which are the basic factors of a network. A node is an entity within an analysis target and represents an intersection in a network. A link is the element connecting between nodes. For example, in a subway, each subway station is a node, and the railways between the stations are the links. The most influential factor in a complex network analysis is the link. The type of link defines the type of network. Depending on the presence or absence of the direction and weight of the link, a network can become directed/undirected or weighted/unweighted. Generally, it is easy to define links in a network where there is a clear connection, such as a road or subway. Otherwise, the researcher must confirm the connectivity of the nodes. The correlation method is widely used to check connectivity, but encompasses some uncertainty, because it relies on the researcher’s individual judgement in choosing a threshold for the coefficient to judge whether there is a connection (Kim et al. 2019). To overcome this disadvantage, Malik et al. (2012) proposed an event-synchronization method. Event-synchronization calculates an indicator of the degree of synchronization between two points by calculating the number of events occurring within a specific period. It does not require setting up a threshold, and has a good applicability. The procedure for calculating the event-synchronization is as follows (Quain et al. 2002):

(a) For two different points A and B, calculate the occurrence time of the target events at each point and then estimate the time interval between the events. The shortest interval \( T^{AB} \) between the events is defined as the as time interval of the target event.

(b) Calculate the events occurring within \( T^{AB} \) in point B based on the target events at point A. If the events occur simultaneously at points A and B, they are assigned 0.5 as a weight.

\[
c(x|y) = \sum_{x=1}^{s_A} \sum_{y=1}^{s_B} J_{xy}
\]
Where, $s_A$ and $s_B$ are the number of target events at points A and B, respectively. $t^A_x$ is the time of the $x$th target event at point A, and $t^B_y$ is the time of the $y$th event in point B.

(c) Lastly, the amount of synchronization is calculated as follows.

\[
Q_{AB} = \frac{c(x|y) + c(y|x)}{\sqrt{(s_A - 2)(s_B - 2)}}
\]

The range of the event-synchronization is from 0 to 1. If the value is 1, the two points are perfectly synchronized. If it is 0, it is interpreted as no correlation, because no common events are shared.

### 2.3 Multilayer complex network analysis

Unlike in the past, as elements with different characteristics often interact in the occurrence of an event, there are limits to expressing the event through a single layer network. The multilayer concept has been applied to address the limitations (Mikko et al 2014). A multilayer network consists of multiple single networks. It has not only links between the nodes in the same layer (intra-layer links) but also links between the nodes in other layers (inter-layer links). Therefore, it is useful for expressing multiple complex phenomena or relationships and can include various factors, because each single layer network can hold different types of nodes. However, as the network contains a more diverse and larger number of elements, it becomes more complicated, and the number of calculations increases exponentially. Nevertheless, as it can derive useful information about a target, it is widely used in various fields, such as genetics, neurology, and sociology.

### 2.4 Network structure analysis

#### 2.4.1 Degree distribution

Each node in the network has a different number of links. The number of links to the node is called its “degree”. In the case of a weighted network, links have their own weights and the total amount of link weight in each node is called its “strength”. The degree of the nodes can be expressed as a probability density function, that is the degree distribution. The degree distribution represents the probability ($p(k)$) that any node has a degree value of $k$. For example, if all nodes have two links, $p(k = 2)$ is 1. The strength distribution utilizes the same concept as the degree distribution but utilizes strength instead of degree. Through the degree and strength distributions, researchers can confirm the distribution of the links.
between nodes and the structure of the network (Michael 2005). Accordingly, we estimated and compared the degree and the strength distribution of the multilayer network and single networks.

### 2.4.2 Rich-club coefficient

The rich-club coefficient shows the number of connections between hub nodes with many links. It is calculated by subdividing the number of links between the hub nodes by the maximum number of links (Eq. 4)

$$\varnothing (k) = \frac{2E_{\geq k}}{N_{\geq k}(N_{\geq k} - 1)}$$

where, $E_{\geq k}$ is the number of links between nodes with a degree greater than or equal to k, and $N_{\geq k}$ is the number of nodes with a degree greater than or equal to k.

As the coefficient increases, the hub nodes share many links with each other, indicating that the network has a very solid structure. For example, a power grid network has a high rich-club coefficient. Generally, a grid is designed to supplement major facilities when they do not work. Accordingly, it can play a role in strong external impact (Csigi et al. 2017). Using the rich-club coefficient, we analyzed the distributions of the hub nodes and their connections.

### 2.5 Network characteristic analysis

#### 2.5.1 Clustering coefficient

The clustering coefficient is an important factor in the analysis of aircraft networks (Hong and Liang 2016). The clustering coefficient quantifies the tendency of three nodes in a network to construct a circular structure. This indicates the probability of a round trip to three airports in an aircraft network. In a general network, it represents the degree of clustering between nodes. The coefficient for a node $i$ is calculated as follows:

$$C(v_i) = \frac{|\{(v_x,v_y)|A_{ix}, A_{iy}, A_{xy}, x \neq y\}|}{|\{(v_x,v_y)|A_{ix}, A_{iy}, x \neq y\}|}$$

where, $A_{xy}$ denotes the connection between node $x$ and node $y$.

The clustering coefficient of each node is the local clustering coefficient, and the average of the coefficient of the nodes in a network is the global clustering coefficient. If the global clustering coefficient of a network has a value close to zero, the connection of the nodes tends to be random; in the opposite case, the network has clear connections of nodes. If the links have weights, the clustering coefficient is calculated by adding the weights of the links.
In the above equation, $W_{xy}$ denotes a link weight between node $x$ and node $y$.

The clustering coefficients were calculated for each single network and the multilayer network, and the results were compared to identify the changes due to the inter layer links.

### 2.5.2 Shortest path and efficiency

The shortest path is the minimum distance between the nodes in a network. The average of the minimum distances is the average distance of a network, and indicates the distance between each node. In a weighted network, the distance with the smallest sum of weights is selected as the shortest path.

$$L = \frac{2}{N(N-1)} \sum_{i,j \in N,i} d_{ij}$$

where, $d_{ij}$ is the shortest path between nodes $i$ and $j$ and $N$ is the total number of nodes in the network.

The shortest path is used to calculate the efficiency of the network.

$$E = \frac{2}{N(N-1)} \sum_{i,j \in N,i \neq j} \frac{1}{d_{ij}}$$

The efficiency of the network indicates how quickly the information is delivered between nodes. Therefore, it can be interpreted that the higher the efficiency, the faster the interactions between the nodes of the network. We used the efficiency to evaluate how quick the weather factors and aircraft interacted.

### 2.5.3 Network assortativity coefficient

To analyze the relationships between all nodes in a network, we applied a network assortativity coefficient. The network assortativity coefficient quantifies the tendency of nodes with similar characteristics to aggregate. It is calculated as follows:

$$r = \frac{M^{-1} \sum_i j_i k_i - \left[M^{-1} \sum_i \frac{1}{2} (j_i + k_i)\right]^2}{M^{-1} \sum_i (j_i^2 + k_i^2) - \left[M^{-1} \sum_i \frac{1}{2} (j_i + k_i)\right]^2}$$
where, \(j_i\) and \(k_i\) are the degrees of the nodes located at the end of the \(i\)th link, and \(M\) is the total number of links in the network.

The network assortativity coefficient ranges from \(-1\) to \(1\). If it is greater than zero, the network is an assortative network. In the opposite case, it is defined as a disassortative network. An assortative network tends to aggregate nodes with similar characteristics and is highly efficient, because the nodes of the network are condensed. In addition, it has high strength and stability (Noldus and Piet 2015).

### 2.6 Centrality analysis

The nodes in a network have different levels of importance according to their location or number of links. Among the nodes, those with high importance have a significant influence on the structure or function of the network. Identifying these nodes in a network is important for both theory and practice (Xiang et al. 2020). For example, if the government identifies the transformers playing key roles in the power grid, it can prepare investment or defense measures for those in advance. A centrality analysis is a methodology for calculating the importance of nodes. Various methodologies have been developed for centrality analysis, from degree centrality, closure centrality and eigen-vector centrality to page rank centrality (Ghalmane et al. 2019). Among the various methods, this study calculated the centrality of nodes in the single networks and the multilayer network through vital node identification. Vital node identification was proposed by Xu et al. (2020) and utilizes information entropy for its calculations. The method is applicable to all types of networks and has shown results in identifying critical nodes more accurately compared to existing methods. Additional details can be found in the work of Xu et al. (2020).

### 3 Study Area And Data Collection

This study constructed a weather-aircraft multilayer network for 14 airports located in South Korea (Fig. 2): (Gwangju(KWJ), Gunsan(KUV), Daegu(TAE), Muan(MWX), Gimhae(PUS), Gimpo(GMP), Yangyang(YNY), Yeosu(RSU), Ulsan(USN), Wonju(WJU), Jeju(CJU), Sacheon(HIN), Cheongju(CJJ), and Pohang(KPO)).

The multilayer network consisted of three single networks (rainfall, wind speed, and aircraft), with each airport as a node. Regarding the aircraft network, we calculated the links and their weights based on the number of aircraft operations from 2009 to 2021 as provided by Korea Airports Corporation. For the two weather networks, we estimated the weight through the event-synchronization method using meteorological station data from a nearby Automated Surface Observation System. The inter-layer links between the rainfall, and wind speed network and the aircraft network were calculated based on the number of aircraft cancellations from each weather factor (Fig. 3). Several previous studies have shown that the wind speed and rainfall are correlated; however, this study did not consider it. This is explained in Section 4.3.

### 4 Analysis Results And Discussion
4.1 Construction of multilayer complex network

4.1.1 Construction of single layer complex network

As explained in Section 3, we constructed single layer networks for rainfall, wind speed, and aircraft. First, the weights were calculated (Fig. 4). If we look at the adjacency matrixes for the rainfall and wind speed, it can be observed that they have a symmetrical shape.

This is because the same value is calculated when same two nodes are reversed. In contrast, an asymmetric form occurs in the aircraft network because the number of flights from each airport to another airport varies. The networks created on the basis of these are shown (Fig. 5).

Comparing the number of links in the three networks, it can be seen that rainfall has an overwhelming number of links (182) and the wind and aircraft networks have similar numbers (Wind speed: 78/ Aircraft: 60). The average weight of the links is in the order of rainfall (0.341), aircraft (0.233), and wind speed (0.188) networks. There is a large difference between the rainfall and wind speed because there is a large gap in the number of events that satisfy the criteria for aircraft cancellation. Table 2 presents the number of events. Except for RSU and MWX, the number of events satisfying the rainfall threshold is much higher than that satisfying the wind speed. Therefore, the weight of the link in the wind speed network was much smaller than that in the rainfall network.
Table 2
Number of events above thresholds of rainfall and wind speed

<table>
<thead>
<tr>
<th>Airport</th>
<th>Rainfall(&gt; 30mm/hr)</th>
<th>Wind speed(&gt; 25kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KWJ</td>
<td>158</td>
<td>3</td>
</tr>
<tr>
<td>KUC</td>
<td>141</td>
<td>25</td>
</tr>
<tr>
<td>TAE</td>
<td>121</td>
<td>0</td>
</tr>
<tr>
<td>MWX</td>
<td>144</td>
<td>120</td>
</tr>
<tr>
<td>PUS</td>
<td>231</td>
<td>76</td>
</tr>
<tr>
<td>GMP</td>
<td>160</td>
<td>2</td>
</tr>
<tr>
<td>YNY</td>
<td>167</td>
<td>2</td>
</tr>
<tr>
<td>RSU</td>
<td>196</td>
<td>338</td>
</tr>
<tr>
<td>USN</td>
<td>146</td>
<td>2</td>
</tr>
<tr>
<td>WJU</td>
<td>140</td>
<td>0</td>
</tr>
<tr>
<td>CJU</td>
<td>169</td>
<td>50</td>
</tr>
<tr>
<td>HIN</td>
<td>214</td>
<td>0</td>
</tr>
<tr>
<td>CJJ</td>
<td>149</td>
<td>0</td>
</tr>
<tr>
<td>KPO</td>
<td>137</td>
<td>4</td>
</tr>
</tbody>
</table>

4.1.2 Construction of multilayer complex network

The multilayer network was constructed from the single networks discussed in Section 4.1.1, based on aircraft cancellation data. First, by looking at the calculated adjacency matrix (Fig. 6) rather than the rainfall network, it can be seen that the wind speed network has strong link weights with the aircraft network. This is because the number of cancellations due to wind speed is significantly higher. The structure of the multilayer network is shown in Fig. 7. The total number of links is 346 (intra-layer links: 320/ inter-layer links: 26). In the case of the MWX and YNY airports, aircraft cancellations were only caused by wind speed, so only the inter layer link between the wind speed and aircraft exists.

4.2 Analysis of multilayer network

In this section, we analyzed the structure and characteristics of the multilayer network using the methods introduced in Sections 2.4 and 2.5. In addition, we compared the results of the multilayer network with those of the single layer networks.

4.2.1 Network structure analysis
We considered the degree and strength distribution to analyze the structure of the multilayer network (Fig. 8). The degree distribution graph shows that the slope is higher at the beginning and end than at the center. This implies that the distribution of the number of links in each node is concentrated at both ends. In the strength distribution graph considering the weights of the link, a higher slope occurs once. This indicates that the number of nodes with a strength value in the corresponding range is significant. Except for the range, the strengths of the other nodes are equally distributed.

The results for the degree and strength distributions of the single layer networks are same as those in Fig. 9. All of the nodes of the rainfall network are the same at 13, and in the case of strength, many nodes are at 4.8 or higher. In the case of the wind speed network, nodes with no links exist. They are generally located in inland areas such as TAE, WJU, HIN, and CJJ. An aircraft network has many nodes with four or fewer links. In addition, all nodes have the same strength of 1, because of the link weight calculation methodology in the aircraft network. Comparing the results from the single and the multilayer networks, it reveals that the characteristics of the multilayer network are reflected by the single networks. In the degree distribution of the multilayer network, the initial sharp slope is caused by the nodes with a low number of links in the wind speed and aircraft networks, and the latter originates from nodes in the rainfall network with a large number of links. The sharp slope in the strength distribution is caused by the nodes in the aircraft network having the same strength values.

We calculated the rich-club coefficient to determine the distribution of hub nodes in the multilayer network (Fig. 10). The range of the number of links was set from 1 to 14.

As shown in Fig. 10, as the degree increase, the coefficient value increases, and the degree rapidly increases after 11. Therefore, we can define a hub node as a node with over 11 links. Regarding the locations of the hub nodes, except for the CJU in the aircraft network, the other hub nodes are located in the rainfall network. The hub nodes are concentrated in a specific layer. Therefore, when examining at the multilayer network in terms of its structure, the rainfall layer network plays the most important role in the weather aircraft multilayer network.

### 4.2.2 Network characteristics analysis

We used three different methodologies (clustering coefficient, efficiency and assortativity coefficient) to analyzing the characteristics of the multilayer network. First, we calculated the clustering coefficient to determine the connections between the nodes (Fig. 11).

When looking at the results of each single layer network (Fig. 11(b)), the global clustering coefficient of the aircraft network is 0.007 and, except for CJU (0.029), GMP (0.027), and PUS (0.011), the other nodes have lower values than the global clustering coefficient. These three nodes have more links than the other nodes. The global clustering coefficient of the wind speed network is 0.227, and local clustering coefficients of four nodes (TAE, WJU, HIN, and CJJ) are 0. This is because these nodes only have one link in the network. The rainfall network has the largest global clustering coefficient (0.465) among the three single layer networks. This is because the rainfall network has a significantly higher number of links than
the other networks. The multilayer network has a global clustering coefficient of 0.144. Comparing the local clustering coefficients of the nodes in the multi and single layer networks, only nodes located in the aircraft network showed an increase. The increase in the coefficient of the nodes located in the aircraft network is due to the inter layer links.

Second, we estimated the shortest path and efficiency between the nodes to determine the efficiency of the networks. Figure 12 shows the results for the average of the shortest paths according to the number of links. In both cases (with and without weight), as the number of links increases, the average minimum distance decreases. The higher the number of links, the higher the number of connections with other nodes. Most nodes have values between 1 and 2 when the weight is not considered. Except for two nodes (WJU (wind speed), and CJJ (wind speed)), the other nodes have value less than 1 in the weighted case. The nodes with a higher average of the shortest path have only one link with a weight is 0.6 or more. Therefore, when calculating the shortest path with other nodes, this link must be included in all cases and results in a higher value. Regarding the calculated shortest path, the multilayer network has efficiency values of 0.671 (without weight) and 16.740 (with weight). To determine the degree of magnitude of the calculated efficiency value, we created two cases where the minimum distance between each node was 1 and 3, respectively, and then calculated the efficiency. The maximum case is set to 3, because the maximum shortest path calculated in the multilayer network was 3. The efficiencies of two cases are 0.983 (for 1) and 0.328 (for 3). The multilayer network has a medium value compared to the two calculated results. The same process was applied to the weighted case, and the results are 9.826 (when all strengths are 0.1) and 0.483 (when all strengths are 2.34). This indicated that the efficiency of the multilayer network is poor.

Finally, network assortativity coefficient was calculated to confirm the relationship between nodes. As in the previous cases, our calculation involved dividing the case considering the weight and that without weight. The results are 0.484 (without weight) and 0.628 (with weight). Therefore, because both have values greater than zero, the multilayer network can be defined as an assortative network. An assortative network has a structure in which nodes with the same characteristics are concentrated. This result is the same as that found in the structural analysis results in Section 4.2.1.

4.2.3 Node centrality analysis

A vital node identification was conducted the importance of the nodes (Table 3). The higher the centrality, the more important or influential the nodes are in the network.
<table>
<thead>
<tr>
<th>Layer</th>
<th>Node</th>
<th>Adjacency information entropy</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>KWJ</td>
<td>3.701</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>KUV</td>
<td>1.872</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>TAE</td>
<td>2.766</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>MWX</td>
<td>3.728</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>PUS</td>
<td>3.274</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>GMP</td>
<td>3.696</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>YNY</td>
<td>2.879</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>RSU</td>
<td>3.062</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>USN</td>
<td>3.969</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>WJU</td>
<td>4.544</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>CJU</td>
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<td>Adjacency information entropy</td>
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The calculated adjacency information entropy of the multilayer network is summarized in descending order, followed by CJU (in aircraft layer), GMP (in aircraft layer), WJU (in rainfall layer), MWX (in wind speed layer), and USN (in rainfall layer). These nodes have a common feature in that they perform hub-node roles in the network. CJU has the highest entropy value because of the social and meteorological characteristics of Jeju Island. Because Jeju is an island, most people usually use aircraft to travel to Jeju Island. There is a high demand for Jeju not only in metropolitan areas such as Seoul, but also in the provinces. Therefore, all airports have an aircraft route forward to CJU. The number of aircraft departing from Jeju or heading to Jeju from 2009 to 2021 accounts for approximately 77% of the total domestic flights. In terms of meteorology, Jeju island frequently experiences high-intensity rainfall and wind speed due to its island characteristics. In addition, because of the location of Jeju island, it is the first location to be affected by weather phenomena such as typhoon and Jangma (rainy season) on the Korean Peninsula. Therefore, Jeju island shares the same weather phenomena with other regions, and CJU is frequently affected by weather. This characteristic is reflected in the values of the event synchronization and makes the CJU contain a high entropy value.
To verify the result from the vital node identification, we calculated the link changes accordingly by removing the nodes. As the nodes with high centrality were removed, the number of links in the network rapidly decreased. We estimated the number of links according to three cases (descending, ascending, and random order) (Fig. 13). The descending order shows the sharpest decrease in links. It has less change in ascending order. A random case exists between the changes in these two cases. From Fig. 13, we determined that the results from the vital node identification are valid.

4.3 Discussions

This study analyzed aircraft cancellations due to weather factors using a multilayer complex network analysis. When building the multilayer network, we considered the relationship between the weather and aircraft layers but did not reflect the relationship between the weather factors. To check the relationship between rainfall and wind speed at each node, we calculated the correlation between the rainfall and wind speed (Table 4). Except for the CJU and KPO, the others did not show significant correlation values. We did not calculate the coefficients for TAE, WJU, HIN, and CJJ because they have no wind speed events exceeding the aircraft cancellation criterion.

<table>
<thead>
<tr>
<th>Node</th>
<th>Correlation</th>
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<td>MWX</td>
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<td>USN</td>
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<tr>
<td>CJU</td>
<td>0.357</td>
</tr>
<tr>
<td>KPO</td>
<td>0.317</td>
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</table>

When we applied event-synchronization methods to calculate the inter layer links between the rainfall and the wind speed networks, the links had small weights (average: 0.063, maximum: 0.264). Unlike this study, if we consider the relationship between meteorological factors, a total of 117 links are added to the
nodes in the climate networks relative to the existing network. It is not necessary for an aircraft network to interact with each climate factor. Therefore, the influence of the aircraft network decreases and the climate networks have a larger effect. In this case, the analysis methods consider the influences of meteorological factors as more important than the impacts of these factors on aircraft operation. Through this phenomenon, we can confirm that it is important to define nodes and links according to the characteristics of the analysis target and research purpose when applying the multilayer complex network analysis.

In Section 4.2.1, we confirmed that the rainfall network played an important role in the multilayer network. However, the number of aircraft cancelations due to wind speed was much higher than that of the rainfall. Why did the analysis result show that rainfall plays such an important role? To find the reason for this, we considered the characteristics of each climate network in terms of its structure. From comparing the inter layer links from each weather network to the aircraft network, it is observed that all the nodes in the wind speed network are linked to the aircraft, whereas in the rainfall network, links exist except for MWX and YNY. Regarding the total weight of the inter layer links, the weight of the wind speed network is 12 times greater than that of the rainfall network. This is because the inter layer links were calculated using the number of aircraft cancellation. However, the intra-layer links show different results. The rainfall network is overwhelmingly large when comparing the number and total weights of the inter layer links (number of links: 182 (rainfall)/78 (wind speed), total weights: 62.04 (rainfall)/14.70 (wind speed)). The results are derived from the generation characteristics of each meteorological event. In the case of rainfall, the same rainfall event is observed in several regions because it occurs over these regions. Therefore, the same rainfall phenomenon is shared at different observation points, and as the observation data accumulates a high correlation between the sites becomes evident. However, in the case of wind, the frequency of occurrence and regional variations are very severe due to the topographical and geographical conditions (Kim et al. 2020). Hence, the wind events are more affected by the characteristics of the area than the rainfall events. When we interpreted the aircraft cancellation by each weather factor using these characteristics, we found out that wind is like an unexpected event occurring suddenly for each region, rather than occurring equally for several regions. However, rainfall affects several points simultaneously, resulting in several cancellation events. Therefore, we can conclude that rainfall has a greater influence on aircraft operation than wind because rainfall generates multiple events at several locations simultaneously, unlike the sudden events caused by wind.

The results from Section 4.2.2 expressed that the multilayer network had low efficiency. This was because of the characteristics of aircraft cancellations due to weather factors. The target event can clearly distinguish between the independent and the dependent variables. The rainfall and wind speed affecting the aircraft operations are independent variables, and aircraft operation is the dependent variable. Thus, the meteorological aspect generally affects aircraft operations. This characteristic appears to be the same in the multilayer network. The aircraft network did not have inter layer links toward rainfall and wind speed networks, whereas it had the links to the other networks. Thus, the information in a multilayer network must be unconditionally transmitted through the aircraft network. In addition, due to the rainfall characteristics, the hub nodes are concentrated in the rainfall network, making
it difficult to deliver information to the network. These results indicate that the network analysis methods reflect the characteristics of the target event.

We applied a multilayer complex network analysis to analyze aircraft cancellations based on weather factors. Using these methods, we expressed the target event as a multilayer network. This simplifies the target so that the characteristics can be understood at a glance. This also helps in the analysis. Compared to the complex network method for a single layer network, the multilayer complex network can transform various elements into one system and consider them simultaneously. In addition, it can reflect the relationships between the elements. However, the building of the multilayer network is very important when applying the multilayer complex network method. If researchers do not consider the characteristics of the target and purpose of the study when creating the multilayer network, the method can yield to incorrect results. Therefore, application of the network should be preceded by an understanding of the targets.

5 Concluding Remarks

In this study, aircraft cancellations due to weather factors were analyzed using a multilayer complex network analysis. The multilayer network consisted of three single-layer networks (rainfall, wind speed, and aircraft) and the inter-layer links were defined by the number of aircraft cancellations due to rainfall and wind speed. We applied several methodologies to analyze the characteristics and the structure of the multilayer network. Vital node identification was used to calculate the node centrality. The results showed that rainfall had a greater impact on aircraft operation than wind speed, and that the structure and characteristics of the multilayer network reflected the features of the target event. In the centrality results, CJU was the most important node in the network, and it was confirmed that the social and meteorological aspects of CJU were reflected in the network. More generally, the multilayer complex network analysis can express complex objects or phenomena through a network and confirm the characteristics of the elements and their relationships. Therefore, they have been widely used in various research fields. However, when applying this method, it is important for researchers to properly set up a network definition method to reflect the characteristics of the analysis target. The multilayer complex network analysis can be used to analyze phenomena caused by various factors in the meteorological or hydrological fields. If a multilayer complex network methodology suitable for the meteorological and hydrological fields is established, useful information and/or analytical results can be derived.

Declarations

Acknowledgments

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Conflict of interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1
Shape of multilayer network

Figure 2
Location of 14 airports in South Korea
Rainfall network

Aircraft network

Windspeed network

Figure 3

Shape of multilayer network
Figure 4
Adjacency matrices of three single networks: (a) rainfall, (b) wind speed, (c) aircraft

Figure 5
Three single layer networks: (a) rainfall, (b) wind speed, (c) aircraft
Figure 6

Adjacency matrix of weather aircraft multilayer network
Figure 7

Weather aircraft multilayer network
Figure 8

Node distribution of the weather-aircraft multilayer network: (a) degree distribution; (b) strength distribution; gray shaded regions represent ranges showing higher slopes
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Node distribution of the single networks: (a) degree distribution of rainfall network, (b) strength distribution of rainfall network, (c) degree distribution of wind speed network, (d) strength of wind speed network, (e) degree distribution of aircraft network, (f) strength of aircraft network
Figure 10

Rich-club coefficient result

Figure 11

Clustering coefficient result: (a) multilayer network; (b) single layer networks
Figure 12

Average shortest path of nodes according to degree (with/without weight)
Figure 13

Changes of the number of links: (a) diamond (descending order), (b) rectangular (ascending order), (c) triangle (random order)