Methodology for the selection of an optimal location of Remote Tower Centre

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Abstract. According to the National transport strategy of Ukraine for the period up to 2030, one of the tasks is to ensure consistent and coherent development of regional airports of Ukraine and the consequent development of the Ukrainian air transportation network. One of the ways to achieve this is to deploy a remote tower concept in small regional airports of Ukraine. The main change introduced by the remote tower concept compared to the conventional air traffic service (ATS) provided from a local tower is that the aerodrome control tower will be provided from a remote location and air traffic control and aerodrome flight information service officers (ATCO/AFISO) do not have to be physically present at the airport. The provision of remote ATS requires a continuous exchange of information between the infrastructure at the airport side and a Remote Tower Module (RTM) to ensure that the data received by ATCO/AFISO can be used to provide safe and orderly control of traffic. The aim of this article is to create a methodology for the selection of an optimal location of Remote Tower Centres (RTC) using a method of gradient descent for finding optimal locations of RTCs to reduce the latency of data transmission. The optimal location of RTC will contribute to the reliability of the ATS systems by balancing safety and economic efficiency brought by the implementation of a remote tower concept.

Keywords: aerodrome flight information service, airport, air traffic control, air traffic management, gradient descent method, regional airport, remote tower centre, remote tower concept.

1 Introduction

A small amount of flights in small regional airports is a common issue for many countries around the world. Most of the small airports struggle to break even, however at the same time provide necessary points of access to remote locations and contribute to the local economic development [1; 2].

According to the National transport strategy of Ukraine for the period up to 2030, one of the tasks for this period is to ensure consistent development of regional airports of Ukraine and consequently the development of the air transportation network of Ukraine. One of the ways to achieve that is to decrease the costs of air transportation for airspace users and attract more flight to regional airports with lower costs [3].

The cost of a flight for an airspace user (e.g. airline) in the world and also Ukraine consists of fuel, maintenance costs, airport charges, air navigation service (ANS) costs [4; 5; 6].

Reduction in one of them could lead to the reduction of the costs of air transportation for the airspace user and make the flight to a certain airport more effective. In aviation is always significant attention is paid to Safety Management [7; 8].

In determining an acceptable level of safety, it is necessary to consider such factors as the level of risk that applies the cost/benefits of improvements to the system, public expectations on the safety of the aviation industry, that is, ensuring a balance between safety and economical effectiveness when the flights' intensity and the corresponding workload on operators and maintenance equipment change [9 -12].

Reduction in air navigation service costs can be achieved through the optimization of operational costs and enhancement of operational efficiency of the air navigation service provider (ANSP). A number of Single European Sky ATM Research (SESAR) solutions have been developed to enhance the current airport operations and provision of air traffic services (ATS) at an airport with an aim of improving operational efficiency [13].

A few of the SESAR solutions describe the implementation of a remote tower concept in different operating environments. The concept offers a possibility to improve the efficiency of operations and enhance safety at airports where maintenance or building of a conventional air traffic service tower is too expensive. The remote tower concept has been successfully validated by the SESAR programme and deployed in a number of countries [14].

2 Analysis of the current airport operations in Ukraine

At the moment, air traffic services at Ukrainian airports are provided from conventional ATS towers in accordance with ICAO Doc 4444, 9426 and EUROCONTROL Manual for Aerodrome Flight Information Service (AFIS) and internal manuals of ANSP by air traffic controllers or aerodrome flight information service officers that are located locally at the airport [4; 8; 15].

The responsibility of the aerodrome control tower is to provide information and clearance to the flight crew to ensure safe, orderly, and efficient flow of air traffic at the aerodrome and in the vicinity of it. Air traffic control officers (ATCO)s at the aerodrome control tower should continuously monitor all flight operations on the aerodrome and its vicinity as well as vehicles and personnel on the manoeuvrings area through visual observation (augmented by ATS surveillance system in low visibility conditions if available).

Functions of the aerodrome control tower may be performed by different control roles such as:

- aerodrome controller – responsible for operations on the runway and in the area of responsibility (AoR) of the aerodrome control tower;

– ground controller – responsible for traffic on the manoeuvring area (with the exception of runways);
– clearance delivery position – responsible for delivery of start-up and air traffic control clearance to departing instrument flight rule (IFR) flights [4].

The main operational requirements for the aerodrome control tower to ensure safe and efficient control of air traffic on and in the vicinity of the aerodrome are:

– The tower must permit the ATCO to visually observe and survey the portions of the aerodrome and its vicinity over which s/he has the control;
– The tower must be equipped to permit the controller rapid and reliable communications with aircraft with which s/he is concerned [8].

The airport network of Ukraine consists of 29 certified airports, 16 of which are capable of serving international flights (equipped with international checkpoints). Airports of Odesa, Kyiv (Boryspil), Kyiv (Zhuliany), Kharkiv, Dnipro and Lviv are considered as strategic airports, however, the main airport of Ukraine is Kyiv Boryspil airport that serves over 67% of the total annual passenger flow of Ukraine and handles more than 44% of all instrument flight rule (IFR) flights in Ukraine [14].

The air traffic control service is provided at 17 airports of Ukraine (those are – Kyiv (Boryspil), Kyiv (Zhuliany), Kharkiv, Chernivtsi, Kropyvnytskyi, Kryvyi Rih, Dnipro, Lviv, Odesa, Poltava, Kherson, Rivne, Sumy, Vinnytsia, Zaporizhzhia, Uzhorod, Ivano-Frankivsk). The AFIS is provided at 4 other airports (Mykolaiv, Cherkasy, Kaniv and Ternopil). Almost half of the traffic is handled by the major airport of Ukraine – Kyiv (Boryspil) while the rest is spread among other airports (Figure 1).

As can be seen from Fig. 1 most of the regional airports in the observation period provided regular air traffic service only to a few flights per day (on average 4 flights per day).

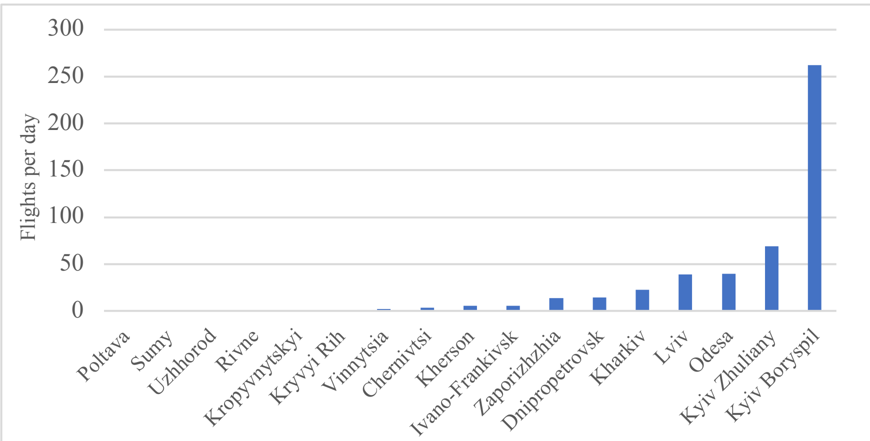

Fig. 1. The average amount of daily flight (only for airports with more than 1 flight/day) for Ukraine airports in the period from June 2016 to November 2019 [16]

This means that the resources of the local air traffic service units were used inefficiently. In addition to that, it is possible to see that a number of airports (e.g Vinnytsia, Kryvyi Rih and Chernivtsi) are affected by the variability of the traffic depending on the season – more flights during the summer season and less or none during winter (Figure 2).

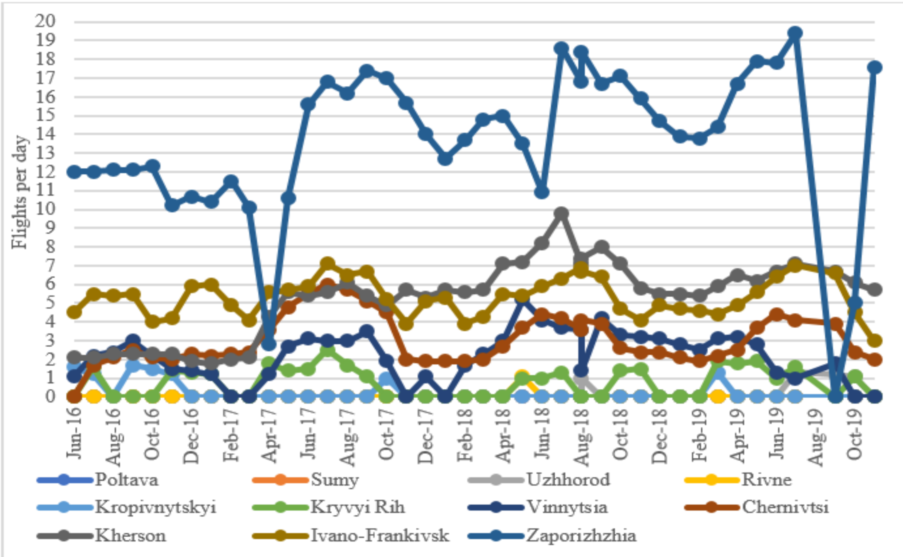

Fig. 2. Seasonal variability of daily flight (only for airports with more than 1 flight per day) for regional airports of Ukraine [16]

That is why it is not economically efficient to maintain the local aerodrome control tower to provide service to a small number of flights per day. One of the ways to optimize the use of resources at small regional airports is to implement a remote tower concept that could provide a more flexible approach to the provision of air traffic service, allocation of resources, through the effective using of RTCs for the performance of functions of the aerodrome control towers in areas with different air traffic intensity.

3 Remote tower concept and examples of its implementation

The main change introduced by the remote tower concept compared to the conventional air traffic service provided from a local tower is that the aerodrome control tower will be provided from a remote location and ATC and AFIS officers do not have to be physically present at the airport constantly.

As described in the previous section, one of the main operational requirements for the provision of air traffic service at an aerodrome is the ability of the ATC/AFIS officers to visually observe and survey the aerodrome and its portions that are under their responsibility.

That is why one of the main challenges for the remote tower concept is to comply with this requirement and provide ATC/AFIS officers with the necessary tools and means to reproduce the out of the window (OTW) view of the aerodrome. The OTW view is received through a number of cameras and can be combined with the data from sensors (e.g. surface movement radar, automatic dependent surveillance–broadcast (ADS-B), etc.) to improve the situational awareness of the ATC/AFIS officers [20].

Besides that, the ATC/AFIS officers should be equipped with a binocular functionality to replace a manual binocular which is currently is in use at conventional aerodrome control towers. Similarly, to the manual binocular, the functionality should allow ATC/AFIS officers to visually survey certain items that could be of interest (e.g. landing gear of an aircraft, runway, etc.) [17].

The controller working position (CWP) is another significant part of the remote tower that allows ATS/AFIS officers to control air traffic from a remote location. To provide air traffic service all necessary systems and tools have to be available to ATC/AFIS officers that's why all systems (e.g. voice communication system, flight strip system, etc.) that are used in the conventional aerodrome control tower should be connected to the CWP in the remote tower.

Within the SESAR Programme a number of possible implementation options for the remote tower concept have been identified:

- Remotely provided ATS for a single airport;
- Remotely provided ATS for multiple airports;
- Remotely provided ATS for contingency cases.

In case of remotely provided ATS for a single airport, a remote tower module (RTM) has to be set up with CWP and OTW View of a single airport. This RTM might have more than one position (e.g. for another ATC officer or supervisor) depending on the complexity of the operating environment. For the remote ATS provision for multiple airports two configurations are possible:

- Sequential – RTM is connected to two or more airports but provide ATS to one airport at a time;
- Simultaneous – RTM is connected to two or more airports and provide ATS to multiple airports at the same time [18; 19].

To maximize the benefits from the implementation of remote tower concept a set of RTMs can be grouped into one centralized facility. This facility might provide ATS to multiple airports from the same location allowing to use resources more efficiently and reduce costs.

A set of RTMs might be grouped into a centralized facility that is known as an RTC. The RTC might house one or more RTMs providing ATS for one or several aerodromes from the same location allowing to optimise resources and costs (Figure 3) [20].

The remote tower concept has been already successfully implemented in a number of airports around the world. The first fully operational remote tower has been set up at Örnsköldsvik airport (Sweden) in 2015. The service is provided from a city Sundsvall that is located around 150 km away from the airport. After some time, the service has been extended to cover also Sundsvall Timra airport, which means that both airports are served from a single RTC [20].

Norway has followed the example of Sweden and started a project to implement the remote tower concept and provide remote ATS from an RTC in Bodø. The aim of the project is to provide remote ATS service to 15 airports in 2020 [21].

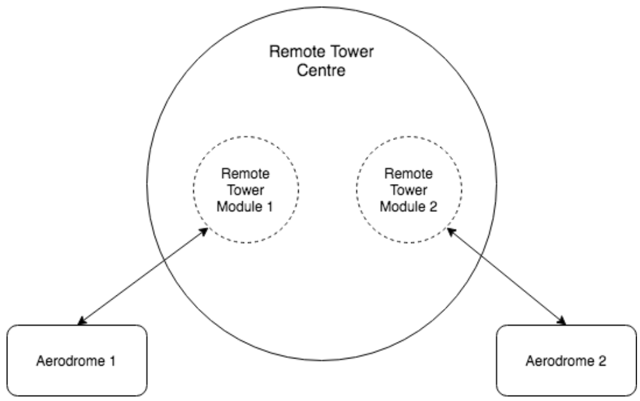

Fig. 3. Example of a set-up of an RTC

The German ANSP – Deutsche Flugsicherung (DFS) has launched a project to set-up an RTC in Leipzig to provide remote service to three international airports of Germany: Saarbrucken, Dresden and Erfurt. The target deadline for the project is the end of 2020 [22].

In addition to the abovementioned projects, a number of other projects have been launched in various countries in Europe and around the world: the United Kingdom, Hungary, the Netherlands, Australia, etc.

As presented above (statistics of Ukraine's air traffic), Ukraine belongs to countries with developed airport infrastructure, but at the same time with an uneven distribution of flights at airports and seasonally. It is necessary to create a methodology for the selection of an optimal location of Remote Tower Centre (RTC) and to take investigations an application of a method of gradient descent to reduce the network latency or data transmission delay by minimizing the distance between the airport sites and RTCs.

4 Selection of an optimal location of a Remote Tower Centre

The provision of remote ATS requires a continuous exchange of information between the infrastructure at airport side and an RTM to ensure that the data received by ATCO/AFISO can be used to provide safe and orderly control of traffic. The typical equipment that is required to provide remote ATS include:

- High-resolution video cameras;
- Pan-tilt-zoom cameras;
- Video signal encoding equipment;
- High-resolution displays to provide the out-the-window view;
- Navigation and light systems;
- Surveillance and meteorological sensors, etc.

Due to the amount of video and audio data that has to be exchanged between an RTM or RTC and the local airport site in addition to other required data such as data from surveillance sensors, meteorological sensors, etc., the requirements for the network connection are very high [22].

However, one of the factors that have a high impact on network performance is latency in time. The network latency or data transmission delay can be defined as an expression of time needed for a data packet or message to travel from one end of the network to another. Ideally, the latency should be as close to zero as possible. The value of the latency depends on three main components [23]:

– Speed-of-light propagation delay that depends on the medium through which the light travels.

– Amount of time to transmit a unit of data that depends on the network bandwidth and the size of the data.

– Queuing-related delays.

This research focuses on the reduction of the propagation delay for the exchange of information to ensure that the latency of the network is as low as possible. The propagation delay can be determined as a ratio between distance over which the data has to travel and speed of the propagation. Since the speed is relatively constant and equals to speed of light in the given medium the only variable that can be changed is the distance. In the context of the remote tower concept, this is a distance between the airport site and RTM (or RTC).

Taking into account that the regional airports of Ukraine with small amounts of traffic are scattered throughout Ukraine, the most optimal way is to ensure the minimal distance between airport sites and RTCs would be grouping airports that are located nearby into segments and deploying RTCs per segment to serve airports within it. The proposed structure for the deployment of the remote tower concept in Ukraine is presented in Figure 4.

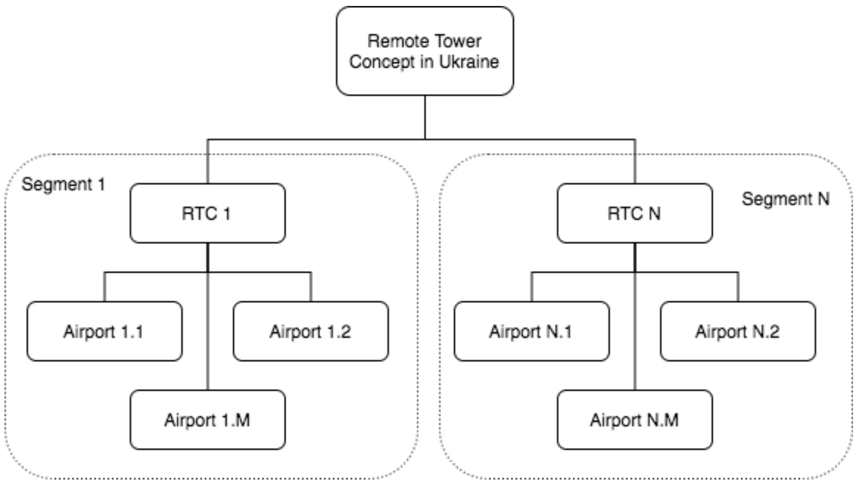

Fig. 4. The structure of the implementation of remote tower concept in Ukraine (N – number of segments; M – number of airports within a segment)

Based on this, a set of steps for the definition of an optimal location of Remote Tower Centre can be defined:

1. Grouping of airports into segments (for example, made in accordance with the map of Ukraine and the location of airports).
2. Calculation of coordinates of the Remote Tower Centre to minimize the distance between Remote Tower Centre and airports within the segment.
3. Refinement of coordinates based on other parameters (density of traffic, availability of resources, etc.).

In the mathematical terms the *Methodology (algorithm)* can be described as following:

STEP 1. For each airport, a list of the closest neighbours K is composed and frequency of appearance ω_j is calculated. For each airport distances among it and other airports are calculated, and based on them three (3) airports with the smaller distances are selected. Then in the list of the closest airports (which contains three closest airports for each airport) a frequency of appearance of an airport in the common list is calculated - ω_j.

If $\omega^* = max\ \omega_j$ then for j airport $1 \leq \omega_j \leq \omega^*$. All airports with the same frequency i are added to the list S_i.

The lower limit for the frequency of appearance is calculated using the following equation:

$$\omega_a = \left[\frac{1}{n}\sum_{i=1}^{\omega^*} i \cdot Z_i\right] + 1 \quad (1)$$

where

Z_i – number of airports in the list S_i;

$[\frac{1}{n}\sum_{i=1}^{\omega^*} i \cdot Z_i]$ – an integer part of a number;

n -number of airports.

STEP 2. Determine the initial set of coordinates for candidate locations of the Remote Tower Centre S_{ω^*}. After that, a set of airports is added in order of decrement of frequencies: $\omega_a \leq l \leq \omega^*$ taking into account that their number is limited by $n/2$.

The initial coordinates of the RTC are calculated as an average of airport coordinates within a segment:

$$x_{RTC} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad (2)$$

$$y_{RTC} = \frac{1}{n}\sum_{i=1}^{n} y_i; \quad (3)$$

where:

x_i, y_i – coordinates of airports within a segment;

n – number of airports in the segment.

These coordinates are used as a start point for the *Method of Gradient Descent* [24; 25].

STEP 3. To refine coordinates and optimize the coordinates of the RTC a method of gradient descent is used. During this step, it is necessary to minimize the sum of distances between an RTC and airports which are served by it. Therefore, for each segment it is necessary to minimize functional:

$$F(x_{RTC}, y_{RTC}) = \sum_{i=1}^{n} \sqrt{\left(x_{RTC}^{j} - x_i\right)^2 + \left(y_{RTC}^{j} - y_i\right)^2} \to min \quad (4)$$

where $x_{RTC} \in Ej$, $y_{RTC} \in Ej$.

Minimization of the functional is made according to this algorithm:

3.1. Perform a search of initial approximation of RTC coordinates with (4). Determine the gradient of the functional $F(x_{RTC}, y_{RTC})$ in the initial approximation point:

$$B_1 = \sum_{i=1}^{n} \frac{x_{RTC}^{j} - x_i}{\sqrt{\left(x_{RTC}^{j} - x_i\right)^2 + \left(y_{RTC}^{j} - y_i\right)^2}} \quad (5)$$

$$B_2 = \sum_{i=1}^{n} \frac{y_{RTC}^{j} - y_i}{\sqrt{\left(x_{RTC}^{j} - x_i\right)^2 + \left(y_{RTC}^{j} - y_i\right)^2}} \quad (6)$$

Calculate $\sqrt{(B_1^2 + B_2^2)} < e$,

where $e \approx 0.01$ – accuracy.

If $\sqrt{(B_1^2 + B_2^2)}$ less than the accuracy than the necessary coordinates are found. Otherwise, move to the point of extreme.

$$x_{RTC}^{j+1} = x_{RTC}^{j} - hB_1 \quad (7)$$

$$y_{RTC}^{j+1} = y_{RTC}^{j} - hB_2 \quad (8)$$

where h – step towards gradient.

After recalculation of coordinates x_{RTC}^{j}, y_{RTC}^{j} by (7) and (8), the new values of functional $F(x_{RTC}, y_{RTC})$ are calculated and verified against $\sqrt{(B_1^2 + B_2^2)} < e$. This process is repeated until the value of the functional decreases. If on a step i the value of the functional increased and the condition $\sqrt{(B_1^2 + B_2^2)} < e$ is not satisfied, proceed to step 3.2.

3.2. During this step, a method of golden-section search. Compared to other methods, it requires the least amount of calculations and ensures the internal narrowing to the given accuracy. Step h is divided into uneven parts. These parts are selected in such a way that the ration of the length of the bigger segment (Z_1) to the length of the whole interval (Z) equals to the ration of the smaller segment (Z_2) to the bigger segment ("golden-section"):

$$\frac{Z_1}{Z} = \frac{Z_2}{Z_1}, Z_1 + Z_2 = Z \quad (9)$$

$$\frac{Z_2}{Z_1} = \left(\sqrt{5} - \frac{1}{2}\right) \approx 0.618 \quad (10)$$

On every step, the interval of uncertainty is decreased by 1/0.618. For the further minimization, an interval of [a; b] is considered, where a= $F\left(x_{RTC}^{j}, Fy_{RTC}^{j}\right)$ and b=$F\left(x_{RTC}^{j+1}, y_{RTC}^{j+1}\right)$. To change the value of the step h let's set $a = h_0$, $b = h_1$. Then, according to the method of golden-section search, the new values of the steps are calculated using (11) and (12):

$$h_2 = h_0 + 0.382(h_1 - h_0); \quad (11)$$

$$h_3 = h_1 + 0.382(h_1 - h_0); \quad (12)$$

Calculate the values of $F\left(x_{RTC}^{j}, Fy_{RTC}^{j}\right)$ using the steps h_2 and h_3 and if $F(h_2) < F(h_3)$ then $h_3 = h_1$ (the right limit has changed), otherwise $h_0 = h_2$ (the left limit has changed). The process is continued until $h_1 - h_0$ does not become less than the given accuracy. After that go back to step 3.1.

The result will be a set of coordinates of optimal locations of RTCs from a point of view of minimization of distances between airports within one segment. However, this is not the only factor that influences the decision of the selection of the location for the RTC, other such as the density of the traffic of airports within a segment, availability of resources at certain airports to house the RTC, availability of human resources, etc. should be also taken into account.

The defined methodology has been implemented as a computer program that takes a set of airports as an input and calculates a number of segments, performs allocation of airports to segments, calculates and refines coordinates of RTCs per each segment. The result of the execution of the computer program is shown in Figure 5. A set of airports is taken as an example and can be changed depending on the variation of the traffic. The received data and the analysis of abovementioned factors can be used to support the decision-making process of the selection of an optimal location for the RTC.

Fig. 5. The example of calculation of optimal locations (to minimize distance) of RTCs for Ukrainian airports (green dots – initial coordinates; blue dots – refined coordinates)

As seen from the received results, further analysis of them is required to select the most optimal locations for the RTCs. For example, the coordinates for the RTC of the Segment 4 point to a location in an open sea which makes it impossible to use it. That's why, as mentioned above, the minimization of distance to reduce the data transmission delay should be used in conjunction with other factors that could impact the location of the RTC, e.g. density of traffic, availability of resources, etc. Based on these other factors it might be considered more efficient to implement the RTC in Kherson or Odesa airport or another site even though it might have an impact on the network latency. Also, as seen, not all airports have been included in segments; it is meant that they will not be controlled remotely. For example, Boryspil has many flights and must be controlled typically, Kharkiv is situated far away from others and distance will not allow providing real-time control from RTC because of delays.

To find the optimal location of the RTC, used the minimax/maximin decision criterion (Wald criterion) under conditions of uncertainty and compose a decision matrix (Table 1). If the Wald criterion is used, a guaranteed solution is obtained:

Wald criterion (maximin): $A^* = \max_{A_i}\left\{\min_{\lambda_j} u_{ij}(A_i, \lambda_j)\right\}$.

The factors that influence on the alternative decision are defined as:

λ_1 – remoteness between RTCs;

λ_2 – location of the airports;

λ_2 – density of traffic;

λ_3 – availability of resources;

λ_4 – technical capabilities;

λ_5 – economic capabilities;

λ_6 –availability of RTCs to connections, etc.

Possible results in a matrix (u_{ij}, $i=1,\dots, n; j=1,\dots, 6$) are determined with the Expert Judgment Method by rating scales or based on statistical data.

Table 1. The matrix of decision making for choosing optimum location of the RTC.

Alternative decisions of location of the RTCs	Factors that influence decision making					
A	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6
A_1	u_{11}	u_{12}	u_{13}	u_{14}	u_{15}	u_{16}
…	…	…	…	…	…	…
A_i	u_{i1}	u_{i2}	u_{i3}	u_{i4}	u_{i5}	u_{i6}
…	…	…	…	…	…	…
A_n	u_{n1}	u_{n2}	u_{n3}	u_{n4}	u_{n5}	u_{n6}

Computer program "Classic Decision Criteria: Wald, Laplace, Hurwitz, Savage" for DM modeling was designed [26].

Therefore, it is necessary to perform an additional study to define and investigate other factors that could have an impact on the selection of the optimal location of the RTC and to enrich the current methodology with the defined factors. Once the methodology is defined completely it can be used also for other countries to select optimal locations for the RTCs.

5 Conclusion

To ensure consistent and coherent development of regional airports of Ukraine and consequently the development of air transportation network of Ukraine, there is a need to increase the level of traffic in the Ukrainian regional airports. One of the ways to achieve that is to decrease the costs of air transportation for airspace users and attract more flight to regional airports with lower costs.

The implementation of a remote tower concept allows to decrease the costs of air transportation through optimization of the use of resources and increase the cost efficiency of the provision of air traffic service at the airport. The remote tower concept has been successfully implemented or in the progress of implementation in multiple airports around the world (Sweden, Germany, Norway, etc.).

To ensure the availability of the necessary data for ATCO/AFISO to provide the safe and orderly remote ATS there is a need for continuous exchange of data between the infrastructure at airport site and RTM or RTC. Due to the amount of video and audio data that has to be exchanged in addition to other required data (surveillance, meteorological data, etc.) the requirements for the network performance are very high. One of the factors that have a high impact on network performance is latency.

This research focused on the reduction of one of the components of latency (the propagation delay) for the exchange of data to ensure that the latency of the network is as low as possible. The propagation delay can be determined as a ratio between distance over which the data has to travel and speed of the propagation. Since the speed is relatively constant and equals to speed of light in the given medium the only variable that can be changed is the distance. In the context of the remote tower concept, this is a distance between the airport site and RTM or RTC.

To minimize the distance between airports and RTCs and select optimal locations of RTCs the method of gradient descent has been used and adapted to fit the context of the regional airports of Ukraine.

The received method provides a set of coordinates of optimal locations of RTCs from a point of view of minimization of a distance between airports within one segment. However, this is not the only factor that influences the decision of the selection of the location for the RTC, other such as the density of the traffic of airports within a segment, availability of resources at certain airports to house the RTC, availability of human resources, etc. should be also considered. A separate follow-up study to define such factors and investigate their influence on the decision of the selection of the optimal location is needed.

Further research it is proposed to find the optimal location of the stations depending on the influence of several factors (the specific location of the RTCs depending on the location of the airports, the current intensity of air traffic, the workload of nearby airports, technical and economic capabilities, the availability of RTCs to connections with existing airports) using decision-making methods under risk and uncertainty [9; 12; 26; 27]. To evaluate the expected outcomes and the formation of the pay-off matrix, it is advisable to use artificial intelligence methods such as Big Data, Data Mining, Expert systems, Collaborative Decision Making, and others. Incorporating the promising approaches and technological advances will allow to evolve according to the increasing demands while offering safety and quality in the operation Air Traffic Management system [28].

In cases of large and complex big data, methods can be integrated into traditional and next-generation hybrid decision-making systems by processing unsupervised situation data in the deep landscape models, potentially at high data rates and in near real-time, producing a structured representation of input data with clusters that correspond to common situation types that is useful for minimizing latency in time when working RTCs and processing large amounts of information [27; 29].

The new methodology will include the process of integration deterministic, stochastic, and non-stochastic uncertainty models in complex situations. The Collaborative Decision-making models an uninterrupted process of presenting information between various interacting participants, as well as providing synchronization of decisions taken by participants and the exchange of information between them. It is important to ensure the possibility of making a joint, integrated solution with different operators at an acceptable level of efficiency. This is achieved by completeness, the accuracy of available information, and optimal solutions obtained [30].

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