Rubric 1. TECHNOLOGIES AND PROJECTS
Field – Transport and Transport & Logistics Systems

DOI 10.17816/transsyst2021715-36

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ANALYSING AND MODELING PERFORMANCES OF A LONG-HAUL AIR ROUTE NETWORK

Abstract. This paper deals with analyzing and modelling performances of a long-haul air route network operating as the queuing network. The network consists of the routes/tracks with flight levels serving aircraft/flights as the "service channels". The main network performances are the "ultimate" and "practical" capacity of "service channels", the aircraft/flight demand, delays before entering and total time of aircraft/flights spending in the network, and the related generalized costs including those of airlines, air passengers, policy makers and society. The analytical models of the particular network performances and three routing or assignment models/procedures for matching the aircraft/flight demand to capacity are developed and applied to the long-haul air route network in the North Atlantic airspace between Europe and North America.

The results have indicated that. the network capacity has been strongly dependent on the number of routes/tracks and flight levels, i.e., "service channels" and their "ultimate" and/or "practical" capacity. The "ultimate" capacity has been mainly influenced by the ATC (Air Traffic Control) separation rules applied between aircraft/flights operating in the same directions. The "practical" capacity has been strongly influenced by the "ultimate" capacity and the average delays imposed on aircraft/flights before entering the network. The rather superior and close to optimal model/procedure for matching demand to capacity has been routing or assignment of the aircraft/flights demand in proportion to the "ultimate" or "practical" capacity of particular "service channels" minimizing the total generalized costs of the actors/stakeholders involved.

Keywords: Long-haul air route network, performances, analysis, modelling, aircraft/flight demand, route/track capacity, assignment models/procedures, evaluation, North Atlantic airspace.

1. INTRODUCTION

The ATC (Air Traffic Control) is considered as one of the main components of the air transport system together with airports and airlines. This includes: i) the controlled airspace established over the particular countries, continents and oceans; ii) technical/technological components such as radio-

Received: 02.01.2021 **Revised: 16.02.2021** **Accepted: 30.03.2021**
Поступил: 02.01.2021 **Одобрена: 16.02.2021** **Принята: 30.03.2021**

navigational facilities and equipment located on the ground and in space (satellites) and their complements at aircraft; and iii) the operating staff (the ATC controllers on the ground) and the aircraft crews. The ATC controllers use the operating rules and procedures in serving its users – aircraft/flights – under given conditions [1–5].

The main objectives of ATC are to serve the aircraft/flights in the airspace safely, efficiently, and effectively. Safety implies serving the aircraft/flights without the risk and occurrence of air traffic incidents/accidents due to the already known reasons. Efficiency implies operating without imposing unnecessary congestion and delays on aircraft/flights. Effectiveness relates to serving the aircraft/flights at as low as possible their and own operating costs [2].

In general, regarding the length, the flights are divided into the short, medium, and long-haul. The short-haul flights (from 0.5 to 3 hours) are usually those between airports in the same country. The medium-haul flights (from 3 to 6 hours) are those between airports in the same large country (for example, U.S., Russia, China) and between different countries. The long-haul flights (longer than 6 hours) are generally those between airports at the ends of the same and different continents [7].

The ATC handles the aircraft/flights in the air route networks established in the airspace of its responsibility. If over the ground, these aircraft/flights are radar-monitored and separated by the ATC minimum horizontal and vertical-distance based separation rules. The over-water (ocean) segments of flights are monitored in discrete time intervals by communicating of ATC controllers and pilots. In these cases, the ATC minimum horizontal time-based and vertical-distance separation rules are applied.

The relatively stable and continuous growth of the world passenger air traffic (in RPK (Revenue Passenger-Kilometres)) at an average annual growth rate of 5.0 % driven by the global growth of GDP (Gross Domestic Product) of 2.8 % since 1995 until the start of COVID-19 pandemic disease, has continuously risen the question of the ATC performances in terms of fulfilling the above-mentioned objectives - providing safe, efficient, and effective services [8]. Despite in the year 2020 the air traffic has dropped for about 61 % compared to the pre-pandemic level, the ATC will continue to deal with the same objectives during and after recovery of air traffic. including that in the recovered long-haul air route networks. Consequently, the performances of these networks such as the spatial configuration, aircraft/flight demand, capacity, their relationship causing the aircraft/flight congestion and delays, and related generalized costs of actors/stakeholders involved would again come of increased research and practical interests.

This paper deals with an analysis and modelling of performances of a long-haul air route network established in the large controlled airspace. The

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

network is modelled as the queuing network serving the aircraft/flights demand by the capacity of its nodes and links. In addition to this introductory, the paper consists of four other sections. Section 2 describes the characteristics of this air route network, pattern of controlling the aircraft/flights there, and the related performances. Section 3 presents the analytical models for estimating these performances including the models/procedures for matching demand to capacity. Section 4 illustrates an application of the proposed models to the transatlantic air route network over Atlantic Ocean serving the air traffic between Europe and North America according to the specified "what-if" scenario(s). the last section summarizes some conclusions.

2. THE AIR ROUTE NETWORK

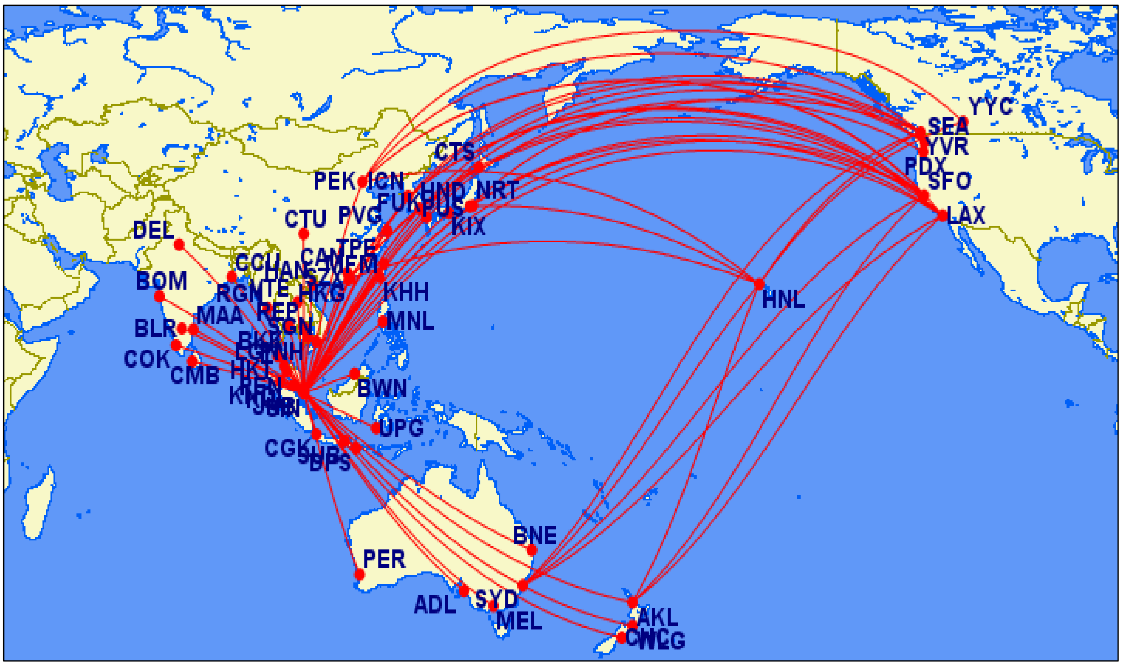
2.1 Configuration. The considered long-haul air route network is characterized by referring to an analogy with the communication networks operating as the queuing networks as follows [9]:

Network "node"	The central ATC centre, which monitors, controls, and manages the aircraft/flights in the network
Network "links"	The routes/tracks, each with the flight levels as the "service channels" of the aircraft/flights requesting service under given conditions.
Aircraft/flight demand	Aircraft/flights are characterized by origin and destination airports and the preferred routes fully or partially passing through the given air route network.
Matching demand to capacity	Models/procedures for routing or assigning the aircraft/flights to the particular network's "service channels" according to the specified rules/criteria.
Aircraft/flight total delays	The sum of the average delays before entering and the average delay-free service time in the particular "service channels" of the network.
Generalized costs	Those of the actors/stakeholders involved.

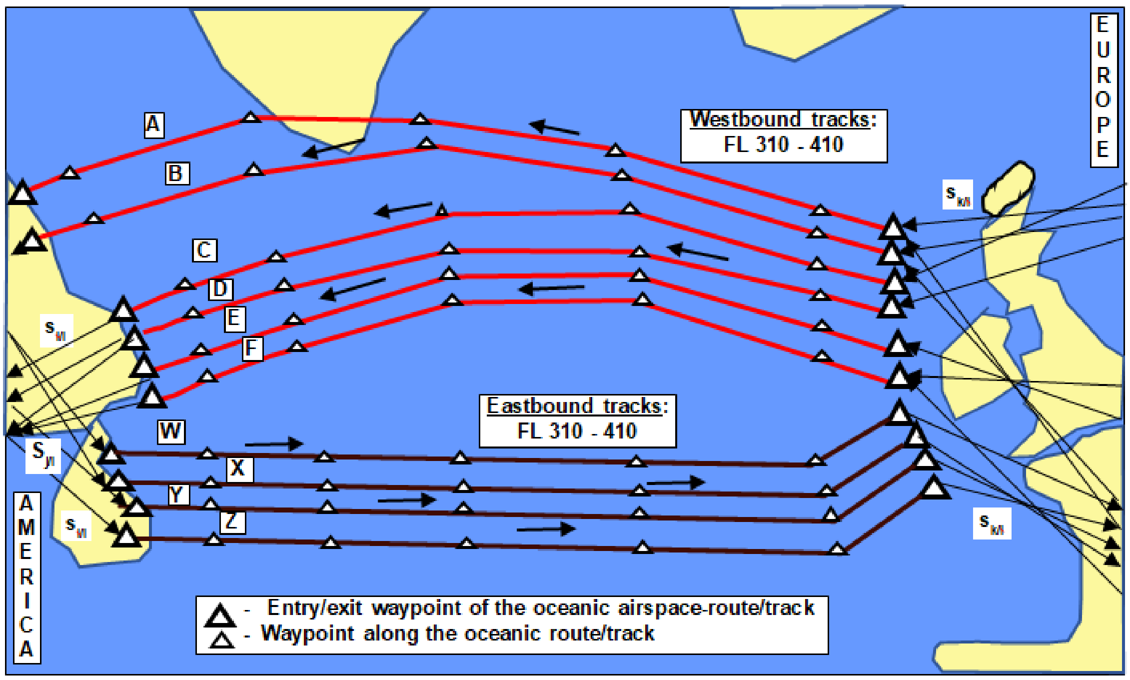
The main actors/stakeholders involved in dealing with the above-characterized air route network are the users – airlines and air passengers, the service provider – ATC, and policy makers and society. The users are mainly interested in the aircraft/flight delays and their related generalized costs. The ATC intends to provide safe, effective, and, efficient services to aircraft/flights under given conditions. The policy makers and society mainly consider the impacts of these aircraft/flights on the environment in terms of global GHG

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

emissions and related costs/externalities. The examples of spatial configuration of the above-mentioned long-haul air route network are shown on Fig. 1 (a, b).



a) Airline-based network - Transpacific airlines [10]



b) ATC-based network - Routes/tracks in the North Atlantic airspace [11, 12]

Fig. 1. Examples of the spatial schemes of long-haul air route networks

Fig. 1a shows the scheme of the long-haul network over Pacific Ocean consisting of the routes of airline flights between the origin and destination

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
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airports on the West Coast of U.S. and East Coast of Asia and Australia. Fig. 1b shows the ATC structured air route network with air routes/tracks over Atlantic Ocean between Europe and North America.

2.2 Performances. The main performances of the above-mentioned air route networks are generally their aircraft/flight demand, capacity, their relationship causing the aircraft/flights congestion and delays, the impacts of GHG emissions on the environment, and related generalized costs of the main actors/stakeholders involved.

The aircraft/flight demand requests service in the air route network during a given period of time, which can be an hour, day or year. For the short-term operational purposes and prediction of the ATC controller's workload up to the certain maximum values and consequently capacity, the daily and hourly number of aircraft/flights is usually relevant [13–15].

The capacity of air route network is usually expressed by the maximum number of aircraft/flights, which can be served during a given period of time under given conditions. These can be the constant demand for service, which refer to the "ultimate" capacity and the average delay imposed on the aircraft/flight before entering the network referring to the "practical" capacity. In general, this capacity is mainly dependent on the network configuration characterized by the number of routes/tracks (i.e., links) and FLs (Flight Levels), and the ATC minimum separation rules applied between the aircraft/flights. The aircraft/flights on the FLs operating in the same direction are separated by the ATC minimum time- or distance-absed horizontal separation rules. Those on different closest FLs operating in the same and/or opposite directions are separated by the ATC minimum vertical separation rules. The capacity based on the corresponding ATC controller's workload is expressed by the number of aircraft/flights, which can be simultaneously controlled in the network during a given period of time under the predefined maximum workload. The short-term period of time for operating and planning the capacity can be an hour or day [2, 16].

The time and spatial interaction between the demand and the air route network capacity can cause congestion and delays of the affected aircraft/flights. In general, these happen as soon as the demand exceeds the capacity of the particular routes/tracks, i.e., links. As such, if predicted/expected in advance, these delays can be realized at the origin airports or otherwise along the corresponding assessing routes to the network [2, 17, 18].

In order to deal with the above-mentioned performances of the long-haul air route networks in the given context the pre-conditions are as follows: i) the network characterized by the number and spatial configuration of routes/tracks (i.e., network links) supported by the facilities and equipment used by the ATC and the aircraft pilots; ii) the pattern of aircraft/flight demand requesting service

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
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during a given period of time in terms of intensity, structure, time and space distribution in the network; and iii) the models/procedures for matching demand to capacity aiming at minimizing the generalized costs of the actors/stakeholders involved.

3 MODELLING PERFORMANCES OF A LONG-HAUL AIR ROUTE NETWORK

3.1 Literature review. The research on analysing and modelling performances of the air route networks similar to that presented in the given context has been scarce and actually not existing in an explicit form. Therefore, this rather short literature review presents the research related to analysing performances of air route networks similar to that presented in this paper and some studies by the air transport industry. For example, this has been the long-standing, exhaustive, and rather matured academic research on the analytical and simulation modelling of the airport and airspace “ultimate” and “practical” capacity based on the stochastic and deterministic queuing theory [2, 17, 19, 20]. The queuing networks have been also the subject of intensive academic research. The analytical models for estimating performances of these networks such as the demand, capacity, average customers delay and the total customers time in the network and related costs, different routing procedures enabling minimization of both previous individually (per customer) and the system (all customers), and prioritizing of particular categories of customers using different criteria have been under focus. The applications of these models have primarily been considered for the computer networks [9, 18, 21, 22].

The research closely related to operations of the long-haul air route networks has mainly dealt with optimization of the aircraft/flight trajectories subject to different criteria. In particular, the effects of new technologies contributing to the aircraft/flight precise guidance, reducing the ATC separation rules, and the impacts of weather intended to more efficient and safer (conflict-free) operations have been under focus in the transatlantic airspace as the most congested overwater airspace in the world [23–27]. Some research has also dealt with the analysis of fuel efficiency of airline flights in the transatlantic airspace [28].

The relevant studies carried out by the aviation industry stakeholders have mostly included the long-term forecasting of the aircraft/flight demand and potential effects of the ATC innovative technologies on the capacity and efficiency of operations of the given (Transatlantic) air route network [29, 30].

3.2 Configuration of the network. The simplified spatial configuration of the long-haul air route network synthesized from that on Fig. 1b and shown on Fig. 2 (a, b) is considered for analysis and modelling performances.

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
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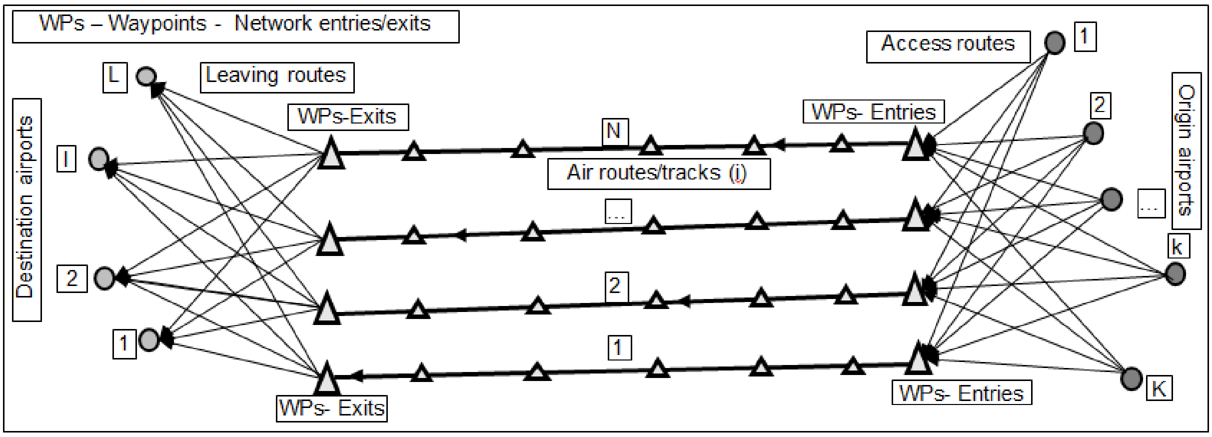
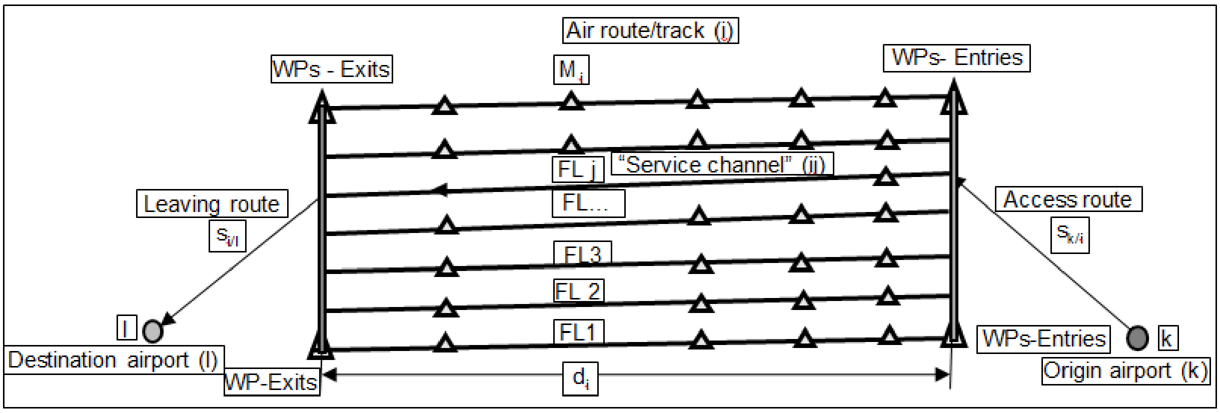


a) Horizontal layout



b) Vertical layout

Fig. 2. Simplified scheme of the air route network for the purpose of analysing and modelling performances

As can be seen, the network consists of *(N)* routes/tracks of the approximately same average length *(d_i)* each with *(M_i)* available FLs (Flight Levels). The aircraft/flights between *(K)* origin and *(L)* destination airports are handled in the network. They access the network along *(K)* routes connecting their origin airports with the entry points of the network defined as the geographical WPs (Way Points). After passing through the network, these aircraft/flights leave the network along *(L)* routes connecting the corresponding network exit WPs and their destination airports.

3.3 Assumptions. In addition to the above-mentioned configuration, modelling of the network performances similarly as that of the queuing network is based on the following assumptions [2, 18]:

- The network consists of the fixed set of routes/tracks of approximately equal length each with several FLs (Flight Levels); they represent the longest (second in order) segments of three-segment long-haul routes spreading between the origin and

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
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destination airports of aircraft/flights where cruising phase of flights is performed. The first in order segments enable access of the aircraft/flights from the origin airports to the entries of particular network “service channels”. The last third in order segments enable the aircraft/flights reaching the destination airports after leaving the network “service channels”;

- The routes/tracks of the network approximately parallel to each other are separated by the ATC specified minimum lateral distance(s);
- The routes/tracks and their FLs operate as the “service channels” independently of each other;
- The aircraft/flights routed or assigned to the particular “service channels” stay there all the time; they are handled by the constant capacity of “service channels” based on the ATC time-based horizontal and vertical minimum separation rules; those on the same FLs maintain approximately the same speed thus eliminating the potential overtaking conflicts and needs for their resolving by changing FLs and/or route/track;
- The intensity of aircraft/flight demand is usually lower than the capacity of particular “service channel(s)” and that of the corresponding ATC controllers; however some delays can be imposed on particular aircraft/flights before entering the network due to the inherent randomness of their arrivals at the entry WPs of particular “service channels’”; depending on their length these delays can be realized at the origin airports just before the aircraft/flight departures in the scope of the “ground holding” procedures and/or along the access routes to the entry WPs”; and
- Different models/procedures for routing or assigning the aircraft/flights to the particular “service channels” depending on their expected performances can be applied under given conditions.

3.4 The models of performances. The models of performances of a given air route network are developed based on the above-mentioned assumptions.

3.4.1 “Ultimate” capacity. The “ultimate” capacity of a given air route network is defined as the maximum number of aircraft/flights, which can be served during the specified period of time under conditions of the constant demand for service [2, 20, 31]. The “ultimate” capacity of the route/track, i.e., the “service channel” *(i)*, can be estimated as follows:

$$\mu_i(\Delta t) = \sum_{j=1}^{M_i} 1/\tau_{ji/min}(\Delta t) \tag{1a}$$

where

$\tau_{ji/min}(\Delta t)$ is the ATC minimum time-based separation rules between the aircraft/flights on the FL *(j)* of the “service channel” *(i)* during time

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(Δt) (min).

Under conditions of the constant demand of “perfectly packed” aircraft/flights separated by the ATC minimum separation rules requesting service in the particular “service channels”, the “ultimate” capacity of the network from Eq. 1a is estimated as follows:

$$\mu(\Delta t) = \sum_{i=1}^{N(\Delta t)} \mu_i(\Delta t) \tag{1b}$$

where all symbols are analogous to those in the previous Eqs.

3.4.2 “Practical” capacity. The “practical” capacity of a given air route network can be expressed by the maximum number of aircraft/flights handled during a given period of time under conditions of imposing an average delay on each of them before entering the network. If the aircraft/flights arrive at the “service channel” *(i)* according to the Poisson processes and are served by the constant “ultimate” capacity (1a), each “service channel” can be considered to operate as *M/G/1* queuing system. Under the steady-state conditions when the intensity of aircraft/flight demand $\lambda_i(\Delta t)$ remains always lower than the “service channel’s” “ultimate” capacity $\mu_i(\Delta t)$, i.e., $\rho_i(\Delta t) = \lambda_i(\Delta t)/\mu_i(\Delta t) < 1$, the average delay imposed on of aircraft/flights before entering it is estimated as follows [2, 18, 32, 33]:

$$\bar{w}_i(\Delta t) = \frac{\lambda_i(\Delta t)\cdot\{1/[\mu_i(\Delta t)]^2 + \sigma_{i/s}^2\}}{2\cdot[1-\lambda_i(\Delta t)/\mu_i(\Delta t)]} \tag{2a}$$

where

$\sigma_{i/S}$ is the standard deviation of the service time of aircraft/flights on route/track *(i)* independent of time (Δt) (min/ac).

After specifying the maximum average delay in (2a) as $\bar{w}_i(\Delta t) \equiv w_i^*(\Delta t)$, the intensity of aircraft/flights representing the “practical” capacity of the “service channel” *(i)* operating under conditions $\rho_i(\Delta t) < 1$ can be estimated as follows:

$$\lambda_i^*(\Delta t) \equiv \mu_i^*(\Delta t) = \frac{2\cdot w_i^*(\Delta t)\cdot[\mu_i(\Delta t)]^2}{1 + 2\cdot w_i^*(\Delta t)\cdot\mu_i(\Delta t) + [\mu_i(\Delta t)]^2\cdot\sigma_{i/s}^2} \tag{2b}$$

where all symbols are analogous to those in the previous Eqs.

3.5 Matching demand to capacity. Matching demand to capacity in the given context can generally be carried out by three models/procedures for routing or assigning the particular aircraft/flights to the network air routes/tracks and their FLs (i.e., “service channels”): i) user-optimizing deterministic; ii) user-optimizing stochastic; and iii) the system optimizing [34]. For such a purpose

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

the utility of each aircraft/flight to be maximized under given conditions needs to be specified. This utility is usually expressed by the generalized aircraft/flight costs and can be maximized by minimizing them. These generalized costs can include the airline operating and air passenger time costs while onboard, and the internalized costs of impacts of GHG (Green House Gases) emissions on the environment. They all directly depend on the total aircraft flying time, i.e., the average delay, through the network. Thus, minimizing this time minimizes the generalized aircraft/flight costs and maximizes their corresponding utilities given the other factors constant.

3.5.1 Model I: User-optimizing deterministic assignment procedure. The user-optimizing deterministic assignment procedure actually starts by submitting the flight plans to the ATC service provider(s) some time in advance. They usually aim at optimizing own (individual) above-mentioned utilities under perfectly expected conditions in the network. This will make the utilities of all aircraft flights approximately equal if assigned to the available routes/tracks and their FLs (i.e., "service channels"). In other words, the utilities of all aircraft/flights are expected to be equal independently on the assigned route/track, i.e., "service channel". This also implies that none aircraft/flight can increase its utility if changes the assigned route/track, i.e., "service channel. If the capacities and total travel times through the network are assumed to be equal for all available routes/tracks, i.e., "service channels", the user-optimizing deterministic procedure implies the uniform routing or assigning aircraft/flights to each of them. For the "service channel" *(i)*, the assigned demand is equal to:

$$\lambda_i(\Delta t) = \frac{\gamma(\Delta t)}{N(\Delta t)}, \text{ for } i \in N(\Delta t) \text{ and } \gamma(\Delta t) = \sum_{k=1}^{K(\Delta t)} \sum_{l=1}^{L(\Delta t)} \gamma_{kl}(\Delta t) \qquad (3)$$

where

$\gamma(\Delta t)$ is the intensity of aircraft/flights demand requesting service, i.e., passing through the network during time (Δt);

$K(\Delta t)$, $L(\Delta t)$ is the number of origin and destination airports of the aircraft/flights demand during time (Δt); and

$\gamma_{kl}(\Delta t)$ is the intensity of aircraft/flights demand between the origin airport *(k)* and destination airport *(l)* during time (Δt).

The other symbols are analogous to those in the previous Eqs.

From (2a) and (3), the average aircraft/flight delays before entering the network can be estimated. Since both demand and capacity at each route/track, i.e., "service channel" are equal, the corresponding average delays will also be equal implying that eventual shifting the "channel" would not increase the utility of corresponding aircraft/flight(s). Otherwise, the utilities of aircraft/flights will

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

be exclusively influenced by different capacities of routes//tracks, i.e., service channels".

3.5.2 Model II: User-optimizing stochastic assignment procedure. The user-optimizing stochastic assignment model/procedure implies the probabilistic choice of route/tracks, i.e., "service channel" by aircraft/flights at the time close to their departure times. The choice is influenced by the inherent randomness of factors influencing the expected utility of aircraft/flights. One of the main causes of such randomness can be uncertainty in predicting weather in the network. Again, each aircraft/flight aims at optimizing its own (individual) utility if the ATC accepts and enables chosen route/track under given conditions.

The user-optimizing stochastic assignment model/procedure routes or assigns the aircraft/flights to the "service channel" *(i)* according to the MNL (Multinomial Logit) model as follows:

$$\lambda_i(\Delta t) = p_i(\Delta t) \cdot \gamma(\Delta t) = \frac{e^{-U_i(\Delta t)}}{\sum_{i=1}^{N(\Delta t)} e^{-U_i(\Delta t)}} \cdot \gamma(\Delta t) \tag{4a}$$

and

$$U_i(\Delta t) = 1/\mu_i(\Delta t) + \tau_i(\Delta t) = 1/\mu_i(\Delta t) + d_i/V_i(\Delta t) \quad \text{for } i \in N(\Delta t) \tag{4b}$$

where

$\tau_i(\Delta t)$ is the delay-free average time of aircraft/flight on the route/track, i.e., in the "service channel" *(i)*, during time *(Δt)* (h); and

d_i is the length of route/track, i.e., "service channel"*(i)* (nm; km).

The other symbols are analogous to those in the previous Eqs.

3.5.3 Model III: System-optimizing assignment procedure. The system-optimizing assignment model/procedure is applied when the ATC acts as the single decision-making entity. In approving the submitted flight plans and realizing the corresponding flights, the ATC aims on the one hand at optimizing their total above-mentioned utilities and on the other its own utility, the latter in terms of maximizing utilization of the available network capacity. The procedure implies an intuitively reasonable assignment of the expected aircraft/flight demand in direct proportion to the "ultimate" or "practical" capacity of particular (available) routes/tracks, i.e., "service channels". The experience so far with optimization of the communication networks operating as the queuing networks has indicated that this is not optimal but close to the optimal assignment enabling minimization of the total aircraft/flights service time, i.e., the total average delay, in the network and consequent above-mentioned utilities as the total generalized costs of the actors/stakeholders involved [18]. This model/procedure is as follows:

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

$$\lambda_i(\Delta t) = \left(\frac{\mu_i(\Delta t)}{\sum_{i=1}^{N(\Delta t)} \mu_i(\Delta t)}\right) \cdot \gamma(\Delta t) \tag{5}$$

where the other symbols area analogous to those in the previous Eqs.
This model/procedure can also be useful for the practical purposes when the capacities of particular routes/tracks, i.e., “service channels”, are not as expected. In most cases they can be compromised in terms of availability of routes/tracks due the fast and intensive-changing weather (head/tail wind, storms, volcanic eruptions). In (5), the “practical” capacities of tracks/routes, i.e., “service channels” instead of their “ultimate” counterparts estimated by (2b) can also be used.

3.6 Evaluation of the models/procedures for matching demand to Capacity. The above-mentioned models/procedures for matching demand to capacity are evaluated based on the above-mentioned generalized costs of aircraft/flights including those of airlines, air passengers onboard, and impacts of GHG emissions on the environment (externalities). These costs directly or indirectly mainly depend on the aircraft/flights total time spending in the network, i.e., the total average delay. In this case, the extra aircraft/flight generalized costs compared to their delay-free time-based counterparts are used for evaluation.

3.6.1 Airline operating costs. When served on the route/track, i.e., “service channel” *(i)*, the average airline operating costs can be estimated by the regression equation using the empirical data as follows [2, 35, 36]:

$$C_{i/a}(d_i, S_i, t_i, \Delta t) = (a_0 + a_1 \cdot d_i + a_2 \cdot S_i) \cdot t_i(\Delta t) \tag{6a}$$

where

$C_{i//a}(d_i, S_i, t_i, \Delta t)$	is the average operating cost of an aircraft/flight on the route/track *(i)* (US/flight);
a_k	is the coefficient of regression equation (k = 1, 2, 3);
S_i	is the average aircraft/flight seating capacity on the route/track *(i)* (seats); and
d_i	is the length of route/track *(i)* (km); and
$t_i(\Delta t)$	is the total average aircraft/flight time, i.e., the total average delay of spending on the route/track, i.e., “service channel” *(i)*, during time *(Δt)*.

The other symbols are analogous to those in (6a). The time $(t_i(\Delta t)$ in (6a) is the sum of average delay before entering and the delay-free time of staying of the aircraft/flights on the route track, i.e., “service channel” *(i)*, as follows:

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

$$t_i(\Delta t) = \bar{w}_i(\Delta t) + 1/\mu_i(\Delta t) + \tau_i(\Delta t) \quad (6b)$$

where all symbols are analogous to those in the previous Eqs.

The total average aircraft/flight time, i.e., the total average delay of spending in the network from Eq. 6a is equal as follows:

$$\bar{t}\,(\Delta t) = \left(\frac{1}{N(\Delta t)}\right) \cdot \sum_{i=1}^{N(\Delta t)} t_i(\Delta t) \quad (6c)$$

where all symbols are analogous to those in the previous Eqs.

3.6.2 Cost of passenger time. The average costs of time of air passengers onboard an aircraft/flight served on the route/track, i.e., in the "service channel" *(i)* of the network is estimated as follows [2], [37], [38]:

$$C_{i/p}(\tau_i, S_i, \alpha_i, \Delta t) = t_i(\Delta t) \cdot S_i \cdot LF_i \cdot \alpha_i \quad (7)$$

where

α_i is the average value of passenger time while onboard of an aircraft/flight in the "service channel", i.e., route/track *(i)* ($US/h).

The other symbols are analogous to those in Eq. 6a.

3.6.3 Environmental costs / externalities. The environmental costs/externalities relate to the impacts of GHG emissions from the consumed fuel of aircraft/flights served in the network.

- Fuel consumption

The average fuel consumed by an aircraft/flight served on the route/track, i.e., in the "service channel" *(i)* is estimated as follows [28], [39]:

$$FC_i(S_i, d_i, \Delta t) = SFC_i \cdot S_i \cdot LF_i \cdot d_i \quad (8a)$$

where

$FC_i(S_i, d_i, \Delta t)$ is the average fuel consumed by an aircraft/flight of the seating capacity (S_i) served on the route/track, i.e., in the "service channel" of length (d_i) during time (Δt) (ton/flight);

SFC_i is the average specific fuel consumption of an aircraft/flight served on the route/track, i.e., in "service channel" i.e., *(i)* (kg/p-km); and

LF_i is the average load factor of an aircraft/flight served on the route/track, i.e., in the "service channel"*(i)*.

The other symbols are analogous to those in the previous Eqs.

- GHG emissions

The average quantity of GHG emissions of an aircraft/flight served on the route/track, i.e., in the "service channel" *(i)*, based on Eq. 8a is estimated as follows [2, 40]:

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

$$Q_{i/CO_{2e}}(d_i, S_i, \Delta t) = CO_{2e} \cdot FC_i(d_i, S_i, \Delta t) \tag{8b}$$

where

CO_{2e} is Carbon Dioxide equivalent (tonCO_{2e}/ton of fuel).

- Cost/externalities of GHG emissions

The average costs/externalities of GHG emissions of an aircraft/flight served on the route/track, i.e., in the "service channel" *(i)* i.e., based on (8b) are estimated as follows [2, 41]:

$$C_{i/e}(d_i, S_i, \Delta t) = c_{CO_{2e}} \cdot Q_{i/CO_{2e}}(d_i, S_i, \Delta t) \tag{8c}$$

where

$c_{CO_{2e}}$ is the avearge cost of GHG emissions based on the GWP (Global Warming Potential) (US/tonCO_{2e}$). The other symbols are analogous to those in the previous Eqs.

3.6.4 Total generalized costs. From (6), (7), (8), the total average costs of an aircraft/flight served on the route/track, i.e., in the "service channel" *(i)*, is equal as follows:

$$C_i(\Delta t) = C_{i/a}(d_i, S_i, \tau_i, \Delta t) + C_{i/p}(\tau_i, S_i, \alpha_i, \Delta t) + C_{i/e}(d_i, S_i, \Delta t) \tag{9a}$$

Under the assumption that these average costs are approximately equal for all aircraft/flights served in the network during the specified period of time, the total extra generalized costs of realized flights based on the difference between their total and delay-free time counterparts are estimated as follows:

$$\Delta C(\Delta\tau) = \sum_{i=1}^{N} \lambda_i(\Delta\tau)\left[C_i(\Delta t) - C_{i/0}(\Delta t)\right] \tag{9b}$$

where

$C_{i/0}(\Delta t)$ is the total avearge cost based on the aircarft/flight delay-free time on the route/track, i.e., in the "service channel" *(i)*, during time *(Δt)* ($US/flight).

The other symbols are analogous to those in the previous Eqs.

4 AN APPLICATION OF THE MODELS OF NETWORK PERFORMANCES

4.1 Configuration and operation of the network. The ATC-based long-haul air route network considered in this paper is established in the NAT HLA (North Atlantic High-Level Airspace) divided into 6 ACCs (Area Control Centres): Bodo, Reykjavik, Gander, Shanwick, New York East, and Santa

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

Maria Oceanic [42]. The airspace is completely overwater and consequently without the ground-based navigational facilities and radar coverage preventing the ATC radar- monitoring and controlling of aircraft/flights. While in this airspace, As shown on Fig. 1b the network consists of the set of almost parallel air routes/tracks with the specified number of FLs (Flight Levels) called OTS (Organized Track System) spreading between two continents. These routes/tracks generally coincide with the great-circles, i.e., the shortest distances between any two points on the globe implying performing the orthodrome-based air navigation. Starting from the year 2015, these routes/tracks have been laterally separated by the standard distance of: $g = 30$ nm called RLSM (Reduced Lateral Separation Minima) instead of the previously: $g = 60$ nm (i.e., from 1 to ½ degree of latitude).

Supported by SLOP (Strategic Lateral Offset Procedure), this separation still guarantees the safe aircraft deviating around the route/track centerlines of about or one or two nm (nm – nautical mile). The network, i.e., OTS set up 24h in advance and based on the prevailing weather (primary wind) conditions aims at reducing the impacts of headwinds and increasing benefits from tailwinds as much as possible including the airline preferences submitted in advance. In general, using the OTS is not mandatory but highly recommended [23, 42, 43].

The sets of WPs along each route/track enable checking the aircraft/flights position where the course, speed, and/or altitude can change. Under such conditions, the aircraft/flights have to perform RNAV (Area Navigation) by using the traditional compass and/or the satellite navigation systems such as GPS (Global Position System) [44].

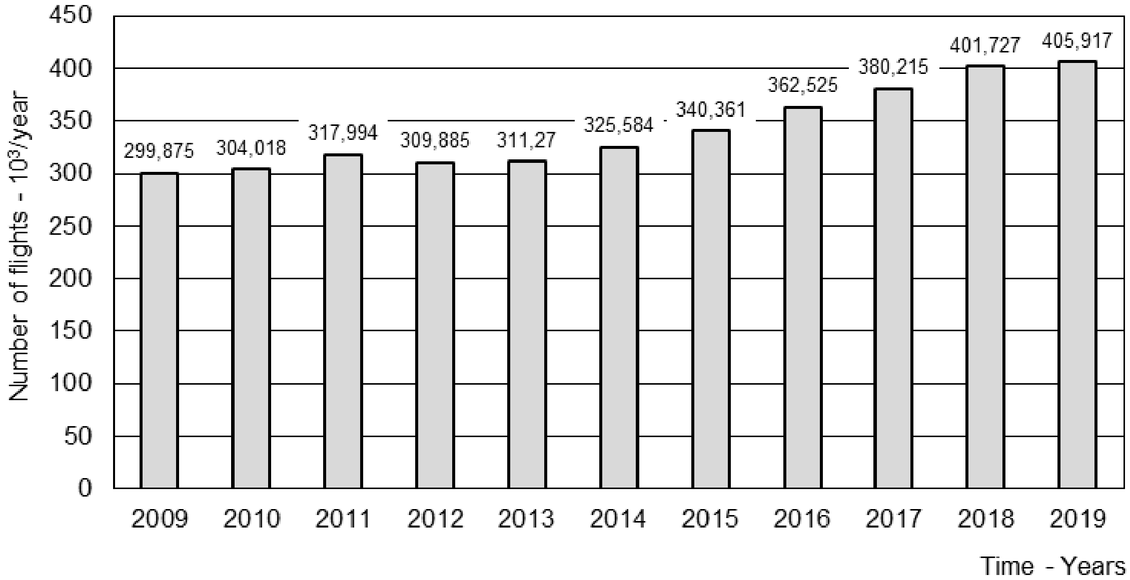
For reporting their positions, the aircraft/flights use the satellite communication CPDLC (Controller-Pilot Data Link Communications), HF (High Frequency) link and/or alternatively ADS-C & ADS-B (Automatic Dependent Surveillance) system. In the latest case, the controller-pilot-controller voice communication is replaced by the automatic downlink transfer of the position reports and the other flight information if necessary [23, 43, 45–47].

Before entering the network, the aircraft/flights contact the ATC Oceanic Center requesting the already assigned routes/tracks including the estimated time of arrival at their entry gates (WPs). This enables the ATC controllers to estimate and establish the required separation between the aircraft/flights and issue the corresponding clearances to pilots. The assigned routes/tracks can coincide or be different from the initial ones, but the aircraft/flights have to follow these assigned the latest.

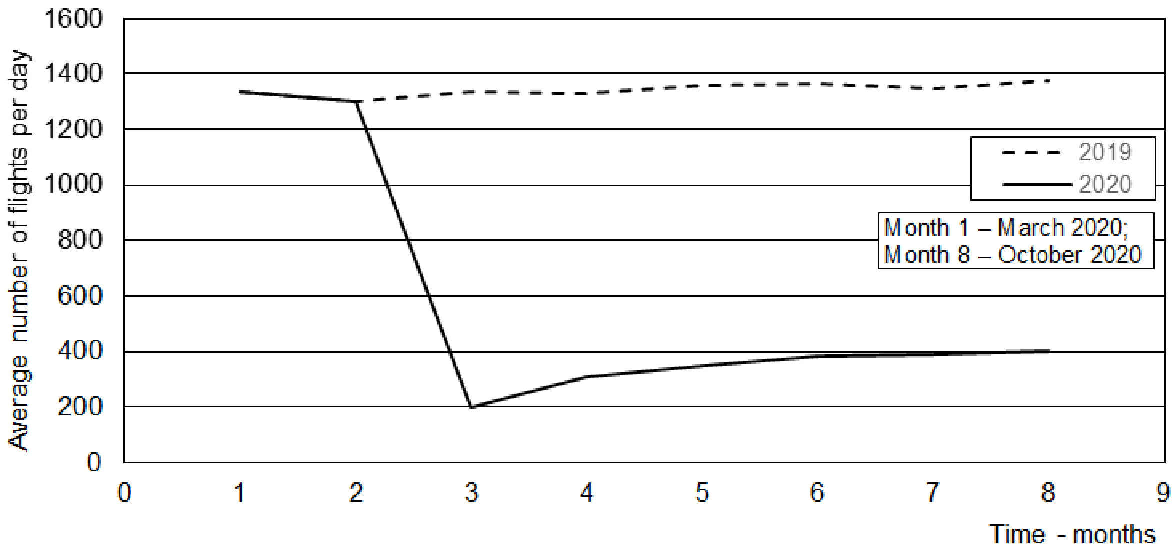
After entering the network, the aircraft have to report their position when crossing the WPs along routes/tracks including predicting the time of crossing the next and the successive WPs ahead as shown on Fig. 1b. In this way, the ATC controllers can “monitor” the safe separation between aircraft/flights while in the network [1, 43, 48].

Received: 02.01.2021 **Revised: 16.02.2021** **Accepted: 30.03.2021**
Поступил: 02.01.2021 **Одобрена: 16.02.2021** **Принята: 30.03.2021**

4.2 Developments of air traffic. The above-mentioned network serves the air transport market between Europe, North, and South America as one of the busiest in the world. Fig. 3 (a, b) shows some relevant development of the air traffic in this market over time.



a) Number of flights: Period 2009-2019



b) Flights per day (westbound + eastbound): Period March-October 2019/2020

Fig. 3. Some relevant characteristics of transatlantic air traffic between Europe and Americas over time [49–52]

Fig. 3a shows that before being affected by COVID-19 pandemic disease at the beginning of the year 2020, which caused complete closure of the airspace and network, the annual number of flights operated by about 20 airlines was increased for about 35 % during the observed period (2009–2019), i.e., by the

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
Accepted: 30.03.2021
Принята: 30.03.2021

rate of about 3.2 % per year[1] [53–55]. Fig. 3b shows the daily number of flights impacted by COVID-9 pandemic disease during the nine months of the year 2020 (March-October). As can be seen, just after the closure of the airspace and network (March 2020), the average number of daily flights decreased for about 85 % compared to its counterpart in the year 2019. Later it has been gradually recovering but not more than up to about 30 % of its counterpart in October 2019 [51].

The developments before the impact of COVID-19 pandemic disease questioned the sufficiency of capacity of this network to handle generally expecting growing aircraft/flight demand safely, effectively, and efficiently. While the COVID-19 crisis has impacted the air passenger demand and corresponding airline capacity hardly, they are expected to return to 2019 level by 2024 and then continue to grow at the rate similar to that before the pandemic. This expectation is based on the similarity with the recovery patterns from the previous crisis [16, 56]. Under such conditions, it is reasonable to expect that the performances of this network will again come to the research and practice agenda.

4.3 Inputs.

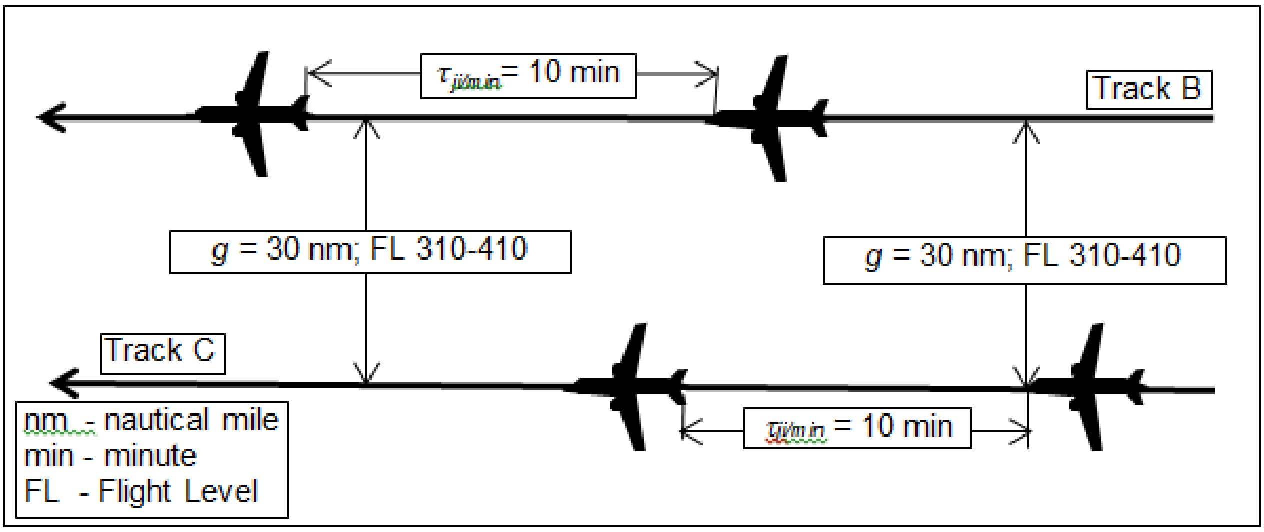
4.3.1 The air route network and traffic pattern. The application of the above-mentioned models to the long-haul air transport network on Fig. 1b (Westbound tracks and traffic). The considered network, i.e., the OTS to handle the westbound traffic between Europe and North America is assumed to consist of: $N(\Delta t)$ = 6 routes/tracks (A, B, C, D, E, F), each with $M_i(\Delta t)$ = 11 most preferred FSs (Flight level(s)) (FL 310 - FL 410). These aircraft/flights typically depart from Europe during the daylight between early morning and late afternoon (11:30h-19:00h UTC (Coordinated Universal Time) at 30^0W) in order to arrive at North America between early afternoon and late evening, i.e., during daylight. The opposite eastbound flights are scheduled to depart from North America to Europe in the evenings (01:00h UTC to 08:00h UTC on the North American side at 30^0W), thus enabling passengers to arrive at their European destinations in the morning.

4.3.2 The ATC separation rules. The aircraft flying along the given route/tracks on the same FLs are longitudinally separated by the ATC minimum time-based separation rules of: $\tau_{ji/min}(\Delta t)$ = 10 min. The ATC minimum vertical separation rules between the closest FLs are: h = 1000 ft thanks to RVSM (Reduced Vertical Separation Minima) program implemented in the year 2004.

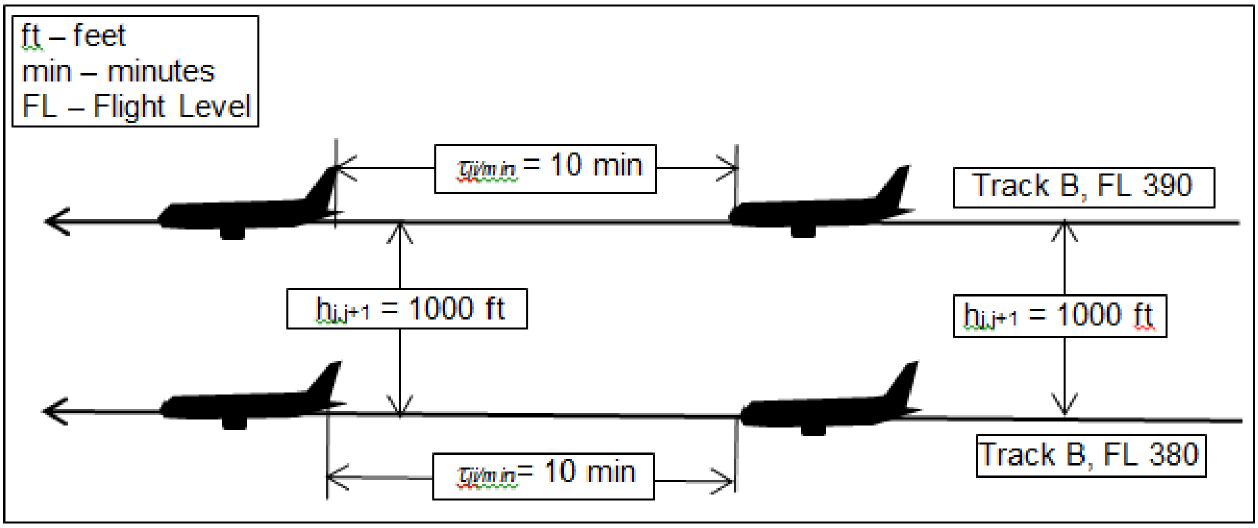
[1] At the same time, the volumes of ASK (Available Seat Kilometres(s)) and RPKs (Revenue Passenger Kilometer(s)) were growing at an annual rate of 3.4 % and 3.9 %, respectively. The average load factor during the period was about 75 % [53–55].

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

Fig. 4 (a, b) shows the simplified scheme of application of these ATC separation rules (nm - nautical mile; ft - feet) [1, 42].



a) Lateral and longitudinal separation rules



b) Vertical and longitudinal separation rules

Fig. 4. Scheme of application of the ATC minimum separation rules to the aircraft/flights in the given example - case of the North Atlantic air route network
(1 nm = 1.852 km; 1ft = 0.305 m)

Recently, the new ATC longitudinal separation rules of: $\tau_{ji/min}(\Delta t)$ = 5 min have been introduced between the adequately equipped aircraft (with ADS-B system) operating on the same flight levels in the Gander and Shanwick area [57].

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
Accepted: 30.03.2021
Принята: 30.03.2021

4.4 Analysis of the results

4.4.1 Capacity

4.4.1.1 "Ultimate" capacity.

Based on the ATC minimum longitudinal separation time of: $\tau_{ji/min}(\Delta t)$ = 10 min, the "ultimate" capacity of the route/track *(i)* with M_i = 11 FLs during the period of (Δt) = 1 h is equal to:

$$\mu_i(\Delta t) = \sum_{j=1}^{M_i} 1/\tau_{ji/min}(\Delta t) = \sum_{j=1}^{11} (1/10) \cdot 60 \ = 66\ ac/h\ .$$

If this route/track "ultimate" capacity is equal for all $(N(\Delta t)=7)$ routes/tracks and their equal number of available FLs, $(M_i(\Delta t) = 11$; i = 1, 2, …, 6), the total network "ultimate" capacity will be:

$$\mu(\Delta t) = N(\Delta t) \cdot \mu_i(\Delta t) = 6 \cdot 66 = 396\, ac/h.$$

If the constant intensity of aircraft/flight demand takes place in the westbound direction during the period: $\Delta\tau$ = 8 h (for example between 11:30 - 19:30 UTC or GMT), the total "ultimate" capacity of the network will be:

$$\mu(\Delta t = 8) = \ 396 \cdot 8 = 3168 \text{ ac/8h}.$$

Similarly, the "ultimate" capacity of the network handling the eastbound traffic under given conditions represented by the given/constant configuration of the air route network and constant demand for service can be estimated.

The average length of 20 busiest routes between Europe and North America has been $D(\Delta t)$ = 3620 nm, of which the oceanic segment (the second in order as mentioned above) has been d_i = 1325 nm (i.e., about 37 % of the total length) (i = 1, 2, …, 7; M_i = 11) [58].

If the aircraft/flight average cruising speed is $V_i(\Delta t)$ = 490 kt, then the average delay-free aircraft flying time along any FL of any route/track is about

$$\tau_i(\Delta t) = d_i/V_i(\Delta t) = 1325/490 = 2.704 \text{ h } (i = 1, 2, \ldots, 7) \text{ (kt - knot)}.$$

Then, under conditions of the constant demand for service, the total maximum number of aircraft/flights, which can simultaneously be handled in the network under given conditions can be:

$$n(\Delta t) = \mu(\Delta t) \cdot \tau(\Delta t) = 396 \cdot 2.704 = 1071 \text{ ac } [59].$$

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

4.4.1.2 "Practical" capacity

Based on the "ultimate" capacity, the "practical" capacity of the given air route network is estimated by specifying the maximum average delay imposed on each aircraft/flight before entering the network (2b). Fig. 5 shows dependence of the network's "practical" capacity on the maximum average delays imposed on an aircraft/flight before entering the network, the standard deviation of average service time, i.e., the ATC minimum time-based separation rules, and the "ultimate" capacity.

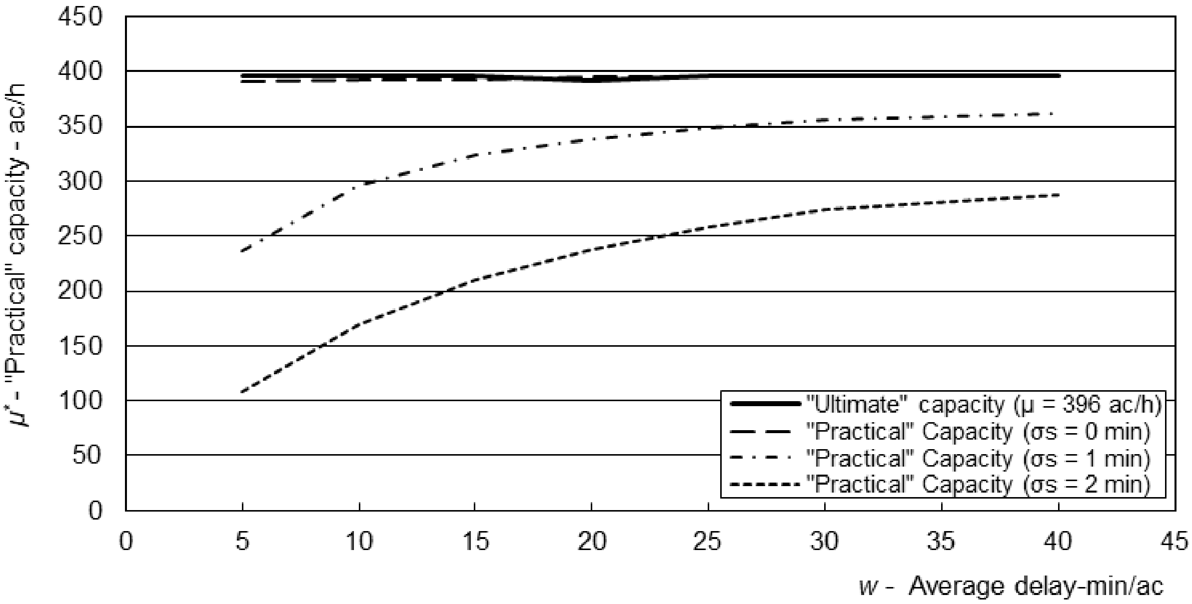


Fig. 5. Relationship between the "practical" capacity of the given air route network, the average delay imposed on an aircraft/flight and the standard deviation of its service time

As can be seen, if the average aircraft service time, i.e., the ATC minimum time-based separation rules are almost perfectly adjusted (i.e., without any deviations), then independently on the imposed delays on the aircraft/flights before entering the network, the corresponding "practical" capacity will remain very close to its "ultimate" counterpart.

If the deviations from the aircraft/flight service time increase even for a couple of minutes, the "practical" capacity will substantively decrease. At the same time, it will increase at decreasing rate with increasing of the average imposed delays and consequently come closer to its "ultimate" counterpart.

4.4.2 Matching demand to capacity

4.4.2.1 Scenario of the network available "ultimate" capacity. The above-mentioned three models of matching demand to capacity are applied by using a part of data related to the North Atlantic air route network shown on Fig. 1b. The scenario of available "ultimate" capacity of the air route network is given in Table 1.

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

Table 1. Scenario of the available "ultimate" capacity of the air route network in the given example

	FL*(j)* (10^3 ft)								
Route/ track (i)	**350**	**360**	**370**	**380**	**390**	**400**	**410**	**Total: $\mu_i(\Delta t)$ (ac/h; ac/8h)**	**Delay-free flying time $\tau_i(\Delta t)$ (h)**
	Available "ultimate" capacity (ac/h; ac/8h)								
1(A)	3;24	5;40	6;48	6;48	6;48	6;48	6;48	38/304	2.704
2(B)	-	-	6;48	6;48	6;48	6;48	6;48	30/240	2.704
3(C)	-	-	5;40	5;40	-	6;48	6;48	22/176	2.704
4(D)	-	-	-	6;48	6;48	6;48	6;48	24/192	2.704
5(E)	-	-	4;32	-	-	6;48	6;48	16/128	2.704
6 (F)	-	-	-	-	-	-	-	-	-
Total: $\mu_j(\Delta t)$	3/24	5/40	21/168	23/184	18/144	30/240	30/240	130/1040	

Table 1 indicates that the total available "ultimate" capacity of the given network is:

$$\mu(\Delta t) = 1040 \text{ ac/8h (Period 11:30-19:30 h).}$$

On average, during that period, $\gamma(\Delta t)$ = 500 ac/8h have requested service in the network (Based on Fig. 3b, Month 1-March 2020). As mentioned above, the total potential "ultimate" capacity of the given network is:$\mu_a(\Delta t)$ = 3168 ac/8h. This implies that the share of available "ultimate" capacity to which the aircraft/flight demand of $\gamma(\Delta t)$ = 500 ac/8h can be assigned is:

$$u(\Delta t) = \mu_a(\Delta t)/\mu(\Delta t) = 1040/3168 = 0.328 \text{ or} \approx 32.8\ \%.$$

In addition, the utilization of the network available "ultimate" capacity is:

$$u_a(\Delta t) = \gamma(\Delta t)/\mu_a(\Delta t) = 500/1040 = 0.48 \text{ or } 48\ \%.$$

In addition, utilization of the potential "ultimate" capacity under given conditions would be:

$$u(\Delta t) = \gamma(\Delta t)/\mu(\Delta t) = 500/3168 = 0.158 \text{ or about} \approx 13.8\ \%.$$

4.4.2.2 Assignment of demand to capacity. By taking into account the available "ultimate" capacity and the total delay-free average flying time along the particular routes/tracks, i.e., "service channels", of the given network, the

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

above-mentioned aircraft/flight demand $\gamma(\Delta t)$=500 ac/8h is assigned by three-above-mentioned assignment procedures/models as shown on Fig. 6.

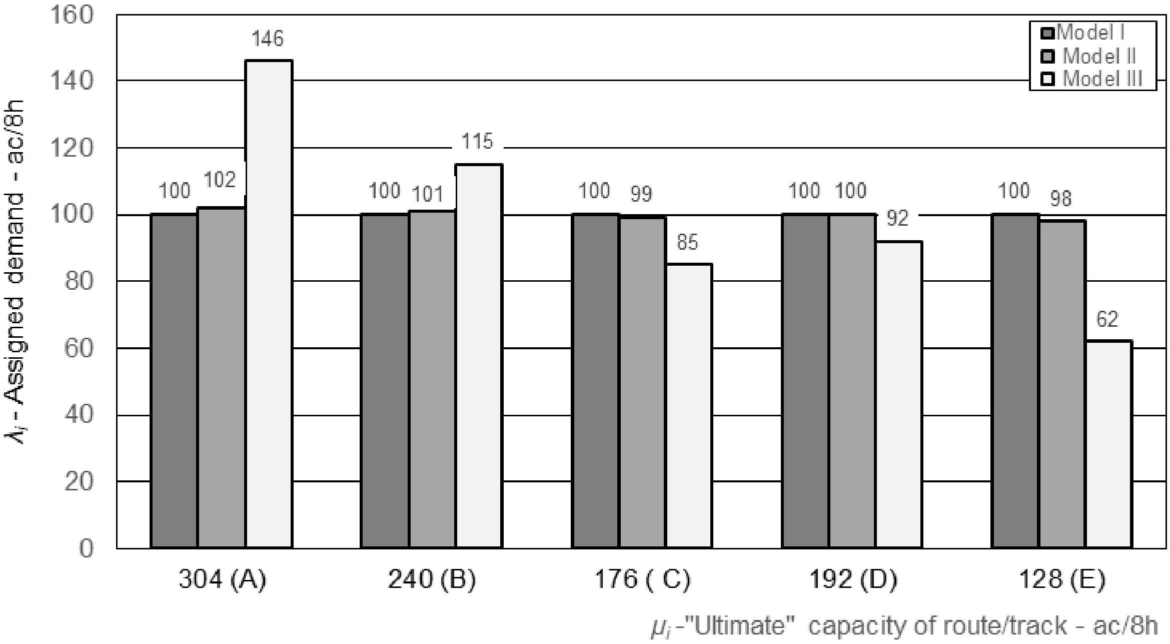


Fig. 6. Relationship between the assigned aircraft/flight demand, "ultimate" capacity of particular routes/tracks of the network, and applied routing or assignment models/procedures in the given example

As can be seen, the Model I-User-optimizing deterministic procedure assignes the demand of 500 aircraft/flights during the period of 8h uniformly to particular routes/tarcks independently on their "ultimate" capacity. The Model II-User-optimizing stochastic procedure tends to assing the higher number of aircarft/flights to the routes/tracks of higher capacity, but with very slight variations. The Model II-System-optimizing procedure assigns the aircarft/flight demand just in proportion to the "ultimate" capacities of the particular routes/tracks, i.e., the higher number of aircafrt/flights is assgned to the routes/tracks with higher "ultimate" capacity, and vice versa.

4.4.2.3 Average aircraft/flight delays. Based on the assigned aircraft/flight demand by the specified assignment models/procedures on Fig. 6 and its relationship with the "ultimate" capacity of particular routes/tracks of the network, the corresponding average delays per aircraft/flight before entering the network are estimated by (2a) and shown on Fig.7 ($\rho_i(\Delta t) = \lambda_i(\Delta t)/\mu_i(\Delta t) < 1$).

As can be seen, in general, the average delays from applying three assignment models/procedures are relatively low (up to about 7 min) particularly if compared to the aircraft/flights delay-free average time of spending in the network (t_i = 2.704 h; i = 1, 2, . . , 5).

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
Accepted: 30.03.2021
Принята: 30.03.2021

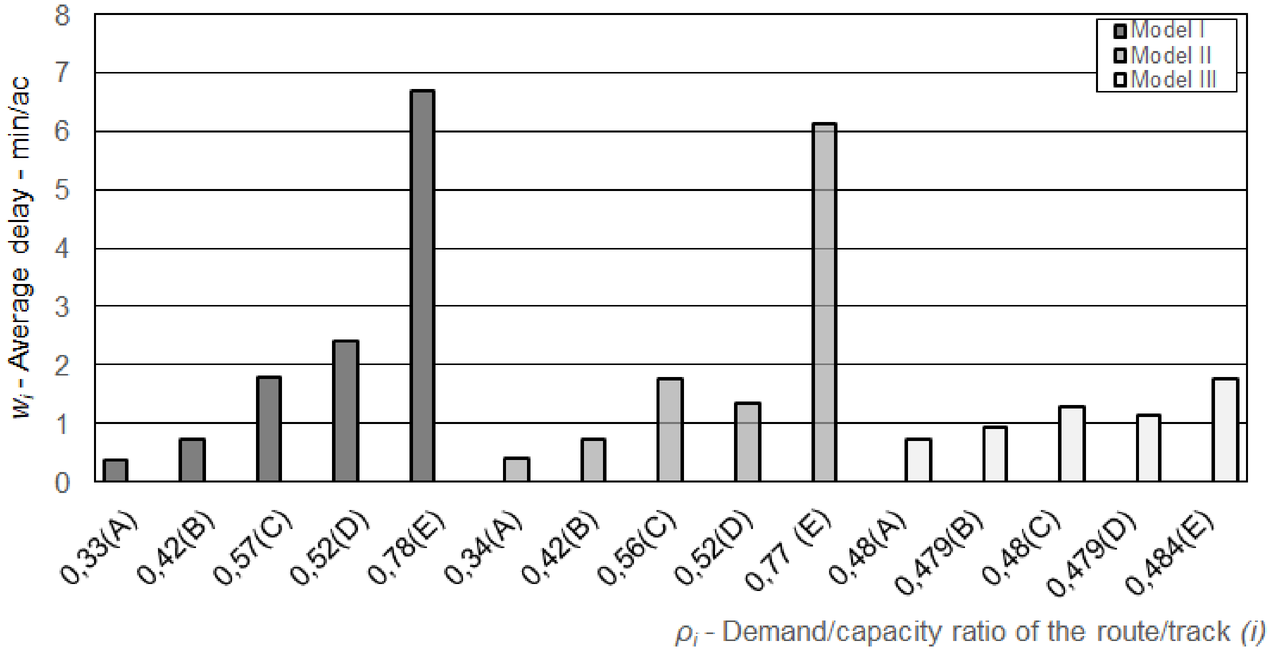


Fig. 7. Relationship between the average delay of an aircraft/flight, demand/capacity ratio of particular routes/tracks, and routing or assignment models/procedures in the given example

When the assignment Model I and Model II are applied, the corresponding average delays will increase more than proportionally with increasing of the demand/capacity ratio of the route/tracks due to the almost uniform assigned demand on the one hand and their lower “ultimate” capacity on the other. Model III will produce generally lower and more uniform distribution of the average delays of aircraft/flights among particular routes/tracks than its two counterparts. The average aircraft/flight delay is generally the highest on the route/track with the lowest “ultimate” capacity independently on the applied assignment model/procedure.

4.4.2.4 Evaluation of the assignment models/procedures. The above-mentioned routing or assignment procedures/models are evaluated by the average extra generalized costs of airlines, air passengers, and environmental externalities, all depending on the total average aircraft/flight delays, i.e., total time spending in the network. The reference case has been the costs based on the average delay-free aircraft/flight time spending in the network. These average extra costs are estimated for the single aircraft/flight and 500 flights/8h (i.e., during the above-mentioned east-west daily shift) served in the network independently on the assigned route/track.

- Airline operating costs

For particular routing or assignment procedures/models, the average delays on Fig. 8 and the aircraft/flight delay-free time spending in the network, the total corresponding times independently on the route/track are estimated by

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
Accepted: 30.03.2021
Принята: 30.03.2021

(6b), (6c), respectively. Then, the airline operational costs per an aircraft/flight are estimated by the regression equation as follows [35, 36]:

$$C_{i/a}(d_i, S_i, t_i) = (177.479 + 0.301 \cdot d_i + 21.956 \cdot S_i) \cdot t_i$$
$$t \qquad (0.285) \quad (1.764) \qquad (4.967)$$

$$R^2 = 0.712;\ F = 82.655; DW = 1.636;\ N = 70,$$

where all symbols are analogous to those in (6a). These and the corresponding airline extra costs compared to the reference delay-free time costs (Model/procedure 0) are estimated and given in Table 2.

Table 2. Airline operating costs (Average for $i \epsilon N; N = 5$)

Element		**Assignment model/procedure**		
	Model 0 Reference Delay-free	***Model I User-optimizing Deterministic***	***Model II User-optimizing Stochastic***	***Model III System-optimizing***
Delay (min/flight) - $\bar{w}$	0	2.40	2.05	1.71
Flying time (h/flight) [1] - $\bar{t}$	2.704 [1]	2.744	2.738	2.732
Cost ($US/flight) [2] - $\bar{C}_a$	19542	19831	19788	19745
Extra cost ($US/flight) - $\Delta\bar{C}_a$	0	+ 289	+ 246	+ 203
Extra costs ($US) - $\Delta\bar{C}_a$ (500 flights)	0	+ 144500	+ 123000	+ 101500

[1] *Based on: $\bar{\tau} = \bar{d}/\bar{V}$ = 1325 nm/490 kts = 2.704 h*

As can be seen, the extra costs per an aircraft/flight and for 500 flights/8h are the lowest as the Model III is applied. Compared to Model III, Model I and Model II produce the higher extra costs for about 42 % and 21 % costs, respectively.

- Air passenger time costs

The air passenger time costs are estimated by (7) and given in Table 3.

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

Table 3. Air passenger time costs (Average for $i \epsilon N; N = 5$)

Element	**Assignment model/procedure**			
	Model 0 Reference Delay-free	***Model I User-optimizing deterministic***	***Model II User-optimizing stochastic***	***Model III System-optimizing***
Passengers (number/flight) [2)] - $\bar{S} \cdot \overline{LF}$	245	245	245	245
Value of time ($US/p-h) [1)] - $\bar{\alpha}$	74	74	74	74
Cost of time ($US/flight) - $\bar{C}_p$	49023	49749	49640	49531
Extra cost ($US/flight) - $\Delta\bar{C}_p$	0	+ 726	+ 617	+ 508
Extra costs ($US) - $\Delta\bar{C}_p$ (500 flights)	0	+ 363000	+ 308500	+ 254000

[1)]Based on 50 % medium- and 50 % high-income passngers on board and their 50 % business and 50 % leisure trips [37], [38]; [2)] $\bar{S}$ = 303 seats/flight; $\overline{LF}$ = 0.81 per flight [28]

As can be seen, these extra costs per an aircraft/flight and for 500 flights/8h are higher than that of the airlines. Again, these costs at Model III are lower than that at the Model I and Model II for about 30 % and 18 %, respectively.

- <u>Environmental costs/externalities</u>

The environmental costs are estimated by (8a), (8b), (8c) and given in Table 4.

Table 4. Environmental costs/externalities (Average for $i \epsilon N; N = 5$)

Element	**Assignment model/procedure**			
	Model 0 Reference Delay-free	***Model I User-optimizing Deterministic***	***Model II User-optimizing Stochastic***	***Model III System-optimizing***
Fuel consumption (kg/flight)[1)] - $\overline{FC}$	17713	17956	17936	17831
GHG emissions (kg/flight)[2)] - $\bar{Q}_{CO_{2e}}$	78355	79429	79341	78877
Cost of GHG emissions ($US/ton CO_{2e})[3)]- $\bar{c}_{CO_{2e}}$	212	212	212	212
Cost of GHG ($US/flight) - $\bar{C}_e$	16818	17066	17029	16992
Extra cost ($US/flight) - $\Delta\bar{C}_e$	0	+ 248	+ 211	+ 174
Extra costs ($US) - $\Delta\bar{C}_e$ (500 flights)	0	+ 124000	+ 105500	+ 87000

[1)][28], [39]; [2)]Based on CO_{2e} = 4.42358 kg/kg of Jet A fuel (6 components) [40]; [3)] High Impact [41]

Received: 02.01.2021
Поступил: 02.01.2021
Revised: 16.02.2021
Одобрена: 16.02.2021
Accepted: 30.03.2021
Принята: 30.03.2021

As can be seen, these extra costs are slightly lower than that of airlines and substantively lower than that of air passengers. Again, Model I and Model II have for about 43 % and 21 % higher extra costs, respectively, compared to that of Model III.

- Total generalized costs

The total generalized extra costs are estimated from the corresponding components in Tables 2, 3, 4, and given in Table 5.

Table 5. Total extra costs (Average for $i \epsilon N; N = 5$)

Element	**Assignment model/procedure**			
	Model 0 Reference Delay-free	***Model I User-optimizing Deterministic***	***Model II User-optimizing Stochastic***	***Model III System-optimizing***
Extra costs ($US/flight) - $\Delta\bar{C}_a + \Delta\bar{C}_p + \Delta\bar{C}_e$	0	+ 1263	+ 1074	+ 885
Extra costs ($US-500 flights) - $\Delta\bar{C}_a + \Delta\bar{C}_p + \Delta\bar{C}_e$	0	+ 631500	+ 537000	+ 442500

Table 5 indicates that despite the total extra costs per single aircraft/flight are relatively low, those per 500 aircraft/flights handled during the period of 8h, i.e., during the east-west daily shift, can be rather substantive. As expected, Model III (System-optimizing procedure) is shown superior with about 30 % and 18 % lower generalized costs than that of Model I (User-optimizing deterministic procedure) and Model II (User-optimizing stochastic procedure), respectively. This indicates the crucial role of the ATC as the central air traffic control/management entity enabling optimizing the system generalized costs of all aircraft/flights served in the network under given conditions.

5 CONCLUSIONS

This paper has presented analyzing and modelling performances of the long-haul air route network operating as the queuing network in the large airspace according to "what-if" scenario(s). These performances have been the network capacity consisting of the capacities of particular routes/tracks as the "service channels", the aircraft/flight demand, and their relationships influencing the aircraft/flight total average delays and related generalized costs of airlines, air passengers, and impacts on the environment/externalities.

The analytical models for estimating the "ultimate" and "practical" capacity of the particular routes/tracks as the "service channels", three

Received: 02.01.2021 Revised: 16.02.2021 Accepted: 30.03.2021
Поступил: 02.01.2021 Одобрена: 16.02.2021 Принята: 30.03.2021

models/procedures for matching the aircraft/flight demand to the "channels" capacity - user-optimizing deterministic, user-optimizing stochastic, and the system optimizing, and the models for estimating particular generalized costs have been developed. They have been applied to the air route network established in the North Atlantic airspace between Europe and North America.

As expected, the "ultimate" capacity of the given network has been mainly influenced and increasing with increasing of the number of available routes/tracks and their flight levels as the "service channels" given the ATC minimum longitudinal time-based separation rules between the aircraft/flights operating on the same flight level(s). The "practical" capacity has been lower than its "ultimate" counterparts, but with decreasing gap with increasing of the average delays imposed on the aircraft/flights before entering the network. Among three routing or assignment models/procedures for matching demand to capacity, the system-optimizing model assigning the aircraft/flights in proportion to the "ultimate" capacity of particular routes/tracks, i.e., "service channels" has appeared superior. It has produced the lowest total average delays and related extra generalized costs compared to its other two counterparts. This has confirmed that the system-optimizing assignment model/procedure elaborated for the communication networks could also be useful for achieving close to optimal matching demand to capacity in the given context. Despite the total extra costs of an aircraft/flight assigned by all three models/procedures have been relatively low, they have shown to be substantive for the number of aircraft/flights handled in the network during the daily-shift period.

Further research could relate to more detailed analysis of operations of the given network by increasing the number of different operating scenarios, approaches to estimating the network's "ultimate" and "practical" capacity (for example applying simulation vs analytical approach), models/procedures for matching demand to capacity, and methods for estimating the generalized costs of the main actors/stakeholders involved. The influence of weather could be of particular interest for more realistic estimation of the above-mentioned performances under different "what-if" scenarios.

The author declares:

The present article does not contain any researches with people involved as the objects of researches.

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Received: 02.01.2021 **Revised: 16.02.2021** **Accepted: 30.03.2021**
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To cite this article:
Janić M. Analysing and Modeling Performances of a Long-haul Air Route Network. *Transportation Systems and Technology*. 2021;7(1):5-36. doi: 10.17816/transsyst2021715-36.

Received: 02.01.2021 **Revised: 16.02.2021** **Accepted: 30.03.2021**
Поступил: 02.01.2021 **Одобрена: 16.02.2021** **Принята: 30.03.2021**