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Modeling resilience, friability, and cost of an airport affected by the large-scale disruptive event

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ABSTRACT

This paper deals with modeling resilience, friability, and cost of an airport affected by the large-scale disruptive event. These events affecting the airport's operations individually or in combination can be bad weather, failures of particular crucial airport and ATC (Air Traffic Control) components, industrial actions of the aviation staff, natural disasters, traffic incidents/accidents and/or terrorist threats/attacks. The affected airport and its users airlines and air passengers can be imposed the additional (usually substantive) cost due to the preventive actions aiming at maintaining both the airport's resilience and safety at the acceptable level under given conditions. These actions include delaying, cancelling, and/or rerouting particular flights.

In order to estimate resilience, friability, and cost of a given airport including those of airlines and their users - air passengers during affection of the large-scale disruptive event, an appropriate methodology consisting of the dedicated models is developed and applied to the selected airport's case.

KEY WORDS: airport, resilience, robustness, friability, large-scale disruptive event, cost, assessment methodology

1 INTRODUCTION

In general, resilience of a given technical system implies its ability to operate under variable and unexpected conditions without significant/substantive compromising the planned performances. In many cases, resilience is considered as the capacity to neutralize impacts of different internal and external disruptive events. In addition, resilience reflects robustness of the given system to operate under unplanned (disruptive) conditions (Foster, 1993). The concept of resilience can also be applied to transport networks consisting of the nodes and links connecting them. The nodes are usually transport terminals of different size as the origins and destinations of scheduled/planned transport services serving the expected demand (passenger and freight flows) during the specified period of time (hour, day, week, month, year). The links are the physical infrastructure (roads, rail lines, air and, sea routes) stretching between particular terminals along which the vehicles of specified capacity carry out transport services. While dealing with resilience of transport networks, the commonly considered are delays and cancellations of particular services due to impact of different disruptive events. The scale and scope of deterioration of these planned/scheduled services or their survival under given impacts reflect resilience and their counterpart vulnerability. In this context, compromising resilience of a given transport network by removing (closing) particular nodes (terminals) and links (services) due to any reason represents the network's friability (Ip and Wang, 2011) .

The disruptive events impacting transport networks can generally be extremely bad weather (dense fog, heavy rain and/or snowfall, hurricanes, tornadoes, etc.), usually unpredictable catastrophic failures of the transport network components, industrial actions of the transport staff, natural disasters (earthquakes, volcanos, tidal waves), traffic incidents/accidents, and terrorist threats/attacks. In some cases, particular events can be interrelated and happened simultaneously. Usually, the affected actors/stakeholders are the network operators, i.e., providers of transport services and their users-passengers and freight shippers/receivers, which all are imposed costs while dealing with deteriorated operations and services, and recovery activities aftermath.

An airport as a node of a given air transport network hosting the incoming and outgoing airline flights from and to other airports of the network can also be affected by the above/mentioned disruptive events. Their impact often implies significant deterioration of the airport's planned/scheduled capacity resulting very often in the long delays and cancellations of many flights.

In addition to this introductory section, the paper consists of four other sections. Section 2 describes the characteristics of an airport and causes and consequences of impacts of particular disruptive events. Section 3 develops a methodology for estimating resilience, friability, and cost of an airport affected by a given disruptive event. Section 4 provides an application of the proposed methodology. The last section summarizes some conclusions.

2 THE SYSTEM AND THE PROBLEM

2.1 An airport

An airport whose resilience, friability, and cost during the impact of disruptive events are considered and modeled as a node of the network consisting of other airports-nodes and the air routes stretching between them as the physical network's links where the scheduled/planned air transport services/flights are carried out by one or several airlines during the specified period of time. This implies that the air routes as the physical links enable carrying out flights, and consequent providing the actual airport's connectivity within the given network. These flights are monitored and controlled by the ATC/ATM (Air Traffic Control/Management) system.

2.2 Resilience of an airport

2.2.1 Definition

The resilience of an airport is defined as its ability to withstand and stays operational at the required level of safety during the impact of a given disruptive vent. This definition does not take into account the recovery actions aftermath but only those undertaken just during the impact of the disruptive event (Chen and Miller Hooks, 2012). These actions include delaying and cancelling particular flights and even closing the affected airport and its incoming and outgoing air routes (links) for all traffic. In the given context, resilience can be considered as static and dynamic. The former refers to the airport's capability to maintain its planned/scheduled function during the impact of disruptive events. The latter implies the airport's speed of recovering up to the desired (specified) state aftermath (Rose, 2007). In both cases, vulnerability of the airport can be considered as the rate of reduction of intensity and quality of services during the impact and the time needed for its recovery aftermath of disruptive event as compared to the planned/scheduled counterparts (Chen and Miller-Hooks, 2012). Commonly, the vulnerability is considered in the qualitative way. However, if being considered quantitatively, this has often been replaced by reliability expressed by the probability that the affected airport can adapt to the external changes (i.e., disruptive events) while still maintaining the specified level of functioning (i.e., serving flights). In addition, in terms of time, resilience and its counterpart vulnerability can be considered in the short-, medium-, and long-term (Njoka and Raoult, 2009; TDM Encyclopedia, 2010).

2.2.2 Framework

Resilience of an airport can be assessed at three-layers: i) physical layer, which deals with the physical affection of airport infrastructure and associated ATC facilities and equipment; ii) service layer, which mainly considers affection of the airline flights; and iii) cognitive layer, which relates to the users/passengers' confidence into the affected and then recovered flights at the given airport (Len at al., 2010).

2.2.3 Tactics and strategies for mitigating losses

In general, the tactics and strategies for mitigating losses of an airport affected by a disruptive event usually expressed by the cost of delayed and cancelled flights at the micro-scale can be as follows (Cox, et al., 2011):

- Conservation implying maintaining operation of the airport but with the reduced number of flights (i.e., mainly due their cancellations);
- Relocation implying repositioning, rescheduling, and rerouting some flights and consequently the aircraft fleet engaged;
- Production recapture implying filling in more the already scheduled and scheduling the additional flights after the end of disruptive event in order to transport the affected remaining passengers from the long-delayed and cancelled flights; and
- Management effectiveness referring to the strategies and tactics of restoration of the affected airport and airline schedules in the network aftermath of the disruptive event.

2.3 Friability of an airport

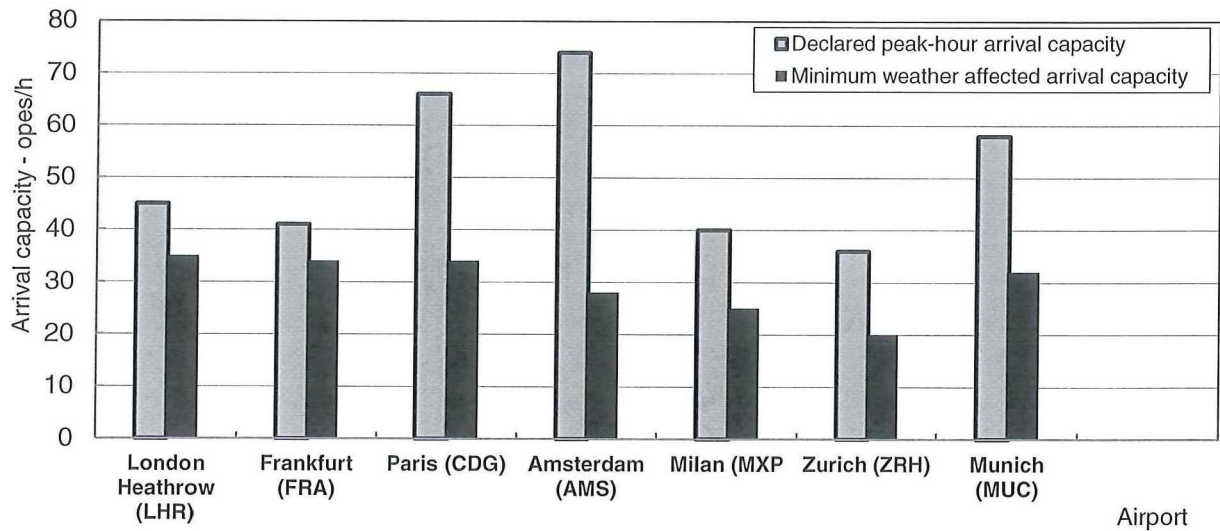
The particular actors in an air transport network such as airports, airlines, ATC service providers, users- air passengers and/or air cargo shippers/receivers, and the authorities at different institutional levels (local, regional, national) are often interested in identifying the least resilient or the most vulnerable airports in the given air transport network. This actually implies identifying the airport whose closure or cancellation, respectively, due to the impact of given disruptive event, would cause the greatest diminishing of the network's resilience it belongs. In practice, these particularly critical elements of a given air transport network are known. However, very often, it is complex to compare their individual importance in the quantitative way. Consequently, the concept of friability enables such qualitative comparison in the systematic way. Therefore, the friability of an airport is defined as its contribution to diminishing resilience of the network's it belongs if it would be removed from it (Ip and Wang, 2011).

2.4 Large-scale disruptions of an airport

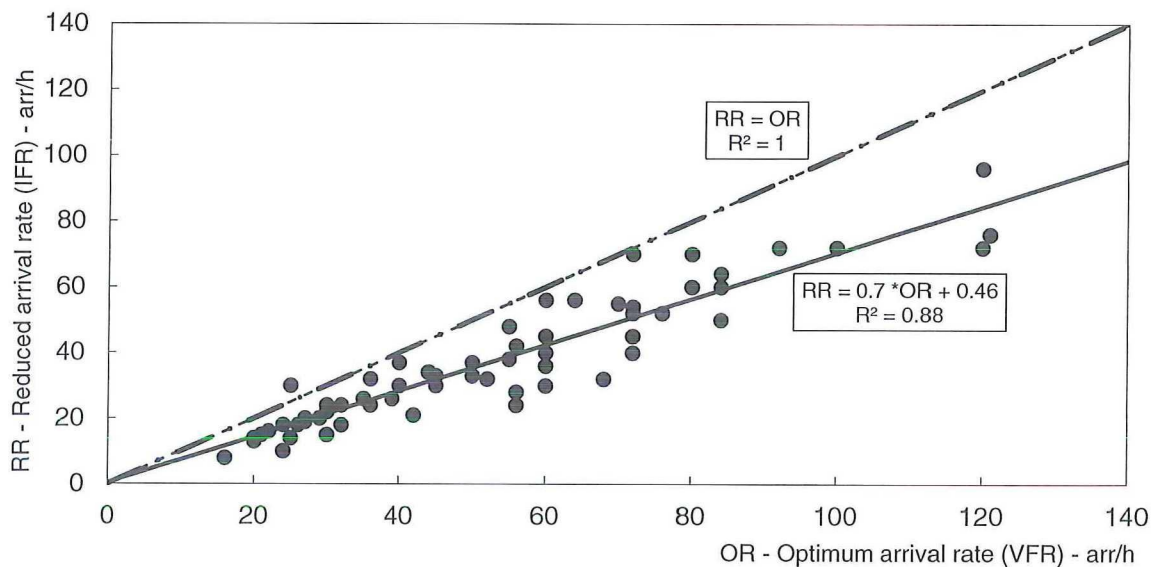
The large-scale disruption of an airport implies that its current operations generally substantively deviate from the planned/scheduled ones. In general, the large-scale disruptions are caused by the impacts of the large-scale disruptive events. These are those whose impacts can cause substantive damage of the airport infrastructure, usually deterioration of its capacity and the planned/scheduled transport services/flights, and an increased risk for people's injuries and lives. Depending on the type of the event, the impact can last from few hours to several days. In general, the large-scale disruptive events affecting an airport are the severe/bad weather, natural disasters, failures of the airport's components, industrial actions of the aviation staff, traffic accidents/incidents, and terrorist threats/attacks. They usually impact the airport runway system's and air routes' capacities, thus imposing delays, cancellations, and/or rerouting of the affected aircraft/flights.

Weather such as low clouds, fog, and/or heavy rain usually reduce visibility, which can consequently require increasing of the ATC/ATM minimum separation rules between landing and taking-off aircraft at the affected airport. This inevitably diminishes the corresponding

runway system capacity as shown in Fig. 1 (a, b) for the largest European and U.S. airports. For example, in the former case, diminishing of the airport arrival runway service rate, i.e., capacity, varies between 22% and 48%. If the current demand still remains below such affected capacities, the average delay of an arriving aircraft/flight will increase for about 30-90%, respectively. In the latter case, this diminishing of the capacity is about 30%, causing similar increase in the aircraft flight delays (Janic, 2005; 2009; EEC, 2005).



a) European airports



b) U.S. airports

Figure 1 Example of light affection of the runway system arrival capacity at the selected airports

Natural disasters can affect an airport by damaging its infrastructure usually causing its closure, which also downs their capacities to zero. For example, the frequent earthquakes in Japan (often of magnitude up to 9.0 Richter scale) affect the airports as nodes of the national (and international) air transport network. However, in this case, thanks to an adequate design and

construction, these airports withstand these impacts, and after being temporary closed for few days, are reopened without substantive damage (http://en.wikipedia.org/wiki/Air_travel_disruption_after_the_2010_Eyjafjallaj_eruption)

Failures of an airport crucial components usually occur at the ATC facilities and equipment affecting operations directly at the airport and indirectly along its aircraft/flight incoming and outgoing routes. For example, on the 26th of September 2008, failure of the ATC/ATM central computer caused closing of the airspace across the south-east of UK. The impact, which lasted several hours, caused cancellation of 88 flights at five London airports and left about 10000 passengers stranded. The impact has also affected the flights at Edinburgh, Glasgow, Aberdeen, Cardiff International, and Manchester airport.

Industrial actions of the aviation staff can affect an airport directly or indirectly in terms of its or airspace around it closure due to the unavailability of staff to carry out the aircraft ground servicing and/or the air traffic control tasks, respectively, the lack of flight crew and flight attendants to carry out flights, etc. For example, on the 11th of June 2013, the industrial action (strike) of the French ATC controllers lasted for about two days and consequently caused cancellation of 1800 of about 7650 flights to and from France, and delays, re-scheduling, and re-routing of many others (<http://edition.cnn.com/2013/06/12/business/france-air-traffic-strike>).

Traffic incidents/accidents have most frequently occurred at airports, i.e., during the flight arrivals and departures. As such, they usually cause temporal closure of the affected airport(s), thus downing their capacities to zero. For example, on the 25th of February 2009, the B737-800 of Turkish Airline flying from Istanbul (Turkey) to Amsterdam (The Netherlands) with 135 persons on-board crashed during landing at Amsterdam Schiphol airport (The Netherlands) into a field approximately 1.5 kilometers north of the runway 18R (Polder Baan). The impact caused death of nine passengers and crew including all three pilots. The airport was immediately closed for all arriving and departing flights for several hours. Some flights were diverted to the neighboring Rotterdam and Brussels airport. After taking care for the people and securing the crash site, the airport was gradually reopening (<http://airsafe.com/events/models/b737.htm>).

Terrorist threats/attacks impact an airport, which can be completely blocked or operating at the substantively deteriorated capacity requiring application of the corresponding emergency procedures for restoring. For example, on 10th of August 2006, the terrorist plot for blowing the aircraft/flights between UK and US was prevented in the UK. Due to the immediate closing of almost all airports of the UK air transport network, about 2300 flights were cancelled and the others imposed long delays during the period of seven forthcoming days. The airline losses of revenues were estimated to be about 50 million € (AEA, 2006).

In general, the impacts of the above-mentioned disruptive events are usually with unpredictable duration and consequences for an airport and other actors/stakeholders involved.

2.5 Flight delays and cancellations as typical consequences

In general, despite the above-mentioned and other disruptive events with lower impacts, most flights at an airport are carried out according to the planned schedule. Fig. 2 shows an example of the relationships between the proportions of the on-time, delayed, and cancelled arrival and departure flights at the U.S. airports.

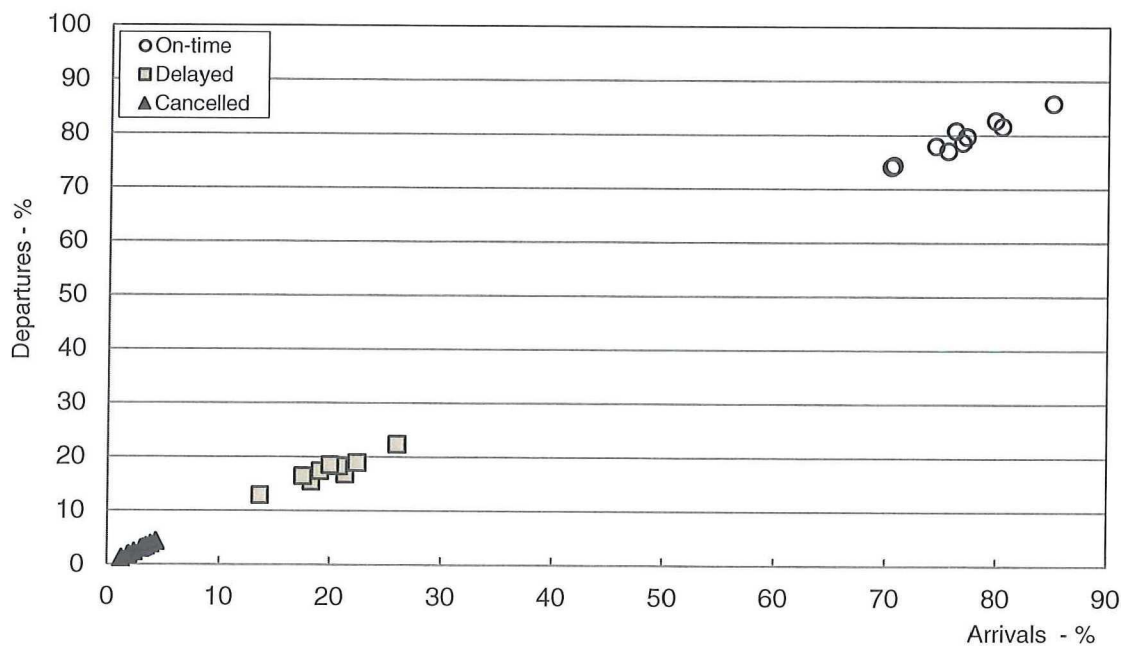


Figure 2 Relationship between arrival and departure on-time performance at the U.S. airports (Period: 2003-2012) (<http://www.transtats.bts.gov/>)

As can be seen, there is a strong correlation between the proportion of the arriving and departing flights of all categories. This implies that if the majority of arrivals are on time, the majority of departures will be on time too. The similar is valid for the delayed and cancelled arriving and departing flights. In addition to the flights on-time, the most frequent have been the flights delayed for 15 or more minutes behind the schedule (10-25% in the example on Fig. 3). The causes of their delays have been different such as: 'airline', 'late arrival', 'security', 'NAS (National Aviation System)', and 'extreme weather' (<http://www.transtats.bts.gov/>).

'Airline'_cause includes airline maintenance or crew problem, aircraft cleaning, baggage loading, unloading, fuelling, etc. 'Late-arrival' cause implies that the previous flight arrived late and caused the present flight to depart late. 'Security'_cause implies evacuation of the airport terminal building partly or fully, re-boarding of the aircraft, malfunction of the passenger and baggage screening facilities and equipment, and the long queues causing waiting longer than 29 min at the security check/screening areas. 'Extreme weather' cause imposes long delays or cancellations (tornado, hurricane, blizzard). 'NAS (National Aviation System)' cause refers to a broad set of conditions, such as non-extreme weather, airport operations, heavy traffic volumes, and ATC.

In general, the delayed and cancelled flights due to any cause impose the additional cost on the air passengers, airlines, airports, and ATC system. They can also escalate, particularly if the impacts of disruptive events spread widely (over the large area with the several airports), when they are strong (closing the affected airports and/or airspace), and when they are relatively long (lasting several hours to several days).

3 A METHODOLOGY FOR ESTIMATING RESILIENCE, FRIABILITY, AND COST OF AN AIRPORT AFFECTED BY THE LARGE-SCALE DISRUPTIVE EVENT

3.1 The previous research and objectives

The previous research on disruptions of airports and air transport networks has primarily been focused on quantification and minimization of the costs of disrupted airline networks due to the aircraft failures and consequent re-scheduling of remaining aircraft to perform the planned flights. In addition, this has been estimation of the cost of impacts of disruptive events affecting the airline hub airport(s). In this research, the resilience and friability of an affected airport and/or air transport networks have not been explicitly considered (Allan et al., 2001; Beatty et al., 1998; Janic, 2005; 2009; Kohl et al., 2007; Mayer et al., 1999, Schaefer and Millner, 2001; Schavell, 2000; Shangyao and Chung-Gee, 1997; Welch and Lloyd, 2001). However, the research on resilience of the inland rail, road, and intermodal transport terminals as the network nodes and the networks themselves including definitions or resilience, vulnerability, and reliability and their interrelations, and algorithms for optimization of the cost of recovery activities within the specified budget aftermath of a given disruptive event has been relatively exhaustive (Berdica, 2002; Chen and Miller Hooks, 2012). The complementary research has been focused on definition of the framework for evaluating resilience of the logistics and resilience and friability of the rail transport terminals and the network as well. Then, the optimization models and algorithms for allocation of the available resources to guarantee security and quality of services in the logistics and the optimal design of the rail terminals and entire network based on their resilience and friability have been developed (Wang and Ip, 2009; Ip and Wang, 2011). Consequently, the main objective of this paper is to develop a methodology for estimating the static, in the short-term, and at the service layer resilience, friability, and cost of an airport as the node of a given air transport network affected by a given large-scale disruptive event. In certain sense, the methodology is based on an analogy of and inspired by the above-mentioned research on the inland transport networks (Chen and Miller Hooks, 2012; Ip and Wang, 2011).

3.2 Basic structure of the methodology

3.2.1 General

The methodology consists of the models for quantifying resilience, friability, and cost of an airport during the specified period of time (τ). This time usually lasting for few hours, and one and/or several days, represents duration of the impact of a given disruptive event. The models imply the actions for mitigating costs and maintaining the required safety of operations during the impact and not aftermath of the disruptive event.

3.2.2 A model for estimating resilience

a) Assumptions

The model for estimating resilience of a given airport is based on the following assumptions:

- The resilience is considered during the time of duration of impact of a given disruptive event; this implies that it does not relate to the actions aftermath of the disruptive event in recovering of the network resilience;
- The operating regime of an airport runway system in terms of demand/capacity ratio can be: i) low to moderate; ii) heavy close to saturation; and iii) at and/or over saturation;
- The peak-period is specified by the highest ratio between the intensity of arrival and/or departure demand and the corresponding runway system capacity during the specified period of time;
- The capacity of the runway system under regular operating conditions is approximately constant over time including the peak-period(s);
- The disruptive event can start just at the beginning of the peak period;
- The disruptive event can impact the runway system capacity with different intensities lasting different times; the last intensity implies return of the affected runway system capacity to its level under regular operating conditions;
- The impacted capacity of a given runway system is always lower than its counterpart under regular operating conditions;
- If its capacity was impacted relatively strongly by a given disruptive event, the runway system would immediately pass from under-saturated to saturated and/or oversaturated operating conditions; and
- The stochastic and deterministic queuing system theory is applied to model the aircraft/flight delays and cancellations at a given airport(s) due to impact of a given disruptive event.

b) Importance/weight of an airport

The the relative importance, i.e., weight of an airport (i) of the air transport network consisting of N airports can be estimated as follows:

$$w_i^{\gamma_i}(\tau_i) = \frac{u_i^{\gamma_i}(\tau)}{\sum_{j=1}^N u_j^{\gamma_j}(\tau)} \quad (1a)$$

where

$u_i^{\gamma_i}(\tau)$ is the number of flights served at the airport (i) operating at the runway system's capacity ratio (γ_i) during the time (τ).

The number of flights served at the airport (i) in Eq. 1, $u_i^{\gamma_i}(\tau)$ can be determined as follows:

$$u_i^{\gamma_i}(\tau) = \sum_{j=1 | j \neq i}^N [f_{ji}^{\gamma_{ai}}(\tau) + f_{ij}^{\gamma_{di}}(\tau)] \quad (1b)$$

$f_{ji}^{\gamma_{ai}}(\tau), f_{ij}^{\gamma_{di}}(\tau)$ is the number of arriving and departing flights served at the airport (i) operating at the runway system's arrival and departure capacity ratios, (γ_{ai}) and (γ_{di}), respectively, during the time (τ).

The ratios $\gamma_{ai}(\tau)$ and $\gamma_{di}(\tau)$ in Eq. 2 can be determined as: $\gamma_{ai}(\tau) = \mu_{ai}^*(\tau) / \mu_{ai}(\tau)$ and $\gamma_{di}(\tau) = \mu_{di}^*(\tau) / \mu_{di}(\tau)$ where $\mu_{ai}(\tau)$ and $\mu_{di}(\tau)$ is the arrival and departure capacity, respectively, of the runway system at airport (i) during time (τ) under regular/planned operating conditions; $\mu_{ai}^*(\tau)$ and $\mu_{di}^*(\tau)$ is the arrival and departure capacity, respectively, of the runway system of the airport (i) impacted by a disruptive event during time (τ). The runway system's regular and affected capacities are generally related as follows: $\mu_{ai}(\tau) \geq \mu_{ai}^*(\tau)$ and $\mu_{di}(\tau) \geq \mu_{di}^*(\tau)$. In addition, these arrival and departure capacities can also be dependent of each other (Janic, 2005; 2009). Consequently, the ratios $\gamma_{ai}(\tau)$ and $\gamma_{di}(\tau)$ can take the values between 1 and 0. The former limit implies that the runway system of the airport (i) operates under regular conditions, as planned. The latter limit implies that the airport is closed for all operations.

c) Self-exhausted importance/weight

The self-exhausted importance/weight of an airport implies that its other connected airports do not include it. Thus, for the airport (i) belonging to the air transport network consisting of N airports, it can be estimated as follows:

$$v_i^{\gamma_i}(\tau) = \frac{u_i^{\gamma_i}(\tau)}{\sum_{j=1/j \neq i}^N u_j^{\gamma_j}(\tau) - u_i^{\gamma_i}(\tau)} \quad (1c)$$

where all symbols are as in the previous Eqs.

d) Resilience

The resilience of an airport (i) can be estimated as the product of the airport's self-exhausted weight and the number or proportion of flights carried as follows:

$$R_i^{\gamma_i}(\tau) = \sum_{j=1/j \neq i}^N v_j^{\gamma_j}(\tau) * [\delta_{ji}(\tau) * m_{ji}^{\gamma_{ai}}(\tau) + \delta_{ij}(\tau) * (m_{ij}^{\gamma_{di}}(\tau))] \quad (1d)$$

where

$m_{ji}^{\gamma_{ai}}(\tau)$, $m_{ij}^{\gamma_{di}}(\tau)$ is the number of arriving and departing flights served at the airport (i) operating at the runway system arrival and departure capacity ratio (γ_{ai}) and (γ_{di}), respectively, during the time (τ); and
 $\delta_{ji}(\tau)$, $\delta_{ij}(\tau)$ is the binary variable taking the value 1 if the airports (j) and (i), and air route in both directions between them are operable, and the value 0 if any or all of them are inoperable, respectively, during the time (τ).

The symbols $m_{ji}^{\gamma_{ai}}(\tau)$ and $m_{ij}^{\gamma_{di}}(\tau)$ in Eq. 1d can be the realized - on-time and delayed - or only the on-time flights. In general, the on-time flights are those being on-time or delayed for most 15 min. The delayed flights are those with delays longer than 15 min. Consequently, the total number of scheduled flights under given conditions is: $f_{ji}^{\gamma_{ai}}(\tau) = m_{ji}^{\gamma_{ai}}(\tau) + n_{ji}^{\gamma_{ai}}(\tau)$ and

$f_{ij}^{\gamma_{di}}(\tau) = m_{ij}^{\gamma_{di}}(\tau) + n_{ij}^{\gamma_{di}}(\tau)$, where $n_{ji}^{\gamma_{ai}}(\tau)$ and $n_{ij}^{\gamma_{di}}(\tau)$ is the number of cancelled arriving and departing flights, respectively, under given conditions. The other symbols are as in the previous Eqs.

3.2.2 A model for estimating friability

The model for estimating friability of an airport is based on the assumption that it is possible to quantify their resilience under given conditions specified in Eq. 1(a-d). This model consists of the following components:

i) Friability

The friability of an airport can be defined as its impact on the resilience of air transport network it belongs, if being removed from it due to any reason. In the given context, this implies the airport's closure due to the impact of disruptive event. Consequently, the friability of airport (i) as the node of the air transport network consisting of N airports can be estimated as follows:

$$F_i^{\gamma_i}(\tau) = R^{\gamma}(N, \tau) - R^{\gamma}(N, \tau/i) \quad (2a)$$

where

$R^{\gamma}(N, \tau/i)$ is the resilience of the air transport network after excluding, i.e., closing the airport (i) under given conditions during the time (τ).

The other symbols are as in Eq. 1d.

ii) Maximum friability

The maximum friability reflects the airport (i) as the weakest element of the air transport network consisting of N airports while being impacted by a disruptive event can be estimated as follows:

$$F_{\max}^{\gamma}(N, \tau) = \max[F_i^{\gamma_i}(\tau) / i \in N] \quad (2b)$$

where all symbols are as in the previous Eqs.

3.2.3 Model for estimating cost

The model for estimating cost of an airport affected by the large scale disruptive event is represented by the sum of the cost of delayed and cancelled flights as follows:

$$C_i^{\gamma_{ai}, \gamma_{di}}(N, \tau) = \sum_{j=1, j \neq i}^N \left\{ \begin{aligned} & c_{aj,ji}(\tau) * F_{aj,ji}[\tau, \gamma_{ai}(\tau)] * d_{aj,ji}[\tau, \gamma_{ai}(\tau)] * \psi_{aj,ji}[\tau, \gamma_{ai}(\tau)] + \\ & + c_{dl,ij}(\tau) * F_{dl,ij}[\tau, \gamma_{di}(\tau)] * d_{dl,ij}[\tau, \gamma_{di}(\tau)] * \psi_{dl,ij}[\tau, \gamma_{di}(\tau)] + \\ & + C_{aj,ji}(\tau) * n_{aj,ji}[\tau, \gamma_{ai}(\tau)] + C_{dl,ij}(\tau) * n_{dl,ij}[\tau, \gamma_{di}(\tau)] \end{aligned} \right\} \quad (2c)$$

where

$c_{aj}(t), C_{aj}(t)$	is the average unit cost of delay and cancelation, respectively, of a flight arriving from the airport (j) at the airport (i) during the time (τ);
$c_{dij}(\tau), C_{dij}(\tau)$	is the average unit cost of delay and cancelation, respectively, of a flight departing from the airport (i) to the airport (j) during the time (τ);
$F_{aj}[\tau; \gamma_{aj}(\tau)], F_{dij}[\tau; \gamma_{di}(\tau)]$	is the number of delayed arriving and departing flights between the airport (j) and (i), and vice versa, while they at the capacity ratios $\gamma_{aj}(\tau)$ and $\gamma_{di}(\tau)$, respectively, during the time (τ);
$d_{aj}[\tau; \gamma_{aj}(\tau)], d_{dij}[\tau; \gamma_{di}(\tau)]$	is the delay of an arriving and a departing flight between the airport (j) and (i), and vice versa, when the airports operate at the capacity ratios $\gamma_{aj}(\tau)$ and $\gamma_{di}(\tau)$, respectively, during the time (τ);
$\psi_{aj}[\tau; \gamma_{aj}(\tau)], \psi_{dij}[\tau; \gamma_{di}(\tau)]$	is the delay multiplier for an arriving and a departing flight between the airport (j) and (i), and vice versa, when the airports operate at the capacity ratios $\gamma_{aj}(\tau)$ and $\gamma_{di}(\tau)$, respectively, during the time (τ);
$n_{aj}[\tau; \gamma_{aj}(\tau)], n_{dij}[\tau; \gamma_{di}(\tau)]$	is the number of cancelled arriving and departing flights between the airport (j) and (i), and vice versa, when the airports operate at the capacity ratios $\gamma_{aj}(\tau)$ and $\gamma_{di}(\tau)$, respectively, during the time (τ).

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

As a general rule, a flight will be cancelled if the cost of its delay is perceived to be greater than the cost of its cancellation. From Eq. 2c, this follows: $C_{aj}(t) > c_{aj}(t) * d_{aj}[\tau; \gamma_{aj}(\tau)]$ for an arriving and $C_{dij}(\tau) > c_{dij}(\tau) * d_{dij}[\tau; \gamma_{di}(\tau)]$ for a departing flight.

3.2.4 Models for estimating flight delays

a) Background

The aircraft/flight delays and cancellations and related costs as elements of indicators of performance are modelled for an airport of a given air transport network operating under regular and disruptive conditions. In the former case, the scheduled arrival and departure demand is usually lower than or at most equal to the airport runway system service rate, i.e., capacity, causing primarily the stochastic aircraft/flight delays. In the latter case, the disruptive event can affect the airport runway system service rate, i.e., capacity, by lowering it below the scheduled demand for the period of its duration. This causes very long expensive deterministic aircraft/flight delays tending to propagate through the aircraft remaining daily itineraries. The affected airlines are usually forced to cancel these directly affected and forthcoming directly unaffected flights, the latest simply due to non-availability of aircraft at the right time at the right location /airport.

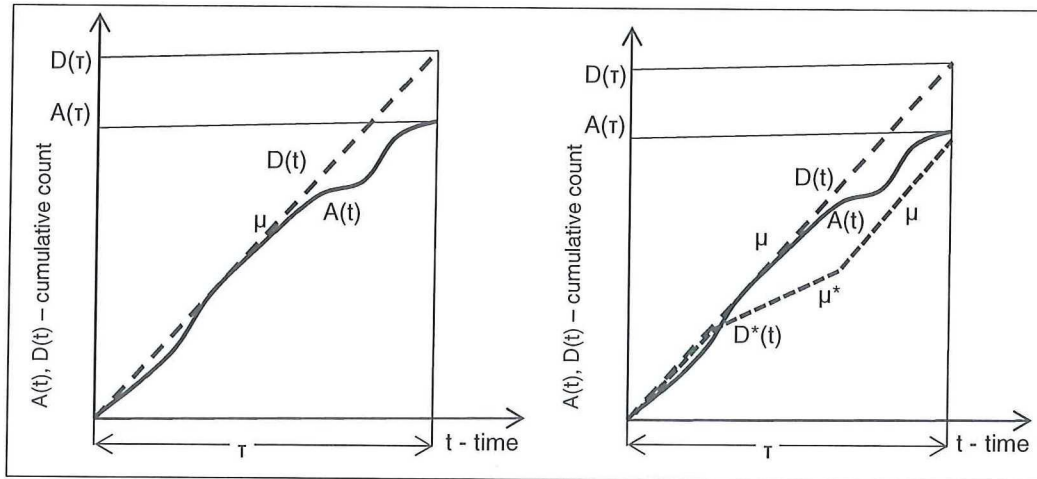
b) Assumptions

Modelling of the aircraft/flight delays and cancellations at an airport of the air transport network is based on the following assumptions:

- Resilience or robustness of a given airport is considered in the short-term, i.e., during the specified period of time, which can be duration of scheduled peaks under regular and/or time for eliminating queues and delays caused by the impact of disruptive event under irregular operating conditions;
- The assessment of resilience or robustness is carried out for a given airport at the service layer;
- The pattern of scheduled/planned demand at given airport of the network and its serving during the specified period of time is given;
- The runway system at the airport consisting of a single or multiple runways is considered to operate as a single server queuing system for arrivals and/or departures during the specified period of time;
- The regular “optimal” service rate, i.e., capacity, of the runway system is approximately constant during the specified period of time;
- The affected service level, i.e., capacity, is always lower than the regular or “optimal” service rate, i.e., capacity, of the runway system;
- The service rate, i.e., capacity, affected by disruptive event can change during the specified period of time; the last change implies its full recovery; and
- If the service rate, i.e., capacity, drops sharply, the airport runway system passes quickly from the conditions of being under saturated to the conditions of becoming oversaturated; and
- The mitigating strategies of the impacts of disruptive events are conservation, and partially relocation and production recapture implying in the given case the flight delays, cancellations and/or rerouting.

c) Aircraft/flight delays and cancellations

The aircraft/flight delays and cancellations and related costs as elements of indicators of performance are modelled for an airport of a given air transport network operating under regular and disruptive conditions. In the former case, the scheduled arrival and departure demand is usually lower than or at most equal to the airport runway system service rate, i.e., capacity, causing primarily the stochastic aircraft/flight delays. In the latter case, the disruptive event can affect the airport runway system service rate, i.e., capacity, by lowering it below the scheduled/planned demand for the period of its duration. Fig. 3 shows as simplified scheme where τ is the specified period of time in which the runway system service rate, i.e., capacity, can change from the declared μ to the affected μ^* ($\mu^* < \mu$). The $A(t)$ is the cumulative count of aircraft/flights requesting service by time (t) ($t \in \tau$). The $D(t)$ and $D^*(t)$ is the cumulative count of aircraft/flights served by time (t) ($t \in \tau$) during operation of the runway system at the declared μ and the affected service rate μ^* , respectively.



a) Declared service rate

b) Affected service rate

Figure 3 Queues of aircraft/flights requesting service at an airport operating at different regular and irregular service rate, i.e., capacity

Operating of a given airport at the affected runway system service rate, i.e., capacity, causes very long expensive deterministic aircraft/flight delays tending to propagate through the aircraft remaining daily itineraries. The affected airlines are usually forced to cancel these directly affected and forthcoming directly unaffected flights, the latest simply due to non-availability of aircraft at the right time at the right location /airport.

1. Scheduled delays – low, moderate, to heavy traffic and capacity undersaturation

The scheduled/planned arrival and/or departure aircraft/flight delays at an airport (i) belonging to the air transport network of N airports depend on the ratio between the intensity of demand and service rate, i.e., capacity, $\rho_i = \lambda_i / \mu_i$ during the specified period of time (λ_i is the intensity of demand; μ_i is service rate, i.e., capacity). At most airports, this ratio is lower than 1.0 thus implying a reasonable/acceptable arrival and/or departure aircraft/flight delays, very often already built in the aircraft/flight/airline schedule. Under such conditions, the average delay of an arriving and/or departing aircraft/flight at the airport (i) can be modelled as the single-server queuing system in the steady-state as given in Table 1.

Table 1 Characteristics of the steady-state queuing system for modelling the aircraft/flight delay at the under-saturated airport runway system

Queuing System	Description	Average Delay
M/M/1	Poisson arrival flow, i.e., exponentially distributed inter-arrival time of demand and exponentially distributed its service time.	$d_{i/q} = \frac{\lambda_i}{\mu_i(\mu_i - \lambda_i)} \quad (3a)$
M/G/1	Poisson arrival flow, i.e., exponentially distributed inter-	

	arrival time of demand and generally distributed its service time. Exact:	$d_{i/q} = \frac{\rho_i^2 + \lambda_i^2 \sigma_{i/s}^2}{2\lambda_i(1-\rho_i)} \quad (3b)$
	Heavy traffic approximation:	$d_{i/q} = \frac{\lambda_i(1/\lambda_i^2 + \sigma_{i/s}^2)}{2(1-\rho_i)} \quad (3c)$
	Error: as compared to the light to moderate and heavy traffic approximation:	$e(d_{i/q}) = \frac{1-\rho_i^2}{\rho_i^2 + \lambda_i^2 \sigma_{i/s}^2} \quad (3d)$
G/G/1	Generally distributed both inter-arrival time of demand and its service time.	$d_{i/q} = \left(\frac{\rho_i}{1-\rho_i} \right) \left(\frac{c_{i/a}^2 + c_{i/s}^2}{2} \right) \frac{1}{\mu_i} \quad (3e)$

where

- ρ_i is demand/capacity ratio for arrivals or departures at airport (i) $\rho_i = \lambda_i/\mu_i$;
- λ_i is the intensity of arrivals or departures at airport (i); and
- μ_i is the service rate, i.e., capacity, for arrivals or departures at airport (i) ($\mu_i = 1/T_s$, where T_s is the average service time per an arrival or a departure);
- $\sigma_{i/s}$ is the standard deviation of the service time of an arrival or a departure at airport (i);
- $c_{i/a}^2$ is the coefficient of variation for the inter-arrival time of arrival or departures at airport (i) ($c_{i/a} = \sigma_{i/a}/\lambda_i$);
- $c_{i/s}^2$ is the coefficient of variation for the service time of arrival or departures at airport (i) ($c_{i/s} = \sigma_{i/s}/\mu_i$); and
- $\sigma_{i/a}$ is the standard variation of the inter-arrival time for arrival or departures at airport (i).

In Eq. 3 (a-e), the particular variables are considered constant during the specified period of time. In addition, Eq. 3 implies that the average delay per an arrival or a departure flight at given airport (i) increases with increasing the level of saturation ρ_i and the variability of the inter-arrival and service time simultaneously, or with each individually. The level of saturation ρ_i can change by changing of one and/or both influencing parameters λ_i and/or μ_i . For example, if the disruptive event affects the service rate, i.e., capacity, μ_i for p_i and if the system still remains in the steady-state, i.e., $p_i = 1 - \rho_i$, the corresponding average delay, depending on the character of the above-mentioned queuing system, will increase by the factor $1/(1-p_i)$ and/or $1/(1-p_i)^2$.

II. Scheduled delays – heavy traffic and capacity saturation and over saturation

The typical scenario of developing the arrival or departure aircraft/flight queues and delays at an oversaturated airport runway system, i.e., when the ratio ρ_i : $\rho_i = \lambda_i/\mu_i > 1$ during the specified period of time, is shown in Fig. 4.

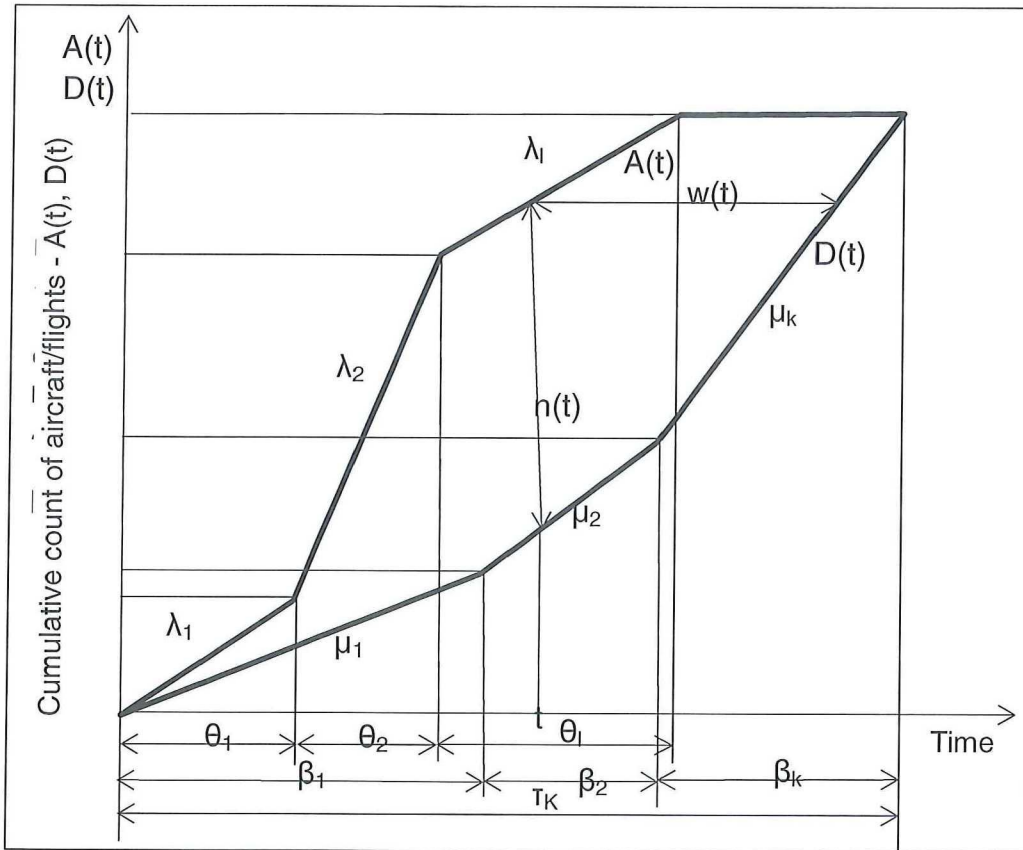


Figure 4 Scenario of developing the arrival or departure aircraft/flight queues and delays at an oversaturated airport runway system

In Fig. 4, the index (i) for given airport is dropped-off without loss of generality. The specified period of time is τ_K during which queues and delays sustain. This time consists of L time segments in which the intensity of arrival demand and K time segments in which the service rate, i.e., capacity, of the runway system change, the former according to the schedule and eventual cancellations of flights, and the latter due to any reason including the impact of disruptive event(s). Under such conditions, the duration of specified time period τ_K is estimated as follows:

$$\tau_K = \frac{\sum_{l=1}^L \lambda_l \theta_l - \sum_{k=1}^{K-1} \mu_k \beta_k}{\mu_K} + \sum_{k=1}^{K-1} \beta_k \quad (4a)$$

where

- λ_l is the intensity of the arrival demand during (l)-th time segment of the observed period;
- θ_l is duration of time segment in which the intensity of the intensity of demand is constant - λ_l ;
- L is the number of segments during observed period in which the intensity of demand changes;

- μ_k is the service rate, i.e., capacity, of the airport runway system in (k)-th segment of the specified period of time τ_K ;
- β_k is duration of the time segment in which the service rate, i.e., capacity, of the runway system is constant - μ_k ; and
- K is the number of segments during the specified period of time τ_K in which the service rate, i.e., capacity, of the runway system changes.

From Fig. 4, the aircraft/flight queue at some time (t) within the time period τ_K can be estimated, as follows:

$$n(t) = \max[0; A(t) - D(t)] \quad (4b)$$

If (t) satisfies the conditions:

$$\sum_{j=1}^l \theta_j < t \leq \sum_{j=1}^{l+1} \theta_j \quad \text{and} \quad \sum_{m=1}^k \beta_m < t \leq \sum_{m=1}^{k+1} \beta_m \quad (4c)$$

then

$$A(t) = \sum_{j=1}^l \lambda_j \theta_j + \lambda_{j+1} (t - \sum_{j=1}^l \theta_j) \quad \text{and} \quad D(t) = \sum_{m=1}^k \mu_m \beta_m + \mu_{m+1} (t - \sum_{m=1}^k \beta_m) \quad (4d)$$

and the delay of the aircraft/flight requesting service at time (t):

$$d(t) = \max \left[0; \left(\sum_{m=1}^{k+1} \beta_m - t \right) + \frac{n(t) - \mu_{k+1} \left(\sum_{m=1}^{k+1} \beta_m - t \right)}{\mu_{k+2}} \right] \quad (4e)$$

In addition, from Fig. 4, the total aircraft/flight delays during the time period τ_K can be estimated as the area between the demand and capacity curve $A(t)$ and $D(t)$, respectively, as follows:

$$D(\tau_K) = \max \left\{ 0; \sum_{l=1}^L \left[\frac{1}{2} \lambda_l \theta_l^2 + (\lambda_l \theta_l) (\tau_K - \sum_{j=1}^l \theta_j) \right] - \sum_{k=1}^K \left[\frac{1}{2} \mu_k \beta_k^2 + (\mu_k \beta_k) (\tau_K - \sum_{m=1}^k \beta_m) \right] \right\} \quad (4f)$$

From Eq. 4f follows that the average delay per an arriving aircraft/flight requesting service during the time period τ_K is equal as follows:

$$\overline{d(\tau_K)} = D(\tau_K) / \sum_{l=1}^L \lambda_l \theta_l \quad (4g)$$

The time specific and the average delay in Eqs. 4 (f, g), respectively, can be used for estimating the cost of aircraft/ flight delay as a criterion for decision if to accept and delay or reject and cancel the affected flight(s).

d) Cost of flight delays and cancellations

I. Cost of delays

The cost of delay $d(t)$ of an aircraft/flight requesting service at the airport runway system during time τ_K can be estimated as follows:

$$c_d[d(t); \tau_K] = c_d[d(t)] * d(t) * \phi[d(t)] \quad (5a)$$

- $d(t)$ is the delay of an aircraft/flight requesting service at the airport runway system at time (t) during the period τ_K ;
 $c_d[d(t)]$ is the unit cost of aircraft/flight delays as the function of the initial delay $d(t)$; and
 $\phi[d(t)]$ is the delay multiplier of the aircraft/flight experiencing delay $d(t)$.

The delay $d(t)$ In Eq. 5a, can be estimated from Eq.4e or Eq. 4g.

II. Cost of cancelation

The cost of cancelled flight, which would otherwise be imposed delay $d(t)$ if requesting service at the given runway system during the period τ_K is estimated as follows:

$$c_c[d(t); \tau_K] = c_c[d(t)] \psi[d(t)] \quad (5b)$$

where

- $c_c[d(t)]$ is the cost of cancelled flight, which otherwise would be imposed the arrival delay $d(t)$; and
 $\psi[d(t)]$ is the multiplier of the costs due to cancelling flight, which otherwise would be imposed delay $d(t)$.

In Eq. 5b, the multiplier $\psi[d(t)]$ depends on the cost of cancelled flights, which would be carried out latter by the same aircraft as the cancelled flight requesting service at the runway system at time (t) .

III. Criteria for cancelling flight(s)

The given flight will be cancelled if the cost of its delays is to be greater than the cost of cancellation. Based on Eq. 5 (a, b), this is represented by the binary function $\Delta(t)$ as follows:

$$\Delta(t) = \begin{cases} 1, & \text{if } c_d[d(t); \tau_K] > c_c[d(t); \tau_K] \\ 0, & \text{otherwise} \end{cases} \quad (5c)$$

Consequently, the total cost of delay or cancellation of a given flight under given conditions can be expressed as follows:

$$C[d(t);\tau_K] = [1 - \Delta(t)]c_d[d(t);\tau_K] + \Delta(t)c_c[d(t),\tau_K] \quad (5d)$$

where all symbols are as in the previous expressions.

From Eq. 5c, the total number of cancelled flights and consequently the vulnerability and friability of a given airport during time period τ_K can be estimated from Eqs. 1-5.

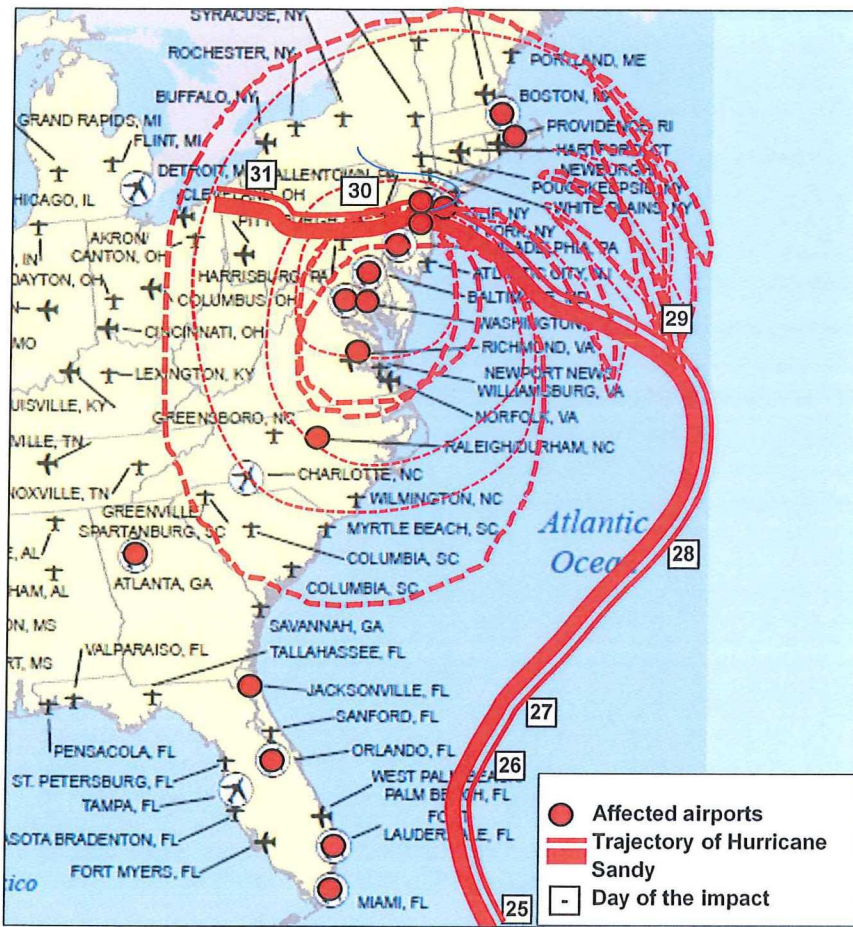
4 AN APPLICATION OF THE METHODOLOGY

The methodology is applied for estimating resilience, friability, and cost of NY LA Guardia airport as one of the sixteen airports of the U.S. air transport network on the north-east coast affected by the large-scale disruptive event - Hurricane Sandy - between 25th and 31st of October 2012.

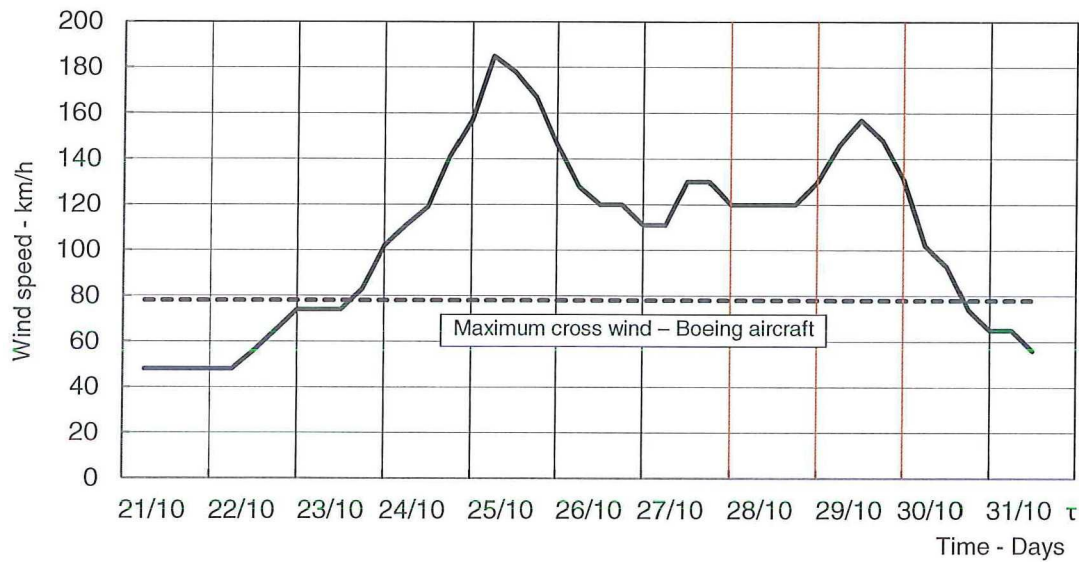
4.1 Inputs

4.1.1 Disruptive event

The disruptive event considered was The Hurricane Sandy, a very large tropical cyclone, which was lasting for the period of ten days, i.e., from the 21st to 31st of October 2012. It emerged around Caribbean Islands and then moved towards the north and north-west as shown in Fig. 5a. During the period from the 25th to 29th of October, the Hurricane was moving mainly above the sea almost parallel to the U.S. east coast. Between the 28/29th and 31st of October it turned to the west towards the coast and further through the continent at the speed of about 20-35 km/h. Its surface wind speed reached the maximum of about 180 km/h on the 25th of October (after it had just passed Cuba Island) and about 160 km/h on the 29th of October (when it strengthen again and turned towards the U.S. north-east cost) as shown on Fig. 5b. At the same time, the Hurricane-force winds and the tropical-storm-force winds were spreading from the center outwards up to 280-300 km and 800-900 km, respectively, thus indicating that its diameter was almost up to about 1800-2000 km. Consequently, the covered/affected area on the ground reached about 2.5-3 million km². In addition, Fig. 5b shows that the Hurricane's speed was most of the time much higher than the maximum speed of cross-wind of about 74 km/h at which the most commercial aircraft could safely operate.



a) The best track position



b) The surface wind speed

Figure 5 Characteristics of Hurricane Sandy (21- 31 October 2012)

(Compiled from: Blake et al., 2013; G. W. H. van Es et al., 2001; <http://www.rita.dot.gov/bts>)

4.1.2 The affected airport(s)

The above-mentioned Hurricane's strong wind accompanied with the very high precipitation impacted sixteen airports at the north-eastern part of the U.S. air transport network as follows: Atlanta (ATL), Boston(BOS), Baltimore/Washington International (BWI), Washington Ronald Reagan National (DCA), NY Newark Liberty International (EWR), Fort Lauderdale-Hollywood International (FLL), Washington Dulles International (IAD), Jacksonville International (JAX), NY John Fitzgerald Kennedy (JFK), NY LaGuardia (LGA), Orlando International (MCO), Miami International (MIA), Norfolk International (ORF), Philadelphia International (PHL), Providence (PVD), and Raleigh-Durham (RDU). The total daily number of affected scheduled arriving and departing flights to, from, and between these airports was 13500-17500 each. This number fluctuated during the disruptive event (<http://www.rita.dot.gov/bts/>). The actions for reducing the cost and maintaining the required level of safety of operations were adjusted according to the strength of impact and included delaying, cancellations and re-routing of the affected flights. On the fifth, sixth, and seventh day when the disruptive event was the closest and its impact the strongest as shown in Fig. 5 (a, b), four, three, and two airports were simultaneously closed, respectively.

4.1.3 Cost of delayed and cancelled flights

The average unit cost of delayed and cancelled flights is estimated by combining the information from different sources. The average unit cost of delayed and cancelled flights is estimated by combining information from different sources. The average delay of delayed either arriving or departing for NY La Guardia airport is estimated to be: $d_{aji}(\tau) = d_{dij}(\tau) = 57.51$ min (these values are reduced for 15 min since flights delayed up to this time are not considered as delayed flights) (<http://www.rita.dot.gov/bts/>; <https://aspm.faa.gov/opsnet/sys/main.asp>). For NY LaGuardia airport the average number of passengers per flight is estimated to be 98 and the average unit cost of delay $c_{aji}(\tau) = c_{dij}(\tau) = 162$ \$US/min (JEC, 2008; PAN&N, 2012). This is multiplied by the factor 1.5 in order to take into account the indirect and induced cost impact of air travel delays on the national (U.S.) economy. The average cost of passenger time is assumed to be 39.04 \$US/h. The average cost of a cancelled flight carried out by a narrow-body 120/150 seat aircraft is assumed to be: $C_{aji}(\tau) = C_{dij}(\tau) = 21800$ \$US/flight. This cost include the service recovery cost (passenger vouchers, drinks, telephone, hotel), the interline cost (rebooking revenue), the loss of future value (cost of individual passenger delay), and the savings in direct operational cost of the cancelled flight (EEC, 2011). The above-mentioned figures indicate that, possibly, at NY LaGuardia airport a flight expected to be delayed longer than about 2.5 h would be canceled under given conditions.

4.2 Results

Resilience of NY LaGuardia airport as one of the sixteen affected airports in the given example is shown on Fig. 6. As can be seen, this resilience expressed by the proportion of realized flights was higher than that expressed by the proportion of on-time flights. Both generally changed during the disruptive event and gradually decreased with increasing of the intensity of its impact.

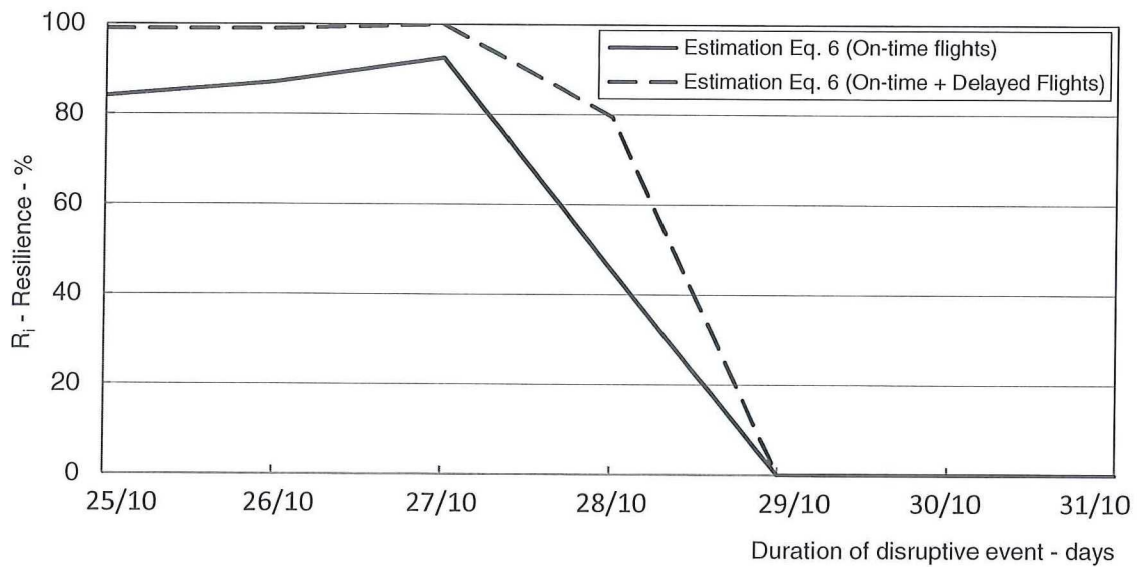


Figure 6 Resilience of an airport in the given example - NY LaGuardia airport

On the fifth day, when the Hurricane was on the scene and with the strongest impact, the airport had to be closed and stayed so until the end of disruptive event resulting dropping its resilience to zero.

Fig. 7 shows friability of the NY LaGuardia and Atlanta International airport in the given example (the latter is shown for the purpose of comparison).

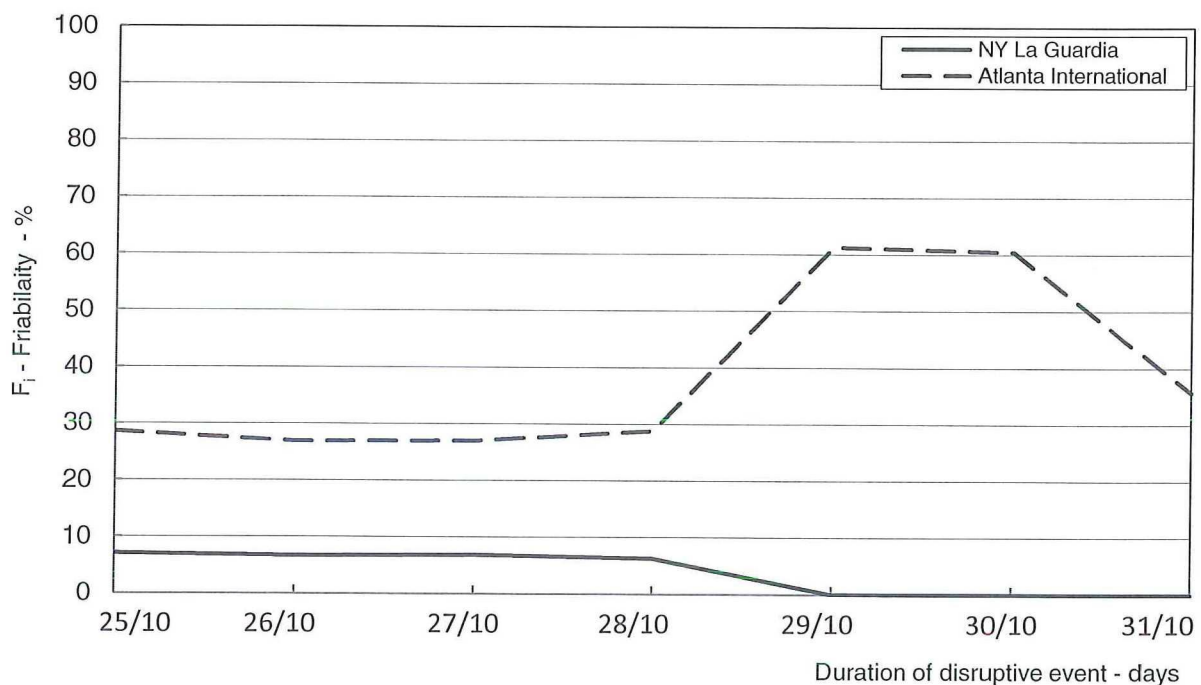


Figure 7 Friability of airports in the given example - NY La Guardia and Atlanta International airport

The former airport is particularly selected because it was closed during the last three days of disruptive event (The main affected airlines were Delta, AirTran, and Express Jet with the market share of about 90%). The latter airport is selected as the largest among the affected but operational all the time (The main partially affected airlines were Delta, American, and US Airways with the total market share of about 41%) (<http://www.transtats.bts.gov/>). The friability is expressed as the rate of diminishing resilience if the given airport would be removed from the network, i.e., closed, under given conditions. As can be seen, the friability of Atlanta was much higher than that of La Guardia airport, thus indicating that its removal, i.e., closing, as the weakest node under given conditions would maximally compromise resilience of the affected network. In addition, its friability was gradually increasing and reached the maximum on the fifth day of the disruptive event, when four other among sixteen affected airports including La Guardia had to be closed. Consequently, closing of this additional fifth airport would have the greatest impact on the remaining resilience of the network. After gradual reopening of the closed airports later on, the Atlanta's friability was diminishing, thus indicating lowering influence on the network's overall resilience in case of its eventual removal, i.e., closure.

The friability of NY LaGuardia airport was much lower than that of the Atlanta International airport indicating that its removal, i.e., closure, had much weaker impact on resilience of the network. When the airport was closed, its resilience failed to zero and consequently its friability reflecting such resilience failed to zero too.

Fig. 8 shows the cost of delayed and cancelled flights at NY LaGuardia airport estimated in the given example by using the above-mentioned inputs.

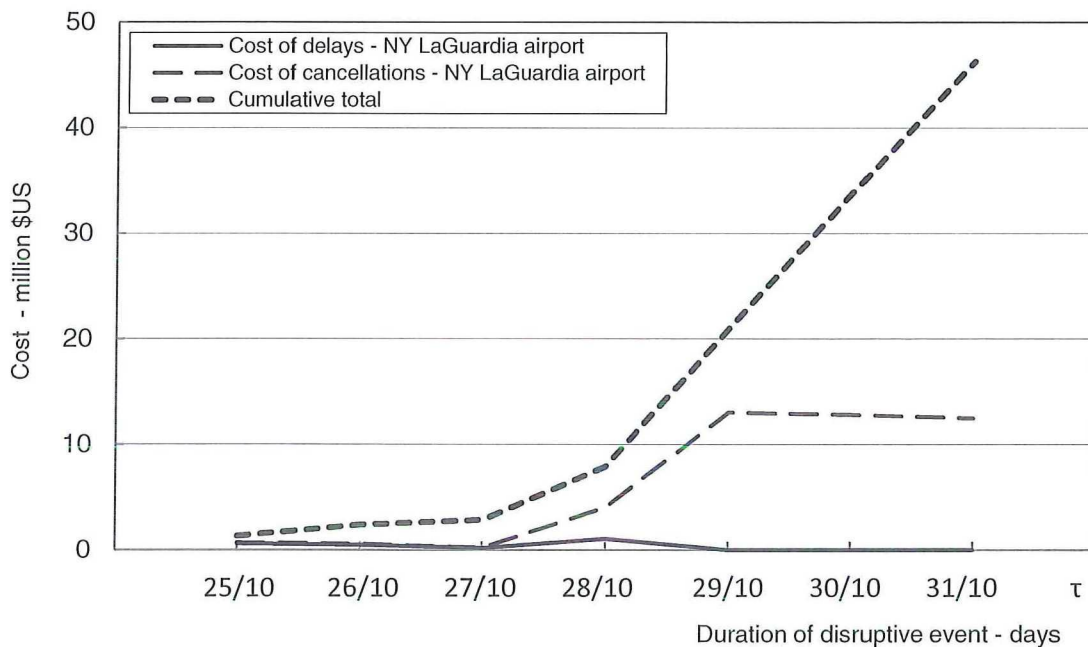


Figure 8 Cost of delayed and cancelled flights in the given example - NY LaGuardia airport

As can be seen, these costs have increased in line with strengthening of the impact of disruptive event - Hurricane Sandy. Fig. 8 shows that costs of both delayed and cancelled flights were imposed during the first half of the impact of disruptive vent. Latter on, because the airport was closed, only the cost of the cancelled flights remained until the end of the disruptive event. But,

the total cumulative cost by the end of the event reached about 45 million \$U.S. This amounted about 10% of the total cost of all delayed and cancelled flights due to the above-mentioned disruptive event.

5 CONCLUSIONS

The paper has elaborated impact of the large-scale disruptive event on resilience, friability, and cost of the given airport as the node of the wider air transport network. For such purpose, the methodology consisting of the corresponding models has been developed. In such context, resilience has been considered as the airport's capability to sustain its planned/scheduled operations during the impact. Friability has been considered as the rate of diminishing resilience of the network to which the airport belongs if the airport would be excluded from it due to the impact. The cost has included the social cost of delayed and cancelled flights at the airport. In certain sense, this cost has reflected the airport's economic efficiency under given conditions.

The methodology has been applied to NY York La Guardia airport as one of the sixteen airports in the north-eastern part of the U.S. affected by Hurricane Sandy in October 2012. The results have indicated that resilience of the NY LaGuardia airport was substantively compromised by the impact of disruptive event and become zero when it had to be closed. For the comparative purposes, friability was higher at larger Atlanta airport than at the smaller NY LA Guardia airport indicating the former airport's higher weakness or the impact on the resilience in case if being removed, i.e., closed, under given conditions.

The cost changed by changing of the intensity of impact of the Hurricane during the observed period and the mitigating undertaken actions in terms of delaying and cancelling flights. At NY LaGuardia airport, the cost consisting of increasing cost of the cancelled and decreasing cost of the delayed flights were the highest when the impact of disruptive vent was the strongest (during the last three days). As such, they amounted about 10% of the total cost of affected sixteen airports and wider.

The above-mentioned application has also implicitly validated the proposed methodology indicating that it could be, originally and/or with the necessary modifications, effectively applied to estimating resilience, friability, and cost of different airports affected by the large-scale disruptive events. This could be carried out both a priori according to the "what-if" scenario approach and/or a posteriorly for the already happened case(s). The precondition for successful outcome from such applications seems certainly to be availability of the relevant data as shown in the given case.

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