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Impacts of unplanned aircraft diversions on airport ground operations

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Abstract

When an unplanned disruption causes the temporary closure of an airport, incoming flights are re-routed to one (or more) nearby ones. As a consequence, traffic in the alternate airport increases and the efficiency, punctuality and regularity of operations may be compromised. The purpose of this work is to determine the impacts on the alternate airport airside operations due to the presence of diverted flights. If the number of aircraft to be serviced increases, ground handling operators are subjected to an additional workload, probably resulting in delayed departures and knock-on delays. A discrete-event simulation model of both aircraft landing-and-takeoff (LTO) cycles and turnaround operations is built by using AnyLogic. The model is applied to the case study of Lisbon "Humberto Delgado" airport. When the number of incoming flights increases upon a certain threshold, departure delays spread over the day, which should call for emergency actions and contingency plans.

Keywords: disruption management; impacts evaluation;airside operations simulation.

1. Introduction

The efficiency of airport operations is often compromised by unplanned disruptive events such as bad weather, strikes or technical failures, which may influence the punctuality and regularity of the operations and cause serious delays and unexpected congestion (Serrano and Kazda, 2017; Malandri et al., 2017). If the disruption causes the temporary closure of the whole airport, incoming flights will be either delayed to arrive after the re-opening time, or diverted to an alternate airport (EUROCONTROL, 2013). In the latter case, the diversion aerodrome can be chosen among a set of possible ones according to two main criteria. First, the remaining fuel of the diverted aircraft, initially made by "mission fuel" plus "reserve fuel" (Ryerson et al., 2015) must be sufficient to travel to the alternate airport.

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Second, the features of the diversion airport – i.e., runways length, spare capacity, apron facilities –must be suitable to receive the affected flights. Besides these two main criteria, several other factors come into play when seeking out a diversion airport, such as the distance and the presence of a base of handling operations (Kohl et al., 2007). There is extensive body of research regarding how flights are diverted to other airports when they cannot land to their intended destination. Most of them deal with the re-routing problem and airport choice when the scheduled destination airport has a lower capacity than anticipated (Thengvall et al., 2001; Zhang and Mahadevan, 2017). These studies propose methods to solve the operations recovery problem through a series of flights cancellations and delaying and reassignments of aircraft (Løve et al., 2002). Several models have been proposed to minimize the total passenger delay (Teodorovic and Guberinic, 1984; Bratu and Barnhart, 2006) or to minimize the period of time in which the flight schedule is disrupted (Yan and Yang, 1996). In addition, Jafari and Zegordi (2010) propose a model that solves simultaneously the aircraft and passengers recovering. Several studies analyse airport outages impacts, mainly in terms of costs, on the disrupted aerodrome operations – for example, Pejovic et al. (2009) examine the monetary impacts of a short time closure at Heathrow airport.

However, airport outages affect not only the operations at the disrupted aerodrome, but also the punctuality and regularity of operations at the diversion airport. In fact, the alternate airport should provide services other than infrastructures – e.g., turnaround operations like disembarkation/boarding of passengers and aircraft refuelling – resulting in additional workload for ground handlers' resources (Wu and Caves, 2000). The increased amount of aircraft to be serviced may affect the ability to process the scheduled traffic at the alternate airport, thus generating knock-on delays and gridlocks for the successive operations due to limited resource reallocation strategies (Malandri et al., 2019). Therefore, even if the alternate airport is not directly affected by the disruption, delays may arise depending on the number of aircraft diverted.

In this paper, the impacts generated by aircraft re-routing due to an unexpected disruption are analysed by focusing on the alternate airport to which flights are diverted. The main aim is to provide a framework that allows evaluating impacts – mainly in terms of delays and additional ground handler resources required to minimize them – on alternate airports due to the traffic increase caused by diverted flights from other airports. The innovation of the proposed approach is twofold. First, the focus is on the effects generated on the alternate airport, and not on the disrupted one. While previous studies analyse airport outages impacts on the disrupted aerodrome operations (Maertens, 2013; Marzuoli et al., 2016), none of them consider the impacts on the operations of the diversion airport. Second, the approach adopted is based on a simulation model that allows to evaluate impacts on operations as a function of the amount of the available resources. Then, the additional efforts required at the diverted airport have been estimated. The remaining of the paper is structured as follows. Section 2 introduces the methodology to model airport ground operations, while Section 3 describes how aftermaths of aircraft diversions on the alternate aerodrome are estimated. In Section 4, the methodology is applied to the real case of a large European hub (Lisbon airport), and results are discussed. Finally, Section 5 gives the main conclusions and discusses potential future research on the subject.

2. Methodology and baseline scenario

The estimate of the effects generated at a diverted airport by disruption occurring at the original destination airport requires modelling airside operations in the current scenario – referred to as "*baseline scenario"*, i.e. in the absence of disruptions - for the target diversion airport A. The implemented airside model consists of two hierarchical sub-systems (Fig. 1). The first one (higher level) describes the landing and take-off cycles (LTO). The second one (lower level) focuses on modelling aircraft turnaround operations by including the other relevant activities as a function of ground handling operators' availability. A sub-model exists for each ground handler m. At the higher level, the organization of the LTO operations copes with the urgency to both provide safe landing to diverted aircraft and speed up take-off for diverted and planned aircraft, in order to keep safety and efficiency at the airport and reduce delays as much as possible. At the lower level, turnaround operations should be organized in order to comply with LTO exigencies while re-scheduling aprons occupancy and handling operations under limited resource constraints. A discrete event approach is adopted to model LTO cycle and turnaround operations, which are both an ordinate sequence of steps that each aircraft must undergo at the airport (Postorino et al., 2018). Given the complexity of both LTO and turnaround processes, simulation is an appropriate method for assessing performances

(Mota et al., 2017). In this perspective, AnyLogic, a generic simulation software also allowing graphical display of the model, has been used. Once the parameters of the baseline scenario have been validated for the given airport, the system model is ready to be used to explore alternative scenarios – such as disrupted ones where flights from airport B are diverted – and provide assessment for each of them in terms of departure delays and turnaround times.

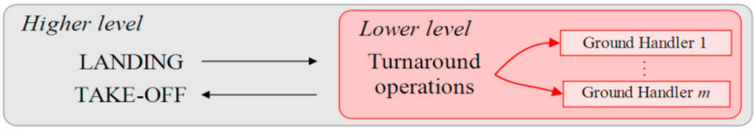

Figure 1. Logic of the model

2.1. LTO cycle model

The main steps of the LTO cycle are represented in Fig. 2, in blue. Let K_A be the set of aircraft movements k_A of airport A in the period T. Starting from landing, the following sequential steps occur (Khammash et al., 2017):

1) aircraft $k_A(a)$, operated by airline a, leaves the runway and following taxiways moves towards its assigned stand, whose allocation depends on some parameters and variables, including aircraft type and airline;
2) at the assigned stand, the aircraft is serviced by the ground handler m ($k_A(a,m)$, described by the turnaround model, see Section 2.2).
3) pushback operations start at the Scheduled Time of Departure (*STD*) with a duration $t_{pushback}$;
4) following the taxi-out procedure, the aircraft arrives at the runway head, where it waits for runway clearance for a time t_{vortex}, which is needed between two consecutive runway utilizations to allow aircraft tail-vortices to dissolve: 60 seconds after narrow body aircraft, 90 after wide body aircraft;
5) additional waiting times at the runway head may be due to queue or expected landing of aircraft within the next two minutes, because departing aircraft must give right-of way to landing ones.

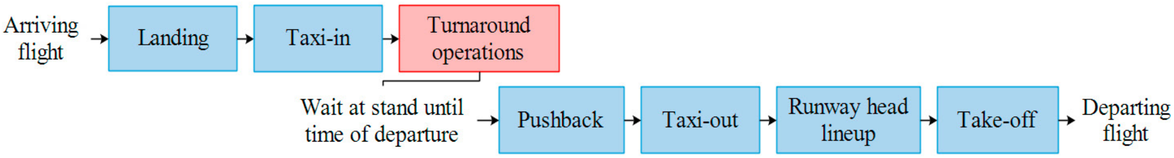

Figure 2. LTO cycle model (in blue)

2.2. Aircraft turnaround model

The turnaround process (Fig. 3) begins when the aircraft reaches its parking position after landing and the chocks are placed in front of the aircraft wheels at the so-called "on-block time". Then, several activities i have to be performed – some sequentially while some others simultaneously (Schmidt, 2017), as depicted in Fig. 3 – to achieve maximum aircraft turnaround efficiency, defined as the ability to execute the required operations within the available time in order to enable a punctual flight departure (Wu and Caves, 2000). Each activity i is composed of several operations o_i each one requiring a time t_{oi}, which is a stochastic variable with a known probability distribution (Table 1). Several service providers - ground handlers, fuel and catering suppliers – have to coordinate with each other in the best possible way to provide an efficient turnaround. When all these activities are completed, chocks are removed and pushback operations start (LTO cycle, see Section 2.1). The following assumptions are made: (1) refuelling takes place between disembarking and boarding, in the absence of passengers; (2) boarding/disembarking times depend on the passengers' number; (3) the aircraft type (narrow or wide body) affects the duration of certain activities; (4) no distinction is made regarding number of doors and hatches of aircraft. The airline's crew is assumed to support and help handling operators in the cleaning, boarding and deboarding operations.

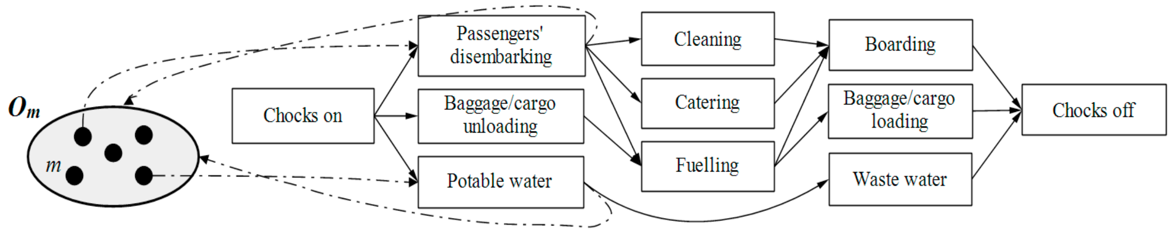

Figure 3. Turnaround model

Let O_m be the set of operators of ground handler m (Fig. 3). Each operation o_i is performed by one or more operators $j \in O_m$, where j=1, …, J_m. Let $k_A(a,m)$ be the aircraft at airport A, operated by airline a and serviced by m. Once o_i is performed, operator j returns available and can perform the subsequent operation. In case O_m is empty, the operation o_i is put on hold until one or more operators j needed to accomplish it are available. Similarly, resources $r_{i\,j}$ - such as catering vehicles, fuel tank, stairs – have to be available to perform the operation i, as they are assumed to be limited in number. Turnaround time $TAT_{kA}\,(m|J_m)$ of aircraft k_A serviced by ground handler m, with J_m operators in O_m, is computed as the difference between the "chocks-off time" $t_{2kA}\,(m|J_m)$ and "chocks-on time" $t_{1kA}\,(m|J_m)$:

$$TAT_{kA}\,(m|J_m) = \sum_i t_{oi} = t_{2kA}\,(m|J_m) - t_{1kA}\,(m|J_m) \tag{1}$$

In the baseline scenario, daily operations are carried out as specified in the schedule and possible delay generally is not due to ground operations inefficiencies. In this scenario, turnaround time is the minimum time required to accommodate the aircraft and prepare it for the following flight.

3. Disrupted scenario and impacts evaluation

In the disrupted scenario, airport A has to manage a set of unplanned aircraft diverted from airport B, supposed to be completely close for a time $T_D = (t_{end} - t_{start})$. Let K_B be the set of diverted arriving aircraft that were expected to land at airport B in the period of disruption T_D. Aircraft are allowed to land in the first available slot given the scheduled flights of the alternate airport A. Two preliminary hypotheses are made: (1) Arriving aircraft - including diverted flights - have right-of-way over departing ones; thus, aircraft expected to take-off have to hold on until no aircraft is approaching to land; (2) Diverted flights cannot hold in the air for more than 45 minutes, according to the regulation on reserve fuel (Ryerson, 2017). It is assumed that airport A has sufficient apron capacity for the aircraft to park. LTO and turnaround models for each diverted aircraft k_B work as described for the base scenario (Section 2). However, some adjustments are necessary to include diverted flights $k_B\,(a,m)$ in the scheduled process (Fig. 4):

1) A will maintain emergency plans to protect airlines from violating the tarmac regulation, which imposes passenger assistance. According to the European Regulation (EU Flight Compensation Regulation 261/2004), if the tarmac delay is more than 1 hour, the airline must offer food, water, access to lavatory and medical care when needed. If the tarmac delay continues, in addition passengers must be disembarked, as also defined in the US regulation. In this study, we assumed that if T_D>3h, passengers are disembarked from aircraft k_B, in line with US regulations;
2) boarding and fuelling operations for diverted flights are unscheduled at A, then their time is assumed equal to t_{oi} + 0,5 t_{oi}, where t_{oi} is the corresponding time in the baseline scenario model;
3) at time $t_{1hour} = t_{end} - 1\ hour$, a notification is given that the disruption at B will we cleared in 1 hour;
4) from time t_{1hour}, there is no need at A to disembark passengers from aircraft k_B, but only refuelling it;
5) at t_{end}, i.e. disruption cleared, diverted flights are prepared to depart according to the following criteria:

- flights landed between t_{1hour} and t_{end} have priority among the others diverted flights, in order to avoid grounding them for more than 3 hours, and they are serviced according to a FIFO rule;
- flights landed before t_{1hour} require also passengers to be re-boarded. They are serviced according to a LIFO scheme, in order to try minimizing delays for the maximum number of flights.

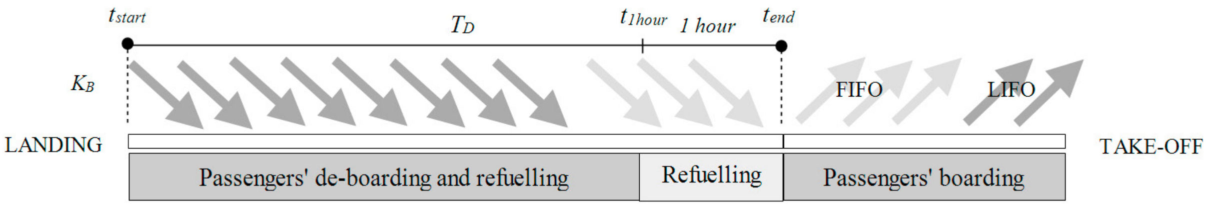

Figure 4. Diversion management model

Impacts on airport A are evaluated in terms of late departures (LD) of flights k_A in the disrupted scenario. Late departures may have two different causes: a) absence of slot/runway availability, related to ATM/infrastructural constraints during the LTO cycle; b) delays in turnaround operations. To evaluate which process is dominant over the other and how the turnaround time influences delays, the average turnaround time of ground handler m over the entire simulation period T is evaluated in both the disrupted and baseline scenarios as a function of J_m:

$$\overline{TAT}\ (m|J_m) = \frac{1}{D_A} \sum_{kA=1}^{D_A} TAT_{kA}\ (m|J_m) \tag{2}$$

where D_A is the number of departing aircraft from airport A. If the number of operators j or resources r_{ij} are not sufficient to bear the additional workload, then the turnaround process could generate a dramatic increase in delays. Therefore, if a higher number of operators are available, delays could be contained. To evaluate at what amount a higher number of operators might contain delays, several scenarios have been simulated by increasing the number of operators of the baseline case, J_m, by a percentage P_m. If the increase of J_m does not produce shorter turnaround times, and then delays are not reduced, late departures are caused by runway capacity constraints (slot availability). Finally, it is assumed that the airport catering vehicles, fuel and water trucks are used at their full extent and r_{ij} is assumed to be constant throughout the simulation period.

4. Results and discussion

Lisbon airport "Humberto Delgado" (LIS), which is the most important Portuguese hub and the 20th largest airport in Europe in terms of passengers, has been considered to test the proposed approach. Lisbon Airport has two crossing runways (RWY). RWY03 – estimated capacity 38 movements/h – is the preferred one, while RWY21 is used in case of bad weather. The airside consists of 10 aprons with 74 stands.

To validate the baseline scenario, both LTO and turnaround processes have been simulated for a period T = 24h, in a summer peak traffic day (4th August 2018), with 209 flights scheduled to depart and varied airlines and aircraft types. In particular, 32 airlines operate at least one flight during the day, among which 12 low-cost carriers summing up as much as 30% movements. The aircraft mix is 95% narrow-body and 5% wide-body. As for the time t_{oi} required to perform each ground operation for each activity (see Table 1), it has been taken from the literature (Bevilacqua et al., 2015; Mota et al., 2017). Fig. 5 shows aircraft arrivals and departures – real flight schedule – per hour during the simulation period. Departures have two peak periods (8:00-11:00 and 18:00-20:00) with approximately 30 movements/h. It is reasonable to assume that, in these periods, the infrastructure is used at almost its entire capacity and undesirable criticalities are expected. The simulation of this baseline scenario by AnyLogic gives an average turnaround time of about 53 min, with a minimum of 48 min and a maximum of 58 min.

In the disrupted scenario, Porto International Airport (OPO) is supposed to be temporarily unavailable, which is realistic due to the strong Atlantic crosswinds affecting OPO Airport's area. In this study, the unplanned disruption is assumed to last 5 hours, from 07:00 to 12:00 AM, during which flights are diverted to the near Lisbon hub. Thus, an additional number of arriving flights is considered at LIS airport during the morning peak period (in grey in Fig. 5), with an average of 10 additional flights/hour. At 11:00, the notification is given that the disruption will be solved in 1 hour. Finally, 5 hours after the beginning of the outage, the disruption is assumed to be cleared and aircraft are prepared to depart for the original destination, following prefixed priority rules (FIFO/LIFO, see Section 3).

Table 1. Turnaround operations and corresponding durations

i	Activity *i*	Operation o_i	Operators *j*	t_{oi}
1	Chocks on / off	-	1	30 secs
2	Passengers disembarking/ boarding	Stairs positioning/removing	2	T* (1.8, 2, 2.3 min)
		Passengers disembarking/boarding	-	12 pax/min
3	Cleaning	Cleaning	2	T (13, 16.5, 19.5 min)
4	Catering	Catering truck connection/disconnection	2	T (0.95, 1.15, 1.3 min)
		Catering loading/unloading		T (10, 12, 14 min)
5	Potable Water	Water truck connection/disconnection	1	T (0.65, 0.8, 0.95 min)
		Potable water replenishment		T (4, 5, 6 min) - *Double for wide-body*
6	Waste Water	Waste water truck connection/disconnection	1	T (0.65, 0.8, 0.95 min)
		Waste Water		T (4, 5, 6 min) - *Double for wide-body*
7	Baggage/Cargo Unloading	Loader positioning/disconnection	3	T (40, 60, 80 sec)
		Arriving baggage/cargo unloading		T (5, 7, 9 min) - *Double for wide-body*
8	Refuelling	Fuel truck connection/disconnection	1	T (1.0, 1.2, 1.4 min)
		Refuelling		T (7, 8, 9 min) - *Double for wide-body*
9	Baggage/Cargo Loading	Loader positioning/disconnection	3	T (40, 60, 80 sec)
		Departing baggage/cargo loading		T (5, 7, 11 min) - *Double for wide-body*

*T is the triangular distribution, characterized by its min, max and mean values: T (min, mean, max)

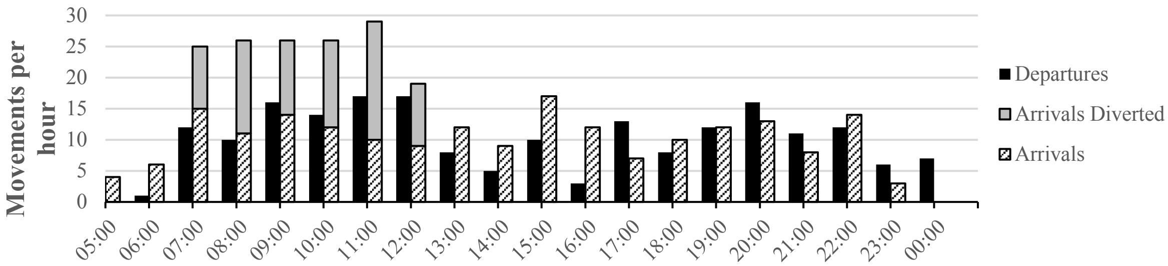

Figure 5. Arrivals and departures per hour at Lisbon "Humberto Delgado" Airport

Fig. 6 shows the percentage of departed flights during the simulation period under several conditions. Normal operations are described by the "base scenario" line. When there are also diverted flights ("J_m=100%" line, corresponding to 100% employment of the operators for the ground handler *m*), scheduled departures cannot be met and delays, significant from the beginning of the disruption (07:00), spread over the day. Some flights (almost 10%) take-off after 23:00, when there are no scheduled departures in the baseline scenario. A flight is considered delayed if its actual departure time (ATD_{kA}) is more than 5 minutes higher than the scheduled "off-block" time (STD_{kA}). By assuming that delays are caused by ground operations (see Section 3), a higher number of ground operators could mitigate them. In this perspective, several disruption scenarios are simulated by considering an increase in the number of available operators by a percentage P_m. As shown in Fig. 6, for J_m=110% delays are only slightly reduced compared to the disrupted scenario with J_m=100%. For J_m=120%, delays are reduced more significantly and, in some periods of the day, departures fit the schedule. With J_m progressively increasing (J_m=130%, J_m=140%, J_m=150%), results are the same in each scenario (coincident lines). In such scenarios, delays are no longer related to turnaround operations and a key role is played by slots unavailability, as flights cannot depart because other ones are landing, or diverted flights are departing. In particular, landing aircraft generally have priority on take-off aircraft, particularly if there are diverted arriving flights. Another offset can be observed between the disrupted and baseline scenarios (18:00 – 21:00) due to runway congestion caused by diverted departing traffic. One of the results provided by the simulation are turnaround times ($\overline{TAT}$, in Table 2). Average and maximum *TAT*s are evaluated for each alternative scenario and then compared to the case of no-disruption. Fig. 7a depicts the average turnaround time $\overline{TAT}$ as a function of J_m. As it can be seen, a quick and significant reduction in $\overline{TAT}$ is observed for J_m increasing up to 125%. After this value, the marginal gain in such times is not as much significant as in the first part, and $\overline{TAT}$ decreases by less than 10% with respect to the previous scenario. As expected, reduced $\overline{TAT}$ allows a reduction in the number of delayed flights (late departures *LD*) (Fig. 7b). It can be observed that for J_m = 120%, on-time departing flights are more than 25% more with respect to the scenario with J_m=100%. However, for J_m > 120% (red line in Fig. 7b), the number of late departures *LD* is almost the same and decreases are small (1-2%), thus indicating that the allocation of further resources would no more increment the departure punctuality.

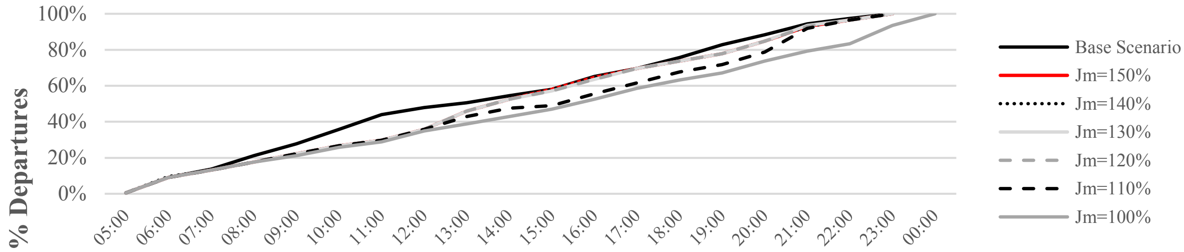

Figure 6. Percentage of departed flight during the simulation period as a function of *Jm*

Table 2. Turnaround times in the disrupted scenario as a function of the number of operators *Jm*.

J_m	$\overline{TAT}$	% increase w.r.t. base scenario	Max *TAT* (min)	St. Dev. (min)
100%	04:15:11	377%	06:10:43	01:23:56
105%	02:36:27	192%	04:49:04	01:17:16
110%	02:35:41	191%	04:22:02	01:02:06
115%	01:49:43	105%	03:38:02	00:51:05
120%	01:26:34	62%	03:03:13	00:37:51
125%	01:12:04	35%	02:08:59	00:20:22

J_m	$\overline{TAT}$	% increase w.r.t. base scenario	Max *TAT* (min)	St. Dev. (min)
130%	01:06:41	25%	02:01:10	00:18:26
135%	01:03:07	18%	01:55:03	00:15:17
140%	00:59:12	11%	01:35:19	00:08:38
145%	00:58:40	10%	01:28:32	00:07:54
150%	00:57:49	8%	01:21:31	00:06:57

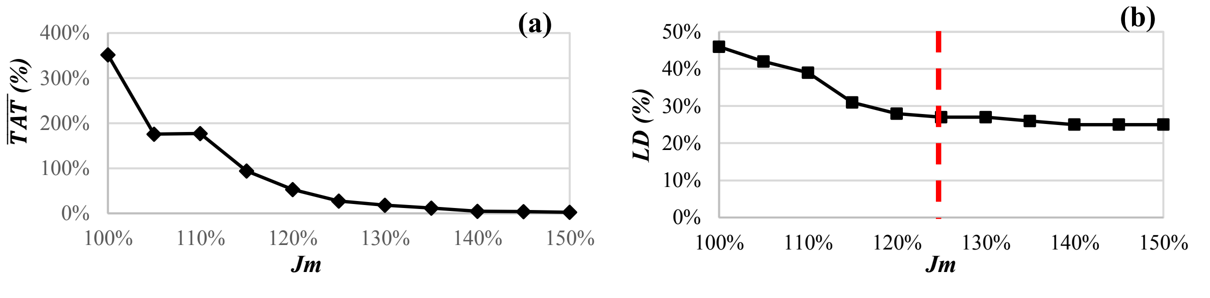

Figure 7. (a) Average turnaround time and (b) % of late flights as a function of *Jm*

5. Mains findings and conclusions

This study has addressed the issue of the impacts caused by flights diverted at an alternative airport due to disruption at the original destination airport. Particularly, the impacts have been estimated in terms of delays imposed to departing flights at the diverted airport, which has to manage unscheduled traffic with the available resources, and at the same time must comply with the need to assure both safe landing to diverted aircraft and scheduled departure for its flights. Two main comments come from the results of this study. First, the number of available operators for each ground handler operating at the diverted airport is generally planned to meet the original scheduled traffic, although some additional resources are considered for safety and efficiency issues. However, in case of significant unscheduled traffic, the number of available operators play a crucial role. As the results depicted in Fig. 7a show, to control delays for departing flights the number of operators should be increased by about 25% in the case study. In other words, 25% of additional resources should be considered at the airport in order not to raise delays over an acceptable threshold. However, disruption has to be considered an infrequent event, then raising resources that will be unused for the majority of the time is not a feasible action for stakeholders. The second comment is linked to the infrastructure availability at the diverted airport. As the simulation showed, after a given threshold – about 125% in the case study – delays are no more due to operators and depend on capacity constraints (lack of available runway/slot). In fact, when the runway capacity is reached (38 movements/h in the case study), flights cannot depart because other ones are landing, which have priority on takeoffs, or diverted flights are departing. It appears that, in both cases, coordinated actions have to be thought among nearest airports in order to manage together the effects of disruption at the original airport. In fact, virtually sharing resources and infrastructure capacity seems one of the best action put in place in order to reduce delays for the involved flights – both scheduled and diverted. Apart from exploring these strategies and their related, multifaceted effects, further developments are expected in the estimation of losses caused by delays included personnel rotation and management.

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