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A method to evaluate the time of waiting for a late passenger

Jacek Skorupski*, Magdalena Wierzbińska

Warsaw University of Technology, Faculty of Transport, 00-662 Warszawa, ul. Koszykowa 75, Poland

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ABSTRACT

The paper presents the problem of searching for the right amount of time needed to wait for a passenger who is late for boarding a plane. This problem, although practically ignored by airline and handling agents' operational manuals, is common and very important for flight punctuality, and thus for both passenger satisfaction and the financial performance of air transport companies. The discrete Dynamic Programming task for finding the minimum amount of time wasted on waiting for a late passenger, depending on the moment in time in which the passenger arrives, is formally defined in this paper. The task is solved based on sample data. Dependence of the results on the average period of time needed to find the luggage of a passenger who did not arrive for boarding is examined. The paper also presents the preliminary results of the impact of the random variable describing the arrival time of the last passenger on the moment when the decision to stop waiting should be made. The function, which allows to determine the expected value of that lost time, was specified for different moments of the end of waiting by taking into account the random characteristics of the arrival of the last passenger. The obtained results show that in each of the analyzed cases there is a global minimum of that function. The moment for which the minimum occurs can be considered as the optimal (in terms of time wasted on waiting) moment to stop waiting for the late passenger.

1. Introduction

Today, time plays a very important role in air traffic, both for airlines and passengers. Air carriers (like any other entrepreneur) expect the largest income at minimum cost. Each carrier's strategic goal is to best utilize its aircraft fleet, thus to carry out a maximum number of flights in the shortest time possible with the greatest occupancy (load factor) of an aircraft (Clark and Vincent, 2012; Mayer and Scholz, 2012).

However, the fastness and timeliness of carriage depends on many factors, one of which is aircraft ground handling. In this paper, the boarding procedure is considered as an important source of primary delays in air transport. According to the International Air Transport Association (IATA) classification, the delay, which the work here refers to has been placed in the group "Passenger and baggage", which consists of nine subgroups of delay causes (IATA, 2014):

– late check-in due to passenger acceptance after the deadline (IATA code: 11 PD)
– late check-in due to congestion in the check-in area (12 PL)
– errors during passenger or baggage check-in (13 PE)
– problems with booking errors, especially overbooking (14 PO)
– discrepancies during boarding, missing checked-in passenger (15 PH)
– problems with a VIP passenger, missing personal items (16 PS)
– late or incorrect order given to the catering supplier (17 PC)
– problems with baggage processing, sorting, etc. (18 PB)
– boarding or deboarding of passengers with reduced mobility (19 PW).

Delays in this group have constituted, in recent years, about 5% of all delays and place fifth among categories of delays caused by the air carrier (Guest, 2007). In recent years, different coding schemes of delay causes have been proposed. Studies demonstrate that these allow for advanced delay analytics, e.g. large-scale delay propagation tracing in an airline network (Wu and Truong, 2014).

1.1. Airlines and the problem of late passengers

Airlines use various and mostly intuitive approaches to the problem of late passengers. The applied procedure gives only a general indication of the action taken. In addition, as will be further

* Corresponding author.
E-mail address: jsk@wt.pw.edu.pl (J. Skorupski).

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revealed, these procedures are often contradictory.

The Ground Handling Manuals of many carriers ignore how to act in such situations. In order to make a decision about waiting for a late passenger it is necessary to consider many factors, not always those related just to cost evaluation of lost time of passengers from a considered flight. One of these factors may be, for example, the weather forecast announcing bad weather at the destination airport. Another factor may be the work time of the cabin crew, which is subjected to certain standards and cannot be exceeded. It is also necessary to take into account the number of transfer passengers in relation to the total number of passengers and their status (VIP, Business Class). Another important factor influencing the decision is the planned arrival time at the destination airport. If it is close to the closing time for the destination airport then the aircraft must arrive on time, and waiting for late passengers is unacceptable. Restrictions on arrivals may result from procedures that have been introduced to reduce noise and emissions. The list of airports with such restrictions is relatively long (Wilder, 2014). Another criterion that must be taken into consideration is whether the late passenger has checked baggage on board. If not then the decision to stop waiting is easier because it is not necessary to search for that baggage.

The most common official position of airlines is that late passengers should not be waited on. The decision to wait, especially in the case of charter airlines, can be made only in exceptional circumstances and only after consultation with the airline operating center (Titan, 2012; SATA, 2011; Neos, 2005). However, some operating instructions clearly indicate that in case of discrepancies in the checked-in and boarding number of passengers, the handling agent should organize a search for the absent person and give an individual announcement about boarding completion and the number of the boarding gate (Rossiya, 2013). This procedure, however, is rare. In addition, in these instructions there is no limitation in the period of time that can be spent on searching for the absent passenger or on waiting for him or her.

For example, one of the largest European airline carriers (which requested anonymity so its name will not be provided), operating on a global scale, also as part of a large airline alliance, believes that the carrier should not wait for a single late passenger.[1] Personnel operating boarding should endeavor to complete it 10 min before the scheduled departure time, and then the aircraft door should be closed. If 12 min before the scheduled departure time it is stated that a passenger who has checked-in baggage does not show up, the personnel should start the procedure of searching for and unloading the luggage. This operation takes approximately 3–10 min for an aircraft in which bags are placed directly in the baggage holds. This time period depends on the location of the luggage (close to the baggage hold's door or further, beneath the other baggage) and if the company has a support system to carry out the procedure of searching. For aircraft in which the bags are first loaded into containers and then into the aircraft, baggage unloading time can be much longer, as it depends not only on the baggage position in the aircraft but also on the availability of special equipment, without which it is impossible to move the containers. If there is insufficient equipment of this type at the airport, it is highly probable that there will be a need to wait for these activities to end. The time needed to wait before unloading the baggage is in this case very difficult to estimate, but it can be as high as several tens of minutes. An essential element of the procedure is the principle that once searching for luggage has started, then even if the passenger arrives for boarding before the end of the search, he or she will not be allowed to board the aircraft.

[1] Airline X, 2014. Procedures in case a passenger is late for boarding, personal communication.

In this article we consider only the situation when luggage is placed directly in the hold of the aircraft, without containers. Even a superficial analysis of the presented procedures shows that the average time needed to unpack luggage of an absent passenger is 7.5 min, which means that it is impossible for the aircraft to be ready to leave the parking area 10 min before the scheduled departure time, as assumed by the airline. As can be seen, this general procedure is internally inconsistent. The absolute priority of the departure time as declared by the respondent airline is, in fact, not executed. The described procedure for boarding also does not take into account the reserve, which in many cases could reduce the departure delay or even allow for departure on time. The way to deliver the passengers to the plane is also not included and can vary considerably. There is, therefore, great potential to improve current procedures, as operating based on fixed values of time, in our opinion, does not give the assumed results.

1.2. Overview of the state of research

In the literature there are many studies on searching for the optimal boarding strategy in which the requirement of minimizing the loading time of passengers has been taken into account, e.g. (Nyquist and McFadden, 2008; Soolaki et al., 2012; Tang et al., 2012; Milne and Kelly, 2014; Bazagran, 2007; Bachmat and Elkin, 2008; Steffen and Hotchkiss, 2012; Steffen, 2008; Qiang et al., 2014) are some of the many interesting papers on the topic. It should be noted, however, that regardless of the boarding strategy, an airline can face the problem of a passenger that is late for boarding the plane. This problem is particularly severe in situations when a passenger has checked-in baggage that has been loaded into the hold of the aircraft. On the one hand, the late passenger should be waited on because, in accordance with the regulations in force (European Parliament, 2008), the aircraft cannot take off if not all owners of baggage located in the holds are on board. Once the decision to stop waiting is made, the baggage of the person absent must be removed from the aircraft. This, of course, requires time and can generate delays. If such a decision is made too early, there is the possibility that the passenger will arrive during the search for his/her luggage. On the other hand, waiting too long may result in loss of the take-off slot, and thus may result in an increase in carrier costs for other passengers, the airport, or even for the crew of the aircraft which is restricted with its working time. Extending the time of occupying a parking space, especially at smaller airports, forces the aerodrome operator to change the use of a fixed timetable of gates and parking areas so that other aircraft can be handled without disruptions.

The decision problem discussed above is an issue that should be considered in a broader context. There are many factors affecting the operation of air carriers in the face of danger or flight delay. Work on this subject was conducted, for example, by Xiong and Hansen (2013), who analyzed the circumstances in which carriers decide to cancel a flight in the event of changes to take-off slots. The issue of the availability of slots was also undertaken in our work. There are many methods for slot reallocation, and these may have an impact on the solution to the decision problem posed in this work (Bard and Mohan, 2008; Torres, 2012; Bertsimas et al., 2011).

The problem of late passengers is relatively rarely undertaken in the literature. Ferrari and Nagel (2005) took it into account as interference in their analysis of the impact of boarding strategy ability to minimize turn-around time. It was also mentioned by Yfantis (1997), who proposed the baggage tracking system as a part of the baggage security services support. Such a system is important from the point of view of our work because it has an impact on the time needed to search for luggage if it is necessary to unload it from the aircraft hold. This time has been included in our model.

One of the key elements included in our model is the probability distribution of the arrival time of the late passenger. This time is dependent on many factors. One of them was analyzed in a work (Lin and Chen, 2013) which addressed the motivations of passengers to make purchases and other commercial activities at airports. Another important element is the level of service for wayfinding in airport terminals, which is the subject of Churchill et al. (2008).

1.3. Concept of the work

The decision-making problem arises – How long do we wait for a late passenger? As can be seen from the literature review, there is no universal approach to this problem. Each air carrier uses a different strategy which is mainly based on an intuitive evaluation of various possible actions. Thus there is a potential for searching for solutions which, on the one hand, will minimize the costs associated with delays and, on the other hand, the carrier will reflect commitment to the service of carriage, even in relation to late passengers.

In our opinion, the analyzed problem is very practical. Making the decision not to wait for a late passenger leads to a baggage search, which sometimes lasts long because different problems resulting from labeling defects, handling agent errors or the need to use additional equipment cannot be excluded. In the meantime, the passenger might show up for boarding. In addition, the person making the decision not only follows some sort of economic calculation but also takes into account the human aspect. A passenger that is not admitted to board the aircraft may have serious business or personal problems and his or her delay may be the result of objective problems rather than carelessness or recklessness. Taking into account the human aspect does not necessarily lead to an economically optimal strategy, which in most cases is a very short waiting period.

The paper's contribution to the subject is a presentation of a mathematical discrete model of this situation and a method that allows to find a satisfying solution. However, the main focus was put on estimating the expected value of the passengers' lost time (PLT) as a function of the random variable describing the time of arrival for boarding of late passengers. Generally, we define PLT as

$$PLT = (t_{of} - t_{bw}) \cdot N \tag{1}$$

where:

t_{of} – time the aircraft finishes the taxiing procedure and is ready for take-off
t_{bw} – time when waiting for late passengers begins; the way t_{bw} is determined will be discussed later
N – number of passengers.

In this paper we look at the problem from the passenger's point of view. This is due to the fact that one of the factors determining the commercial success of an air carrier is the confidence and sympathy of passengers. A carrier that strictly uses the slightest passenger delay to refuse the service must take into account a loss of customers, and thus lower profits. On the other hand, by waiting too long a carrier is liable to dissatisfaction of passengers who came on time. In this sense, PLT is a component of the cost function of the carrier. There is no analysis of this issue in the literature, thus our work seeks to fill this gap.

2. The optimization problem of the waiting time period for a late passenger

The model of time dependencies describing the procedure of boarding was formulated in order to provide a formal definition of the task of optimizing the waiting time for a late passenger. In this paper it will be called the boarding model. This will be an extended version of the model presented in Skorupski and Wierzbińska (2013).

Let t_c be the nominal end time of the passengers' check-in at the gate, understood as the moment of servicing last passenger. Nominal boarding time period should be chosen in such a way that all passengers can take their places on the plane, to be able to perform all pre-departure activities (such as checking seat belts or presenting the safety instructions) and taxiing for take-off. In the analysis it will be assumed that the appropriate basic take-off slot has been determined and defined by the interval $S^0 = [t_b^0, t_e^0]$. In Europe, introduction of the so-called airport co-ordination, whose use is take-off slots, is regulated by the (European Council, 1993). About 50% of European airports have coordinated departure traffic.

It is important that the aircraft is ready to perform departure at moment $t_r \in S^0$. This moment can be determined as follows (Fig. 1):

$$t_r = t_c + d_{tr} + d_o + d_c + d_{TX} \tag{2}$$

where:

d_{tr} – time needed to transfer passengers to the plane, which varies depending on the technology used, e.g. by passenger loading bridge, bus or on foot
d_o – time required for preparatory activities with the door of the plane open
d_c – duration of preparatory activities with the door of the plane closed, at the same time it is assumed that at this time it is no longer possible to let in a late passenger
d_{TX} – taxi time.

Depending on the current situation, including the existing delay, some of the above times may vary slightly, but at this stage we assume that these times are fixed and minimal, i.e. they cannot be shortened. Furthermore, we assume that after the decision to stop waiting for a late passenger has been made, he or she will not be allowed to enter the aircraft even if he or she arrives while the baggage search is taking place.

All passengers who arrive at the gate before time t_c can board the plane without any problems, without causing delays or additional costs.

The situation when an aircraft is ready for take-off before the beginning of the first slot ($t_r < t_b^0$) is possible. In this case the aircraft is not allowed to depart but has to wait until t_b^0. This constitutes a kind of reserve, i.e. the time when the boarding gate service can freely wait for a late passenger without any costs regarding PLT. Thus this reserve may be taken into account at time t_c (Fig. 2). The reserve equals:

$$r = t_b^0 - t_r \tag{3}$$

After $t_c + r$, in the case of single late passengers it is still possible

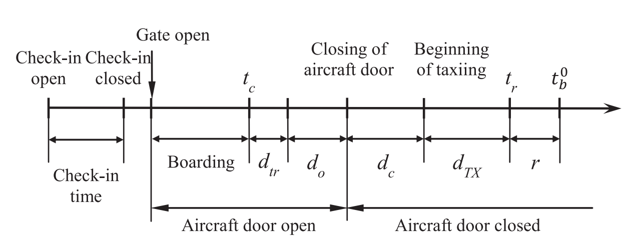

Fig. 1. Timeline of take-off preparatory steps.

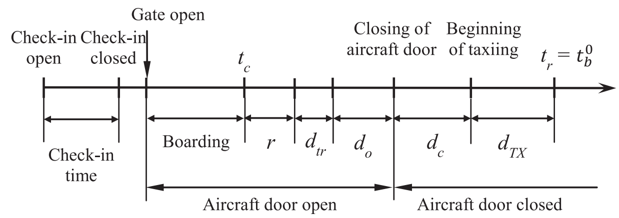

Fig. 2. Timeline of take-off preparatory steps, reserve r moved to the beginning of the waiting process.

to let them on the plane without generating additional costs, if the moment of their arrival t_l satisfies the condition:

$$t_l < t_c + r + d_o \tag{4}$$

Let t_0 be the moment from which further waiting for a late passenger involves additional costs resulting from wasted time, having characteristics as discussed above. This time was designated t_{bw} in Formula (1). Moment t_0 can be calculated from the equation

$$t_0 = t_c + r + d_o \tag{5}$$

The time period starting from moment t_0 will be treated as discrete and the following moments will be denoted by t_i, $i = 1,2,\ldots$. Generally, the discretization interval may adopt any value, but in this paper we assumed that it equals 1 min. For each of these moments a binary decision variable will be defined as x_i receiving a value of 0 if at moment t_i it was decided to wait for a late passenger, and value 1 if at moment t_i it was decided to stop waiting and to start the procedure of searching for the late passenger's baggage to unload it from the baggage hold. In addition, it is assumed that the full pre-departure procedure will be carried out after unloading the baggage of a passenger who did not show up on time for boarding.

With this specific boarding model we can formulate the task of searching for the optimal time to wait for a late passenger. On the one hand, starting the procedure of searching for luggage belonging to a passenger who did not show up on time for boarding too early may result in costs associated with the search itself and, in consequence, in departure delay, including possible loss of the take-off slot. On the other hand, long waiting also generates costs associated with loss of the other passengers' time. In addition, it may be ineffective because the missing passenger may not arrive at all and the procedure for searching and unloading his or her baggage will still have to be performed.

In the analyzed case we are faced with a decision made in conditions of elapsing time. For each subsequent point of time it is necessary to decide whether to wait for the missing passenger(s) or to stop waiting and proceed with the baggage search procedure. We therefore propose to formulate a Dynamic Programming (DP) task that can serve the search for the optimum waiting time for a late passenger, with the optimization criterion consisting in minimizing PLT. Further work will also search for a solution of this problem for other optimization criteria, such as cost criteria (total cost or average cost per passenger). Dynamic Programming is a mathematical optimization method which is ideal for dealing with multi-stage decision problems. At every stage the decision is of a similar nature, but the set of admissible decisions is affected by the so-called state variable. The typical way of solving the Dynamic Programming problem is based on recursive relationship formulation, so that we can begin the search for optimal solutions from the last stage and then increase the analyzed subproblems. In the last step we obtain a solution for the whole initial problem.

We suggest the following formulation of the DP problem.

1. Specify the maximum horizon of waiting T. This value should be defined by taking into account organizational and cost criteria. This may result, for example, from the maximum working time of the crew, airport opening hours due to noise or emissions restrictions, the time after which it will be necessary to cancel the flight due to the impossibility of realizing the rotation, etc. Since the model does not consider air carrier costs in detail, variable T can be used as a constraint which does not allow to generate a solution that is unacceptable due to costs.
2. At the i-th stage we decide if at time t_i we should stop waiting for late passengers, which means: we specify the value of binary decision variable x_i.
3. System state variable y is the remaining time period to the end of the horizon of waiting T.
4. $f_i(y,x_i)$ describes the optimization function and is equal to total minimum PLT in moments $t_i,t_{i+1},\ldots,T$ under the condition that the remaining time to the end of the horizon of waiting is y and that it was decided x_i, thus indicating whether to continue waiting ($x_i = 0$) or to stop waiting and start searching for the baggage of the absent passenger ($x_i = 1$).
5. $f_i(y)$ – total minimum PLT in moments $t_i,t_{i+1},\ldots,T$ if the remaining time to the end of horizon of waiting is y. This means that function $f_i(y)$ expresses the lowest value of the goal functions $f_i(y,x_i)$ obtained at the best possible decision x_i for a given value of the state variable y.
6. Denoting by N the number of passengers on board the aircraft and by $\overline{d_S}$ the expected average search time of the absent passenger's baggage, we can define the following recursive relations:

$$f_i(y,x_i) = \begin{cases} (t_{i+1} - t_i)\cdot N + f_{i+1}(y - (t_{i+1} - t_i)), & \text{for } x_i = 0 \\ \left(\overline{d_S} + d_o + d_c + d_{TX}\right)\cdot N, & \text{for } x_i = 1 \end{cases} \tag{6}$$

$$f_i(y) = \min(f_i(y,0) + (d_o + d_c + d_{TX})\cdot N, f_i(y,1)) \tag{7}$$

Of course, Formula (6) has a different form for the decision to wait and not to wait. In the former case it consists of a waiting time period in the i-th stage and in all subsequent stages beginning from $i+1$. In the latter case it consists of the baggage search time period together with the time associated with preparatory operations for take-off.

Both the decision to wait for a passenger as well as to start searching for his/her baggage may result in a situation when the aircraft is ready to take off after the slot. To take this into account it is necessary to define other possible take-off slots $S^n = [t_b^n, t_e^n]$, but it is considered only for those slots S^n for which the following condition is satisfied

$$t_b^n \le T + d_{pr} \tag{8}$$

where $d_{pr} = d_o + d_c + d_{TX}$ is the time needed to prepare for departure after the procedure of waiting for a late passenger or the procedure of unloading the baggage of a passenger who did not arrive for boarding has taken place.

For each stage i of the decision-making process a function determining the value of additional delay associated with exceeding the current take-off slot can be defined. This function is given by

The first line of Formula (9) corresponds to the situation when

$$g_i(x_i) = \begin{cases} 0, \; if \; \left(x_i = 0 \wedge \exists n: \; t_{i+1} + d_{pr} \in S^n\right) \vee \left(x_i = 1 \wedge \exists n: \; t_i + \overline{d_S} + d_{pr} \in S^n\right) \\ t_b^n - \left(t_{i+1} + d_{pr}\right), \; if \; x_i = 0 \wedge \exists n: t_e^{n-1} \le t_{i+1} + d_{pr} \le t_b^n \\ t_b^n - \left(t_i + \overline{d_S} + d_{pr}\right), \; if \; x_i = 1 \wedge \exists n: t_e^{n-1} \le t_i + \overline{d_S} + d_{pr} \le t_b^n \end{cases} \tag{9}$$

after any decisions have been made the aircraft is ready for take-off in the time period that belongs to the take-off slot. The second line is the situation when after the decision to wait has been made the aircraft is ready for take-off in the time period between two slots. The third line is similar to the second one, but after the decision not to wait has been made.

Finally, the recursive relations (6–7), after taking into account function (9), take on the form of

$$f_i^*(y, x_i) = \begin{cases} (t_{i+1} - t_i + g_i(0)) \cdot N + f_{i+1}^*(y - (t_{i+1} - t_i + g_i(0))), \quad for \; x_i = 0 \\ \left(\overline{d_S} + d_{pr} + g_i(1)\right) \cdot N, \quad for \; x_i = 1 \end{cases} \tag{10}$$

$$f_i^*(y) = \min\left(f_i^*(y, 0) + d_{pr} \cdot N, f_i^*(y, 1)\right) \tag{11}$$

Variable x_i^* will denote the decision in time t_i that corresponds to the shortest time $f_i^*(y)$. In further calculation experiments the recursive relation given in Equations (10) and (11) will be used.

3. Analysis results using the boarding model

The Dynamic Programming task presented in Section 3 does not solve the problem of the waiting time period for a late passenger without analyzing the probability distribution of the arrival time of the last passenger. Section 5 will be devoted to this issue. The model enables, however, to determine the minimum passengers' lost time for a given time of arrival of the last passenger, on condition that the optimal decision x_i^* was made. We consider cases with one delayed passenger and with a few delayed passengers. In addition, we present a modification of the model for the case when the take-off slots are not used.

3.1. Calculations for the basic model with one late passenger and take-off slots

The following parameters of the boarding model were taken into account: $d_{tr} = 3$ min, $d_o = 3$ min, $d_c = 3$ min, $d_{TX} = 7$ min, $N = 120$ passengers, $\overline{d_S} = 7$ min, take-off slots: S^0=[20,25], S^1=[35,40], S^2=[55,60], S^3=[70,80].

For the assumed input data the dependence of the minimum PLT that can be achieved, knowing when the last passenger will arrive, with the appropriate decision being made, on the last passenger's arrival time, was obtained. The last passenger's arrival time is counted from t_c, i.e. from the end of the passengers' check-in at the gate (Fig. 3). This graph can be interpreted as follows:

- if the last passenger arrives within 7 min from the end of nominal boarding completion, waiting for him or her will not cause any departure delay because it is still before t_0 which represents the starting point of costs generation; t_0 is computed in the following way:

$$\begin{aligned} t_0 &= t_c + r + d_o = t_c + t_b^0 - t_r + d_o \\ &= t_c + t_b^0 - t_c - d_{tr} - d_o - d_c - d_{TX} + d_o = t_b^0 - d_{tr} - d_c - d_{TX} \\ &= 20 - 3 - 3 - 7 = 7 \end{aligned}$$

- if the last passenger does not arrive exactly in the 7th minute, i.e. at moment t_0 and the decision to stop waiting is made, the cost associated with the time of finding and unloading luggage will incur, amounting to 3360 min; this value was determined by g_{min} and computed in the following way:

$$\begin{aligned} g_{min} &= \left(\overline{d_S} + d_{pr} + t_b^1 - \left(t_0 + \overline{d_S} + d_{pr}\right)\right) \cdot N = \left(t_b^1 - t_0\right) \cdot N \\ &= (35 - 7) \cdot 120 = 3360 \end{aligned}$$

- by t_{max} the maximum waiting time has been designated which corresponds to the last moment in which the delay associated

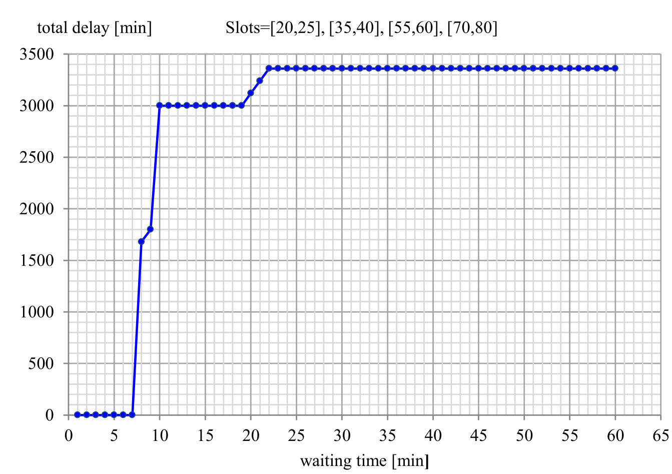

Fig. 3. Minimum total delay time of all passengers, depending on the time of waiting for the last passenger.

with waiting for a passenger is less than or equal to g_{min}; in the case being analyzed $t_{max} = 22$ *min*, which is computed in the following way: if the passenger comes at t_{max} then the aircraft is ready for take-off at $t_{max} + d_o + d_{tr} + d_c + d_{TX} = 22 + 16 = 38$ and the corresponding waiting time is $(t_{max} - t_0 + d_{pr}) \cdot N = 28 \cdot 120 = 3360 = g_{min}$.

– if the last passenger arrives before t_{max} then the right decision is to wait for him or her because the delay resulting from the waiting is less than that of a baggage search; if the last passenger does not arrive before t_{max} then the right decision is to stop waiting at some moment t_x; if it is not made before t_{max} then the need to unload the luggage will increase the delay; in the presented example this is up to 5760 min; this value was designated by g_{max} and computed in the following way: if we stop waiting at time t_{max} then the aircraft is ready for take-off at $t_{max} + d_o + d_c + d_{TX} + \overline{d_S} = 22 + 20 = 42$, which is outside the take-off slot and means that it is necessary to wait until time $t_b^2 - (d_{tr} + d_c + d_{TX} + \overline{d_S}) = 35$, and the corresponding waiting time equals $g_{max} = (t_b^2 - t_0) \cdot N = (55 - 7) \cdot 120 = 5760$.
– part of the graph between the 10th and 19th minute where there is a constant value of total delay means that if the last passenger does not come before the 10th minute the first take-off slot is lost and the need to wait for the beginning of the next slot makes the delay constant for a certain period of time.

As was already indicated in Section 2, there are many factors affecting the decision to either stop waiting or to continue waiting for a late passenger. Among the elements included in the presented boarding model, the most interesting is the dependence on t_{max}, g_{min}, and the PLT as a result of waiting on the value of $\overline{d_S}$, i.e. the average time of searching for the passenger's baggage. Values specified by the carrier, whose strategy was discussed in Section 2, were used.

$$\overline{d_S} \in [3, 10] \cap \mathbb{N} \tag{12}$$

Table 1 shows the results of calculations carried out for different values of searching and unloading luggage time $\overline{d_S}$, which indicate that although the maximum waiting time for a passenger is either 9 or 22 min, we should not wait longer than to moment t_x as defined in the last column. This time period defines the last minute for which we can achieve cost g_{min} upon the decision not to wait for the absent passenger. A longer waiting period causes a significant increase in costs for the decision to terminate waiting. If the decision maker has no information about the probability distribution of the arrival of the last passenger, a strategy for ending the waiting in the time interval $[t_0, t_x]$ should be taken.

Table 1
Results of model analysis for various values of baggage search time.

$\overline{d_S}$	t_{max}	g_{max}	g_{min}	t_x
3	9	2160	1920	7
4	9	3360	2040	7
5	9	3360	2160	7
6	22	5760	3360	16
7	22	5760	3360	15
8	22	5760	3360	14
9	22	5760	3360	13
10	22	5760	3360	12

t_x – last moment when making the decision to not wait g_{min} can be achieved.
g_{max} – cost (delay time) when making the decision to not wait at moment t_{max}

3.2. *Calculations for the model with more than one late passenger and take-off slots*

An interesting and special case in the model under consideration is when the passenger has more than one piece of checked-in baggage or when the number of missing passengers is larger than one. In such a situation it is necessary to search for several bags, which is quite difficult due to the amount of space in the hold of the aircraft and to the number of people employed in putting the baggage in the hold. In our model it requires a change in the parameter which is the average time of baggage search.

Determining the dependence of the time needed to search for baggage on the number of missing bags is an interesting research topic. In the current version of the model we assume that, based on information from the check-in, the number of bags which should be sought is known. We denote this by m_b. The modification of the basic model still requires a definition of the number of people that can simultaneously seek luggage. We denote this by m_h. With these designations the mean time necessary for searching for baggage $\overline{D_S}$ will in this case equal

$$\overline{D_S} = \frac{m_b}{m_h} \cdot \overline{d_s} \tag{13}$$

Variable $\overline{D_S}$ replaces $\overline{d_s}$ in the recursive relation (10) used for Dynamic Programming model implementation. Table 2 shows the results of calculations for different values m_b and m_h; the values of the other parameters are as in the basic model.

Analysis of the calculation results shows that the increase in the number of sought baggage and, consequently, the increase in the total time of the baggage search causes an increase in PLT, which is obvious. It also increases the time after which the decision to not wait is better than the decision to wait, which can also be explained by the increase in the total time of searching for baggage. The final result is, however, influenced by the planning horizon *T*, which in this case equals 80 min, because after that time period the aircraft will not obtain permission for take-off.

3.3. *Calculations for the model with one late passenger and without take-off slots*

Organization of departing traffic at many airports does not provide the use of take-off slots. Aircraft are given a place in a departure line when they are pushed out of the gate. In the line, overtaking is not possible, so the line is handled on a first come-first served (FCFS) principle. Depending on the amount of traffic at an airport, the taxi time in such a case may vary considerably.

In our model, taking into account this kind of airport traffic organization means that we will not be using the g_i function given by Formula (9) to modify the recursive relation, but we will use the basic version of these relations as given by Formulas (6) and (7). The results of the calculations using this model are shown in Table 3.

Regardless of the taxi time (dependent on the position in the line), the recommended strategy is the same. Stopping waiting in the third minute allows us to achieve g_{min} minutes of lost time. This

Table 2
Results of calculations when more than one piece of baggage is missing.

m_b	m_h	$\overline{D_S}$	t_{max}	g_{max}	g_{min}	t_x
1	1	7	22	5760	3360	15
3	2	10.5	22	5760	3360	11
2	1	14	22	5760	3360	8
5	2	17.5	24	5760	3660	7
3	1	21	42	8280	5760	21

strategy is a very restrictive approach, as it is difficult to expect that late passengers will arrive at the departure gate during this time. However, if late passengers arrive until time t_{max}, then the total lost time will be less than g_{min}, so in this case it may be advisable to wait until $t_{max} = 10$ minutes.

situation. In further calculations we assume that this time is designated by d_{mp} and equal to 300 min, which is the average trip delay for passengers on canceled itineraries in the USA (Sherry, 2011). The only change in our basic model is the new form of Equation (10), which will now take the form

$$f_i^*(y, x_i) = \begin{cases} (t_{i+1} - t_i + g_i(0)) \cdot N + f_{i+1}^*(y - (t_{i+1} - t_i + g_i(0))), & \text{for } x_i = 0 \\ \left(\overline{d_S} + d_{pr} + g_i(1)\right) \cdot N + d_{mp}, & \text{for } x_i = 1 \end{cases} \tag{14}$$

3.4. Calculations for the situation when a missing passenger has no checked-in baggage

On domestic and short-haul flights it is very common that passengers do not have checked-in baggage. In such a case the decision to stop the waiting is free from additional costs associated with searching for luggage in the hold of the aircraft. This corresponds to the situation in our basic model when the average time for searching for baggage $\overline{d_S}$ equals 0. Just as in the basic model, for the calculations we take into account the presence of the take-off slots and the fact that after the decision has been made to discontinue waiting the full preparatory take-off procedure will be carried out. The results for this case are shown in Table 4.

As one can see, it is recommended to stop waiting in the 7th minute, which is at time t_0. This is not surprising, as in the case of a missing passenger with no checked-in baggage the carrier can stop waiting with almost no additional waiting time costs.

3.5. Calculations for the model when taking into account time lost by a passenger who was not allowed on board

None of the previously examined cases included the cost of time lost by a passenger who was not allowed to board the plane due to the decision to not wait. This approach is understandable because such a passenger, as a principle, should be held accountable for both the delay and the additional costs incurred for both the carrier and the other passengers who came to the boarding gate on time. However, given that we are analyzing the costs for the carrier resulting from passenger dissatisfaction, even such a troublesome passenger (or more precisely the time he or she has lost) can be the basis to extend the waiting time. This is especially true when this is a passenger traveling in an upper class or a VIP.

Consideration of this case in our model requires determining the time lost by the passenger who was not allowed on board. This time may be taken as equal to the time for the next available connection in the same relationship. It can vary greatly depending on the

Table 3
Results of calculations for the case without take-off slots.

d_{TX}	t_{max}	g_{max}	g_{min}	t_x
7	10	3240	2400	3
14	10	4080	3240	3
21	10	4920	4080	3

Table 4
Results of calculations for the case when a missing passenger has no checked-in baggage.

$\overline{d_S}$	t_{max}	g_{max}	g_{min}	t_x
0	7	1560	1560	7

Results of calculations for this version of the model are shown in Table 5.

The results show that in this case the time in which we recommend to stop waiting remains unchanged (compared to the basic model) and for most input data this is the fifteenth minute. However, if one decides to wait for the missing passenger longer, the time in which this decision proved to be correct is increased slightly – up to 24 min. But if we are dealing with a small aircraft ($N = 50$) and a group of three missing passengers ($d_{mp} = 3 \cdot 300 = 900$ minutes), time t_{max} takes on the value of 40 min.

4. Probability of the arrival of a late passenger

In a work by Sudzińska (2011), measurements were presented of boarding time for a group of 52 flights operated by Embraer ERJ 170/175/190/195, which took on board up to 70–122 passengers. The results showed that the average boarding time for these conditions was 8 min. However, more important from the average value was the probability distribution of the arrival time of the last passenger. As is known, most passengers come to the departure gate long before the time indicated on the boarding pass. This means that boarding is done with maximum intensity, determined by the number of employees at the departure gate and the flow capacity of the barcode readers or other devices being used to verify and collect data about the passengers.

In order to verify these assumptions, in August 2014 we conducted detailed measurements of boarding times for flights departing from Warsaw Chopin Airport. Sample results for a few of these flights are presented in Table 6.

As we can see from the conducted measurements, the average boarding time per passenger is approximately 7.7 s, which for $N = 120$ passengers give a boarding time equal to 930 s, i.e. about 15.5 min.

The nominal boarding time corresponds to a situation where all passengers arrive at the gate before it opens. It was assumed that all longer boarding times noted in Sudzińska (2011) mean that it was necessary to wait for late passengers. In this study, unfortunately, no information was provided whether in all flights all passengers arrived for boarding or whether it was necessary to close the gate and look for luggage. To specify the results it will be necessary to repeat the measurements in the future by taking into account all of the requisite elements.

Table 5
Results for the model considering the time lost by the missing passenger.

$\overline{d_S}$	t_{max}	g_{max}	g_{min}	t_x	N	d_{mp}
7	24	6060	3660	15	120	300
7	40	3550	2300	15	50	900

Table 6
Measurement results of the boarding times for flights departing from Warsaw Chopin Airport.

Flight	Boarding begins	Boarding ends	Boarding time [sec]	Pax number	Pax boarding time [sec]
P78015	5:38	5:50	720	105	6.9
P78093	5:39	6:00	1260	178	7.1
P78199	5:46	6:00	840	108	7.8
P78019	5:40	5:50	600	52	11.5
P78819	5:47	6:00	780	179	4.4
P78839	11:53	12:15	1320	132	10
P78009	10:40	10:55	900	137	6.6

Assuming that the boarding times noted during the measurements correspond to the times after which the last passengers arrived, it is possible to analyze the probability distribution of that time. In the absence of detailed measurements it was assumed that the random variable T_W describing the waiting time for the arrival of the last passenger is described by three example probability distribution functions: exponential, normal and Rayleigh. Based on measurements in Sudzińska (2011), we determined that the average waiting time for the last passenger $E(T_W)$ was 4.5 min and standard deviation $\sigma(T_W) = 2.54$.

With the expected value $E(T_W)$, the probability density function of the arrival of the last passenger for the exponential distribution can be presented in the form of:

$$f(\tau) = \lambda \cdot e^{-\lambda\tau} \tag{15}$$

where:

$$\lambda = \frac{1}{E(T_W)} \tag{16}$$

and the cumulative distribution function, i.e. the probability that the waiting time for the last passenger will be no longer than τ minutes as

$$F(\tau) = 1 - e^{-\lambda\tau} \tag{17}$$

Analogously, the cumulative distribution function was set for other distributions.

With the distribution function of the random variable describing the time of arrival of the last passenger, the expected value of time lost by the passengers can be designated in the case of deciding to wait for the last passenger to a certain moment t_i. This can be done using the following equation

$$E(S(t_i)) = F(t_i) \cdot G_+(t_i) + (1 - F(t_i)) \cdot (G_-(t_i)) \tag{18}$$

where:

$S(t_i)$ – total time lost while waiting until moment t_i

$F(t_i)$ – probability that the last passenger will show up before moment t_i

$G_+(t_i)$ – time lost when the last passenger arrives before moment t_i, defined on the basis of recursive relations (10–11) of the dynamic programming problem. This is the value of the transformed function $f_i^*(y, x_i)$ for $x_i = 0$ and $y = T - t_i$.

$G_-(t_i)$ – time lost when the last passenger does not arrive before moment t_i, and thus there will be a need to search for and remove his or her luggage (defined on the basis of recursive relations (10–11) of the dynamic programming problem). This is the value of the transformed function $f_i^*(y, x_i)$ for $x_i = 1$ and $y = T - t_i$.

Table 7
Expected value of time lost for the example under consideration (exponential distribution).

t_i	$F(t_i)$	$G_+(t_i)$	$G_-(t_i)$	$E(S(t_i))$	t_i	$F(t_i)$	$G_+(t_i)$	$G_-(t_i)$	$E(S(t_i))$
7	0.7889	1560	3360	1940	17	0.9771	3000	3600	3014
8	0.8310	1680	3360	1964	18	0.9817	3000	3720	3013
9	0.8647	1800	3360	2011	19	0.9853	3000	3840	3012
10	0.8916	3000	3360	3039	20	0.9883	3120	3960	3130
11	0.9132	3000	3360	3031	21	0.9906	3240	5760	3264
12	0.9305	3000	3360	3025	22	0.9925	3360	5760	3378
13	0.9444	3000	3360	3020	23	0.9940	3480	5760	3494
14	0.9554	3000	3360	3016	24	0.9952	3600	5760	3610
15	0.9643	3000	3360	3013	25	0.9961	5400	5760	5401
16	0.9714	3000	3480	3014	26	0.9969	5400	5760	5401

Determined in accordance with Equation (18); the expected values of lost time for the example under consideration are presented in Table 7.

According to the previous statements, immediate termination of boarding without waiting for a late passenger is unfavorable because it leads to the need to search for and unload his or her baggage. There exists a reserve r that allows to wait until the seventh minute without additional time lost. If we stop waiting at $t_i = 7$ we may expect the lowest PLT. The expected value of lost time if we stop waiting in the following moments ($t_i = 8, 9, \ldots$) depends on the cumulative distribution function of the probabilistic variable describing the time of arrival of the last passenger. Table 7 presents the calculations for the exponential distribution function. The local minima are marked with a gray background.

A similar analysis was also performed for other times of luggage search $\overline{d_s}$. In each case the expected value function of the lost time had some local minima. For the example shown in Table 7, the minima occur for $t_i = 15$ and $t_i = 19$. In all analyzed cases the global minimum was at the shortest waiting time. However, other possibilities cannot be excluded – further studies are needed.

To compare the impact of the probabilistic characteristics of a late passenger's arrival process, additional analyses were conducted for the other two probability distributions. The results for moments in which the local minima were observed are shown in Table 8.

As can be seen, minima occur in different places but, more importantly, the expected value of the time lost by passengers is different. This points to the need for continued research for a better understanding of the probabilistic characteristics of a late passenger's arrival process.

Table 8
Results comparison for various probability distributions.

t_i	Exponential	Normal	Rayleigh
	$E(S(t_i))$		
7	1940	1600	Not a minimum
8	Not a minimum	Not a minimum	1821
15	3013	3000	3000
19	3012	3000	3000

5. Recommendations for gate operators

Our model along with its variants can serve as a basis to propose a procedure for gate operators. It differs slightly depending on whether information about the probability distribution of the arrival of missing passengers is available. The algorithm of this procedure is presented in the form of a pseudocode in Fig. 4. Just as in sections 3.1–3.5, we described several variants of the model; the algorithm presented here adopted the designation of models equivalent to the number of the section in which they are described.

6. Conclusions

The paper presents the problem of searching for the best time period to wait for a passenger that is late for boarding. This problem, although in principle ignored by ground handling manuals, is common and is important for the punctuality of flight operations, and thus for passenger satisfaction and the financial performance of airlines.

Solving the problem of how much waiting time is needed for a late passenger is not easy for several reasons. These may include: the random character of late passengers' arriving process and the process of searching for baggage in the hold of the aircraft. Furthermore, in the case of using take-off slots, cost functions vary nonlinearly (stepwise). In addition, decisions made are mostly subjective; they are affected by factors not directly related to cost analysis, such as passenger satisfaction with the level of service or inconvenience caused by the decision to end waiting and deny boarding.

The study allows us to make some conclusions regarding several important issues. First, in many cases there is a time reserve which allows costless waiting for a late passenger. This reserve may even be long enough that the probability of a passenger's arrival is quite large.

Second, the applied model and computational method using Dynamic Programming theory allow to determine a characteristic moment, t_{max}, in which the value of PLT in the case of an immediate end of waiting is equal to the time lost if the late passenger arrives for boarding at time t_{max}. A comparison of time t_{max} with the expected value of the random variable describing the time of arrival of the last passenger may be an important indication when determining the time to stop waiting.

Third, even an immediate end of waiting and the following searching for baggage may cause the aircraft to be ready for departure after the first take-off slot. This causes the time reserve, as mentioned earlier, to increase even more. Thus, it may be found that this reserve becomes long enough that the probability of the arrival of a late passenger is very close to 1. Therefore, it can be shown that in some situations it is worth being patient and wait for a late passenger without generating additional costs.

Fourth, the calculations performed here confirmed that if a late passenger does not have checked-in baggage or when there are no take-off slots (the FCFS strategy), then the best scheme of action is to stop waiting very quickly. On the contrary, if it is expected that the time of searching for baggage is long (several bags, many late passengers), it is favorable to wait. However, in this second case the results are not that obvious because of the nonlinearity (stepwise increase) of the function describing the passengers' lost time.

Fifth, it is possible to take into account the random variable describing the time of arrival of the late passenger. The results show that in each of the analyzed cases there is a global minimum of the function defining the expected value of wasted time. The moment for which the minimum occurs can be considered as the optimal (in terms of time wasted on waiting) moment for the end of waiting for the late passenger. However, further research on the characteristics of the random arrival times of passengers and the impact on the result of other factors, which were accepted as constant in the study, is necessary.

The considerations presented in this paper should be a starting point for further discussion and exploration of new solutions and extensions to the problem of waiting time for a late passenger. For example, other optimization methods can be considered. Dynamic Programming is just one of many possible approaches to solve the problem. In our opinion, it is well suited to the specific nature of the problem, since the cost functions are time dependent and are often stepwise. In this case, the problem can be considered as a multi-stage decision making process in the time domain. Hence the proposal to use Dynamic Programming. However, other optimization methods also can be used – from the classic to the methods based on artificial intelligence, for example Petri nets and fuzzy logic.

In the study two cases of decision-making situation were analyzed. First, with total uncertainty, when the carrier does not have any additional information about late passengers. Second, when the carrier has some information about the probability distribution of the time of passenger's arrival. There are, however, also other situations. The carrier may have information about the reasons for the delay. The passenger could arrive late to check-in, there may be a large queue to security screening, etc. Taking into account this kind of situation will expand the area of analysis, increase the usability of our method, but it can also require the expansion of the model. However, it will not be necessary in every case. If, for example, we have to deal with a passenger who is known to the carrier from the fact that he or she used hidden city ticketing tactics, then we may suspect his or her delay as just another case of this kind. This situation occurs when a passenger buys the connecting flight ticket, but uses only the first flight. In such cases, a version of the model presented in Section 3.4 applies, because no luggage is needed to be retrieved from the aircraft. A similar situation takes place in the case of throwaway ticketing.

This issue also requires extension of the analysis to the case when a carrier uses an overbooking strategy. In this case, passenger

```
begin main_algorithm
  input parameters N, dtr, ds, do, dc, dTX, dmp;
  if number_of_missing_pax=0 then wait_time=0;
  else
    if late_passenger_appearance_distribution is_available
      then procedure_2 else procedure_1
  wait wait_time;
  close boarding;
end;

procedure_1:
if takeoff_slots_are_used then
  if number_of_checked_bags=0 then wait_time=tx(model_3.4);
  else
    mb:=number_of_checked_bags;
    mh:=number_of_people_searching;
    calculate ds;    /** formula (13)
    wait_time=tx(model_3.2);
else wait_time=tx(model_3.3);
end;

procedure_2:
use model_3.1;
for ti:=1 to T do
  g+(ti):=fi(T-ti,wait);
  g-(ti):=fi(T-ti,don't_wait);
  calculate(E(S(ti));     /** formula (18)
wait_time:=min(E(S(ti));
end;
```

Fig. 4. Procedure for gate operators to determine the time of waiting for a late passenger.

no-shows may be beneficial to the carrier. This applies to situations where an airline may refuse to take a passenger on board due to the lack of seats. Solutions used by carriers, consisting of the analysis of the probability of passenger's arrival and taking into account the different types of costs, are not directly applicable here. These are in fact the static probabilities, while in our analysis we are talking about the dynamically varying probability. It is necessary therefore, to extend the research on this area.

The time lost by the passenger (PLT), analyzed in the article, is a component of the cost function of the carrier. An important area to extend the consideration is the analysis of network effects omitted in this paper as we assumed that the delay is relatively small. However, a deeper look at this problem shows that even a slight delay can cause troubles for transfer passengers who may lose their connections and for carriers who need to realize rotation.

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Nomenclature

List of variables and parameter definitions used in the article:

t_c	nominal end time of passenger check-in at the gate
t_r	moment when the aircraft is ready for take-off
t_l	moment of arrival of late passengers
t_0	moment from which further waiting for a late passenger involves additional costs
d_{tr}	time needed to transfer passengers to the plane
d_o	time required for preparatory activities with the door of the plane open
d_c	duration of the preparatory activities with the door of the plane closed
d_{TX}	duration of taxi time
$\overline{d_S}$	expected average search time of a single absent passenger's baggage
d_{pr}	time to prepare for departure after the procedure of waiting for a late passenger or the procedure of unloading the baggage of a passenger who did not arrive for boarding
d_{mp}	time lost by a passenger who was not allowed on board
S^0	basic take-off slot
S^n	n-th take-off slot
r	duration of the reserve, i.e. the time when waiting for a late passenger does not generate any costs
x_i	decision variable, receiving a value of 0 or 1
T	maximum horizon of waiting
y	system state variable; the remaining time to the end of the horizon of analysis T
$f_i(y,x_i)$	total minimum delay time of passengers in moments $t_i,t_{i+1},\ldots,T$, if the remaining time to the end of the horizon of waiting is y and it was decided x_i
$f_i(y)$	total minimum passengers' delay time in moments $t_i,t_{i+1},\ldots,T$, if the remaining time to the end of horizon of waiting is y
N	number of passengers on board the aircraft
g_{min}	cost (delay time) when making the decision to not wait at moment t_0
t_{max}	maximum waiting time, which corresponds to the last moment in which the delay associated with waiting for a passenger is less than or equal to g_{min}
g_{max}	cost (delay time) when making the decision to not wait at moment t_{max};
t_x	the last moment when making the decision to not wait, g_{min}, can be achieved
T_w	random variable describing the waiting time for the arrival of the last passenger
$E(S(t_i))$	expected value of time lost by passengers
$S(t_i)$	total time lost while waiting until moment t_i
$F(t_i)$	probability that the last passenger will show up before moment t_i
$G_+(t_i)$	time lost when the last passenger arrives before moment t_i
$G_-(t_i)$	time lost when the last passenger does not arrive before moment t_i

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