Airport Gate Assignment Considering Ground Movement

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Abstract. Airports all over the world are becoming busier and many of them are facing capacity problems. The actual airport capacity strongly depends on the efficiency of the resource utilisation. Although simultaneously handling all of the problems may result in more effective resource utilisation, historically different types of airport resources have been handled independently. Despite introducing new support systems the historical separation has often remained. This may increase congestion, which has a negative impact on both the passengers' comfort and the environment. This paper focuses on modelling the gate allocation problem taking into consideration possible conflicts at taxiways around gates. Introducing the taxiway information in the early stage of the allocation planning is a step forward in integration of the two airport operations. Various configurations of the model have been tested using a real data set to evaluate how the new anti-conflict and novel towing constraints influence the final allocation.

Keywords: Airport Gate Assignment, Mathematical Modelling, Mixed Integer Programming

1 Introduction

Air traffic is increasing all over the world. Airports are becoming busier and many of them are facing capacity problems. Effective resource management therefore has a key importance for airports.

Airport resources can be divided into an air-side part, which consists of runways, taxiways and gate areas, and a land-side part which includes terminal buildings. In practice different parts of the airport are often managed and maintained in isolation from each other, often due to the fact that they had to be solved manually in the past, and by different organisations. So, conflicting objectives are common. An airport may, for example, prefer to allocate a flight to a particular gate because of a lower traffic in its neighbourhood while an airline prefers to use a different gate which is closer to the runways. If the whole airport was managed as one inseparable operation, its operations would be smoother, but this may require major changes in the airport management structure. This is starting to happen (especially as a part of Airport Collaborative Decision

Making [1] project), and this paper considers moving another step forward in the integration of airport operations.

The presented paper discusses a model for the gate allocation problem taking into consideration the expected traffic around the gates in order to improve the early stage of gate allocation planning. Gate allocation aims to find appropriate gates for aircraft at an airport. There are many rules and constraints which are used to decide the value of an allocation. In contrast to previously published models, the one presented here contains a new constraint which limits the number of aircraft which are expected to block each other while manoeuvring at the area close to the gates. The possible blockages are identified in groups of gates which are reached using similar routes. Including the expected blockages in the early stage of planning should result in smoother operation during the day. We believe this is a good first step in the process of integrating gate allocation with ground movement, never discussed before. Additionally a novel approach to the towing procedure is also presented. This is modelled in a flexible way which may be more practical than some other published models.

Other blockages which occur on taxiways could be modelled similarly and handling by adding appropriate constraints. This moves the system closer towards a ground movement system is planned future work.

The problem description and the background literature are introduced in Section 2 and Section 3. The model formulation is given in Section 4. Experimental settings and the data used in the experiments are described in Section 5. Section 6 presents the results, where we discuss how the various model constraints influence the final allocation. Finally conclusions and potential future work are presented in Section 7.

2 Problem description

There are many operations which need to be synchronized at airports. For example, departing aircraft are routed from gates to runways and the routes that they take and their take off sequence both have to be considered. Similarly arriving aircraft also need to be sequenced and, once on the ground, they must be routed from runways to gates. There are usually several taxiways which could be used to get from one point to another. The chosen taxiway should normally be the shortest possible route without conflicts. Terminal 1 of Manchester Airport is shown in Figure 1 as an example. Observe that some gates are placed behind bottlenecks, for example the gates at $GR1$. Access to those gates is limited and a poor quality allocation plan can result in severe delays during the day of operation. However, a good plan created in advance which considers the physical limitations could potentially reduce delays, by limiting the number of aircraft planned to pass the bottlenecks at the same time.

Examples of physical blockages which can be taken into account in the early stage of planning are push-back blocking (Figure 2a) and taxi blocking (Figure 2b). Push-back blocking occurs when a departing aircraft is ready to leave a gate but cannot due to another aircraft is blocking its push-back trajectory. This

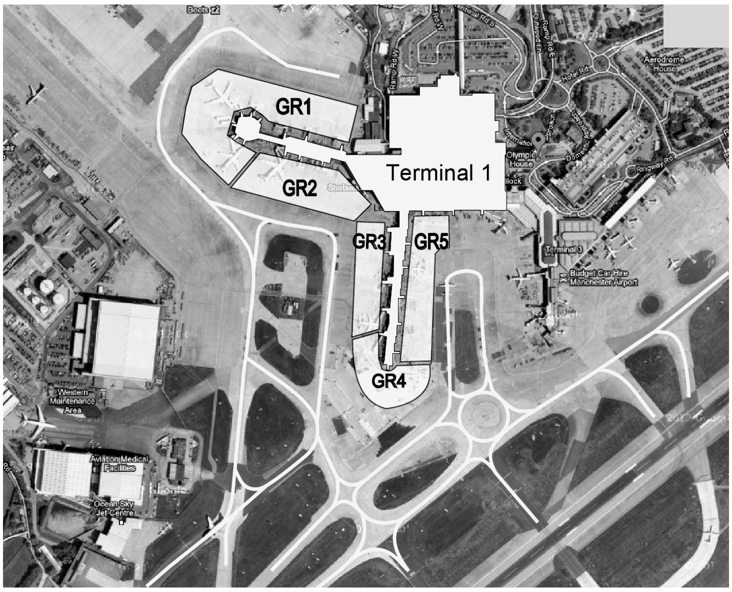
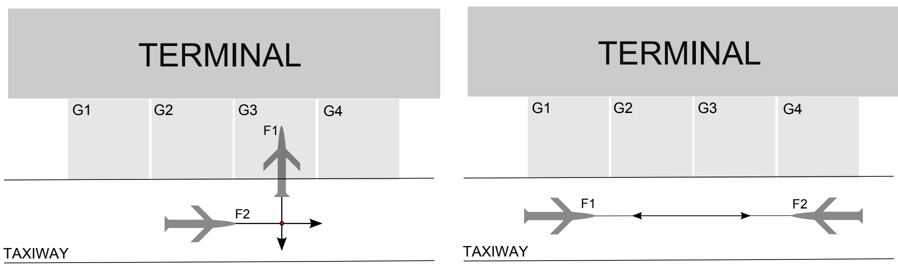


Fig. 1. Map of Manchester Airport showing Terminal 1, the taxiways and groups of gates, Google satellite map, Imagery ©2013 TerraMetrics, Map data ©2013 Google.

type of blocking can be observed only at the area close to the gates. Figure 2a shows an example of push back blocking where flight $F1$ is pushing back towards flight $F2$. One of the aircraft needs to wait until the other has finished.



(a) push-back blocking (b) taxi blocking

Fig. 2. Two different types of conflicts

Taxi blocking occurs either when there are two aircraft going in opposite directions along a straight piece of a taxiway, as shown in Figure 2b, or when two taxiways cross and two aircraft happen to be at the crossing point at the same time. Taxi blocking may occur not only at the gates but also further along the taxiways, for aircraft on the way to/from the runway. It occurs especially around bottlenecks where multiple taxiways converge. Only the area at the gates is considered in our experiments but we plan to include the bottlenecks in the future and the model can handle this by including some time offsets to allow for the time reach the bottlenecks.

The model of the gate allocation problem (GAP) which is presented here is meant to be an early stage planning tool which attempts to resolve conflicts at gates. Gates are divided into groups and the number of conflicting allocations is limited within each of the groups. The groups which are visible in Figure 1 have been introduced based upon the layout of the taxiways and our understanding of the problem.

Gate constraints, which result from gate attributes, are also modelled. A gate is an area adjacent to a terminal building where an aircraft can park so that passengers can easily be loaded and unloaded. While an aircraft is on a gate all necessary work such as fuelling, cleaning, baggage loading and offloading are also performed. The work and time that an aircraft needs on a gate depends primarily upon the airline that is operating it and the flight destination. There are also areas which are not attached to terminals where aircraft can park, called remote stands. When an aircraft is on a remote stand passengers are usually transported to and from a terminal building by bus. The remote stands are usually used only when all gates are occupied or if specifically requested by an airline. A number of constraints result from the gate attributes, such as size restrictions and/or shadowing restrictions (see Section 4.2). Some aircraft will need to be allocated to different stands for their arrival and departure processes, for instance due to different security requirements for the arriving and departing flights. These may require a tug operation in between them to move the aircraft between stands. Such aircraft can be modelled as two flights within this model, although the experimental data used for these results does not detail such aircraft and these are not the main focus of this work.

The GAP for one day (whole airport) can be very hard to solve using exact methods. However, the whole airport problem can usually be decomposed by terminals, since it is rare for an aircraft to be moved between terminals (all passengers would have to change which terminal they checked in at) and airlines usually have agreements with airports specifying which terminal (and sets of gates) they will use. Allocating flights to a different terminal would be very inconvenient for the airline because all of the necessary ground services would have to be moved to a different part of the airport. However, synchronisation of terminals could be needed later (when bottlenecks are included) since some of taxiways are used to reach multiple terminals.

The proposed terminal based decomposition allowed the solution of instances used in the experiments. But the solution process is slow due to the number of possibilities that have to be checked. Similar problems have been reported by other researchers working on the GAP [2, 10]. It would be very hard to solve larger instances for busy hub terminals to optimality, hence future work will consider potential decompositions of the problem and/or heuristic approximations to generate additional constraints and prune the search space.

Like many real world problems the GAP has several objectives. The presented model includes four objectives, which mirror the interests of the two sites involved in this problem: an airport and an airline. From the perspective of an airport one of the most important objectives is to obtain a robust allocation, i.e. an allocation with gaps between flights which are allocated to the same gate are as large as possible. It allows the absorption of minor delays and maintains smoother airport operation. Another airport related objective is to use the gate space effectively, i.e. to match the size of the aircraft. The aim is to avoid using unnecessarily large gates, keeping the larger gates free since these have more flexibility for use by flights which have to be moved on the day of operation. Airline related objectives involve specific gate preferences and avoiding remote allocation where possible. The multi-objective character has been modelled here using a weighted sum of several objectives. This is a commonly used procedure which results in the optimal solution potentially being strongly dependent on the chosen weights. This is sufficient for the aims of this paper, however different multi-objective approaches [3], which allow the analysis of the trade-off and/or tuning of the weights for the various objectives will be investigated in future.

3 Previous Literature

The multi-objective nature of the problem has been gradually acknowledged by researchers working on this problem. Initially research focused mainly on various passenger comfort objectives. For example, Haghani and Chen [10] and Xu [14] minimised the distance a passenger walks inside a terminal to reach a departure gate. Yan and Hou [15] introduced an integer programming model to minimise the total passenger walking distance and the total passenger waiting time.

Ding et al. [6, 7] shifted the research interest slightly from passenger comfort to airport operations and solved a multi-objective IP formulation of the GAP with an additional objective: minimization of the number of ungated flights.

Dorndorf et al. [8] went further and claimed that not enough attention has been given to the airport side when solving the GAP. They focused on three objectives: maximization of the total flight to gate preferences, minimization of the number of towing moves and minimisation of the absolute deviation from the original schedule. Perhaps surprisingly at the time, in the context of many previous publications, they omitted the walking distance objective, arguing that the airport managers do not consider it an important aspect of the GAP. Our experience with airports indicates that this is probably correct, which is why the objective function presented in Section 4 does not consider passenger walking distance but aims instead to reduce the conflicts by the gates, to allocate gates so that the airline and the size preferences are maximised and to ensure that the time gaps between two adjacent allocations are large enough.

The constraints that we have modelled in Section 4 include other aspects of the problem which have already been discussed by other researchers. Dorndorf et al. discussed relative sizes of gates and aircraft, airline preferences and shadowing restrictions [8, 9]. Similarly the importance of the maximisation of time gaps between allocations and the robustness of solutions was discussed by Bolat [2] and Diepen et al. [5]. This is also included in our objective function. We aim to avoid small gaps by maximizing the time gaps within a defined time window.

Dorndorf et al. [8, 9] and Kumar et al. [12] included towing in their models. They modelled the towing using three flights: (arrival)+(tow away); (tow away)+(tow back); and (tow back)+(departure). In this paper we assume that there are always enough remote stands for towed aircraft and model it using two flights: arrival+tow away and tow back+departure. This reduces the number of variables used by the model and eliminates the associated constraints. In both the current and the previous models, the decision about an exact towing time has been left in controllers' hands: they can pick the most appropriate time within an established time period.

Cheng [4] analysed the push-back conflicts that can be observed between adjacent gates. He analysed flights which can be in conflict due to scheduled departing/arriving times and did not allow these to be allocated to neighbouring gates. His idea of detecting conflicts and resolving them by introducing hard constraints into his model is similar to the idea used in our model. Our extension allows a gate to be a member of one of the arbitrary defined groups of gates which are considered, rather than only considering neighbouring gates. Kim et al. [11] introduced probable conflicts into the model as a soft constraint and minimised them. That approach introduces many new variables into the model, which makes it harder to solve. Moreover, it is dedicated to a specific architecture of an airport, where gates are grouped on ramps and two non-crossing taxiways which lead to them are present. However, at many airports the taxiways cross and there are often bottlenecks which make access to gates harder.

4 Model Formulation

A Mixed Integer Programming model has been used here to model the problem.

4.1 Notation and Definitions

- F - the set of all flights
- n - the total number of flights
- $f \in F := \{1, ..., n\}$ - a flight
- e_f - the on-gate time of flight f, a constant for each flight f
- l_f - the off-gate time of flight f, a constant for each flight f
- G - the set of all gates
- m - the total number of gates available
- $g \in G := \{1, ..., m\}$ - a gate
- $F(g)$ - the subset of flights that can use gate g
- Sh - the set of pairs of gates that cannot be used simultaneously due to shadow restriction
- $GR \in \{GR1, ..., GR5\}$ - a subset of gates (group of gates)
- M - the number of conflicting flights allowed to be allocated to one GR
- $X_{g,f}$ - a decision variable that takes the value 1 if flight f is allocated to gate g or 0 if not

- U_{g,f_1,f_2} - an indicator variable that is 1 if the two flights f_1 and f_2 are both allocated to gate g
- p_{f_1,f_2}- the constant penalty function for each flight pair which indicates the penalty to apply if flights f_1 and f_2 are both allocated to the same gate.
- $r_{f,g}$ - the constant penalty for each gate-flight pair which indicates the penalty to apply if flight f is smaller than the maximal size of flight that can be allocated to gate g
- $a_{f,g}$ - the constant penalty for each gate flight pair which indicates how strongly gate g is preferred by an airline that is operating flight f
- $freq_{f,g}$ - the constant which indicates how often an airline which is operating flight f has used gate g, based upon statistic data analysis
- d - the constant penalty for usage of 'dummy gate'
- $C_d(f)$,$C_a(f)$ - a set of flights which can be in conflict with the departure time ($C_d(f)$) or arrival time ($C_a(f)$) of flight f if the flights are allocated to the same group of gates.

4.2 Constraints

$$X_{g,f} = 0,\ \forall f \notin F(g), \forall g \in G. \tag{1}$$

$$U_{g,f_1,f_2} = 0,\ \forall (f_1 \vee f_2) \notin F(g), \forall g \in G. \tag{2}$$

Each flight has to be allocated to a gate. A 'dummy gate' (gate $m+1$) is also included in this constraint to which ungated flights will be allocated:

$$\sum_{g=1}^{m+1} X_{g,f} = 1, \qquad \forall f \in \{1, ..., n\}, \tag{3}$$

No two flights can be allocated to the same gate at the same time. If two flights overlap or are within a minimum time gap of each other then they must be assigned to different gates, Inequality 4. This gap is set to 10 minutes, since some time is needed to clear the gate, however the precise value is not important for these experiments, since there is an objective to increase these gaps.

$$X_{f_1,g} + X_{f_2,g} \leq 1, \begin{array}{l} \forall f_1, f_2 \in F(g),\ \forall g \in G, f_1 \neq f_2, \\ (e_{f_2} \geq e_{f_1}) \wedge (e_{f_2} - l_{f_1} \leq 10). \end{array} \tag{4}$$

The mathematical formulation of the time gap constraint is given below, it introduces a new variable which is set if two flights are allocated to the same gate. The constraint is introduced only for gaps smaller than 1.5 hour, which are more than sufficient. The gaps which are smaller than 1.5 hour are maximised in the objective function using the new variable so that potential, minor delays on the day of operation can be absorbed.

$$U_{g,f_1,f_2} \geq X_{f_1,g} + X_{f_2,g} - 1, \begin{array}{l} \forall f_1, f_2 \in F(g),\ \forall g \in G, f_1 \neq f_2, \\ (e_{f_2} \geq e_{f_1}) \wedge (10 < e_{f_2} - l_{f_1} < 90). \end{array} \tag{5}$$

Some gates cannot be used simultaneously, because usage of one gate blocks usage of another one, this constraint is called a 'shadow restriction' [9]. Moreover sometimes one large gate can be treated as either two smaller gates (for smaller aircraft) or one large gate (for a single large aircraft). These large gates are modelled as three separate gates with a shadowing constraint between them. Figure 3 shows a large gate ($G3$) which would be modelled as three gates: $G3F$ (full size gate), $G3L$ (the left half of $G3$) and $G3R$ (the right half of $G3$). $G3L$ and $G3R$ could be used at the same time by two small aircraft ($F2$, $F3$) but if there is a large aircraft ($F1$) on $G3F$ then neither $G3L$ nor $G3R$ can be used. Let Sh denote the set of pairs of gates which have to be used exclusively (pairs $(G3F, G3L)$ and $(G3F, G3R)$ would belong to this set). The 'shadow restriction' can than be described as follows:

$$X_{f_1,g_1} + X_{f_2,g_2} \leq 1, \forall f_1 \in F(g_1),\ \forall f_2 \in F(g_2),\ \forall (g_1, g_2) \epsilon Sh, f_1 \neq f_2, \\ (e_{f_2} \geq e_{f_1}) \wedge (e_{f_2} - l_{f_1} \leq 10). \quad (6)$$

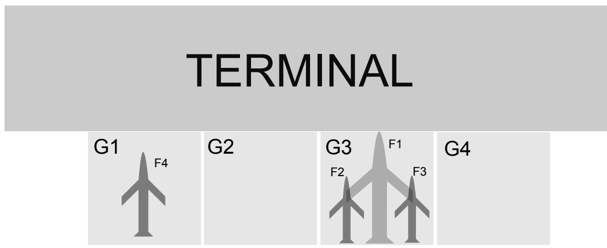


Fig. 3. Large gates can be used as two small gates by small aircraft

When an aircraft is at the airport for a long time, it is often towed from a gate to a remote stand so that it is not occupying a gate that could be used by other aircraft at that time. The aircraft is then usually towed back to the same or a different gate some time before the scheduled departure time. Although having many towing operations is not desired by airports (towed aircraft may cause additional conflicts on the taxiways) there is often no other option if a terminal does not have enough gates to serve all aircraft. It is assumed in this model that an aircraft is towed away from a gate if it is going to stay at the airport for more than 4 hours. This time can be changed according to airport preferences and has been chosen based upon the data set that has been used in the experiments. These long flights are modelled as two one-hour long flights. The first flight represents the arrival and lasts one hour starting from the scheduled arrival time. The second flight starts one hour before the scheduled departure time. As previously discussed, the middle part is not modelled and sufficient remote stands are assumed, which it is usually the case for most airports. According to the data used in our experiments, an aircraft needs no more than an hour to do all servicing after it arrives and no more than one hour before it departures, the towing procedures are considered to be included in this hour. An exact time of towing is not specified in the model, so the controllers may decide when to tow the flight and do so when the procedure causes fewest conflicts.

The conflict constraint is defined as follows:

$$X_{f_1,g_1} + \sum_{g \epsilon GR} \sum_{f \in C_d(f_1)} X_{f,g} \leq M, \forall f_1 \in F(g_1), \ \ \forall g_1 \in GR, \\ \forall GR \in \{GR1, ..., GR5\} \tag{7}$$

where GR is one of the gate groups from Figure 1 and $C_d(f_1)$ is a set of flights which can be in conflict with the departure time of flight f_1 if the flights are allocated to the same group of gates. The flights which are in $C_d(f_1)$ are identified from the scheduled arrival and departure times. It is assumed that arrivals up to 10 minutes before/after the departure of f_1 can conflict (i.e. a 10 minute long time gap is required). Similarly if an aircraft departs close to the departure time of f_1 it would be in $C_d(f_1)$, but the time margin can be shorter because it is a less conflicting situation so a 3 minute long time gap has been used. The 10 and 3 minute gaps can be set to any values desired, but have here been set to be large values to investigate and illustrate the effects of this constraint. An analogous set exists for arrival time conflicts so there is a separate set $C_a(f_1)$ which contains all flights which are in conflict with the arrival of f_1 and a constraint equivalent to Constraint 7 is applied. This idea of finding conflicting flights can also be viewed as a type of time window method. The conflicts within time windows would be identified by two windows for the arrival conflicts (short and long gaps) and two windows for the departure conflicts. But in a typical time window approach an artificial step size would usually be used to move the windows along the problem whereas here the positions of the windows are implicitly defined by the flight times, with consequent benefits of avoiding time discretisation problems. Our constraint allows up to M flight movements for each group of gates. The number of allowed flights should be chosen depending on the particular airport preference. For this paper, the concept is the important element, resulting in lower congestion on the taxiways close to the gates.

Objective The objective function is a weighted sum of four elements. It aims to ensure that time gaps between allocated flights are large enough to absorb minor delays, that the gate spaces are used effectively, that the airline preferences are maximised and that the number of remote ('dummy gate') allocations is minimised. The following function is minimised:

$$\sum_{f_1=1}^{n} \sum_{f_2=1}^{n} \sum_{g=1}^{m} p_{f_1,f_2} U_{g,f_1,f_2} + \sum_{f=1}^{n} \sum_{g=1}^{m} r_{f,g} X_{f,g} + \sum_{f=1}^{n} \sum_{g=1}^{m} a_{f,g} X_{f,g} + \sum_{f=1}^{n} d X_{f,dummy} \tag{8}$$

The first component of the function refers to the time gaps, the variable U_{g,f_1,f_2} is forced to be one if two flights are at the same gate (see Inequality 5). The gap cost function p_{f_1,f_2} that is used in the objective function to penalise such allocations is given by Equation 9:

$$p_{f_1,f_2} = \begin{cases} \frac{90}{(gap_{f_1,f_2})+1} & \textit{if } 10 < gap_{f_1,f_2} < 90 \\ 1 & \textit{if } \quad gap_{f_1,f_2} \geq 90, \end{cases} \tag{9}$$

where $gap_{f_1,f_2} = e_{f_2} - l_{f_1}$ if $e_{f_2} > e_{f_1}$ or $gap_{f_1,f_2} = e_{f_1} - l_{f_2}$ if $e_{f_1} > e_{f_2}$. The shape of p_{f_1,f_2} is appropriate for the problem since the smaller gaps are penalised much more heavily than the larger gaps. Moreover p_{f_1,f_2} saturates, which means that the penalty for really large gaps is fixed (equal to 1). It is reasonable to argue that only the gap from the immediately preceding flight on the gate should matter, and that gaps from earlier flights should be irrelevant.

The second component refers to effective usage of the gate space. The size of a flight that is allocated to a gate should correspond to the size of a gate, possibly being equal to the maximal size ($maxSize$) that gate g can absorb. It cannot be larger, which is guaranteed by the first constraint (Equation 1). When it is smaller, then such allocation is penalised, to keep the larger gates clear in case they are needed later if flights have to be reallocated. The gate-flight size function $r_{f,g}$ that is used to penalise the allocation is given by Equation 10, where $biggestGateSize$ refers to the size of the biggest gate at a terminal.

$$r_{f,g} = \frac{maxSize(g) - size(f)}{biggestGateSize}, \tag{10}$$

The third component of the objective function refers to the airline preferences. The preferences are established based upon statistical data analysis, by checking how often particular gates have been used by particular airlines. The airline preference factor $a_{f,g}$ which is used in the objective function to weight the allocation of flight f to gate g is calculated according to Equation 11, where $maxFreq$ is the maximal value of all frequencies and refers to the most frequently used gate by the most popular airline at the terminal.

$$a_{f,g} = \begin{cases} 1 - \frac{freq_{f,g}}{maxFreq} & \textit{if } freq_{f,g} > 0 \\ 1 & \textit{if } freq_{f,g} = 0, \end{cases} \tag{11}$$

The last component refers to the 'dummy gate' allocations. 'Dummy gate' symbolises remote stands or holding places at an airport representing aircraft which cannot be allocated to gates so usage of it is strongly penalised.

5 Experimental Settings

The data which is currently used in the experiments has been provided by Manchester Airport and contains a record of five days of airport allocations: both the planned allocation and the final actual allocation, and includes information about gate usage (which gates have been used by which aircraft types and airlines), size group information for aircraft (that divides aircraft into groups according to their sizes) and sizes of gates. It is for Terminal 1 which is the busiest terminal at the airport. The numerical results shown in Section 6 have been obtained by solving five days of airport operations one after another.

Information about occupied gates for flights that arrive one day and depart the next day has been passed from day to day. Information about the airlines and airport preferences is hard to capture because it often relies on human knowledge. In this research it has been estimated using statistical analysis of the data. For example, how often each airline uses each gate was measured and used as an estimation of airline preferences.

As mentioned in the previous sections the model contains several settings, which have been determined based upon our observations in relation to Terminal 1 at Manchester Airport and these are summarised in Table 1.

Table 1. Model settings

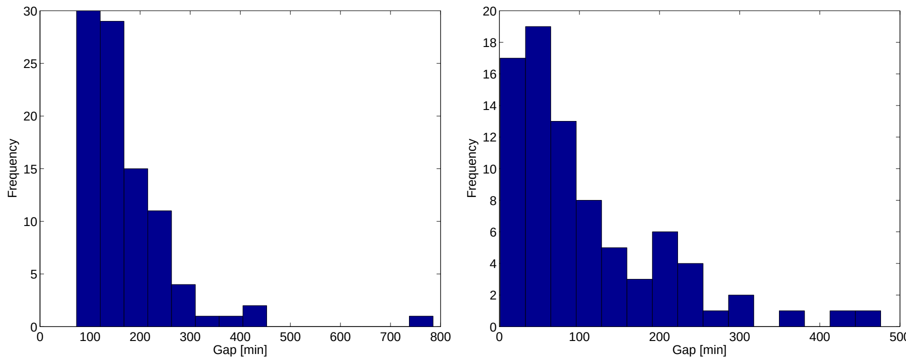
Name	Symbol	Value
Average number of flights per day	n	110
Number of gates	m	25
Time at which flights are split for towing		240 min
Size of the gap for which p saturates		90 min
Penalty for remote allocation	d	90
Minimal allowed size of the gap between flights		10 min
Shortest time margin for conflicts within group of gates		3 min
Longest time margin for conflicts within group of gates		10 min
Maximal number of conflicting flights per GR	M	2

There was only one shadowing constraint in the data, for the large gate 12, which can be divided into two smaller gates, left 13 and right 14. Figure 1 shows the groups of gates for Terminal 1. The gate-group adherence is as follows: GR1: 22, 24, 26, 28, 29, 32, 31; GR2: 21, 23, 25, 27; GR3: 2, 4, 6, 8; GR4: 10, 12, 13, 14; GR5: 1, 5, 7, 9, 11, 15.

6 Results and Discussion

The first part of this section shows how the new conflict constraint influences the final allocation. Results for one chosen day are displayed and allocations obtained for the model with and without the conflict constraint are briefly compared with the actual recorded allocation. The second part of the section shows numerical results obtained using five days of data. For these calculations the full configuration (with the conflict constraint) of the model has been used. The results are compared against the actual allocations recorded during the day of airport operation. All results have been obtained using CPLEX (version 12.2) executed on a reasonable powerful desktop PC (24GB RAM, 500GB disk space, 3.06 GHz Intel i7-950). An optimal solution was reached for each of the calculated days.

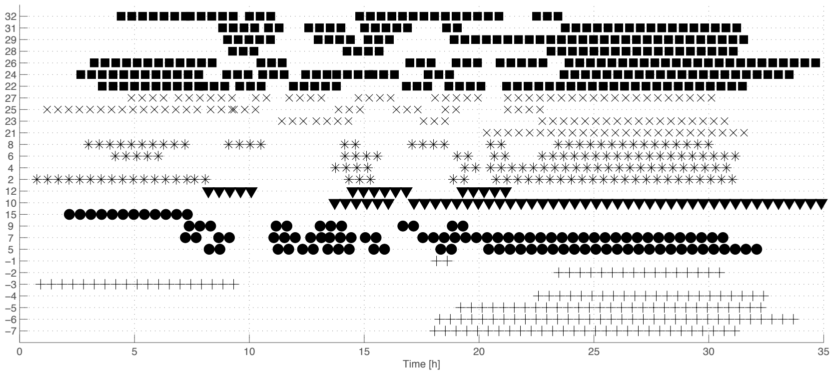
More detailed results are also shown for an illustrative day having 111 flights. Figure 5 compares three allocations for the day: Figure 5a shows the real allocation, Figure 5b the allocation obtained for the model without the conflict constraint and Figure 5c the allocation for the model with the conflict constraint. The horizontal axis of each of the charts shows time and the vertical axis the names of the gates, flights are symbolised by chains of markers. The gates are grouped, with each of the groups introduced in previous sections being assigned a different marker, so that it is easier to observe how the conflict constraint changes the allocation and resolves possible conflicts. All of the flights that have been assigned to the group of gates called GR1 are displayed as chains of squares (■, effectively rectangular bars), GR2 as chains of x-shaped markers (×), GR3 as chains of star-shaped markers (∗), GR4 as chains of triangles (▼) and GR5 as chains of dots(•). The remote allocations are also shown on the charts as chains of crosses (+). The negative gate numbers symbolise remote gates. Each remote allocation has been allocated to a different remote gate, so that it is easier to see how many remote allocations there are. Note that in practice the towed flights can be excluded from the conflict constraint thanks to the flexible implementation of towing. Since no strict towing time is assumed for each tow, the potential conflicts can be resolved by controllers by postponing or speeding up some tows if necessary. Four important observations can be made based upon the graph: (1) The number of conflicting allocations is reduced. (2) The real solution has fewer towed flights, since the long flights are kept on the gates in most cases, resulting in lack of gates available for flights more often, and therefore: (3) the remote stands having to be used more often. (4) The size of the time gaps between allocations is much bigger in the model solutions.



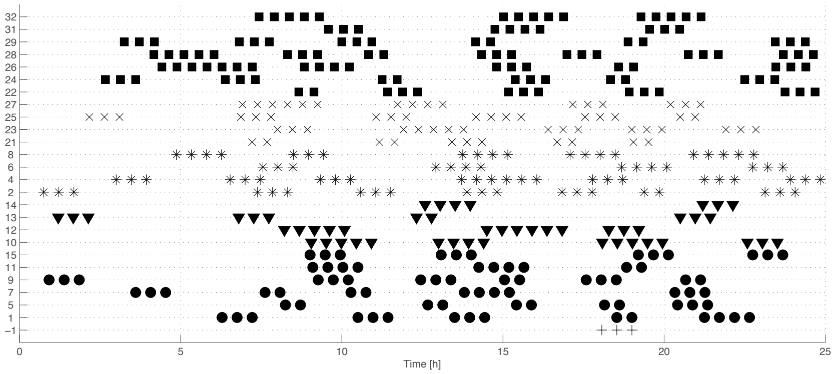
(a) Model solution (b) Recorded allocation

Fig. 4. Gap size distribution

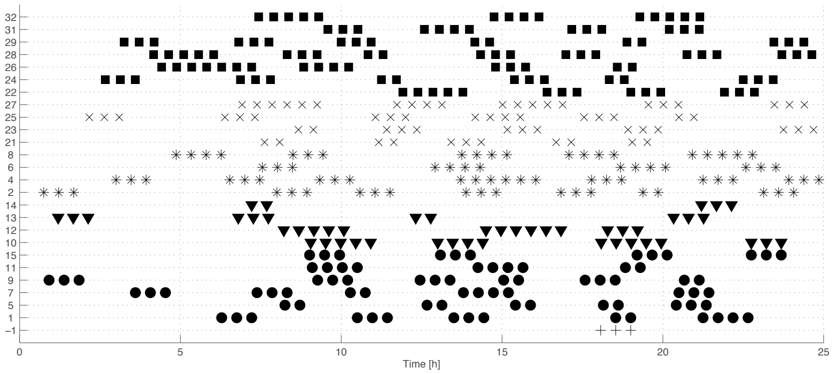
An important objective of the presented model is maximisation of time gaps between allocations (increasing the robustness of the solution). Figure 4 is introduced in order to show the distribution of the gap sizes in the allocation



(a) Real allocation



(b) Model without conflict constraint



(c) Model with conflict constraint excluding tows

Fig. 5. Results obtained for the example day: the real allocation (a), model without conflict constraint (b) and model with conflict constraint excluding towed flights (c).

obtained for the full model (a) and for the real situation (b). The smallest gap in the model solution is 90 minutes while in the real situation there were many gaps which were smaller than that. The numerical results obtained for five days are presented in Table 2. The first column of Table 2 shows the total number of flights in the five days, the second one shows the percentage of on-pier allocations, the third the percentage of the remote allocations and the last the number of conflicts which have been resolved by the introduction of the new constraint.

There are fewer remote allocations in the generated solution and 34 conflict constraints have been resolved. However, it can be observed based upon the total number of flights that the model introduces more tows into the solution, which may not be good, especially at very busy periods. Another drawback of the presented solution method is the calculation time, since it took in total over three days to calculate the five days of allocations and therefore heuristic methods will be considered now that the effects of the model have been established.

Table 2. Numerical results

	Flights in total	On-Pier [%]	Remote [%]	Resolved conflicts
Model	680	95	5	34
Real	626	92	8	0

7 Conclusion

This paper considers the gate allocation problem and the conflicts which occur on the taxiways close to the gates. Integration of various airport operations is gaining increasing importance due to the increasing air traffic. Closer integration of different parts of airports could potentially result in smoother operations, fuel burn reductions and lower harmful gas emissions. The model of the gate allocation problem which is presented here moves this integration a step closer by incorporating some of the taxiway conflicts into the allocation process.

The major gains of the presented model compared to the real solution are an increase in the robustness of the solutions and a reduction in both the number of conflicts around the gates and the number of the remote allocations. However, there are significant differences in the number of tow operations. Having the towing procedure in the objective instead of explicitly splitting all the long flights would probably improve the performance of the model in this regard. Changing the conflict constraint into a soft constraint may be also a good idea, as the number of remote allocations and the resolved conflicts could then be balanced by setting appropriate weights in the objective function. The long calculation times indicate that alternative solution methods should be considered.

Future work will consider potential decompositions of the problem and/or heuristic approximations to speed up the calculations. Moreover a deeper analysis of the conflicts which occur on taxiways, not only close to the gates but also further away and incorporating this into the allocation process appears to be worthwhile area for future work. An analysis of the ground movement with a view to integration has already been provided by Atkin et al. [13]. Their system assumes that the gates are already allocated and provides routing information based upon the assumed gate allocations. Integration of these approaches is an interesting research area moving forward. Finally, an assessment of the impact of the parameters and weights used in the model on the obtained results is also important future work.

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