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Modelling the effects of gate planning on apron congestion

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One of the infrastructural components that limits airport capacity is the available gate capacity. In order to use existing airport infrastructure, especially gates, more efficiently, one can look at new techniques to relieve congestion. One such technique is introducing so-called gate pit-stops. By introducing gate pit-stops, aircraft will be towed to a remote parking position between arrival and departure from the gate, in order to make space for other flights in the meantime [1]. The main risk of introducing gate pit-stops in airport operations is that the additional towing movements will inevitably increase the number of apron movements, potentially interfering with other traffic on or near the apron. As such, the main challenge in introducing gate pit-stops is modelling and integrating gate and apron movements, where a tradeoff can be made between gate utilization, towing movements, turnaround times and gate flexibility. Additionally, technological innovations such as an Electric Taxi System (ETS) need to be assessed as they can have a big impact on apron operations. Therefore, the effectiveness of gate pit-stops needs to be assessed, as well as the impact of factors such as gate utilization, towing movements and turnaround times on the effectiveness of such gate pit-stops.

I. Introduction

One of the infrastructural components that limits airport capacity is the available gate capacity. Several Level 3 airports are currently facing gate capacity issues, especially at peak times. An example of this is Amsterdam Airport Schiphol, The Netherlands (AMS). The Dutch airport has grown rapidly over the past few years, welcoming over 63 million travellers in 2016 [2]. This success comes at a price however, as current terminal infrastructure cannot cope with this steep increase in passenger numbers; since the onset of the Summer 2017 schedule, gate capacity restrictions have forced the dominant hub carrier KLM to handle select long-haul flights remotely on stands instead of directly at the gate [19]. The Dutch airport is not unique in this regard. Multiple airports worldwide face the same challenges as AMS, where increased traffic which has prompted the construction of additional terminal real estate or even entirely new airports, as in Mexico City and Istanbul [3,4]. The construction of new terminal real estate with additional gate capacity comes at a premium and existing real estate is traditionally scarce, which makes gate capacity an expensive resource. It is therefore imperative that gate infrastructure is utilized as efficiently as possible. The rapid growth in air traffic coupled with the push for more efficient airport infrastructure utilization has led to many studies since the seventies into more efficient use of airport real estate, including gates, taxiways and apron areas. Examples of this include the Gate Assignment Problem (GAP), which deals with assigning flights to a set of gates while making sure that a predefined set of criteria is met [5] and the Ground Movement Problem, which looks at optimizing all airside operations [6].

A. Gate Scheduling

When looking at airport operations, one of the most important aspects is the assignment of aircraft to specific gates throughout the day. Creating a gate schedule that deals with the operational needs of the airport and airlines alike is very challenging. For a few decades, many researchers have looked at solving this complex problem which is often referred to as the Gate Assignment Problem (GAP). In order to research the effectiveness of gate pit-stops, the assignment of aircraft to gates needs to be considered and modelled together with the apron movements.

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The most commonly found rules and constraints that a well-constructed gate assignment schedule should satisfy are [7]:

1. One gate can process only one aircraft at the same time
2. Service requirements and space restrictions with respect to adjacent gates must be fulfilled
3. Minimum ground time and minimum time between subsequent aircraft have to be assured
4. The number of un-gated (open) aircraft activities has to be minimized
5. Preferences of certain aircraft for particular gates have to be maximized

Note that above list is not exhaustive, additional constraints have also been found in literature, for example when assigning a wide body aircraft to a particular gate, a constraint may be introduced that only allows adjacent gates to be occupied by narrow body aircraft.

One of these aspects is how this model formulation allows for flights with a long layover to be modelled. In this approach, flights with a long layover are modelled as three separate parts in the GAP, which are:

- Flight arrival: Aircraft arrives at the gate
- Remote parking between flights: Aircraft is towed away from gate and parked at a remote stand
- Flight departure: Aircraft is back at the gate for departure

This allows for simulating and modelling flights that can be considered for gate pit-stops. An advantage of using this approach to schedule flights with a gate pit-stop is that each activity can be assigned a different gate or parking position in the GAP. Therefore, a flight can be modelled arrive at a fictitious Gate A, be towed by a tow tractor to a desired stand in between arrival and departure after which it can depart from a different Gate B. As the model in this research has three objectives that need to be satisfied, the objective function becomes considerably complex since it is a combination of the three partial objectives. Depending on the scale of the eventual model and the exact objectives, this research may serve as an example model, however it is expected that the gate assignments in the thesis research will be less complex, especially in the initial model.

Currently, only flights that stay at the gate for longer than three hours in AMS are considered long-stay flights and therefore eligible for remote towing in between arrival and departure. Flights with a shorter turnaround will be considered as well to determine the effectiveness of pit-stops for flights with a shorter turnaround time.

B. Apron Operations

In order to model the apron movements, an accurate insight into the operating environment at the apron is required. This section discusses various apron layout design parameters that influence the apron capacity. Additionally, standard operating procedures of apron movements are detailed in the next section in order to accurately model these movements at a later stage. The design parameters and typical apron layouts that will be discussed allow for an initial apron design which serves as a starting point for the thesis research.

The first design parameter that has an influence on apron capacity is the type of aircraft that will be handled at the gates. The chosen aircraft type(s) has an effect on the gate type (as not all gates can handle all aircraft sizes), the number of gates (when working with a given amount of space, the aircraft size has a direct influence on the available number of gates), as well as pushback procedures, engine start up (ESU) and engine start up time (ESUT). In order to reduce model complexity, it has been decided that the apron will be modelled for typical single-aisle aircraft such as the Boeing 737 and Airbus A320 series, as they are the most commonly used aircraft at large airports such

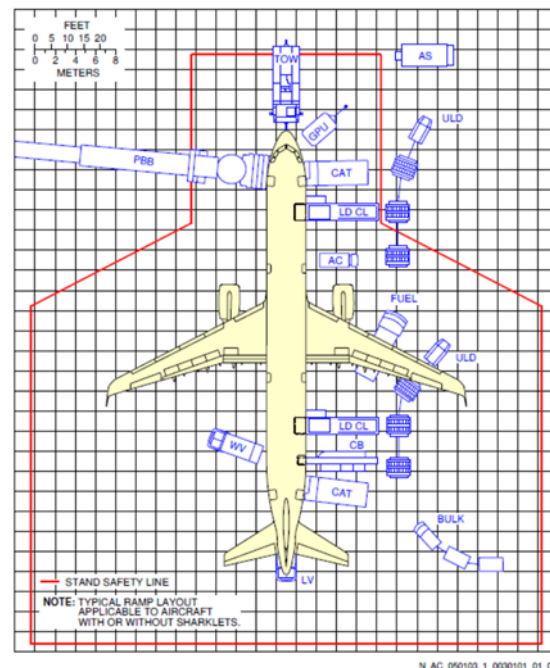


Figure 1: A321 apron spacing [8]

as Amsterdam Airport Schiphol, The Netherlands (AMS) [9].

At airports worldwide, aircraft gates and the surrounding apron are sized according to the aircraft category that will be serviced there, since aircraft of different sizes require different types of gates. The aforementioned regulatory bodies have set guidelines for gate sizing per aircraft category handled at a particular gate. For Category C aircraft, EASA guidelines stipulate a spacing of no less than 40.5 meters between two aircraft stand taxi lanes (see Table 3.2, column 11). Hence, when setting up a simulation model, the minimal spacing between two adjacent gates will initially be set to 40.5 meters. This spacing is consistent with guidelines set by Airbus for apron servicing of its A320 family aircraft, as shown in figure 1.

Next to the gate spacing, a closely related design parameter is the aircraft parking type. The aircraft parking type refers to the way in which the aircraft are positioned relative to the terminal building and it affects the angle the aircraft makes with the terminal building. The parking type also affects aircraft maneuvering to enter or exit the parking area at the gate and the total apron area. According to [10], there are four different aircraft parking types, namely Nose-In Parking, Angled Nose-In Parking, Angled Nose-Out Parking and Parallel parking. All four parking types are visualized in Figure 2.

For the gate pit-stop research, a Pier concept terminal will be used initially, where the apron movements inside of the 'fork' will be taken into account. Initially, four gates on each side of the 'fork' will be modelled, with one apron taxi lane running through the middle of the apron area from north to south, and one taxiway that runs from east to west (and vice versa) outside of the apron area. This taxiway, which connects the apron area that will be modelled to the rest of the airport, will be referred to as the main taxi lane. The number of gates may be varied later in the modelling phase to assess its effect on the effectiveness on gate pit-stops. Additionally, the location and/or number of apron taxi lanes can be varied in a later stage as well. A visualization of the initial situation of the gate and apron model taken into account is provided in Figure 3. Note that there is one entrance/exit to the apron area at the top fork opening, though if the terminal were to have additional gates, an extra entrance/exit at the bottom of the fork may be added at a later stage. As the aircraft will be parked Nose-In, pushback movements will be required in order for the aircraft to taxi out.

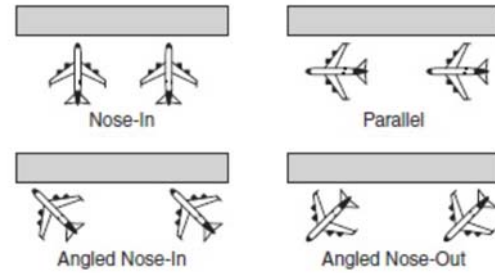


Figure 2: Parking types [10]

C. Apron Movements

In order to properly model every movement to determine gate pit-stop effectiveness, the exact procedure and the estimated time each procedure takes to be performed will be evaluated as an initial starting point.

Taxi-in entails the movement of the aircraft from the apron entrance until the aircraft has fully crossed the apron safety line at the gate area. In order to accurately model the taxi-in maneuver, the distance travelled across the apron to the gate area and the apron taxi speed need to be known. The distance travelled depends on the gate at which the aircraft is parked and the separation between the gates.

When the aircraft has completed the taxi in maneuver, it will be serviced at the gate, a process referred to as turnaround or turnaround operation. In aviation, turnaround is defined as the ground operation process to service an aircraft from the moment it is parked at the gate until it is ready to depart again, also referred to as the on-block and off-block times [11].

Once the aircraft has completed the turnaround operation (either with or without remote towing as part of a gate pit-stop), it will depart from the gate. With the decision to model the apron with Nose-In gate positions only, the requirement for pushback has arisen as the current generation of aircraft with wings span class C are not allowed to reverse from the gate autonomously.

In case the aircraft will taxi out of the apron area on its own power, its engines need to be started.

Engine start up (ESU) takes place simultaneously with the pushback

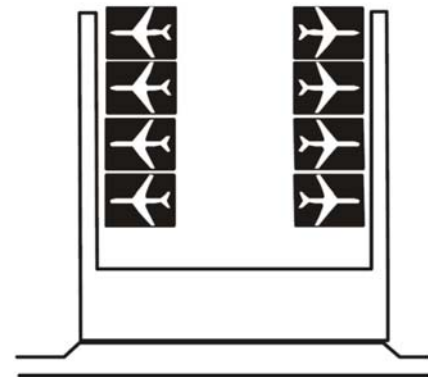


Figure 3: Pier model

maneuver. This is possible only if the ESU time (ESUT) is shorter than the time to push back the aircraft itself, which was estimated to take about 3 minutes. Otherwise, ESU will partly take place while the aircraft is parked on the apron taxi lane, blocking it for other aircraft.

As the aircraft has been pushed back and has started its engines, it can taxi out. This maneuver, the taxiout maneuver, is closely related to the taxi in maneuver. After the aircraft has been pushed back from the gate, it will taxi out of the apron area onto the main taxi way. In this case, the taxi-out maneuver will happen under the aircraft's own power.

In case the aircraft will perform a gate pit-stop, the taxi-out maneuver will not take place under its own power. The aircraft will be pushed back, after which it will be towed by a tug to a designated remote parking position, where it will wait before it will be towed back to the gate again. The towing movements will be modelled up to the apron entry/exit. As such, the towing distances are virtually the same as the taxi in and taxi-out distances. From [12], an average towing speed of about 5 kts can be assumed using a tug, concluding the final apron movement that will be considered.

D. Electric taxi systems

Since airport surface movements, including those discussed previously in this chapter, take place with running aircraft engines at (very) inefficient speeds or using polluting tugs, alternatives for power during taxi are being developed. The most promising solution for an alternative taxi power source is an Electric Taxi System (ETS) [13]. An ETS powers the nose or one of the main gears of an aircraft during taxi and pushback by use of an electric motor powered by the Auxiliary Power Unit (APU). As such, an ETS reduces fuel consumption, since the need for a tow truck is eliminated, as well as the need for running the aircraft's engines on the ground. Next to reducing fuel burn and emissions, an ETS may increase the efficiency of the pushback procedure, as aircraft can push back autonomously with an ETS [1].

One of the advantages of an ETS according to [14] is that aircraft equipped with an ETS are able to maneuver at higher speeds with a higher acceleration and deceleration respectively. This will have an effect on the apron movements discussed, including taxi-in and taxi-out as well as the pushback operation. The authors expect a reduction in taxi-in and taxi-out times of 10 up to 20 %. For the pushback procedure, a maximum velocity of 7 knots using an ETS can be attained whereas the regular pushback procedure is assumed to take place at an average of 3.5 knots.

In [1] it is argued that, especially at congested airport like AMS where gate pit-stops are not yet commonly used, the use of ETS can be of essential importance to increase the number of gate pit stops. This is mainly because ETSs eliminate the need for tow trucks and therefore no extra demands are placed on tow truck resources when introducing gate pit-stops with ETS equipped aircraft. While the possibility of increased gate pit-stops using ETS is introduced, an analysis of the impact of gate pit-stops on the apron operations at the airport has not been done.

II. Apron modelling

In the past years, several simulation tools used for analysis of ground traffic have been developed and used at airports worldwide. These include the FAA's SIMMOD Plus and SIMMOD Pro tools, Eurocontrol's RAMSPlus, TAAM by the Preston Group, Sabre's DPM, CAST and AirTOP. These programs all offer the ability to fast-time simulate airside traffic (including the apron area) on a microscopic level. As such, they are of great importance for airport planning, as they are able to model existing and planned traffic operations very well. Additionally, airports can be defined in these programs in very high detail, as both physical and operational constraints at airports can be modelled with high accuracy. In order to work with such tools, the first step usually consists of building the airport model, after which the effects of varying levels and modes of traffic can be assessed by inputting a schedule. Also, the effect of changes in the physical layout of airports, such as new gates and stands, can be assessed in a relatively quick way. Because of this capability, these programs enable airports to make the most efficient decisions when it comes to traffic planning as well as making physical changes (like adding gates for example) [15]. A prerequisite for accurate results with such tools is that the input data supplied is of sufficient quality. This data usually consists of a detailed schedule of traffic at the airport (or airport model) under study.

According to [16], calibrating and validating models of airports in simulation tools like SIMMOD is extremely difficult. Consequently, in-depth knowledge of the exact workings of an airport under study is required in order to provide meaningful information on the effect of improvements at the airport (such as adding extra gates). Another downside of these tools is that they sometimes lack in automatically improving operations, a feature that other

optimization systems do possess [17]. Similarly, in [18] it is argued that while aforementioned simulation software is very advanced and detailed, these tools require a significant amount of training. Coupled with a very steep learning curve, this might make them unsuitable for the purposes of this research,

A. Node and link model

With the set up to create a node and link model of a hypothetical airport, the appropriate scope needs to be defined. It has been decided that the node and link model will cover the apron area, including the gates, however runways are not included and therefore outside of the scope of the model. Several design choices for the physical characteristics of the model have been taken which are summarized below.

- The apron movements will be modelled for Category C aircraft
- Gate sizing will be adapted to Category C aircraft
- A hypothetical airport with sets of two opposite gates in pairs of two will be used for the model with a pier-concept terminal
- Aircraft will be parked nose-in at the gate
- Pushback can be done using a pushback truck (no autonomous pushback)
- The main apron taxiway is bidirectional

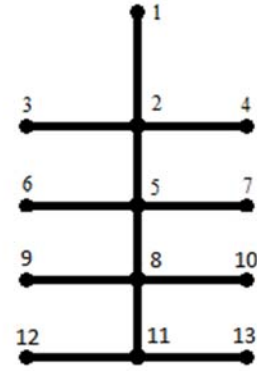


Figure 4: Model with 8 gates.

The number of gates under study varies between four, six and eight gates. Figure 4 shows the node-link model with eight gates.

Table 1 shows the travel times for arrivals and departure. The difference in travel time from the gates is due to the total pushback time, where it is assumed that ESU takes places simultaneously.

Table 1: Travel time for arrivals (left) and departures (right)

From Node	To Node	Time (s)	From Node	To Node	Time (s)
1	2	18	2	1	18
2	3	12	3	2	180
2	4	12	4	2	180
2	5	18	5	2	18
5	6	12	6	5	180
5	7	12	7	5	180

B. Mathematical model

The main goal of the simulations is to assess whether gate pit-stops can serve to increase gate capacity at airports, and whether using gate pit-stops will (significantly) increase delays on the apron. As such, the problem has been formulated as an optimization to minimize the delay of every aircraft at each node and to minimize the number of remote stand assignments. The optimization has been formulated using multiple constraints to ensure aircraft do not collide and minimum separation between different aircraft at each node is guaranteed. Additionally, the model may allow for switching the order of two consecutive aircraft if this reduces delays. The most appropriate approach is to use a MILP formulation, as this allows for a combination of binary decision variables as well as integer decision variables.

The objective of the initial model is to minimize the sum of the delay (1) for each arriving (a) and departing (d) aircraft k at each node i , the gate preference g for aircraft k at gate g and a penalty ($M=50000$) for each aircraft parked remotely.

$$\text{Min } Z = \sum_{i \in I} \sum_{k \in K} \sum_{g \in G} (Da_{ik} + Dd_{ik} + g_{kg} + Mr_k) \quad (1)$$

The departure time at a node i for aircraft k is equal to the arrival time plus the delay (2). Delay can thus only be incurred on a node. 2a is for an aircraft arriving, 2b is for departing.

$$tsa_{ik} + Da_{ik} = taa_{ik}, i \in I \cup k \in K \quad (2a)$$

$$tsd_{ik} + Dd_{ik} = tad_{ik}, i \in I \cup k \in K \quad (2b)$$

The arrival time at the next node j is equal to the departure time at the previous node i in the route plus the travel time between the nodes ij , if aircraft k is allocated to gate g (3).

$$tsa_{jk} - taa_{ik} - tt_{ij} - Mg_{kg} \geq M, i \in I, j \in I, i \neq j, k \in F, g \in G \quad (3a)$$

$$tsd_{jk} - tad_{ik} - tt_{ij} - Mg_{kg} \geq M, i \in I, j \in I, i \neq j, k \in F, g \in G \quad (3b)$$

If aircraft k' comes after arriving aircraft k the time must be larger equal to the time separation (4a). If the order is the other way around, this constraint will be lifted by adding a factor M . The opposite constraint (4b) then comes into play, as (5) makes sure at least one of the options is true. 4c and 4d do the same between departing aircraft. For computational reasons, switching orders is only allowed for aircraft within a limited time span of each other. 4e and 4 then finally assure separation between arrivals and departures at each node.

$$-taa_{ik} + taa_{ik'} - MO_{kk'} - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k, k' \in K, k \neq k', g, g' \in G \quad (4a)$$

$$taa_{ik} + taa_{ik'} - MO_{k'k} - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k, k' \in K, k \neq k', g, g' \in G \quad (4b)$$

$$-tad_{ik} + tad_{ik'} - MO_{kk'} - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k, k' \in K, k \neq k', g, g' \in G \quad (4c)$$

$$tad_{ik} + tad_{ik'} - MO_{k'k} - Mg_{kg} - Mg_{k'g'} - T_{sep} \geq -3M, i \in I \cup k, k' \in K, k \neq k', g, g' \in G \quad (4d)$$

$$taa_{ik} - tad_{ik'} - MO_{kk'} \geq -M + 30, i \in I \cup k, k' \in K, k \neq k' \quad (4e)$$

$$taa_{ik} - tad_{ik'} - MO_{k'k} \leq 30, i \in I \cup k, k' \in K, k \neq k' \quad (4f)$$

$$O_{kk'} + O_{k'k} = 1, k, k' \in F, k \neq k' \quad (5)$$

Every gate must be assigned to one aircraft at a time at most. For each aircraft a set $K(k)$ is created of aircraft k' which are at the airport at the same time as aircraft k . No other aircraft may be assigned to gate g if aircraft k is (6).

$$\sum_{k' \in K_{conflict}(k)} g_{kg} + g_{k'g} \leq 1, k \in K \cup g \in G \quad (6)$$

Every aircraft k must be assigned to one gate or a remote stand (7).

$$\sum_{g \in G} g_{kg} + r_k = 1, k \in K \quad (7)$$

C. Scenarios

The flight schedule consists of 30 flights, arriving every five minutes, to which a uniform distributed random delay of up to five minutes is added. The departure time is set at +40 minutes, with the exception of a random two flight of the first 8 (for 80 and 100 minutes) or 5 (for 120 minutes), which are increased to the extended turnaround

time, which can be 80, 100 or 120 minutes. The aircraft with long turnaround are either set to a long stay at the gate, or towed twenty minutes after arrival and towed back 20 minutes before departure.

The number of gates on the pier is set to either 4, 6 or 8. If not enough gates are for a flight without a delay of more than five minutes, the aircraft is parked remotely. Mainly arrivals are delayed before departures, as departures usually have a fixed departure time at the runway.

Each scenario is run 50 times to get average results

III.Results

Table 3: Remote assignments per scenario

#gates	80 minutes		100 minutes		120 minutes	
	Long stay	Pit stop	Long stay	Pit stop	Long stay	Pit stop
4	17.2	18.0	17.1	17.3	17.2	16.8
6	12.0	13.2	12.2	12.8	12.7	12.3
8	8.3	8.2	7.9	7.5	8.6	7.9

Table 4: Average delay [sec] per aircraft per scenario

#gates	80 minutes		100 minutes		120 minutes	
	Long stay	Pit stop	Long stay	Pit stop	Long stay	Pit stop
4	43.9	53.1	44.0	59.3	47.7	59.8
6	211.9	239.9	219.0	245.9	209.5	266.2
8	308.6	450.2	311.1	385.4	273.1	404.5

For the scenario with four gates, in figure 5 and table 3, about 13 aircraft can be parked at the gates. It can be observed that adding pit stops with a turnaround of 80 minutes has a negative effect on the this number. Apparently the extra 40 minutes gate space that becomes available cannot effectively be used and actually causes an increase in the amount of flights which have to be parked remotely. For 100 minutes, the results are similar and only for 120 minutes does adding a the pit stop actually show any benefit. Also, as shown in table 4, the delay increases by using pit stops for all scenarios with a long turnaround of 80, 100 and 120 minutes long turnaround, respectively.

Comparing the long stay scenarios, with 6 and 8 gates in table 3, figure 6 and figure 7, we see that the number of aircraft parked remotely goes down with around 5 if we go from 4 to 6 gates and down by about 4 if we go to 8 gates. Apparently, the congestions of pushbacks and taxi ins means that each additional gate in the cul-de-sac actually seems to be less effective, due to the congestion of push-backs and taxi-ins in combination with the timings of the additional flights are less beneficial. Also using pit stops seems to be less effective. With respect to delay increases significantly due to congestion, especially when adding pit stops. The duration for the long stay has a varying effect.

Finally, table 5 shows the effect of reducing the pushback times from 180 to 120 seconds for the scenario of a 120 minute turnaround with a pit stop, which could be accomplished by (for example) using an electric taxi system. As can be seen. The effect on the amount of aircraft which can be parked at the gates is quite limited, but the average delay reduction of around 30 seconds is half the reduction in the pushback time.

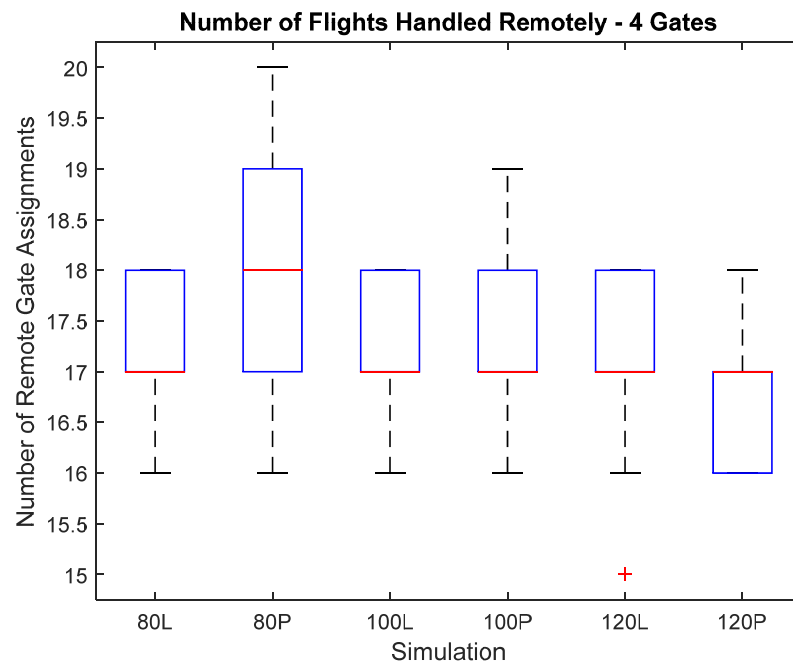


Figure 5: Boxplots for 4 gates and 180 second pushbacks

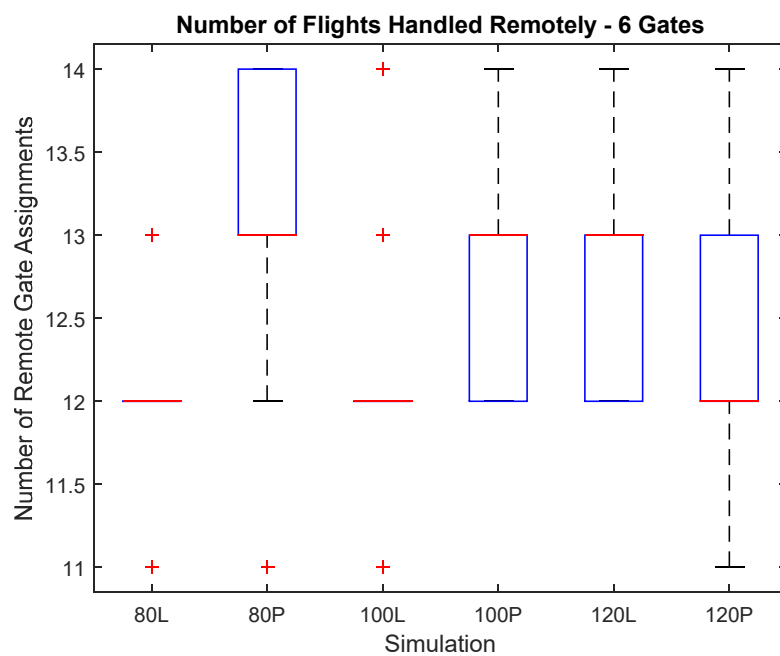


Figure 6: Boxplots for 6 gates and 180 second pushbacks

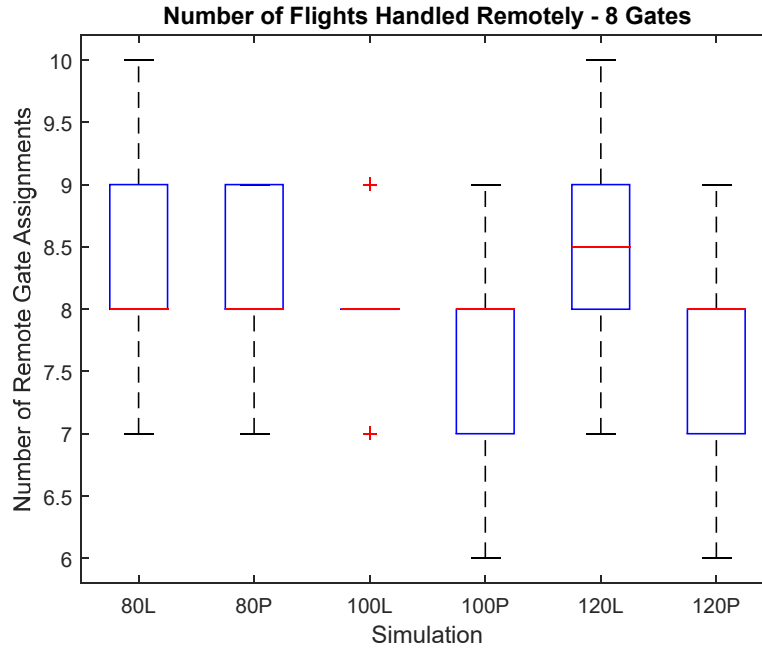


Figure 7: Boxplots for 8 gates and 180 second pushbacks

Table 5: Effect reducing pushback times 180 to 120 seconds on 120 minute turnaround

#gates	Remote assignments		Delay [sec]	
	Long stay	Pit stop	Long stay	Pit stop
6	12.3	12.3	266.2	231.2
8	7.9	7.7	404.5	376.0

IV. Conclusions and recommendations

Adding pit stops to a finger pier configuration with a single taxiways, generally has some effect if the turnaround time for long stay flights are 120 minutes or more. Otherwise the extra movements and associated congestion does not seem to weigh up to the increase in flights handled at a gate instead of a remote stand. Especially for the scenarios with four and six gates in the cul-de-sac, pit-stops only seem effective with a long turnaround time of 120 minutes. For the scenario with eight gates, adding pit-stops with a long turnaround time of 100 minutes has a positive effect on the number of remotely handled flights. It seems that increasing the number of gates in the cul-de-sac decreases the minimum turnaround time at which pit-stops become effective.

In addition to the effect of the number of gates, limiting pushback times has a definite effect on wait times for aircraft. Using ETS instead of conventional pushback significantly reduces delays for aircraft waiting to enter the apron area. Additionally, for the scenario with 8 gates, a reduction in the number of remote gate assignments can be noticed as well.

For future research, this research can be expanded to look at other effects of both the physical layout and the type of movements that take place. These include investigating the effect of two-lane taxiways, mid field configurations which are open on both sides and different aircraft types.

Finally, to decrease computation times for scenarios using real airport data for significant time spans, possibly some simplifications should be made to the model to keep optimizations times acceptable.

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