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# Runway capacity management – An empirical study with application to Doha International Airport

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ABSTRACT

This paper examines a three-faceted approach for runway capacity management, based on the runway configuration, a chosen scheduling approach, and an aircraft separation standard. These factors prompt alternative runway settings that are encapsulated using a classical mixed-integer formulation. The optimal solution for each runway setting is compared against our proposed optimization-based heuristic. This integrated approach is applied to investigating the transition from the (Old) Doha International Airport to the New Doha International Airport. Our empirical study based on historical data reveals that the proposed heuristic consistently yields optimal or near-optimal schedules, with considerable savings in fuel cost and reductions in delays, while preserving the spirit of an FCFS sequencing policy.

## 1. Introduction

In recent years, new flight patterns – facilitated by the advent of larger aircraft – and ever-increasing air traffic loads have required airlines and airports to seek new frontiers in operations efficiency. In 2012, Airports Council International (ACI) reported over 6 billion passengers in domestic and international flights worldwide. By 2025, it is anticipated that this figure will increase by at least 50%, with over 9 billion passengers in global air traffic. The growing air traffic trends necessitate the construction of new airports, major capacity expansions at busy airports, a commensurate adjustment of aviation infrastructure, and the identification of operational policies and managerial directives that best avail of existing capacity. In particular, airports are faced with persistent challenges related to runway scheduling, a key bottlneck in the air transport system.

The Middle East is serving as a hub for global trade and transport and has witnessed rapid air traffic growth over the last years. According to the *International Civil Aviation Organization* (ICAO), international air traffic amounts to nearly 60% of the total passenger traffic, 10% of which occurs in the Middle East. In this context, the United Arab Emirates and Qatar are making large investments in aviation infrastructure and host three major airlines, *Emirates Airline* based in Dubai, *Etihad Airways* based in Abu Dhabi, and *Qatar Airways* based in Doha.

Our work is predicated on the notion that runway capacity should be analyzed in light of three primary factors: (i) The runway physical configuration and operating mode (segregated vs. mixed); (ii) The adopted aircraft scheduling approach which spans heuristics, metaheuristics, and optimization approaches; and (iii) The specific standard adopted for aircraft separation. Two of the commonly used aircraft separation standards are stipulated by the *Federal Aviation Administration* (FAA)

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and the *International Civil Aviation Organization* (ICAO) and are examined in this paper. To the best of our knowledge, no comparative study has empirically examined such complementary planning factors that influence the performance of runways.

Most of the studies in the literature focus on a specific exact or heuristic solution approach to the aircraft sequencing problem. In this paper we adopt a more integrated approach. As depicted in Fig. 1, we examine the combined effect of the specific runway configuration, including the physical layout of runways and their operation mode (mixed or segregated), the aircraft scheduling policy, and the aircraft separation standards. In particular, we contrast the case of a single-runway airport (as in Doha International Airport, DOH) with the two-runway newly constructed (Hamad International Airport, HIA), under mixed vs. segregated mode. The runway performance under alternative settings is assessed using the proposed optimization-based approach and aims at quantifying fuel burn savings (and accompanying delay reductions). Furthermore, our study demonstrates the importance of assignment decisions, an aspect that is commonly overshadowed by discussions on sequencing decisions. Our results indicate that, even under an FCFS policy within the departure and arrival queues respectively, optimizing aircraft assignment decisions can yield overall very near-optimal solutions. This, in turn, can be beneficial to air traffic controllers, as the focus is not so much on adopting a complex sequencing procedure that could be inhibited by airport layout considerations in practice; rather it is on the benefit of effective aircraft-runway assignment decisions.

The remainder of the paper is organized as follows. Section 2 positions the present work in the context of the extensive literature on aircraft sequencing problems. Section 3 presents a classical optimization model for runway scheduling. This model can readily encapsulate the three-faceted planning approach that we adopt and is enhanced via preprocessing routines. We also propose heuristics that are grounded in the optimization model and the FCFS sequencing policy. In Section 4, we discuss data related to runway operations at Doha International Airport and present our computational results for alternative runway settings using the proposed solution methodology. Section 5 concludes the paper with a summary of our findings and directions for future research.

## 2. Literature review

At an operational level, runway scheduling problems seek to determine effective aircraft schedules over one or multiple runways using pertinent cost objectives or performance criteria. There exists a large body of literature on aircraft sequencing approaches that is grounded in seminal works on machine scheduling. Bennell et al. (2011) offer a survey of runway scheduling problems, covering modeling approaches, solution techniques, and performance criteria. Popular solution techniques for runway scheduling problems include dynamic programming (Bayen et al., 2004; Brentnall, 2006; Balakrishnan and Chandran, 2006), branch-and-bound/cut algorithms (Brinton, 1992; Abela et al., 1993; Ernst et al., 1999; Beasley et al., 2000), and a broad spectrum of constructive/greedy heuristics and metaheuristics (Bianco et al., 1999; Hansen, 2004; Capri and Ignaccolo, 2004; Hu and Chen, 2005). Most studies tend to focus on either departure or arrival aircraft sequencing, in isolation, with a few exceptions that consider mixed-mode operations.

*Literature on optimization models.* Noting the similarity between aircraft sequencing problems and machine scheduling problems with sequence-dependent set up times and time-windows for the completion of jobs, Ernst et al. (1999) proposed an optimization model that is tackled using a heuristic based on branch-and-bound algorithms. In a similar spirit, Beasley et al. (2000) proposed a disjunctive mixed-integer program (MIP) for single and multiple-runway aircraft sequencing problems which is widely used in the literature. Further, Ghoniem et al. (2013) presented an asymmetric traveling salesman problem-based (ATSP) model for combined arrival-departure aircraft sequencing problems over a single runway. The computational tractability of this formulation was significantly enhanced using valid inequalities and preprocessing routines.

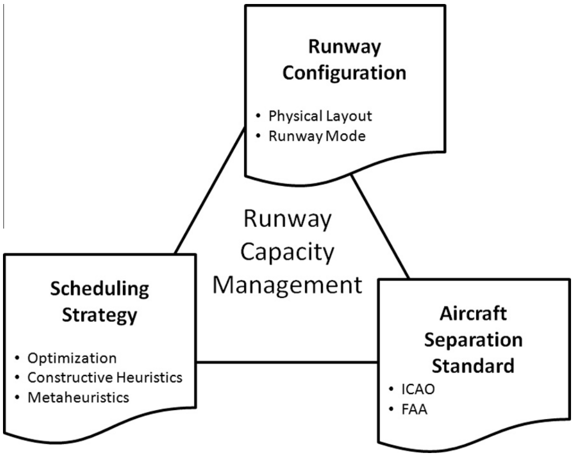

**Fig. 1.** Key factors related to runway capacity.

*Studies specific to airports.* Several studies in the literature address runway operations management with application to specific airports. Using landing time intervals at Logan Airport, Venkatakrishnan et al. (1993) demonstrated that aircraft sequences that outperform those identified by controllers could be constructed, thereby reducing flight delays by up to 30%. Idris et al. (1999) examined the interaction between key elements of an airport system, including runways, taxiways, ramps, and gates. Focusing on aircraft departures at Logan Airport, the authors concluded that runways constitute the principal bottleneck in the flow of airport operations and their management significantly impacts system-wide efficiency. Also, motivated by an application to London Heathrow Airport, Beasley et al. (2001) proposed a metaheuristic to improve the sequencing of landing aircraft. Atkin et al. (2008) developed a metaheuristic approach for the sequencing of departing aircraft as a decision support tool for runway controllers at Heathrow airport.

*Alternative objective functions.* Key stakeholders in aircraft operations management include the airport, airlines, and governmental authorities (Bennell et al., 2011). Depending on the planner's interest, different performance criteria and objective functions can be considered for runway scheduling. For instance, minimizing the makespan, or equivalently maximizing the runway throughput, optimizes the start-time of the last aircraft to access the runway and is viewed as an airport-driven target. This performance criterion can, however, be detrimental to the mean aircraft delay (Lee and Balakrishnan, 2008), an objective that is more important to airlines and passengers. Beasley et al. (2000) and Ernst et al. (1999) employ an objective function that minimizes the total aircraft earliness and tardiness, measured as the weighted deviation from target landing/departure times. Such objective functions are advantageous to airlines and passengers, but also contribute to smoothing airport-wide operations. Recent studies increasingly use direct monetary costs related to fuel burn (Lee and Balakrishnan, 2008; Sölveling et al., 2011), passenger delays, or crew costs (Sölveling et al., 2011).

## 3. Optimization model and heuristic approaches

In this section, we discuss how the proposed three-faceted approach can be readily encapsulated using a classical 0–1 mixed integer program (MIP). Under a given runway configuration and operating mode, the model seeks to simultaneously assign aircraft to runways and to determine an optimal aircraft sequence over each individual runway, while conforming to a chosen separation time standard. Each planning setting is reflected in the input parameters of the model. Thereafter, we propose optimization-based heuristics where the MIP is embedded with additional constraints that heuristically guide the sequencing of aircraft.

### *3.1. Mixed-integer program*

We consider a set of $J$ aircraft arrivals and departures to be scheduled over a set of $N$ parallel independent runways during a particular planning horizon. Each aircraft $j \in J$ is characterized by the following attributes: (i) its operation type $\mathcal{O}_j$ (Departure/Arrival); (ii) its weight class (Heavy, Large, or Small); (iii) a ready-time $r_j$ and a due date $d_j$ which enforce a time-window over which aircraft $j$ should access a runway and start its operation; and (iv) a fuel burn cost, $w_j$, which depends on its operation type and weight class. Aircraft arrivals have substantially larger fuel burn costs per hour and, therefore, the model automatically assigns higher priority to arrivals over departures, as is the case in practice. We denote by $p_{j_1 j_2}$ the minimum separation time between a leading aircraft $j_1$ and a following aircraft $j_2$, which depends on their respective operation types and weight classes and is numerically specified by a chosen standard (ICAO or FAA), as discussed in Section 4.1.

An assignment binary variable $z_{ij}$ is introduced; it equals 1 if and only if aircraft $j \in J$ is assigned to runway $i \in N$. We also introduce a sequencing binary variable $y_{j_1 j_2}$ to determine the relative order of a pair of aircraft $j_1$ and $j_2$ if they are assigned to the same runway. The continuous decision variable, $t_j$, establishes the time at which aircraft $j$ accesses its assigned runway. Given specific input parameters as described above, the runway capacity management problem is formulated as the following 0–1 MIP, which we refer to as **RCM**:

$$\textbf{RCM}: \text{Minimize} \sum_{j \in J} w_j (t_j - r_j) \tag{1a}$$

$$\sum\nolimits_{i \in N} z_{ij} = 1, \quad \forall j \in J \tag{1b}$$

$$r_j \leqslant t_j \leqslant d_j, \quad \forall j \in J \tag{1c}$$

$$t_{j_2} \geqslant t_{j_1} + p_{j_1 j_2} - M(1 - y_{j_1 j_2}), \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2 \tag{1d}$$

$$y_{j_1 j_2} + y_{j_2 j_1} \geqslant z_{ij_1} + z_{ij_2} - 1, \quad \forall i \in N, j_1 \in J, j_2 \in J, j_1 < j_2 \tag{1e}$$

$$y, z \text{ binary}. \tag{1f}$$

The objective function (1a), where the term $\sum_{j \in J} w_j r_j$ is a constant, minimizes the total fuel cost resulting from the deviation of aircraft start-times from their respective ready-times. We refer to this metric in the objective function as the total *excess fuel cost*; if all start-times equal their associated ready-times in a given schedule, then no excess fuel cost is incurred. Constraint (1b) assigns every aircraft to exactly one runway. Ready-time and due date restrictions are enforced in Constraint (1c). The disjunctive constraint (1d) introduces a minimum separation time between any pair of aircraft, whether consecutive or not, that are assigned to the same runway. It involves a sufficiently large scalar $M$, which we validly set to $M \equiv d_{j_1} - r_{j_2} + p_{j_1 j_2}$. Constraint (1e) guarantees that precedence between any pair of aircraft must be established if they are assigned to the same runway. Constraint (1f) specifies binary restrictions on decision variables. Although Model RCM is stated for a multiple-runway configuration, it can be adjusted for a single-runway configuration by relaxing Constraints (1b) and (1e) and eliminating the $z$-variables.

### 3.2. Preprocessing routines

We develop preprocessing routines with the objective of fixing the relative order of certain aircraft, without loss of optimality, and, therefore, enhancing the computational tractability of Model RCM. Such preprocessing routines can be identified by analyzing input parameters related to aircraft and separation times. For example, Constraint (2) states that if the preceding of aircraft $j_2$ to aircraft $j_1$ would cause the latter to violate its due date, then this relative order should be precluded to ensure feasibility:

$$y_{j_2j_1} = 0, \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2,\ r_{j_2} + p_{j_2j_1} > d_{j_1}. \tag{2}$$

Constraint (3) considers two equivalent aircraft that have the same fuel cost $w_{j_1} = w_{j_2}$, which implies that they have the same operation type (both are arrivals or departures) and weight class (both are Heavy, Large or Small), and where one of the aircraft has an earlier time-window. From an aircraft separation point of view, both aircraft in Constraint (3) are equivalent and, therefore, the earlier aircraft can be required not to follow the later one, without loss of optimality.

$$y_{j_2j_1} = 0, \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2,\ r_{j_1} < r_{j_2},\ d_{j_1} \leqslant d_{j_2},\ w_{j_1} = w_{j_2}. \tag{3}$$

Constraint (4) considers a similar situation, but caters for the special case where the two aircraft have identical time windows. It is conceivable to require the lower-indexed aircraft not to follow the higher-indexed one, without loss of optimality:

$$y_{j_2j_1} = 0, \quad \forall j_1 \in J, j_2 \in J, j_1 < j_2, r_{j_1} = r_{j_2}, d_{j_1} = d_{j_2}, w_{j_1} = w_{j_2}. \tag{4}$$

There could be additional cases where a pair of aircraft $j_1$ and $j_2$ are not equivalent, but they introduce the same separation times (i.e. $p_{j_1k} = p_{j_2k}$ and $p_{kj_1} = p_{kj_2}$, for any aircraft $k$, which we simply represent as $p_{j_1,*} = p_{j_2,*}$ and $p_{*,j_1} = p_{*,j_2}$). Constraint (5) identifies aircraft with such symmetric separation times and requires, without loss of optimality, the aircraft with an earlier time-window and larger fuel cost not to follow the other aircraft:

$$y_{j_2j_1} = 0, \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2, r_{j_1} \leqslant r_{j_2}, d_{j_1} \leqslant d_{j_2}, p_{j_1,*} = p_{j_2,*}, p_{*,j_1} = p_{*,j_2}, w_{j_1} > w_{j_2}. \tag{5}$$

### 3.3. Optimization-based heuristics

We propose in this section two optimization-based heuristics that are grounded in the use of the MIP model RCM and the FCFS sequencing policy. The overarching objective here is to develop heuristics that yield optimal or near-optimal solutions, while largely preserving the structure of the FCFS sequence (for practical reasons and in order to maintain fairness among aircraft). We also use the global optimal schedule produced by Model RCM and the FCFS schedule as two benchmarks for comparison with the proposed MIP-based heuristics, as delineated next.

(a) FCFS sequencing policy with segregated-mode runways (**FCFS-SEG**). Considering segregated runways, either dedicated to departures or arrivals, aircraft on a given runway are sequenced in the nondecreasing order of their ready-times. If the problem involves two runways, one is dedicated to the arrivals and the other to departures. If multiple runways are devoted to the same operation type, e.g. departures, there is a need to both assign aircraft to suitable runways and to sequence them using FCFS over the same runway. FCFS-SEG can be implemented using Model RCM. To this end, we consider $N_d$ and $N_a$, the subsets of runways dedicated exclusively for departures and arrivals, respectively, along with $J_d$ and $J_a$, the subset of aircraft departures and arrivals, respectively. We then enforce the following restrictions in Model RCM:

$$z_{ij} = 0, \quad \forall i \in N_d, j \in J_a \tag{6}$$

$$z_{ij} = 0, \quad \forall i \in N_a, j \in J_d \tag{7}$$

$$t_{j_1} \leqslant t_{j_2}, \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2 \mid r_{j_1} < r_{j_2} \text{ and } \mathcal{O}_{j_1} = \mathcal{O}_{j_2}. \tag{8}$$

(b) Heuristic 1 – FCFS sequencing policy with mixed-mode runways (**FCFS-MIX**). In contrast with FCFS-SEG, runways operate in a mixed mode, allowing arrivals and departures to share runways. This proposed heuristic ranks aircraft based on their ready-times and iteratively assigns aircraft to the first available runway. Under this strategy, all aircraft assignments follow the FCFS order and no aircraft is allowed to overtake an earlier aircraft in the sequence. FCFS-MIX can be implemented by appending the following restrictions to Model RCM:

$$t_{j_1} \leqslant t_{j_2}, \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2 \mid r_{j_1} < r_{j_2}. \tag{9}$$

(c) Heuristic 2 – FCFS sequencing policy with optimized assignment (**FCFS-OPT**). Under this proposed heuristic, the assignment of aircraft to runways is optimized with the restriction that no aircraft can overtake another aircraft in its queue (i.e. aircraft of the same operation type, whether arrival or departure). However, an aircraft is allowed to overtake other aircraft of the opposite operation type if deemed pertinent from a cost reduction point of view. For example, an arriving aircraft can overtake a departure aircraft with an earlier time-window. Consequently, the FCFS order applies only within each queue of arrival and departure aircraft, but not across the two queues. The heuristic enables an optimized interweaving of both queues and can be implemented using Model RCM by enforcing the following constraint:

$$y_{j_2 j_1} = 0, \quad \forall j_1 \in J, j_2 \in J, j_1 \neq j_2 \mid r_{j_1} < r_{j_2} \text{ and } \mathcal{O}_{j_1} = \mathcal{O}_{j_2}. \tag{10}$$

(d) Optimal Schedule (**OPT**): We also consider the setting where the assignment and sequencing of aircraft are optimized, independently from any FCFS considerations, using Model RCM. Although this setting does not directly make provision for fairness amongst aircraft, we use it as a benchmark for the best possible performance under a given runway/data input setting.

Fig. 2 provides an illustrative example with six aircraft sequenced over a single runway and highlights aircraft position shifts from one sequencing policy to another. The FCFS policy provides a base sequence for a combination of arrivals and departures and different aircraft weight classes. In this single-runway example, the FCFS-MIX heuristic does not alter the FCFS sequence. Under the FCFS-OPT heuristic, the FCFS order is preserved within the arrival and departure queues but not across the two queues. For example, arriving aircraft 6 is moved to the third position, overtaking departing aircraft 3, 4, and 5, with the implication that this decision produces a better solution (from a fuel cost viewpoint). Under the optimal schedule, the FCFS order may be violated within and across arrival and departure queues. For example, departing aircraft 5 precedes departing aircraft 3 and 4, although the latter have earlier ready-times.

## 4. Computational study and key findings

Our study is anchored in the analysis of data on Doha International Airport that we obtained from *Qatar Civil Aviation Authority* in 2011. We analyzed aircraft movement patterns using SAS 9.3 and implemented all heuristic and optimization approaches using AMPL/CPLEX 12.4 on a desktop with Windows 7 professional 64-bit operating system, an Intel Core i7–2600 CPU with 3.40 GHz, and 12 GB RAM.

### *4.1. Empirical data on Doha International Airport*

DOH currently operates with a single runway (see Fig. 3(a)), one of the longest at civil airports with a length of 4,570 meters. It employs an FCFS policy for aircraft sequencing and the ICAO aircraft safety separation standard. The main terminal at DOH has been expanded several times over the last years in order to accommodate sharply increasing air traffic loads (see Table 1). In 2008, the airport witnessed a 38.8% growth in aircraft movement and ranked amongst the 100 busiest airports worldwide. Further, DOH was the world's 27th busiest airport by cargo traffic in 2010, with over 15 million passengers. In 2012, DOH ranked 25th in international passenger traffic and experienced the second largest growth of 19%, after Istanbul with 25%, over the previous year. Table 1 further summarizes the 2007–2012 traffic at DOH, reflecting sustained growth rates in passenger, cargo, and aircraft movements over the last few years.

To manage the growing air traffic and to better prepare the country for hosting the Qatar 2022 FIFA World Cup and the Qatar 2030 Strategic Vision, the *New Doha International Airport*, to be officially called *Hamad International Airport* (HIA), was constructed as a distinct, new facility with two parallel independent runways. It is expected to replace the single-runway DOH in a near future. The first phase of HIA is planned for inauguration with one runway offering a capacity of 29 million passengers. It is designed to ultimately operate with two parallel independent runways, as depicted in Fig. 3(b), and a

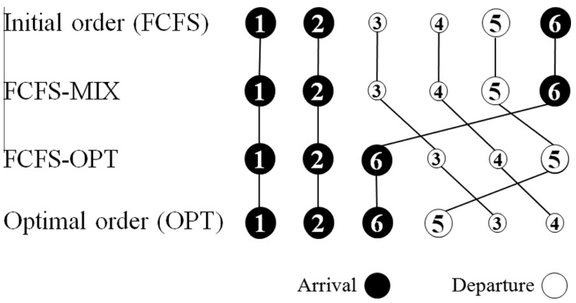

**Fig. 2.** Illustration of alternative sequencing policies.

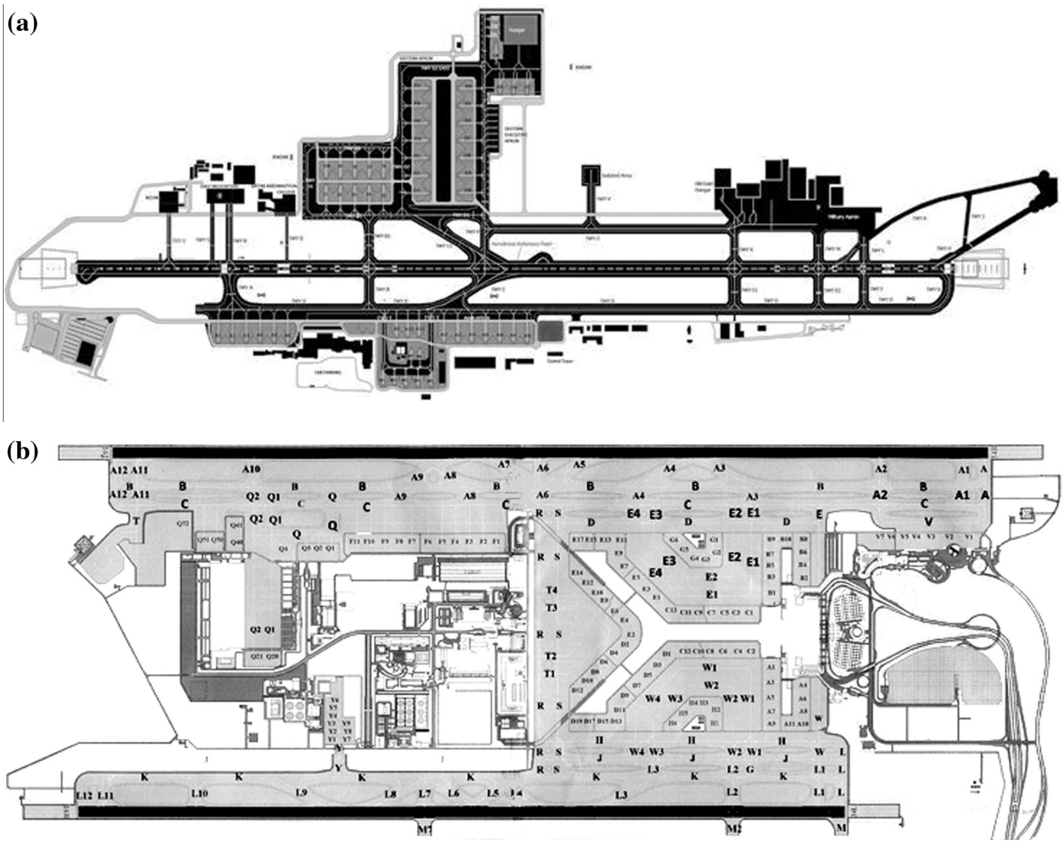

**Fig. 3.** (a) (Old) Doha International Airport (airportguide.com). (b) New Doha International Airport (ndiaproject.com).

**Table 1**
Air traffic volumes at Doha International Airport (www.dohaairport.com).

| Year | Passenger | % Increase | Cargo (kg) | % Increase | Aircraft movement | % Increase |
|---|---|---|---|---|---|---|
| 2007 | 9,459,812 | – | 247,163,753 | – | 65,373 | – |
| 2008 | 12,272,505 | 29.7 | 409,462,811 | 65.7 | 90,713 | 38.8 |
| 2009 | 13,113,224 | 6.9 | 522,920,986 | 27.7 | 101,941 | 12.4 |
| 2010 | 15,724,027 | 19.9 | 699,941,401 | 33.9 | 118,751 | 16.5 |
| 2011 | 18,108,521 | 15.2 | 795,558,797 | 13.7 | 136,768 | 15.2 |
| 2012 | 21,163,382 | 16.9 | 826,669,094 | 3.9 | 155,671 | 13.8 |

capacity of up to 50 million passengers, two million tons of cargo, and 320,000 aircraft landings/take-offs per year upon its completion in 2015 (www.ndiaproject.com).

Our study is grounded in air traffic and aircraft movement projections in anticipation of increasing loads that HIA would have to handle. There are about 685 operations per day in typical data instances which are examined using our proposed solution approaches. This corresponds to nearly 80% of the HIA expected nominal capacity after the completion of its final construction phase, i.e. about 857 operations/day or 320,000 operations/year. The alternative runway settings (runway configuration, scheduling policy, and separation times) are encapsulated in Model RCM with the objective of minimizing the total excess fuel cost. Aircraft fuel consumption (see Appendix A) is adapted from fuel burn data in Cook et al. (2004). For each aircraft model, we employ an average fuel burn (gal/min) associated with its ground or final approach operations. We used jet fuel costs based on recent IATA data on fuel prices (3.132 USD/gal in the Middle East and Africa on March 1, 2013). In our post-solution analysis, we also record the total delay incurred under each runway setting.

In about 50% of the day, 30 operations or more take place in a time-window of one hour. The combined number of departures and landings peaks to over 45 operations, potentially causing delays and requiring careful planning. Fig. 4(a) and (b) provide a higher level of detail by depicting the number of aircraft arrivals and departures, separately, while categorizing aircraft by their weight classes (Heavy, Large, and Small). In our Doha dataset, aircraft are predominantly heavy and large (39% H, 55% L and 6% S). Our analysis indicates that the inter-operation time (time lapse between the occurrence of two

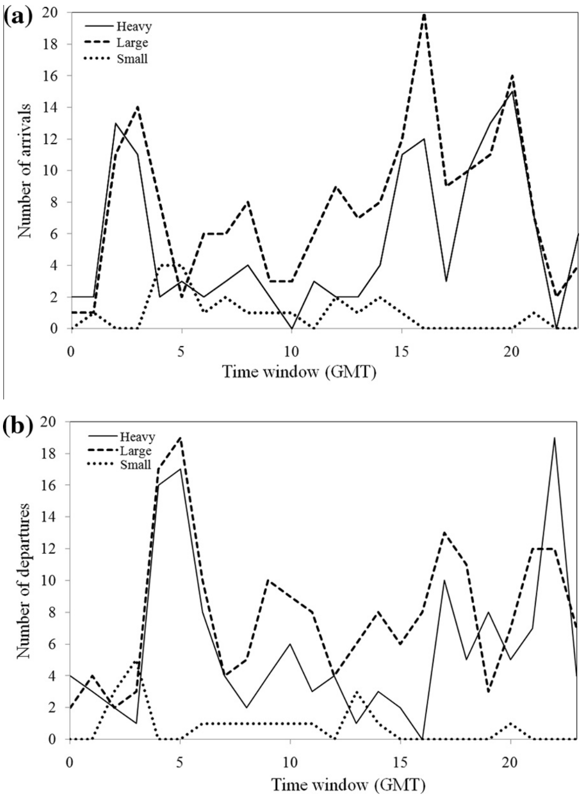

**Fig. 4.** (a) Aircraft arrival trends. (b) Aircraft departure trends.

operations on the runway) ranges from 80 s to 6 min during different hours of the day, with a two-minute inter-operation time at an average. This is indicative of non-uniform air traffic operations throughout the day at DOH, as is typical of international airports.

Doha faces heavier air traffic activity during three main time-windows of the day. As far as arrivals are concerned, busier activity takes place around hours 3, 15, and 20 GMT – Doha time being GMT +3:00. In contrast, congested hours for departures are around hours 5, 17, and 22 GMT. There is approximately a three-hour difference between the busier hours for arrivals and departures that is reflective of common aircraft layovers at airports, as an arriving aircraft gets serviced and becomes ready to depart again. Small aircraft are less present at DOH and have milder peaks of activity. It is worth noting that if aircraft operations were uniformly distributed throughout the day with a two-minute inter-operation time, then even a single runway would accommodate 720 aircraft. In practice, the capacity of the runways at Doha does not seem to be reached most of the day. However, certain hours of the day are particularly congested, require careful planning, and cause excess fuel and delay costs.

### 4.2. Minimum separation standards

Aviation authorities enforce aircraft separation times between runway operations in order to obviate the dangers of wake turbulence. The magnitude of these separation times depends on the weight class of the leading/following aircraft and their operations types (landing or departure). Such separation times are typically *asymmetric*, due to the higher vulnerability of smaller aircraft to air turbulence. There exist different safety separation time standards, each resulting in a specific runway capacity utilization and airline fuel cost. We consider two different standards in our study, namely, the ICAO standard (currently adopted at DOH) and the one enforced by the FAA at airports in the United States and contrast their effects on runway operations if employed in Doha.

The ICAO standard classifies aircraft along three main weight classes (Heavy, Medium, and Light) based on their maximum takeoff weight (MTOW). It requires a minimum separation of 2 min between any pair of operation for any weight class unless a *light landing* follows a *heavy or medium landing*, in which case a 3-min minimum separation time must be enforced. Likewise, FAA categorizes aircraft into similar weight classes (Heavy, Large, and Small). However, it introduces different separations based on minimum distances (in nautical miles) in compliance with the Instrument Flight Rules (IFR) that have to be maintained between aircraft operations. These nautical distances can be converted to minimum separation times in

**Table 2**
Aircraft separation times (in seconds) following the FAA standard.

| Departure → Departure Case | | | | Departure → Arrival Case | | | |
|---|---|---|---|---|---|---|---|
| Leading \ Following | Heavy | Large | Small | Leading \ Following | Heavy | Large | Small |
| Heavy | 90 | 120 | 120 | Heavy | 60 | 60 | 60 |
| Large | 60 | 60 | 60 | Large | 60 | 60 | 60 |
| Small | 60 | 60 | 60 | Small | 60 | 60 | 60 |
| Arrival → Departure Case | | | | Arrival → Arrival Case | | | |
| Leading \ Following | Heavy | Large | Small | Leading \ Following | Heavy | Large | Small |
| Heavy | 75 | 75 | 75 | Heavy | 96 | 157 | 196 |
| Large | 75 | 75 | 75 | Large | 60 | 69 | 131 |
| Small | 75 | 75 | 75 | Small | 60 | 69 | 82 |

seconds assuming nominal aircraft speeds as in de Neufville and Odoni (2003), and are summarized in Table 2 (Lee, 2008) for different cases of Arrival/Departure considering runway occupancy times for different aircraft weight classes.

In addition to being asymmetric, the FAA separation times do not always satisfy the triangular inequality. In certain cases, the separation of consecutive aircraft is not sufficient to properly separate certain nonconsecutive aircraft in the sequence. The need to separate all pairs of aircraft that share the same runway, whether consecutive or not, is readily enforced in Model RCM with the $y$-variables and the disjunctive Constraint (1d).

### *4.3. Empirical results on Doha dataset*

Our results are summarized in Tables 3 and 4 using alternative runway settings under ICAO and FAA separation time standards, respectively. Column 1 provides hourly time-windows of airport operations in Greenwich Mean Time (GMT). Columns 2–6 report the total excess fuel cost in US dollar (USD). An objective value of 0 reflects that all aircraft start at their ready-times and there are no deviations that result in added fuel costs. Column 2 reports excess fuel costs for a single runway setting operating under an FCFS sequencing policy, as currently implemented in DOH. Columns 3–6 report results for a setting with two parallel independent runways, as planned for HIA, under the three scheduling heuristic policies FCFS-SEG, FCFS-MIX, and FCFS-OPT and an optimal schedule (OPT).

In our computational runs, we used the excess fuel cost as the objective function (see Appendix A) in Model RCM and delays were recorded in the post-solution analysis. The greedy aircraft runway-assignment policy enforced by FCFS-MIX is dictated by the ready-times of aircraft and results in slightly better delays than FCFS-OPT. FCFS-OPT seeks to optimize

**Table 3**
Fuel costs under alternative runway settings (ICAO separation standard).

| Time of the day | Single runway | Two runways | | | |
|---|---|---|---|---|---|
| (GMT) | FCFS | FCFS-SEG | FCFS-MIX | FCFS-OPT | OPT |
| 0–1 | 0 | 0 | 0 | 0 | 0 |
| 1–2 | 206 | 206 | 69 | 69 | 69 |
| 2–3 | 34,355 | 16,816 | 4513 | 3849 | 3849 |
| 3–4 | 126,516 | 29,878 | 852 | 754 | 754 |
| 4–5 | 145,979 | 13,864 | 2391 | 1886 | 1886 |
| 5–6 | 235,131 | 33,901 | 2289 | 2206 | 2206 |
| 6–7 | 205,463 | 15,954 | 2047 | 1228 | 1228 |
| 7–8 | 142,652 | 938 | 3 | 3 | 3 |
| 8–9 | 129,623 | 1352 | 219 | 219 | 219 |
| 9–10 | 55,666 | 1234 | 172 | 172 | 172 |
| 10–11 | 26,327 | 317 | 162 | 162 | 162 |
| 11–12 | 16,867 | 1020 | 206 | 206 | 206 |
| 12–13 | 4020 | 1336 | 716 | 716 | 716 |
| 13–14 | 4803 | 1683 | 523 | 304 | 304 |
| 14–15 | 12,321 | 5632 | 2908 | 2183 | 1963 |
| 15–16 | 16,920 | 5724 | 1606 | 1547 | 1547 |
| 16–17 | 121,249 | 36,369 | 4196 | 3319 | 3319 |
| 17–18 | 112,657 | 2028 | 746 | 646 | 646 |
| 18–19 | 187,234 | 6155 | 2046 | 1890 | 1890 |
| 19–20 | 295,523 | 21,057 | 4582 | 3977 | 3977 |
| 20–21 | 448,154 | 21,083 | 3509 | 3005 | 3005 |
| 21–22 | 344,028 | 15,071 | 4225 | 3171 | 3124 |
| 22–23 | 230,337 | 11,950 | 921 | 871 | 871 |
| 23–24 | 251,911 | 2570 | 321 | 321 | 321 |
| Total fuel cost (USD) | 3,147,942 | 246,139 | 39,221 | 32,707 | 32,440 |
| Total delay (min) | 31,327 | 2516 | 476 | 511 | 511 |

**Table 4**
Fuel costs under alternative runway settings (FAA separation standard).

| Time of the day | Single runway | Two runways | | | |
|---|---|---|---|---|---|
| (GMT) | FCFS | FCFS-SEG | FCFS-MIX | FCFS-OPT | OPT |
| 0–1 | 0 | 0 | 0 | 0 | 0 |
| 1–2 | 172 | 172 | 34 | 34 | 34 |
| 2–3 | 10,152 | 8512 | 2727 | 2671 | 2671 |
| 3–4 | 12,853 | 5105 | 316 | 306 | 306 |
| 4–5 | 6825 | 2971 | 862 | 862 | 862 |
| 5–6 | 5121 | 3169 | 1141 | 1141 | 1141 |
| 6–7 | 4838 | 1772 | 301 | 301 | 301 |
| 7–8 | 531 | 346 | 0 | 0 | 0 |
| 8–9 | 1017 | 653 | 124 | 124 | 124 |
| 9–10 | 1090 | 469 | 77 | 77 | 77 |
| 10–11 | 452 | 199 | 97 | 97 | 97 |
| 11–12 | 1032 | 586 | 129 | 129 | 129 |
| 12–13 | 1498 | 885 | 394 | 394 | 394 |
| 13–14 | 1019 | 673 | 87 | 87 | 87 |
| 14–15 | 4642 | 3513 | 1184 | 972 | 972 |
| 15–16 | 5803 | 4450 | 508 | 508 | 508 |
| 16–17 | 14,345 | 11,646 | 1745 | 1745 | 1745 |
| 17–18 | 2877 | 904 | 241 | 200 | 200 |
| 18–19 | 7003 | 4577 | 1050 | 1050 | 1050 |
| 19–20 | 16,402 | 13,018 | 3138 | 3138 | 3138 |
| 20–21 | 13,237 | 9898 | 2241 | 2241 | 2241 |
| 21–22 | 13,702 | 4757 | 411 | 411 | 411 |
| 22–23 | 3135 | 2776 | 584 | 584 | 584 |
| 23–24 | 1753 | 1077 | 140 | 140 | 140 |
| Total fuel cost (USD) | 129,497 | 82,128 | 17,531 | 17,211 | 17,211 |
| Total delay (min) | 1262 | 696 | 205 | 209 | 209 |

the excess fuel cost and can, therefore, result in slightly higher delays compared to FCFS-MIX since it gives higher priority to arrivals over departures and larger aircraft over smaller ones.

Our proposed heuristic FCFS-OPT yields notable improvements in reducing the excess fuel cost over FCFS-SEG and FCFS-MIX, and provides near-optimal solutions that are very comparable to the optimal schedules produced by OPT. Although FCFS-OPT forces aircraft on the same runway to follow an FCFS order within the same stream of operations (departure/landing), it optimizes aircraft-runway assignments in a way that yields overall optimal or near-optimal solutions when compared to OPT results. This achieved by optimizing the interweaving of the departure and arrival queues over the same runway. This highlights that aircraft-runway assignments are crucial and can yield excellent results, even when the aircraft sequence follows an FCFS policy within the same stream of operations. In contrast, swapping aircraft positions or optimizing their sequencing within the same stream of operations does not result in notable savings. This underscores the importance of aircraft assignment decisions in reducing excess fuel costs, an aspect that is often overlooked, as more attention has been devoted to sequencing strategies. This also explains why FCFS-OPT dominates FCFS-MIX with respect to excess fuel cost, as the latter adopts myopic/greedy aircraft-runway assignments.

Table 5 summarizes the results from our analysis of FCFS-MIX, FCFS-OPT, and OPT. Columns 2 and 3 report fuel costs (USD) and anticipated savings for FCFS-OPT and OPT compared to FCFS-MIX. Likewise, Columns 4 and 5 summarize the associated delays and savings. Column 6 reports the percentage of the operations that are shifted from their initial FCFS position in the sequence, whereas the last column provides the number of aircraft position shifts in the FCFS-OPT and OPT solutions from the sequence produced with FCFS-MIX. Both the optimal sequence (OPT) and our proposed heuristic (FCFS-OPT) resulted in less than 2 aircraft position shifts at an average, per shifted operation (Fig. 5). That is, optimal or near-optimal schedules can be achieved via very limited position shifts, which largely preserves the FCFS-MIX sequence. This is due to the fact that, under multiple runways, aircraft assignment decisions have a substantial impact on the final excess fuel cost than that of the sequencing strategy. This indicates that, under data trends at Doha, our proposed FCFS-OPT heuristic not

**Table 5**
Benefits of FCFS-OPT over other heuristics (under ICAO standard)

| | Fuel cost | | Delay | | Shifted | |
|---|---|---|---|---|---|---|
| Heuristic | Total (USD) | Saving % | Total (minutes) | Saving % | operation | Position Shifts |
| FCFS-MIX | 39,221 | – | 476 | – | 0 | 0 |
| FCFS-OPT | 32,707 | 16.61 | 511 | −7.4 | 31.8% | 2 |
| OPT | 32,440 | 17.29 | 511 | −7.4 | 49.0% | 2 |

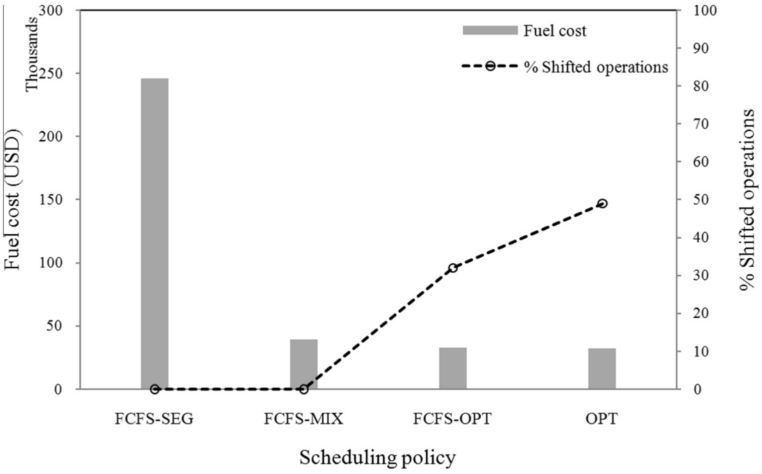

**Fig. 5.** Comparison of heuristic results on DOH data.

only ensures fairness amongst aircraft by exhibiting limited deviation from FCFS-MIX, but also empirically provides optimal or near-optimal results with respect to the fuel burn cost.

Further, we assessed the benefit of adopting two runways vs. a single runway depicted in columns 2 and 3 of Tables 3 and 4. By transitioning operations from DOH to HIA, an anticipated savings of nearly 3 million dollars per day can be achieved. Our results also indicate that a segregated mode, as in FCFS-SEG, results in over 240 thousand dollars of excess fuel cost per day, as opposed to 39,221 dollars under a mixed mode. Under increasingly higher volumes of aircraft movements, especially when arrival and departure peaks are not occurring during the same time-windows, a mixed mode utilization of the runways can yield significant fuel savings.

We also examined the anticipated gains accruing from the adoption of the FAA aircraft separation standard in lieu of the ICAO standard. Our results suggest that substantial reductions in fuel cost and average delays can be achieved using the FAA standard. Although using the FAA standard does not necessarily result in important fuel costs and delay reductions in every time-window of the day, it is overall very beneficial at the aggregate level. Limited savings with FAA usually occur when the mix of aircraft weight classes involves a significant proportion of small/large aircraft that follow heavy aircraft, which requires slightly larger separation times under the FAA standard.

## 5. Conclusion

This paper proposed a three-faceted approach for the assessment of runway management strategies. This approach is encapsulated in a 0–1 mixed-integer program in order to investigate alternative runway configurations and settings. We developed an optimization-based heuristic that employs the MIP model, while preserving the FCFS sequencing policy. Empirical results on aircraft operations at Doha International Airport show that the proposed heuristic preserves fairness among aircraft and does not cause aircraft to deviate by more than two positions, at an average, from their base FCFS sequence. The heuristic further produces optimal or near-optimal solutions, resulting in substantial fuel burn savings and delay reductions. The results indicate that aircraft-runway assignment decisions, an aspect that is often overlooked in aircraft scheduling problems, play a significant role in reducing costs and largely reveal the structure of optimal schedules. By putting the focus on aircraft-runway assignment decisions, while adopting FCFS sequencing policy, this can prove beneficial to air traffic controllers. In fact, such an approach obviates elaborate sequencing procedures that can conflict with the practice of controllers or the physical and layout constraints at specific airports. Our empirical results also indicate that international airports such as the Hamad International Airport can significantly benefit from using the FAA aircraft separation standard in lieu of the ICAO standard.

Although illustrated with data for Doha International Airport, the approach presented in the paper and the proposed heuristic can be of general benefit to other airports, especially during busier hours of activity during the day. The anticipated savings in fuel costs can directly benefit airlines, airports, and governmental authorities that are concerned with environmental effects and emissions. We recommend for further investigation an analysis of the impact of alternative runway settings on additional airborne or ground-based operations related to taxiway routing, gate assignments, and workload at terminals.

**Table 6**
Fuel burn consumption (gal/hour).

| | Heavy | Large | Small |
|---|---|---|---|
| Arrival | 5043 | 2063 | 206 |
| Departure | 1614 | 658 | 66 |

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## Appendix A. Fuel Consumption Estimates

Fuel costs are calculated based on fuel burn/minute for an aircraft, which depends on the aircraft operation and its weight class. We employed the base fuel burn of the aircraft models categorized by Cook et al. (2004) and used estimates for average fuel burn (gallons per block hour of operation) for the existing aircraft models operating in DOH. The following table reports the average estimates of fuel burn (gal/hour) for aircraft weight categories based on the operation type at DOH (see Table 6).

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