The impact of heterogeneous arrival and departure rates of flights on runway configuration optimisation

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Declarations of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data used to support the research findings of this paper are obtained from a licensed API from *FlightGlobal*.

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Abstract

The rapid growth of the airline industry has caused an enormous demand in the context of air transport and air traffic congestion in several hub airports. In order to alleviate this situation and resolve the imbalance between the arrival and departure rate, efficient runway usage in airport capacity management is an immediate and feasible solution as compared to airport expansion and runway construction. Air Traffic Control (ATC) operators could optimise their runway capacity by operating dynamic runway configuration in switch mode runways based on the air and airport traffic conditions. A semi-mixed mode runway is considered in this paper, wherein some runways are configured for either landing or take-off operations, while others are operated in switch mode. The demand for arrival and departure is subject to the passengers demand, flight availability and timings, preferred flight schedule and frequency of flight schedule service, and usually vary in different hours (peak and non-peak hours). Given this feature, ATC can reconfigure the runway mode responding to the current demand for arrival and departure and further seize the runway capacity via systematic approach. Under the semi-mixed mode situation, formulating the coordination of dynamic runway configuration planning and the Aircraft Sequencing and Scheduling Problem is proposed. The air traffic pattern in Hong Kong International Airport (HKIA) is used as a test case to evaluate the performance of this proposed model. Based on the test results, it was found that this dynamic runway configuration planning and semi-mixed runway design can utilise runway capacity more efficiently. In the numerical study, the dynamic runway configuration planning achieved 71.6%% and 37.08% reduction of flight tardiness than the two segregated runways systems (two landing and one take-off runways and one landing and two take-off runways) in HKIA.

Keywords: Dynamic runway configuration planning; mathematical modelling; runway scheduling; semi-mixed mode runway operation; air traffic control; airside operations

1. Introduction

Runway capacity is usually regarded as the bottleneck of the turn-a-round process, and the runway is the interlink between the terminal airspace and airport network. For most of the international hub airports, the number of runways in their runways system is usually ranging from 2 to 5. One should note that additional runway construction may not be feasible within five to ten years as the construction of runway is usually limited by the geographical constraints and the limited land space in the airport surface. Therefore, the increase in runway engineering capacity is not easy. Apart from increasing the runway physical capacity, we can seek for a system approach to increase the number of throughputs of the runways. The number and the pattern (peak and non-peak hour) of aircraft traffic movements (ATMs) for arrival and departure in each hour are different. Runway configuration switch provides the feasibility of switching runways between landing mode and take-off mode. This engineering system designs could provide a better match of runway demand for arrival and departure. For example, in the Hong Kong International Airport (HKIA), a new runway is under construction, and a three-runways system with switchable runway setting will be designed to handle air traffic. In segregate runways systems, all the runways are predetermined as landing runway or take-off runway (Rajendran & Srinivas, 2020; C. Yin, Lu, Xu, & Tao, 2020). In semi-mixed mode runways system, certain runways are operated in segregated mode, while certain runways are operated in switch mode (Aheleroff et al., 2020; Amankwah-Amoah, 2020; Barmpounakis, Vlahogianni, Golias, & Babinec, 2019).

Majority international airport hubs are facing the differences between for arrival and departure, as the demand for arrival and departure is subject to the traffic pattern, air traffic demand for particular route, passengers preferred time for on-board and arrival (Xue, Ng, & Hsu, 2020). It is intuitive that better runway configuration can better match the demand for arrival and departure in different time intervals and achieve better airborne delays. In this research, we attempt to evaluate the outcomes and impacts of airborne delay between segregate runways system and dynamic runway configuration planning under semi-mixed mode runway operation. The proposed model can observe and determine the best runway configuration planning responding to the traffic demand for each decision horizon (1-hour interval) in a day.

The impact of outstripped air and airport capacity, sustainable growth on the traffic volume of civil aviation, terminal traffic situation and terminal weather have significantly influenced approaching delay (Abdelrahman E.E. Eltoukhy, Chan, & Chung, 2017; C. K. M. Lee et al., 2018; Ng, Lee, Chan, & Lv, 2018; Qin, Chan, Chung, Qu, & Niu, 2018; Wen, Xu, Choi, & Chung, 2019). The global airline industry is currently experiencing an enormously increasing demand because of globalisation and the introduction of low-cost carriers (Abdelrahman E. E. Eltoukhy, Wang, Chan, & Chung, 2018; Ng, Lee, Chan, & Lv, 2018; Qin, Chan, Chung, Qu, et al., 2017). Many hub airports are currently running at nearly full capacity (Wu Deng et al., 2018; Givoni & Chen, 2017; C. K. M. Lee et al., 2018; Qin, Chan, Chung, & Qu, 2017; Qin, Chan, et al., 2018; Qin, Wang, Chan, Chung, & Qu, 2018, 2019). Consequently, the problems associated with massive congestion and frequent flight delays have become serious. Meng, Zhang, and Li (2011) explained that the bottleneck of air traffic is caused by the airport runway capacity instead of the en route segment. Besides, a runway is often regarded as the major bottleneck for the efficiency of the turnover procedure (Balakrishnan & Chandran, 2010; Harada, Ezaki, Wakayama, & Oka, 2018; Idris et al., 1998). Therefore, the runway capacity is a critical resource for reducing the probability of flight delays and congestion (Ng, Tang, & Lee, 2015; Soomer & Franx, 2008). In real-life situations, the arrival and departure rate, environmental parameters such as weather, visibility and other attributes are all taken into consideration when evaluating the actual usage of the runway. Air Traffic Control (ATC) may want to take advantage of operating mixed runways or semi-mixed runways in order to improve flexibility in their runway configuration planning (Pal & Chunchu, 2019; Patnaik, Agarwal, Panda, & Bhuyan, 2020; Yaylali, Çelik, & Dilek, 2016; L. Yin et al., 2017; Zhao, Verhagen, & Curran, 2015). Thus, it is crucial to optimise runway capacity and resolve arrival-departure imbalances with a well-defined Aircraft Sequencing and Scheduling Problem (ASSP) model in terminal traffic flow management in order to cope with the current traffic situation (H. Lee, Li, Rai, & Chattopadhyay, 2020; Ng, Lee, Chan, Chen, & Qin, 2020; Paielli, 2018; Wee, Lye, & Pinheiro, 2019).

Runway operation can be classified into three major types: Aircraft Landing Problem (ALP) (Beasley, Sonander, & Havelock, 2001; Bencheikh, Boukachour, Alaoui, & Khoukhi, 2009; Caprì & Ignaccolo, 2004; Hancerliogullari, Rabadi, Al-Salem, & Kharbeche, 2013; Hansen, 2004; Hu, Ng, & Qin, 2016; Ng & Lee, 2016; S. Wang, Wan, Li, & Zhang, 2016), Aircraft Take-Off Problem (ATP) (Atkin, Burke, Greenwood, & Reeson, 2008; Hancerliogullari et al., 2013) and ASSP with mixed-mode operations (Bennell, Mesgarpour, & Potts, 2011; Lieder & Stolletz, 2016; Ng, Lee, Chan, & Qin, 2017) and ASSP with runway configuration switch (Ng, Lee, & Chan, 2017; Ng, Lee, Chan, & Zhang, 2018). There are several types of runway configurations. Segregated runway operation is a runway system that a runway can be exclusively applied for landing, another runway can be exclusively allocated for take-off and runways can be worked independently. In this regards, the runway system can be formulated as ALP or ATP. ASSP considers runway operations in both ALP and ATP in one model. ASSP with mixed-mode operations is that landing and take-off are interspersed on both runways. ASSP with runway configuration switch is a model that runways have switching properties between landing and take-off. A semi-mixed mode runways system is that runway can be worked as a mixed/switch mode, while other runways are in segregated mode. The ASSP receives considerable attention because it is a real-life combinatorial problem that defines the assignment of flights to airport runways, the ideal landing and take-off sequence of aircrafts as well as the landing and departing time of flights on the runway while considering physical and operational constraints (Hancerliogullari et al., 2013; Ng, Lee, Chan, et al., 2017; Sölveling, 2012). The layout and configuration policies of the ground resources system come along with the modelling of the ASSP and the ground operations, which together construct a high-complexity problem in airports (H. Wang, Song, & Wen, 2018).

In this research, a complete formulation of dynamic runway configuration planning and the ASSP under semi-mixed mode runway operation is proposed. The proposed model is formulated in accordance with the runway model of HKIA, with an aim to enhance the applicability of this paper. HKIA is world's 3rd busiest international passenger airport and currently under a three-runway system expansion that is expected to be complete in 2024. At that time, a new runway on the northern side will be used for landing, while the central and south runways will be used for take-off and mixed mode respectively. Based on the arrival and departure rate during a specific period, the configuration of the south runway can alternate between landing and take-off modes. It is believed that HKIA could benefit from this semi-mixed mode operation with the proposed model by facilitating the switching process for both landing and take-off, thus enhancing the runway capacity. The solution quality is measured by exact method and compare its optimal solutions to verify the contributions of runway configuration (Falk, 1976; Selin Hulagu & Celikoglu, 2018; S. Hulagu & H. B, 2019; Saharidis, Conejo, & Kozanidis, 2013). After conducting numerical experiments, the time deviation between the actual and preferred runway operation is further minimised, which smoothens the runway schedule and reduces flight delays by considering the traffic pattern of airborne and airport delay (Ng & Lee, 2017).

2. Related studies

The First-Come-First-Serve Approach (FCFS) is a practical method in Air Traffic Control (ATC) to create the aircraft arrival and departure sequence based on the appeared order on the radar system (S. Wang et al., 2016). However, there are several of safety considerations, such as size, the altitude of aircraft and separation time between two consecutive aircrafts, that are interdependent and need to be considered when scheduling the arrival and departure sequence (Balakrishnan & Chandran, 2010). In order to provide an advanced solution for dealing with the ASSP, scholars and researchers have studied the problem using different techniques and objectives, which can be summarised in two main streams: deterministic scheduling and scheduling under a postulated uncertainty set.

Under the deterministic approach, the model only simulates ideal flights scheduled by computing precisely determined data (Zhang, Xu, Yang, & Liu, 2014). Previous deterministic ASSP literature has focused on objectives such as maximising runway throughput, minimising the makespan (Harikiopoulo & Neogi, 2011; Ma, Xu, Liu, & Huang, 2014), minimising the total or weighted tardiness of flights (Ng, Lee, Chan, et al., 2017; Pinol & Beasley, 2006; Sabar & Kendall, 2015; Salehipour, Modarres, & Moslemi Naeni, 2013) and minimising the total, average or weighted delay of all flights (Lieder & Stolletz, 2016; Liu, 2011; Samà, D'Ariano, D'Ariano, & Pacciarelli, 2015). Farhadi, Ghoniem, and Al-Salem (2014) proposed a Constrained Position Shifting (CPS) for dynamic runway scheduling model, which aims to reduce the inefficiencies of the FCFS principle. Thereafter, scholars have explored various approaches in different directions to resolve the ASSP. It is worth noting that these studies were simply focused on single runway scheduling instead of multiple runways. In the recent decade, more research efforts have been made for multi-runway scheduling and mixed mode operation in order to narrow down the research and practice gap (Hancerliogullari et al., 2013; Villegas Díaz, Gómez Comendador, García-Heras Carretero, & Arnaldo Valdés, 2019). Other than deterministic based research, stochastic and robust scheduling were proposed to counteract the upstream uncertainty and absorb the minor disturbances in flight schedules (Cai, Jia, Zhu, & Xiao, 2015). The stochastic approach resolves the model with the known probability distribution of uncertain variables (Choi, Wen, Sun, & Chung, 2019), whereas robust optimisation is a risk-averse approach employed to safeguard against worst-case scenarios (Ng, Lee, Chan, et al., 2017). The outcome achieved by a stochastic approach may vary from the historical data; whereas, the strict robust model results in a higher runway throughput, as there is a higher level of protection against uncertainties (Ng et al., 2020).

Runway configuration includes single runway, segregated runway and interdependent runway systems. For a multi-runway airport, the segregated runway configuration implies that one runway is allocated for landing, while the other is for take-off. Mixed mode operation allows landing and take-off on both runways (Bombelli, Santos, & Tavasszy, 2020; Herrema et al., 2019; H. Lee et al., 2020). Similarly, for semi-mixed mode operation, at least one runway is exclusively used for landing or take-off, and another runway operates in runway configuration switch, which means that the runway can switch between landing and take-off based on the rate of inbound and outbound flights. Jacquillat, Odoni, and Webster (2017) suggested that the runway configuration switch could enhance the flexibility of runway utilisation as well as the imbalance problem in arrival and departure rates. Based on recent research on the latest publications in ASSP (Ng & Lee, 2016, 2017; Ng, Lee, Chan, & Lv, 2018; Ng, Lee, Chan, et al., 2017; Ng, Lee, Chan, & Zhang, 2018; S. Wang et al., 2016), the ASSP under semi-mixed mode operation can be further studied and analysed to cope with the increased complexity of airport operation. In this research, we aim to review the potential of using semi-mixed runway operations in our case airport. The case airport is undergoing the construction of a new runway, and the airport authority has reviewed that one of the runways can be operated with configuration switch property. Therefore, this research attempt to investigate the performance between segregated ASSP and ASSP with runway configuration switch when a three-runways system in the case airport is fully operated. The general form of the mathematical formulation of the ALP and ASSP models can be found in (Hansen, 2004; Ng & Lee, 2016; Ng, Lee, Chan, et al., 2017; Pinol & Beasley, 2006; Salehipour et al., 2013; S. Wang et al., 2016). With the support of soft computing techniques (exact method, heuristics, meta-heuristics and soft computing), we can optimise and solve the integrated combinatory problem to support daily or near-time decision-making in engineering applications (W. Deng, Liu, Xu, Zhao, & Song, 2020; W Deng, Xu, Song, & Zhao, 2019; W. Deng, Xu, Song, & Zhao, 2020; Khan, Chung, Awan, & Wen, 2019; Khan, S., Awan, & Wen, 2019).

The contributions of this research are outlined below. First, the mathematical formulation of coordinating the ASSP and the settings of dynamic runway configuration are proposed. The assumptions of the model and mathematical formulation are illustrated in this section. To further testify the applicability of the proposed model, the air traffic pattern in HKIA and the three-runway configuration are considered, followed by computational experiments. The results from the computational experiments proved that the proposed model surpasses the runway setting without runway configuration switch, which also indicated that the adoption of a semi-mixed mode runway system could enhance runway capacity.

In this paper, the background is first introduced, and an in-depth literature review on ASSP approaches is illustrated in **Sections 1 and 2**. In **Section 3**, the ASSP model with a semi-mixed mode runway configuration is proposed, and its assumption is presented. Thereafter, the computational findings of the experiments based on the real-life situations in HKIA are analysed and discussed in **Section 4** in order to provide insights on handling the ASSP in airports. Finally, the concluding remarks are presented in **Section 5**.

3. Mathematical modelling

3.1. Assumption of the model

The following assumptions were made before the formulation of the model. First of all, in this proposed model, we only consider landing, take-off and switch runway in a three-runway system for simplicity of computation. Second, it is assumed that the length of all runways is sufficient to perform semi-mixed mode operation and flight landing operation while neglecting the flight size and classes. Further, the probabilities of equipment failure, missed arrival and departure, pilot error, runway incursions and abnormal operation are also neglected in this model. Third, the separation requirements caused by the runway's physical properties, such as terrain constraints of the airports' surrounding and noise abatement procedures, are assumed to be minimal.

3.2. Mathematical formulation

In the proposed model, let I be the set of flights. Each flight belongs to the set of approaching flights I_L or the set of departing flights I_T. Let R be the set of runways. Each runway r belongs to the set of landing runways R_L, take-off runways R_T or switch-mode runways R_W depending on the predetermined configuration of the airport layout and other constraints. The primary objective of this dynamic runway configuration and runway scheduling problem is to minimise the time deviation between the actual landing/take-off time T_{ir} and the preferred landing/take-off time PTO_i. The maximum number of flights in the system is n, and flight is indicated as $i \in I_L \cup I_T \in I$, where the flight can be classified as either arrival $i \in I_L$ or departure $i \in I_T$. The estimated operation time on a particular runway ETO_{ir} represents the earliest time of operations. Since the runway operation must adhere to safety constraints and air traffic situation, the assigned operation time T_{ir} is not always equal to PTO_i. Moreover, separation time S_{ji} is the operation time deviation between two consecutive flights on the same runway to reduce the adverse effect of the vortex generated by leading flights.

There is at least one take-off or landing runway and at least one switch or mixed-mode runway involved in the semi-mixed mode runway system. In this case, the maximum number of runways is m and must be greater than 2 to meet the basic practical requirements. The runways can be divided into landing runway $r \in R_L$, take-off runway $r \in R_T$ and switch runway $r \in R_W$. Inbound flights $i \in I_L$ are only allowed to land on landing or switch runway $r \in R_L \cup R_W \in R$, whereas outbound flights can only use take-off or switch runway $r \in R_T \cup R_W \in R$. Due to the unique property of the switch runway, the runway configuration parameter b is assigned for each group of adjacent arrival and departure flights. In order to perform runway configuration switching, runway clearance k is enforced between b and $b+1$ if the neighbouring flights' operation τ_{ji} does not belong to the same family. Furthermore, the start and completion time for the configuration switch on the runway are denoted by ST_{rb} and CT_{rb} respectively. Finally, the runway schedule solution X is represented by runway assignment x_{ir}, and the sequential relationship between flights j and i on same runway by y_{jir}. Further, the decision variable z_{irb} for flight i belongs to any group of b in the switch runway, and the sequential relationship of adjacent flights on the same group b on switch runway γ_{jirb}. The auxiliary variable, defining the situation wherein no flight was assigned to group b on the switch runway, is denoted by U_{rb}. **Fig. 1**illustrates the idea of runway configuration switch with variables. The notations and decision variables are illustrated in **Table 1**. **Table 2** presented the separation time requirement on runway. The runway separation requirement can ensure the safe landing and take-off operations, operation stability and reduce the discomfort level of runway operations by accommodating the wake vortex from the leading flights. In this regard, we can make sure that the runway schedule satisfies the ATC regulation.

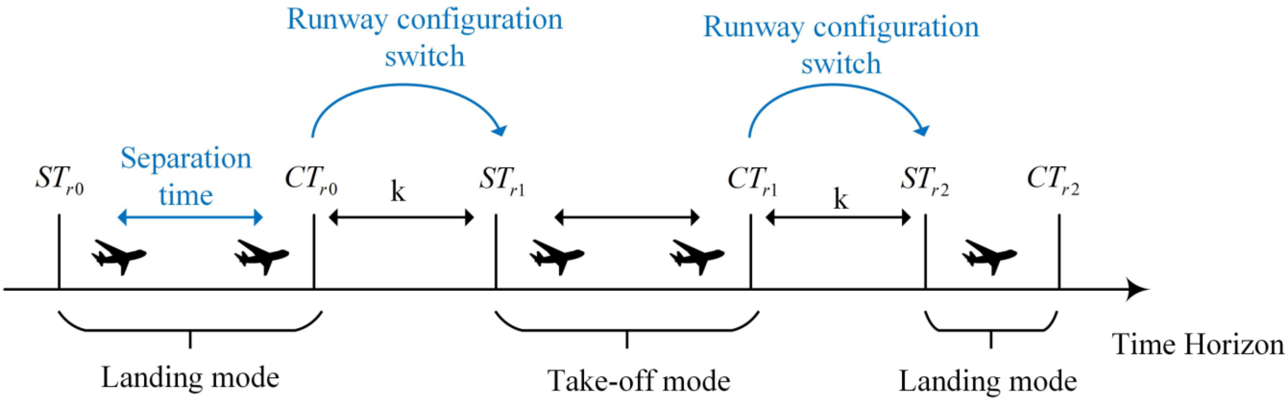

Fig. 1. The schematic diagram of runway configuration switch

Table 1

Notations and decision variables

Notations	Explanation
i,j	Flight ID, $i \in I = I_L \cup I_T \in I$
n	The maximum number of flights
R	Runway ID, $r \in R = R_L \cup R_T \cup R_W$
m	The maximum number of runways
S_{ji}	The fight operation-based separation time between aircraft i and j scheduled on the same runway, $S_{ji} \geq 0$
ETO_{ir}	The estimated landing/take-off time of aircraft i on runway r
PTO_i	The preferred landing/take-off time of aircraft i on runway r
τ_{ji}	1, if aircraft i and j belong to the same operation mode; 0, otherwise
b	Runway configuration index, $b \in B$
k	The duration of runway clearance k on switch model $r \in R_w$
ST_{rb}	The start time of landing or take-off configuration on switch model runway $r \in R_w$

CT_{rb}	The completion time of landing or take-off configuration on switch model runway $r \in R_w$
M	The large number associated with the artificial variable
α_i	The penalty of tardiness operation of flight i
β_i	The penalty of earlier operation of flight i
Decision variables	Explanation
X	A runway schedule X is constructed by $x_{ir}, y_{jir}, z_{ib,} \gamma_{jib}$ and T_{ir}
x_{ir}	1, if aircraft i is assigned to runway r; 0, otherwise
y_{jir}	1, if aircraft j is before aircraft i on the same runway r (not necessarily immediately); 0, otherwise
z_{irb}	1, if aircraft i is assigned to the same landing or take-off configuration b on the switch runway $r \in R_W$; 0, otherwise
γ_{jirb}	1, if aircraft j is before aircraft i to the landing or take-off configuration b on the switch runway $r \in R_W$; 0, otherwise
U_{rb}	An auxiliary variable, 1, if there is at least one aircraft at configuration b on the switch runway $r \in R_W$; 0, otherwise
T_{ir}	The assigned operation time for aircraft i, $T_{ir} \geq 0$

Table 2

Separation time (in second) between two consecutive flights with safe operations (Balakrishnan & Chandran, 2010)

			Trailing aircraft					
			Arrival			Departure		
			SSF	MSF	LSF	SSF	MSF	LSF
Leading aircraft	Arrival	SSF	82	69	60	75	75	75
		MSF	131	69	60	75	75	75
		LSF	196	157	96	75	75	75
	Departure	SSF	60	60	60	60	60	60
		MSF	60	60	60	60	60	60
		LSF	60	60	60	120	120	90

In order to minimise the total tardiness of operations (time deviation between assigned operation time and preferred operation time of all flights), the objective function is illustrated below:

$$f(X) = min \sum\nolimits_{i}^{n} (\alpha_i + \beta_i) \tag{1}$$

Fig. 2 illustrates the calculation of the penalty cost for earlier or late operations (landing or take-off). Based on the real-life situation, several constraints are applied to this problem. Constraints (2) and (3) guarantee that y_{jir} is equal to 1 if flight i is assigned after flight j on the corresponding runway r (not necessarily immediately), otherwise y_{jir} will be 0. Constraint (4) restricts each flight i to be assigned to only one runway r for landing/take-off schedule. Constraints (5) and (6) ensure arrival flights $i \in I_L$ are not allowed to land on a take-off runway $r \in R_T$ or vice versa. Constraint (7) indicates that the assigned time of operation T_{ir} must be larger than its estimated time ETO_i. Furthermore, Constraint (8) confirms that T_{ir} must be greater than the assigned time of operation of the leading flight T_{jr} and separation time S_{ji}.

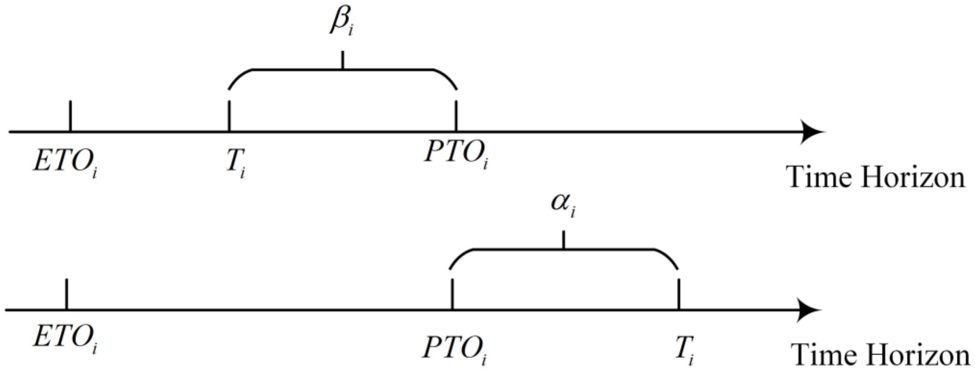

Fig. 2. The schematic diagram of penalty cost in the objective function

Runway assignment and scheduling constraints

$$x_{ir} + x_{jr} \leq 1 + y_{ijr} + y_{jir}, \forall j, i \in I, j \neq i, \forall r \in R \tag{2}$$

$$y_{ijr} + y_{jir} \leq 1, \forall j, i \in I, j \neq i, \forall r \in R \tag{3}$$

$$\sum_{r=1}^{m} x_{ir} = 1\,, \forall i \in I \tag{4}$$

$$x_{ir} = 0, \forall i \in I_L, \forall r \in R_T \tag{5}$$

$$x_{ir} = 0, \forall i \in I_T, \forall r \in R_L \tag{6}$$

$$T_{ir} \geq ETO_i - M(1 - x_{ir}), \forall i \in I, \forall r \in R \tag{7}$$

$$T_{ir} - T_{jr} \geq S_{ji} - M\left(1 - y_{jir}\right), \forall j, i \in I, j \neq i, \forall r \in R \tag{8}$$

$$\sum_{b=0}^{B} z_{irb} = 1, \forall i \in I, \forall r \in R_w \tag{9}$$

$$\gamma_{jirb} + \gamma_{ijrb} \leq \tau_{ji}, \forall j, i \in I, j \neq i, \forall r \in R_w \in R, \forall b \in B \tag{10}$$

$$z_{jrb} + z_{irb} \leq 1 + \gamma_{jirb} + \gamma_{ijrb}, \forall j, i \in I, j \neq i, \forall r \in R_w, \forall b \in B \tag{11}$$

Constraint (9) illustrates that if flight i is assigned to switch runway $r \in R_w$, flight i can only be assigned to one and only one switch runway and must fall into only one period b of the runway configuration mode. Constraint (10) illustrates that if flights j and i do not belong to the same family τ_{ji}, then both flights cannot be assigned to the same runway configuration mode. Constraint (11) explains the relationship between the decision variables z_{irb} and γ_{jirb}.

The interval of runway operations con in the same mode (either landing or take-off) constraints

The start time of the first configuration mode on each switch runway $r \in R_w$ must be equal to 0 in Constraint (12). If flight i is assigned to runway configuration mode b, then the assigned time of operation T_{ir} must equal to or greater than its estimated time of operation ETO_i and the start time of the configuration mode on switch runway ST_{rb} as explained in Constraints (13) and (14). Constraint (15) calculates that the completion time of configuration mode b on the switch runway must be equal to or greater than the assigned time of operation T_{ir} for those flights that are assigned to configuration mode b on switch runways.

$$ST_{r0} = 0, \forall r \in R_w \tag{12}$$

$$T_{ir} \geq ETO_i - M(1 - z_{irb}), \forall i \in I, \forall r \in R_w, \forall b \in B \tag{13}$$

$$T_{ir} \geq ST_{rb} - M(1 - z_{irb}), \forall i \in I, \forall r \in R_w, \forall b \in B \tag{14}$$

$$CT_{rb} \geq T_{ir} - M(1 - z_{irb}), \forall i \in I, \forall r \in R_w, \forall b \in B \tag{15}$$

Runway clearance constraints for switching between landing and take-off mode

The auxiliary variable U_{rb} indicates the non-empty set of the configuration mode on switch runways by

Constraint (16) using binary representation. If the configuration mode on switch runways is a non-empty set, the runway clearance k is considered between the completion time before the runway configuration switching using Equation (17). Constraint (18) explains that the completion time of the runway configuration must be larger than its start time.

$$U_{rb} \geq z_{irb}, \forall i \in I, \forall r \in R_w, \forall b \in B \tag{16}$$

$$ST_{rb+1} \leq CT_{rb} + kU_{rb}, \forall r \in R_w, \forall b \in B \tag{17}$$

$$CT_{rb} \geq ST_{rb}, \forall r \in R_w, \forall b \in B \tag{18}$$

The domain of the parameters

The deviation between the assigned time of operation T_{ir} and preferred time of operation PTO_i is determined by α_i and β_i by Equations (19) - (22). α_i represents the time of the late arrival or departure of flight i, while β_i indicates the earlier arrival or departure time. Constraints (23) - (26) illustrate that x_{ir}, y_{jir}, z_{irb} and γ_{jirb} are binary variables.

$$\alpha_i \geq 0, \forall i \in I \tag{19}$$

$$\beta_i \geq 0, \forall i \in I \tag{20}$$

$$\alpha_i \geq T_{ir} - PTO_i - M(1 - x_{ir}), \forall i \in I, \forall r \in R \tag{21}$$

$$\beta_i \geq PTO_i - T_{ir} - M(1 - x_{ir}), \forall i \in I, \forall r \in R \tag{22}$$

$$x_{ir} \in \{0,1\}, \forall i \in I, \forall r \in R \tag{23}$$

$$y_{jir} \in \{0,1\}, \forall j, i \in I, j \neq i, \forall r \in R \tag{24}$$

$$z_{irb} \in \{0,1\}, \forall i \in I, \forall r \in R_w, \forall b \in B \tag{25}$$

$$\gamma_{jirb} \in \{0,1\}, \forall j, i \in I, j \neq i, \forall r \in R_w, \forall b \in B \tag{26}$$

After the explanation of the constraints of the model, the following is the two models that we would like to compare. As for segregation mode of runway operation, each runway operates as either landing runway or take-off runway. As for the semi-mixed mode runway configuration switch operation, runway can be landing runway, take-off runway or switch mode runway. We assumed that the number of runways must be larger than two and there must be one landing and one take-off runways as the input of the model.

The segregation mode of runway operation

(1)

$s.t.$

Constraints (2) – (8) and (19) – (24)

The semi-mixed mode runway configuration switch operation

(1)

$s.t.$

Constraints (2) – (26)

4. Computational experiments

4.1. Description of the real-life case study

A set of real data from HKIA for April 2018 was obtained from a licensed API from *FlightGlobal* and evaluated in the computational experiments. **Fig. 3** presents the average arrival and departure of aircraft movement in the interval of a 1-hour horizon from the historical data of the number of arrival and departure in April 2018 in HKIA. The data from **Fig. 3** shows that the number of arrival and departure flights is sometimes imbalance in hourly interval. For instance, the number of departure flights from 0 am to 3 am and 8 am to 10 am is significantly higher than the number of arrival flights, while we can see more arrival flights from 3 am to 7 am. The imbalance of number of arrival and departure flights are the major cause of the non-optimum situation of existing runway configuration. The number of arrival flights is exogenous factor in the system. Therefore, we seek for a runway configuration switch approach to review the possibility of enhancing runway capacity in regards to the imbalance demand of runway usage.

We are interested in the runway configuration setting in the analysis. Therefore, we compare the results using the same instance based on different runway configurations, including $2R_L1R_T$, $1R_L2R_T$ and $1R_L1R_w1R_T$ in a three-runway system, as shown in **Fig. 4**. The computation unit was equipped with an Intel Core i7 3.60GHz CPU and 16 GB RAM in a Microsoft Windows 7 operating system. An exact method using *IBM ILOG CPLEX Optimisation Studio 12.8.0 in C# language* was adopted.

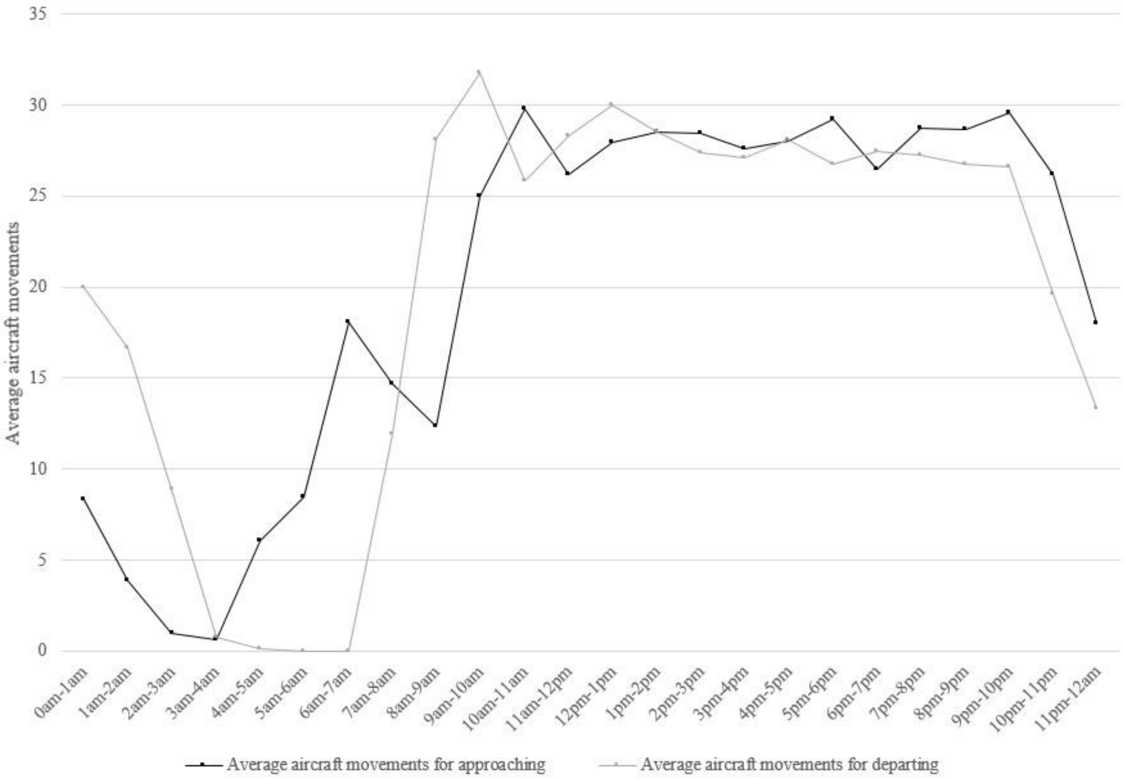

Fig. 3. The average arrival and departure of aircraft movement in April 2018

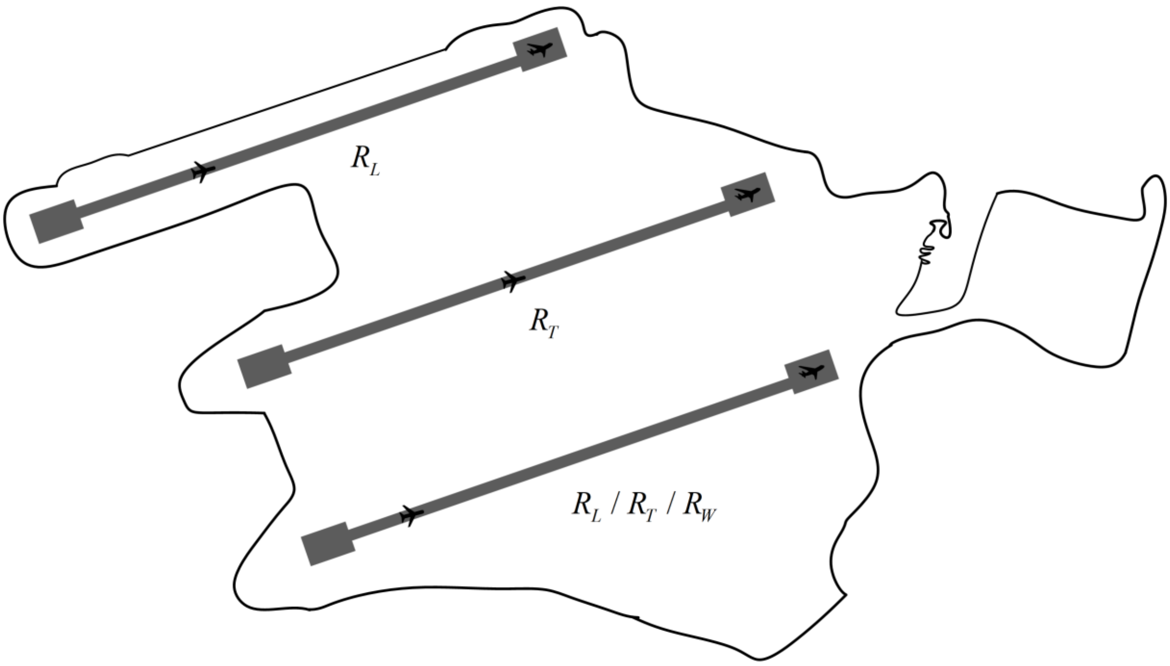

Fig. 4. The possible runway configuration in HKIA (proposed by the Hong Kong Airport Authority)

Each instance was given a maximum computation time of 3600 s to solve the instances in order to provide the same baseline for the comparison of the different settings of the runway configuration switch. All the solutions are in optimal condition in the numerical experiments. The global optimum of the instance using a switch model runway in their system must be better than or equal to the results from another runway setting, as the objective value can be further decreased by introducing the switch runway property. If this is not the case, their objective value should be the same, as a switch runway can be configured purely for landing or take-off.

4.2. Case example

For the sake of explanation of the model, we illustrate the optimal solution of a real-life case (1st April 2018 from 08:00 to 09:00 in HKIA) under different runway configuration modes using a Gantt chart. There are 40 flights, including 13 approach flights and 27 take-off flights in the dataset. We aimed at investigating the performance of switch mode runway configuration. As the actual schedule from the real-life case was performed in a two runways system, direct comparison between the simulated results from three runways system and the actual schedule may not be appropriate. We, therefore, performed the computation of the three runways system using the real-life case in a simulation environment. **Fig. 5** explains the symbols used in **Fig. 6** to **Fig. 8**. Flights symbols with black colour and with blur colour represent take-off flight and landing flight, respectively. A single straight line indicates a situation that the flight is approached or departed at its preferred time of operation PTO_i. If the preferred time of operation PTO_i and assigned time of operation T_i are not identical, a red straight line indicates the time duration of lateness or earliness of operation in a schedule. ATC usually performs a schedule in hourly decision horizon.

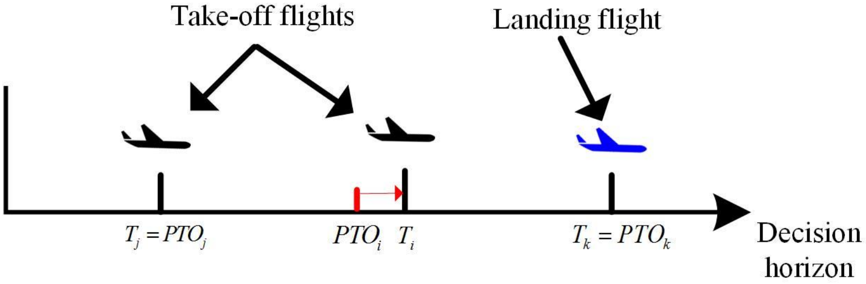

Fig. 5. Graphic illustration of the symbol used in the Gantt chart

The duration of runway configuration switch k is assumed to be 5 minutes in the simulation experiment. The Gantt chart representation of the optimal solution of the case instance using $2R_L1R_T$, $1R_L2R_T$ and $1R_L1R_w1R_T$ are illustrated in **Fig. 6**, **Fig. 7** and **Fig. 8** and the total penalty cost are 159, 198 and 9 seconds, which indicate that the switch mode runway configuration $1R_L1R_w1R_T$ achieves the lowest penalty cost. In **Fig. 8**, the runway performed three time configuration switch in a schedule and yielded a better solution with regard to the objective function than the runway configuration modes $2R_L1R_T$ and $1R_L2R_T$. Only flight 7 was affected due to the separation time requirement and other flights could operate at exactly the same as its preferred time of operation PTO_i.

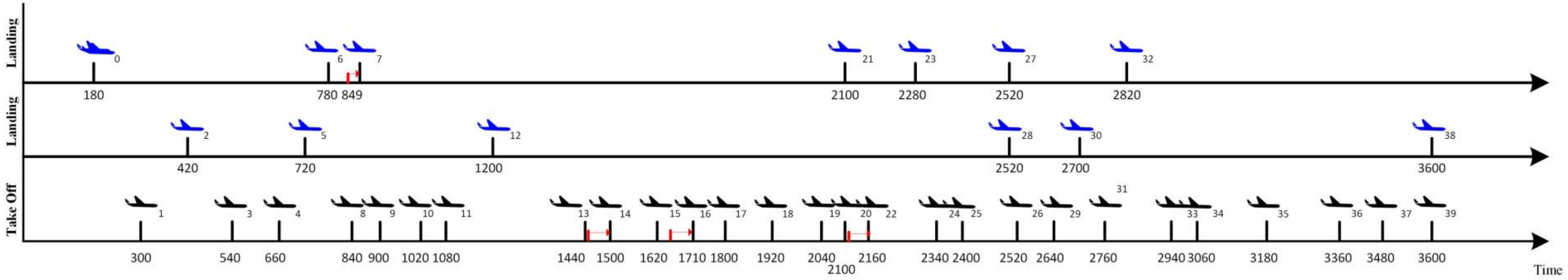

Fig. 6. Optimal solution for the instance from 08:00 to 09:00 on 1st April 2018 using 2-Landing-1-Take-off runways system

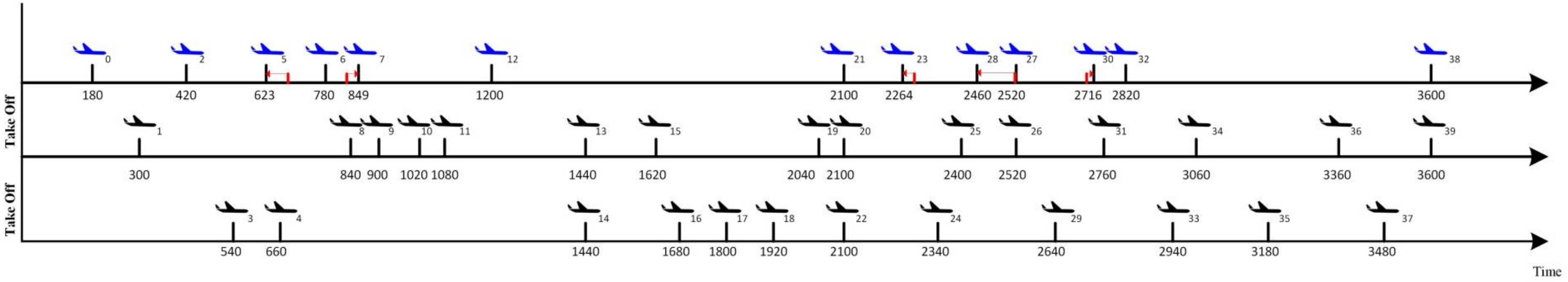

Fig. 7. Optimal solution for the instance from 08:00 to 09:00 on 1st April 2018 using 1-Landing-2-Take-off runways system

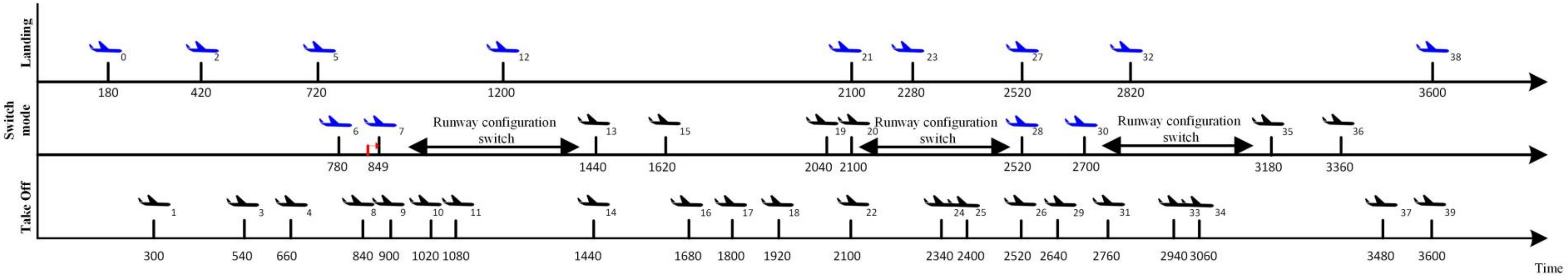

Fig. 8. Optimal solution for the instance from 08:00 to 09:00 on 1st April 2018 using 1-Landing-1-Switch-mode-1-Take-off runways system

4.3. Analysis on the impact of runway configuration planning

After the illustration of the mechanism and solution representation of dynamic runway configuration planning in ASSP model, in this section, we explain the benefit of adopting dynamic runway configuration planning in terms of the optimal value to investigate the relative percentage improvement. After trimming the dataset into 1-hour interval instances, a total of 695 instances was obtained. For each instance, we solve the problem under three runway configuration settings ($2R_L1R_T$, $1R_L2R_T$ and $1R_L1R_w1R_T$) and compare their objective value. Only two scenarios will be considered in the numerical computational analysis. For example, if the optimal value from $1R_L1R_w1R_T$ is identical to the setting of $2R_L1R_T$, the solution indicates that the switch mode runway R_w is employed as a landing runway R_L. If the optimal value obtained from $1R_L1R_w1R_T$ is lower than the setting of $2R_L1R_T$, this solution implies that the switch mode runway could reduce the penalty cost by switching the runway mode between the landing and take-off modes in the decision horizon. In this connection, the optimal value from the runway setting of $1R_L1R_w1R_T$ must be lower than or equal to the optimal solution either from $2R_L1R_T$ and $1R_L2R_T$.

We are interested in measuring the degree of improvement by using switch mode runway in the analysis. As for the same time interval of the instances, the air traffic patterns are similar. Therefore, we solve 695 instances under three types of runway settings (total of 2085 instances). Then, we present the statistical differences by comparing the solutions under three different runways settings for the same 1-hour interval. For this interval, the maximum, average and minimum optimal value from three types of settings from 30 instances (from 1st to 30th April 2018) are presented in **Fig. 9**, **Fig. 10** and **Fig. 11**. **Fig. 9 - Fig. 11** indicate that the runway configuration mode in $1R_L1R_w1R_T$ yielded the best solutions as compared to the runway modes of $2R_L1R_T$ and $1R_L2R_T$.

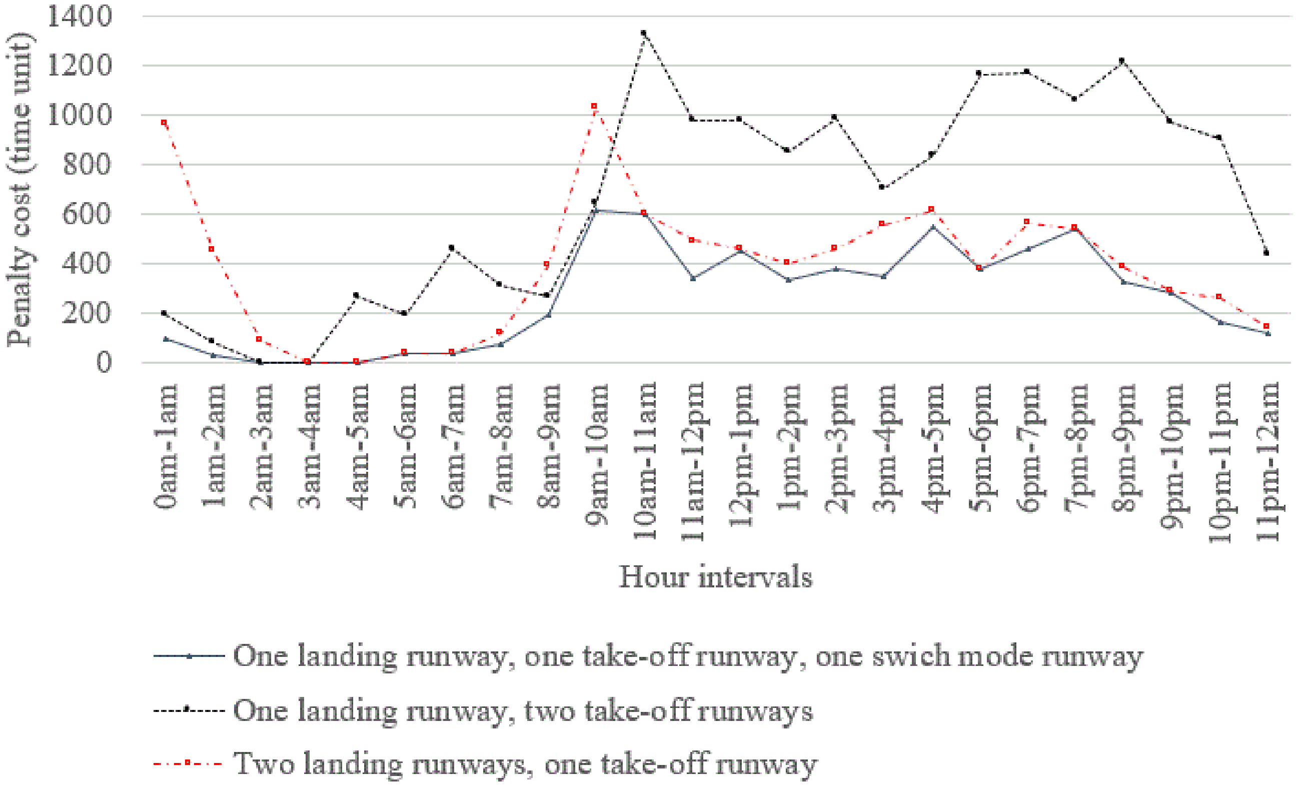

Fig. 9. The maximum optimal value of penalty cost for the same time intervals as of the instance

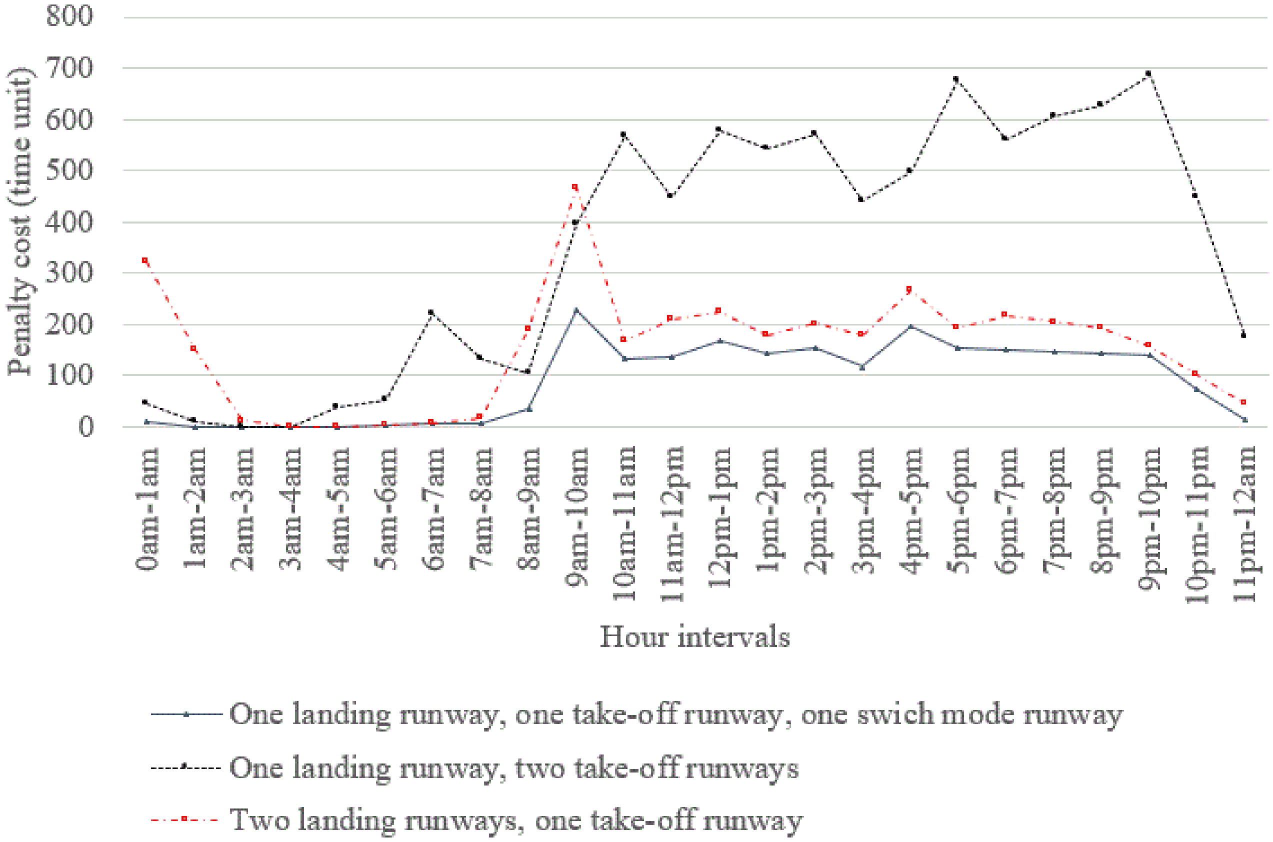

Fig. 10. The average optimal value of penalty cost for the same time intervals as of the instance

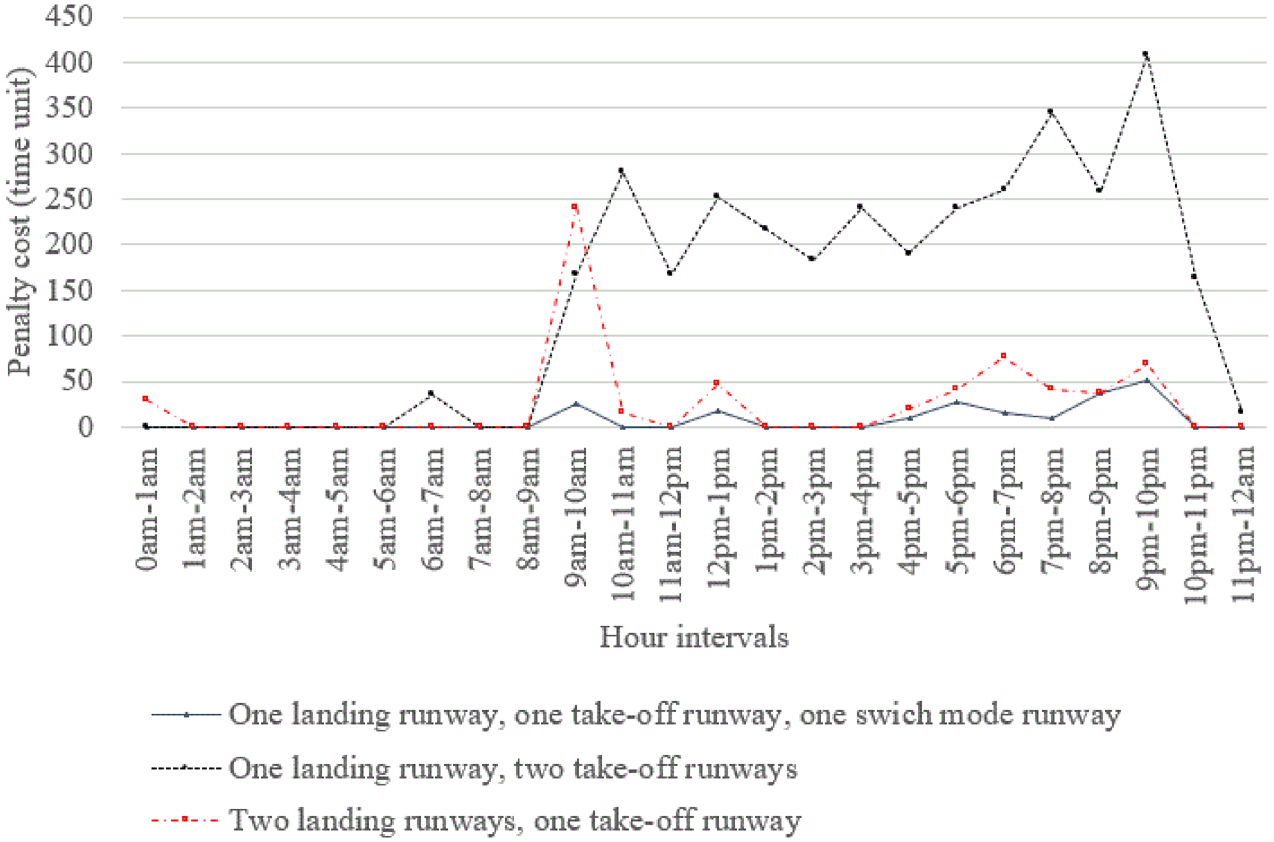

Fig. 11. The minimum value of penalty cost for the same time intervals as of the instance

We compute the average percentage gap between runway configuration modes using Equation (27). f^* is denoted as the optimal value, and Δ is a sufficiently small value. In

Table 3, the average percentage gap of $1R_L1R_W1R_T$ from $2R_L1R_T$ and $1R_L2R_T$ is used to evaluate the improvement when using the runway configuration switch using the real-life instances from HKIA. The runway configuration with switch mode operations contribute to a 71.66% and 37.08% reduction of penalty costs as compared to the runway configuration modes of $2R_L1R_T$ and $1R_L2R_T$ respectively. The results indicate that runway configuration planning with switch operations could further enhance the utilisation of runway capacity and cope with the arrival/departure patterns. **Table 4** provides the summary of the computational times and aircraft traffic movements in different time intervals.

$$\text{Gap} = {(f^*_{other} - f^*_{1R_L1R_W1R_T})}\big/{(f^*_{other} + \Delta)} \tag{27}$$

Table 3

Average percentage gap between runways switch mode and segregated mode configurations

Average percentage gap between runway configuration mode	$1R_L 1R_w 1R_T$ v.s. $2R_L 1R_T$	$1R_L 1R_w 1R_T$ v.s. $1R_L 2R_T$
0am – 1am	75.06%	96.58%
1am – 2am	89.25%	99.34%
2am – 3am	0.00%	100.00%
3am – 4am	0.00%	0.00%
4am – 5am	100.00%	0.00%
5am – 6am	96.58%	0.00%
6am – 7am	97.58%	0.00%
7am – 8am	94.27%	57.93%
8am – 9am	67.11%	81.62%
9am – 10am	42.38%	50.90%
10am – 11am	76.64%	21.00%
11am – 12pm	69.37%	34.87%
12pm – 1pm	70.89%	25.54%
1pm – 2pm	73.90%	20.90%
2pm – 3pm	73.07%	23.82%
3pm – 4pm	73.50%	34.04%
4pm – 5pm	60.77%	26.70%
5pm – 6pm	77.46%	20.13%
6pm – 7pm	72.99%	30.64%
7pm – 8pm	75.88%	28.41%
8pm – 9pm	77.29%	26.43%
9pm – 10pm	79.79%	11.36%
10pm – 11pm	83.83%	28.85%
11pm – 12pm	92.34%	70.80%
Average	71.66%	37.08%

Table 4

Computational performances

	ATMs		ATMs for arrival		ATMs for departure		CPU time of $1R_L1R_w1R_T$			CPU time of $2R_L1R_T$			CPU time of $1R_L2R_T$		
	min	max	min	max	min	max	min	avg	max	min	avg	max	min	avg	max
0am – 1am	23	39	5	13	15	29	00:01.23	02:01.92	20:01.00	00:00.50	00:25.09	02:53.33	00:00.10	00:07.63	01:31.28
1am – 2am	14	27	2	9	10	23	00:00.58	00:19.00	01:51.67	00:00.11	00:06.88	00:37.50	00:00.05	00:01.13	00:05.47
2am – 3am	7	13	0	4	7	11	00:00.02	00:00.92	00:04.44	00:00.01	00:00.41	00:01.47	00:00.01	00:00.25	00:00.88
3am – 4am	2	4	0	2	1	3	00:00.00	00:00.17	00:00.55	00:00.00	00:00.18	00:00.50	00:00.00	00:00.14	00:00.50
4am – 5am	4	9	4	9	0	1	00:00.01	00:00.36	00:01.47	00:00.01	00:00.23	00:00.93	00:00.00	00:00.37	00:02.02
5am – 6am	3	14	3	14	0	0	00:00.05	00:00.90	00:08.50	00:00.01	00:00.26	00:01.67	00:00.03	00:00.66	00:05.06
6am – 7am	14	24	14	24	0	0	00:00.19	00:09.89	01:49.30	00:00.03	00:00.68	00:02.28	00:00.12	00:05.27	00:27.69
7am – 8am	17	34	8	21	6	15	00:01.41	02:04.18	30:01.00	00:00.23	00:04.12	00:14.78	00:00.13	00:06.16	00:33.89
8am – 9am	35	47	10	18	24	33	00:21.45	06:21.64	30:02.00	00:03.98	00:37.83	02:56.14	00:00.64	00:12.41	02:15.70
9am – 10am	48	62	20	29	27	37	05:02.00	23:12.46	53:27.39	00:09.78	02:22.27	32:08.80	00:06.49	02:40.89	23:41.77
10am – 11am	48	64	25	33	20	31	01:29.87	19:12.63	56:40.17	00:04.32	01:24.37	07:40.20	00:09.16	02:05.61	10:10.25
11am – 12pm	44	66	21	32	22	35	04:47.62	16:34.43	34:36.23	00:02.94	01:05.65	05:55.91	00:02.83	01:07.84	05:48.97
12pm – 1pm	48	65	22	33	25	36	02:10.96	15:24.71	44:41.90	00:05.88	01:58.89	11:30.58	00:04.92	01:59.48	06:43.39
1pm – 2pm	44	66	21	32	23	34	00:25.39	17:08.75	43:18.80	00:04.03	01:34.82	07:19.92	00:03.41	02:50.91	24:37.88
2pm – 3pm	50	62	24	33	23	31	04:17.04	18:56.09	48:53.48	00:07.91	01:38.48	05:26.83	00:00.00	02:41.45	13:40.41
3pm – 4pm	46	62	23	31	23	32	01:26.69	15:52.70	42:57.89	00:05.63	01:15.24	04:52.41	00:04.37	01:09.77	03:20.78
4pm – 5pm	48	63	24	31	22	34	01:33.90	12:55.91	46:57.47	00:07.48	01:21.95	07:37.52	00:06.52	02:03.43	12:40.14
5pm – 6pm	48	65	24	32	22	34	02:44.79	14:48.32	28:34.36	00:08.75	01:46.16	07:25.36	00:07.89	02:05.54	12:40.14
6pm – 7pm	42	63	22	33	20	32	00:00.00	14:06.30	34:47.77	00:00.00	01:28.78	07:14.66	00:00.00	02:28.16	31:08.00
7pm – 8pm	48	62	25	33	20	32	01:11.93	14:44.66	58:44.66	00:05.88	01:43.78	06:27.05	00:04.53	01:48.68	08:35.45
8pm – 9pm	48	63	21	32	20	31	03:17.74	16:15.58	29:57.61	00:04.34	01:44.44	13:20.89	00:09.56	01:55.38	11:30.61
9pm – 10pm	48	65	25	35	20	31	01:20.44	18:22.73	36:10.17	00:15.74	01:43.38	06:20.77	00:19.07	02:48.38	12:15.44
10pm – 11pm	35	55	20	30	7	28	01:55.03	14:28.44	44:36.97	00:02.54	00:35.38	01:24.50	00:05.39	01:07.67	03:50.97
11pm – 12pm	13	43	12	28	1	18	00:00.48	03:52.45	21:00.08	00:00.28	00:09.37	01:07.23	00:00.29	00:19.43	01:52.05

ATMs: Aircraft traffic movements, min: minimum, avg: average, max: maximum

5. Concluding remarks

In this paper, we propose the formulation of the ASSP model under semi-mixed mode runway operation. Terminal traffic is usually limited by runway capacity. Typically, the arrival and departure rate of an airport is imbalanced during particular operating hours. A static runway configuration system may not provide a resource-utilisation approach for the ASSP model and, further induce the possibility of efficiency loss of runway usage. Providing a switchable runway configuration, ATC can determine a better runway configuration setting to handle on-going traffic demand while satisfying the safety regulation. The coordination of dynamic runway configuration planning and the ASSP model can further enhance the system's capacity to tackle the imbalanced runway usage problem. From a managerial aspect, the switch property of the runway will not reduce capacity in the formation of a runway schedule. Apart from the terrain constraints and complexity of air traffic control, semi-mixed mode runway operation is preferable for managing the imbalance of air and ground traffic. The numerical experiments also suggest that dynamic runway configuration planning obtains better results than the segregated mode.

The proposed model attempts to determine a runway schedule and determine the optimal setting of runway configuration responding to the demand differences between landing and take-off operations. We could expect that the flight can perform the landing and take-off operations at the agreed time of operations, which is an ATC and pilot agreed time of operation. The model can also determine the level of tardiness (early or delay operations) when insufficient capacity or separation time requirement are happened. Since runway scheduling is the interconnection point between the airspace and airport. Early or delay operations will affect the subsequence operations, including agreed taxiing time, gate time and ground manoeuvring operations. We attempt to optimise and design a runway schedule with a tardiness objective function.

However, in our mathematical formulation, the problem is far more complicated than in the static case. The exact method is not able to compute optimal results, given the computational limit of one hour. Further research is recommended below. (1) The adoption of meta-heuristics is favourable for large-sized instances, as the solution quality of the meta-heuristics (if proper algorithmic components are considered to enhance the convergence rate) would be better than the solution obtained by the exact method. (2) In practice, the holding pattern is one of the methods employed to handle air traffic. The proposed model can also be extended while considering the number of holding flights and holding time of each flight.

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