DYNAMIC SEMI-MIXED MODE RUNWAY CONFIGURATION PLANNING AND RUNWAY SCHEDULING

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ABSTRACT

An imbalance of the arrival and departure rate causes inefficient runway usage in airport capacity management. Dynamic runway configuration allows air traffic control to adjust the configuration of the switch mode runways in order to cope with the latest air and airport traffic situation. In practice, not all the runways can be designed as switch mode runways due to terrain constraints. Therefore, we consider the situation of a semi-mixed mode runway setting, which implies that several runways are configured for purely landing or take-off operation, while several runways are set to switch mode operation. In this paper, the formulation of the coordination of dynamic runway configuration planning and aircraft sequencing and scheduling problem under semi-mixed mode operation is proposed. The test instance followed the traffic pattern of Hong Kong International Airport. The results show that dynamic runway configuration planning and semi-mixed runway design can further enhance runway capacity.

Keywords: dynamic runway configuration, semi-mixed-mode-runways systems, runway scheduling

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1 INTRODUCTION

Because of the rapid growth of the airline industry such as free flights and the introduction of low-cost carriers in Western countries, people have found it easier and been more likely to take air transport for travel and trade over the past few decades. Consequently, the airline industry has experienced enormous demand which causes the problem of massive congestion and frequent delays. Recent research shows that that the bottleneck of air traffic is airport runway capacity instead of the en-route segment Meng, et al. [1]. In order to reduce the chance of flight delays and congestion, runway capacity has become a critical resource Soomer and Franx [2]. However, a runway's actual usage is affected by different considerations such as weather, visibility condition and arrival and departure demand. Instead of continuously constructing new runways, considering a dynamic runway configuration with a well-defined aircraft arrival sequencing and scheduling problem (ASSP) model could increase runway capacity to cope with the traffic situation due to an imbalance in arrival and departure rates.

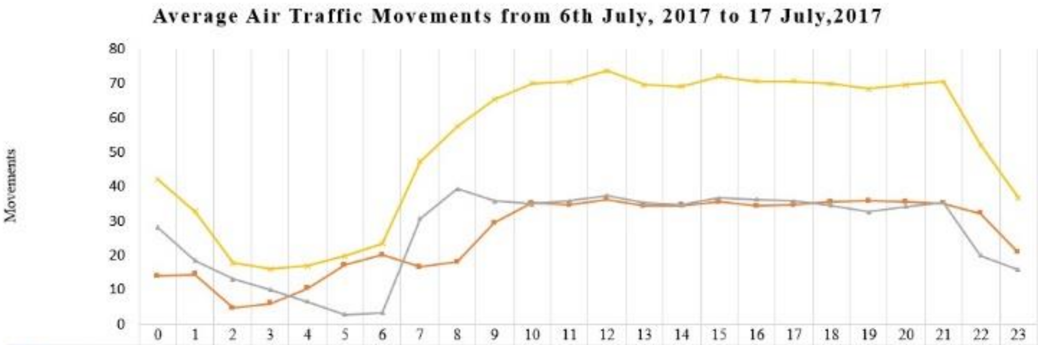
ASSP aims to reassign the sequence of arrival and departure flights regarding their predicted time Ji, et al. [3]. It ensures that the controller in air traffic control (ATC) can assure a safe and efficient environment for air traffic. ATC plays an important role as it needs to plan the sequence of flights arriving at the Terminal Manoeuvring Area (TMA). This is challenging as several factors, and uncertainties need to be considered, such as the separation time between the different size of aircraft and the dynamic change under the weather and visibility conditions. Improper handling can cause safety risks and flight delays Ji, et al. [3]. A well-planned schedule can help the controller in ATC to arrange landings and take-off of flights on a specific runway efficiently and safely.

There are several types of runway configurations; for instance, a runway can be exclusively applied for landing and another runway may be exclusively allocated for take-off (segregated runway operation), landing and take-off are interspersed on the same runway (mixed-mode operation), one runway is exclusively applied for landing or take-off while the other runway is applied for a mixture of landing and take-off (semi-mixed mode operation) and switching the properties of the runway according to the rate of take-off and arrivals (runway configuration switch) Ng, et al. [4]. The major consideration of using semi-mixed mode operation is inspired by the imbalance between arrival and departure and surplus of runway resources.

Generally, if there is an imbalance between arrival and departure, in reality, applying a runway for landing or take-off exclusively will not optimise the usage of the runway Jacquillat and Odoni [5] and Jacquillat, et al. [6]. In practical situations, the best way is to switch the configuration to landings and take-off to reduce the problem of imbalance Ng, et al. [7]. A mixed-mode operation can further enhance runway capacity for landing and take-off. However, it will burden ATC's workload. Uncertainties like unpredictable delay will disturb the original schedule, which will exacerbate the problem if there is improper handling. To lessen the complexity and consequences caused by improper handling in mixed-mode operation, considering semi-mixed mode operation is another way to alleviate the effect of any contingent events. Since only part of a runway will be applied for both landing and take-off, if the runway operation in mixed-mode worsens due to contingent events, another runway with the exclusive function will still be used for handling landing or take-off.

Many research efforts have been made to cope with the ASSP problem considering runway configuration. For segregated runway operation, Beasley, et al. [8] consider the aircraft Landing Problem (ALP) to optimise the sequence of landing only on a specific runway. In contrast, Atkin, et al. [9] consider the aircraft Take-off Problem (ATP) to optimise the sequence of departure. For mixed-mode operation, Lieder and Stolletz [10] consider this operations for further increasing runway capacity, but this also increases ATC's workload. As there is no or scant research that considers the ASSP problem under semi-mixed mode operation, it is one of the new areas that can be further analysed.

Figure 1 indicates that the arrival and departure rate of each hour varies. The discrepancy of the imbalance causes inefficient runway usage. The average number of flights operating during the peak hour is roughly 65 flights, including approaching and departing flights, in Hong Kong. However, the number of arrivals and departure exceed the planned arrival and departure by 15 and 20 respectively as shown in **Figure 1**. The number of movements and runway capacity can be further enhanced by the coordination of the dynamic runway configuration.



Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Arrival	14	14.33	4.583	5.917	10.25	17.08	20.08	16.58	18.08	29.42	35.17	34.58	36.17	34.33	34.5	35.42	34.33	34.67	35.42	35.75	35.42	35	32.08	20.75
Departure	28.08	18.42	13.08	10	6.583	2.75	3.25	30.67	39.33	35.83	34.83	35.83	37.42	35.25	34.67	36.58	36.17	35.83	34.42	32.58	34.17	35.33	19.92	15.83
Average total	42.08	32.75	17.67	15.92	16.83	19.83	23.33	47.25	57.42	65.25	70	70.42	73.58	69.58	69.17	72	70.5	70.5	69.83	68.33	69.58	70.33	52	36.58

Figure 1: Average air traffic movement from 6th July to 9th July, 2017

In order to enhance the applicability of the paper, we formulate the model in accordance with the runway model in Hong Kong International Airport (HKIA). HKIA is currently constructing a third runway for expansion. After the construction, the north, middle and south runways will be used for landing, take-off and mixed, respectively. For the south runway, the configuration will be a switch to either landing or take-off according to the arrival and departure rate in a specific period. With a well-planned model, we believe that the semi-mixed mode operation in HKIA can enhance the capacity for both landing and take-off by handling the switch process properly.

In this paper, we propose a complete formulation of dynamic runway configuration planning and ASSP under the semi-mixed mode of operation. The numerical experiments support the time deviation between the actual and preferred runway operation being further minimised in order to smooth the runway schedule and reduce the delay by considering the traffic pattern of airborne and airport delay.

2 DYNAMIC RUNWAY CONFIGURATION AND RUNWAY SCHEDULING PROBLEM

The primary objective of the dynamic runway configuration and runway scheduling problem is to minimise the time deviation between the preferred landing/take-off time PTO_i and the actual landing/take-off time T_{ir}. The notation and decision variables are shown in **Table 1**. Flight is denoted by $i \in I_L \cup I_T \in I$, where the flight can be either an arriving flight $i \in I_L$ or departing flight $i \in I_T$. The maximum number of flights in a system is n. At least one take-off or landing runway and at least one switch or mixed-mode runway are involved in the semi-mixed mode runway system. The runway can be classified as landing runway $r \in R_L$, take-off runway $r \in R_T$ and switching mode runway $r \in R_W$. The maximum number of runways is m. m must be greater than 2 to achieve the requirement of basic practice. In our model, we only consider landing, take-off and switch runway for simplicity.

As for approaching flights and departing flights, the estimated operation time on the particular runway ETO_{ir} and preferred operation time PTO_i are considered in the model. The deviation between ETO_{ir} and PTO_i is the ground travelling time, and it may satisfy $PTO_i \geq ETO_{ir}, \forall r \in$

R. The assigned operation time T_{ir} is not always equal to the PTO_i as the runway operation must satisfy the safety constraints and the air traffic situation. The separation time S_{ji} , as stated in **Table 2**, is the operation time deviation between two flights on the same runway to reduce the adverse effect of the vortex generated by leading flights.

Approaching flights $i \in I_L$ can only land on the landing runway or switch runway $r \in R_L \cup R_W \in R$, while departing flights can only take-off on the take-off runway or switch runway $r \in R_T \cup R_W \in R$. Additional constraints on the switch runway are imposed. For each group of adjacent landing or take-off flights on the switch runway, runway configuration index b is assigned. If the neighbouring flights' operation does not belong to the same family $(\tau_{ji} = 1)$, runway clearance k is enforced between b and $b + 1$ for the sake of runway configuration switching. The start and end time of configuration switch on the switch runway are denoted by ST_{rb} and CT_{rb}.

The solution of a runway schedule is X, which is determined by the combination of x_{ir}, y_{jir}, z_{irb}, γ_{jirb} and T_{ir}. The runway assignment is denoted by x_{ir}. y_{jir} illustrates the sequential relationship between flights j and i on the same runway r. If flight i is assigned to the switch runway $r \in R_W$, then flight i must belong to any group of b by decision variable z_{irb}. γ_{jirb} a explains the sequential relationship of adjacent flights on the same group b on the switch runway. U_{rb} is the auxiliary variable to define the situation that no flight was assigned to the group b on runway $r \in R_W$. The Artificial large variable M is a method to enforce the associate variables and constraints not being part of the optimal solution.

Table 1. Notation and decision variables

Notations	Explanation
i, j	Flight ID, $i \in I = I_L \cup I_T \in I, (i = 1,2, \dots, n)$
n	The maximum number of flights
r	Runway ID, $r \in R = R_L \cup R_T \cup R_W, (r = 1,2, \dots, m), m \geq 2$
m	The maximum number of runways
S_{ji}	The flight operation-based separation time between aircraft i and j scheduled on the same runway, $S_{ij} \geq 0$
ETO_{ir}	The estimated landing/take-off time of aircraft i on runway r
PTO_i	The preferred landing/take-off time of aircraft $i \in I$, $PTO_i \geq ETO_{ir}, \forall r \in R$
τ_{ji}	1, if aircraft j and i belong to the same operation mode, $i, j, i \neq j \in I_L$ or $i, j, i \neq j \in I_T$; 0, otherwise
b	Runway configuration index, $b \in B$
k	The duration of runway clearance k on switch model runway $\mathrm{r} \in R_w$
ST_{rb}	The start time of landing or take-off configuration on switch model runway $\mathrm{r} \in R_w$
CT_{rb}	The completion time of landing or take-off configuration on switch model runway $\mathrm{r} \in R_w$
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}, γ_{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 a sec) between two consecutive flights with the safe operation

			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

SSF = Small size flight; MSF = Medium size flight; LSF = Large size flight

2.1 Problem Formulation

The objective function is to minimise the time deviation between assigned operation time and preferred operation time of all flights by the variables α_i and β_i.

Constraints (2)-(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, the y_{jir} takes a 0 value. Constraint (4) ensures that each flight i is restricted to being assigned to only one runway r for the landing/take-off schedule. Constraints (5)-(6) restrict landing flights $i \in I_L$ such that they are not allowed to land on a take-off runway $r \in R_T$, and vice versa. Constraint (7) confirms that the assigned time of operation T_{ir} must be larger than its estimated time of operation ETO_i, while constraint (8) computes that the assigned time of operation T_{ir} must be greater than the assigned time of operation of the leading flight T_{jr} and the separation time requirement S_{ji}. 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 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 start time of the first configuration mode on each switch runway $r \in R_w$ must equal 0 in constraint (12). If flight i is assigned to runway configuration mode b, then the assigned time of operation T_{ir} must equal or be 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)-(14). Constraint (15) calculates that the completion time of configuration mode b on the switch runway must equal or be greater than the assigned time of operation T_{ir} for those flights which are assigned to configuration mode b on switch runways.

The auxiliary variable U_{rb} indicates the non-empty set of 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.

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.

$$f(X) = \min \sum_{i}^{m} (\alpha_i + \beta_i) \quad (1)$$

$$s.t.$$

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

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

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

$$x_{ir} = 0, \forall i \in I_L, r \in R_T \in \mathrm{R} \quad (5)$$

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

$$\sum_{b=0}^{B} z_{irb} = 1, \forall i \in I, r \in R_w \in R \quad (6)$$

$$\gamma_{jirb} + \gamma_{ijrb} \leq \tau_{ji}, \forall j, i, j \neq i \in I, r \in R_w \in R, b \in B \quad (7)$$

$$z_{jrb} + z_{irb} \leq 1 + \gamma_{jirb} + \gamma_{ijrb}, \forall j, i, j \neq i \in I, r \in R_w \in R, b \in B \quad (8)$$

$$ST_{r0} = 0, \forall r \in R_w \in R \quad (9)$$

$$T_{ir} \geq ETO_i - M(1 - z_{irb}), \forall i \in I, r \in R_w \in R, b \in B \quad (10)$$

$$T_{ir} \geq ST_{rb} - M(1 - z_{irb}), \forall \mathrm{i} \in \mathrm{I}, \mathrm{r} \in R_w \in R, b \in B \quad (11)$$

$$CT_{rb} \geq T_{ir} - M(1 - z_{irb}), \forall \mathrm{i} \in \mathrm{I}, \mathrm{r} \in R_w \in R, b \in B \quad (12)$$

$$U_{rb} \geq z_{irb}, \forall i \in I, r \in R_w \in R, b \in B \quad (13)$$

$$ST_{rb+1} \leq CT_{rb} + kU_{rb}, \forall r \in R_w \in R, b \in 1, \ldots, B \quad (14)$$

$$CT_{rb} \geq ST_{rb}, \forall r \in R_w \in R, b \in B \quad (15)$$

$$\alpha_i \geq 0, \forall i \in I \quad (16)$$

$$\beta_i \geq 0, \forall i \in I \quad (17)$$

$$\alpha_i \geq T_{ir} - PTO_i - M(1 - x_{ir}), \forall i \in I, r \in R \quad (18)$$

$$\beta_i \geq PTO_i - T_{ir} - M(1 - x_{ir}), \forall i \in I, r \in R \quad (19)$$

$$x_{ir} \in \{0,1\}, \forall i \in I, r \in R \quad (20)$$

$$y_{jir} \in \{0,1\}, \forall j, i, j \neq i \in I, r \in R \quad (21)$$

$$z_{irb} \in \{0,1\}, \forall i \in I, r \in R_w \in R, b \in B \quad (22)$$

$$\gamma_{jirb} \in \{0,1\}, \forall j, i, j \neq i \in I, r \in R_w \in R, b \in B \quad (23)$$

3 COMPUTATIONAL EXPERIMENTS

3.1 The instance setting

Since there is no benchmark instance set for the dynamic runway configuration and ASSP under semi-mixed mode operation, randomly generated instance sets were adopted in this research. The estimated operation time $ETO_{ir} = [0, \overline{ETO_{ir}}]$ is generated by uniform dia stribution, where $\overline{ETO_{ir}}$ is obtained by $60 \times n/_m$ to represent 1 hour's traffic situation in Hong Kong International Airport (HKIA). The preferred time of operation PTO_i is generated by a uniform distribution of $[30,60]$. The runway clearance is set to be 300 seconds. The maximum number of group b on each switch runway is 5. The distribution of the small, medium and large-sized flights are 10%, 20% and 70% of the maximum number of flights of each instance respectively. Given a different number of flights and distribution of flight operations and runway configuration as stated in **Table 3**, 18 instances were generated. The computation herein was aimed to evaluate the effectiveness of switch runways in terms of the objective function.

The instance ID explains the basic setting of the instance setting (e.g.: 1_E_a). In order to compare the computational results with a similar instance setting, the number of flights n, estimated time of operation ETO_{ir} and preferred time of operation PTO_i are the same for those instances with the same first digit in their ID (e.g.: 1_E_a, 1_E_b and 1_E_c). The second digit indicates the distribution of the flight operation. "E" represents an equal distribution of landing and take-off flights. "L" denotes a dominant number of landing flights in the system, while "T" illustrates the counter-situation of dominant na umber of take-off flights. In the computational results, we compare the similar setting of the set of instances by changing their combination of runway configuration. The last digit "a" of the ID indicates a multiple-runway system with two landing runways and one take-off runway. As for the last digit "b" of the ID, it denotes two take-off runways and one landing runway in the setting. The ID with the last digit of "c" illustrates a three-runway system with one landing, one take-off and one switch runway.

Table 3. Description of the test instances

ID	n	I_L	I_T	m	$\#R_L$	$\#R_T$	$\#R_W$
1_E_a	10	5	5	3	2	1	0
1_E_b	10	5	5	3	1	2	0
1_E_c	10	5	5	3	1	1	1
1_L_a	10	7	3	3	2	1	0
1_L_b	10	7	3	3	1	2	0
1_L_c	10	7	3	3	1	1	1
1_T_a	10	3	7	3	2	1	0
1_T_b	10	3	7	3	1	2	0
1_T_c	10	3	7	3	1	1	1
2_E_a	60	30	30	3	2	1	0
2_E_b	60	30	30	3	1	2	0
2_E_c	60	30	30	3	1	1	1
2_L_a	60	42	18	3	2	1	0
2_L_b	60	42	18	3	1	2	0
2_L_c	60	42	18	3	1	1	1
2_T_a	60	18	42	3	2	1	0
2_T_b	60	18	42	3	1	2	0
2_T_c	60	18	42	3	1	1	1

#: "The number of …"

The configuration of the computation unit was equipped with an Intel Core i7 3.60GHz CPU and 16 RAM under a Microsoft Windows 7 operating system. An exact method using *IBM ILOG CPLEX Optimization Studio 12.8.0* was adopted, and the algorithm was written in C# language.

3.2 The effectiveness of dynamic runway configuration switch

Each instance was given a maximum computation time of 3600s to solve the instances to provide the same baseline of the comparison of the different settings of the runway configuration switch. The global optimal 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. Otherwise, their objective value should be the same, as a switch runway can be configured for purely landing or take-off. However, the computational time of the model is limited, and the complexity of a semi-mixed mode runway system is complicated. Therefore, the objective value for the instances under a semi-mixed mode runway system is not always lower than the value obtained in other runway systems for large-sized instances. The objective function for the instances under a semi-mixed mode runway system is denoted by $f(X_{semi})$, while the objective function for the instance with the combination of landing and take-off runways is indicated by $f(X_{other})$. The deviation between the objective value is computed by the following equation.

$$ObjGap\% = \frac{f(X_{semi}) - f(X_{other})}{f(X_{other})} \tag{24}$$

3.3 Computational results

In this section, we explain the benefit of the adoption of dynamic runway configuration planning in the ASSP model regarding the objective value. **Table 4** shows the computational results of the test instances, including the objective value, computation time and $ObjGap\%$.

Table 4. Computational results

Instance ID	Objective value	CPU (seconds)	$ObjGap\%$
1_E_a	401*	0.34	0.00%
1_E_b	565*	0.08	-29.03%
1_E_c	401*	681.3	N/A
2_E_a	24039	-	-11.45%
2_E_b	25150	-	-15.36%
2_E_c	21287	-	N/A
1_L_a	328*	0.53	0.00%
1_L_b	1175*	0.05	-72.09%
1_L_c	328*	24.85	N/A
2_L_a	19857	-	-2.83%
2_L_b	55744	-	-65.39%
2_L_c	19295	-	N/A
1_T_a	1129*	0.36	-69.35%
1_T_b	346*	0.42	0.00%
1_T_c	346*	99.65	N/A
2_T_a	41942	-	-68.42%
2_T_b	13095	-	1.15%
2_T_c	13245	-	N/A

*: Global optimal; −: Over computational limit

As aforementioned, 0.00% in $ObjGap\%$ indicates the same runway schedule and configuration setting. In this scenario, the switch runway was configured as purely a landing or take-off runway and no switch property was considered in the system. The results show that the runway configuration planning of the instance “1_E”, “1_L” and “1_T” are identical to the setting in switch runway planning.

The contribution of the imposed runway configuration planning is illustrated by the $ObjGap\%$ if both values in the same set of instances are negative. As for the instance “2_E”, the $ObjGap\%$ from “2_E_a” and “2_E_b” are -11.45% and -15.36% respectively, which indicates that the solution under semi-mixed mode operation (one landing, one take-off and one switch runway system) surpasses the runway settings of “two landing and one take-off runway system” and “one landing and two-take-off runway system” in terms of the objective value. We also evaluated the test instances with the dominant number of landing flights in “2_L”. The range of the $ObjGap\%$ for the instance “2_L” is [-65.39%,-2.83%]. Therefore, the adoption of a semi-mixed mode runway system further enhances runway system capacity.

$ObjGap\%$ is expected to be a negative value, as the runway configuration using switch mode operation must outperform the solely landing and take-off runway system. However, in our numerical experiment, the results of test instance "2_T_b" obtained a positive value. This is because the solution is not a global optimal given a computational limit of one hour. We observed that the problem complexity of the ASSP with semi-mixed mode operation is hard to converge to the optimal than in the ASSP model.

4 CONCLUDING REMARKS

In this paper, we propose a formulation of the ASSP model under semi-mixed mode runway operation. Terminal traffic is usually limited by runway capacity, which leads to a delay prorogation in air and airport traffic. 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. 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. In the managerial aspect, the switch property of the runway will not reduce the 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 number of flights in the test instance is up to 60 flights. The numerical experiments also suggest that dynamic runway configuration planning obtains better results. Indeed, the complexity of the system may increase the ATC's operations difficulties and workload. However, with the assistance of the semi-mixed mode ASSP solver, ATC could rely on the solution in handling aircraft runway schedule.

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 a computational limit of one hour. Further research is recommended as follows. (1) The adoption of meta-heuristics is favourable for large-sized instances, as the solution quality of the meta-heuristics (if proper algorithmic components to enhance the convergence rate are considered) would be better than the solution obtained by the exact method. (2) In practice, the holding pattern is one of the methods to handle air traffic. The proposed model can also be extended with consideration of the number of holding flights and holding time of each flight.

Several interesting aspects can be considered for future work. First, the uncertainty of flight operation time may also be included in the system. For instance, delay propagation may affect the overall system performance. Therefore, including the uncertain parameters in the model may enhance the robustness of the system. Second, extreme weather and current air route traffic control may also further improve the system reliability in operational aspect.

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