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A Simulation Study on Air Traffic Control Strategies

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***Abstract*—Air Traffic Control (ATC) plays a crucial role in the modern air transportation system. As a decentralized system, every control sector in the ATC network system needs to use all sorts of available information to manage local air traffic in a safe, smooth and cost-efficient way. A key issue is: how each individual ATC sector should use global traffic information to make local ATC decisions, such that the global air traffic, not just the local, can be improved. This paper reports a simulation study on ATC strategies aiming to address the above issue. The coming-in traffic to sectors is the focus, and the ATC strategy means how to define and apply various local ATC rules, such as first-come-first-served rule, to the coming-in traffic according to the global traffic information. A simplified ATC network model is set up and a software simulation system is then developed. The simulation results reveal that, even for a same set of ATC rules, a bad strategy of applying them can cause heavy traffic congestion, while a good strategy can significantly reduce delays, improve safety, and increase efficiency of using airspace.**

I. Introduction

As an extremely complicated network system, Air Traffic Control (ATC) aims to meet the rapidly increasing air traffic volume in terms of safety, capacity and cost-efficiency [1]-[4]. Enormous efforts have been made to research and develop various centralized ATC automation and intelligent technologies, e.g., see [5]-[10]. However, many real-world ATC practices still heavily exhibit a decentralized agent-based nature. This is partially because of the unreliability of such centralized ATC automation and intelligent technologies (for example, the ironic failure of the baggage system at London Heathrow Airport T5 on 27 March 2008). The commercialization and deregulation of civil aviation industry also make the ATC system heavily de-centralized, because multiple stakeholders with different interests play and compete together in the ATC system [4], [10]-[15].

The network of ATC sectors is a typical example of such a decentralized agent-based system. As the brain of the whole ATC system, the network of ATC sectors plays a dominant role to make most of airspace and manage air traffic in it. The performance of the network largely depends on the behaviour of each individual ATC sector. Particularly, it is believed that the global performance of the network mainly depends on how each individual ATC sector uses global traffic information to make local ATC decisions [16]. Unfortunately, in the reality, local ATC decision making process is mainly based on local traffic information, which could cause very poor global management performance, e.g., a short-sighted local decision in an ATC sector could cause serious congestion conditions to its neighbouring ATC sectors, which could then propagate through whole network.

Then, how to improve the global management performance of a decentralized agent-based ATC system? As is well known, the macro-level collective performance of a decentralized agent-based system usually emerges from micro-level individual agent behaviour based on certain simple rules. For instance, in the evolutionary process, the rule of natural selection can make an eco-system thrive in a dynamic environment [17]. In the study of pedestrian traffic, the rule of social force may well explain escape panic [18]. In the ATC system, there are also some simple rules that help ATC sector controllers to deliver good performance [19]. It should be noted that there is usually no one-size-suit-all rule in the ATC system. The first-come-first-served rule may be the most straightforward rule in the case of under-congestion, but may not necessarily deliver a satisfactory traffic flow in the case of over-congestion. Thus, the question is: what is the best way for ATC sector controllers to apply various rules? In this study, we call the way of applying various ATC rules as ATC strategy. Despite many publications on the behaviour of ATC sector controllers (e.g., [19]), which often mainly focus on human factors, a systematic study on ATC strategy, a non-human factor, still need more efforts. The goal of this study is to investigate and to develop strategies for individual ATC sectors to properly use more global traffic information to make local ATC decisions.

II. Simplified Air Traffic Control Network System

Air Traffic Control (ATC) system can be considered as a network of many ATC sectors, where ATC sectors are the nodes in the network while the neighbouring relationships are the links between nodes. The global air traffic control is achieved through each individual ATC sector which focuses to independently manage the air traffic within its own airspace. It is reasonable to think that, in order to achieve a global optimal air traffic control, each individual ATC sector, rather than simply carrying out its daily routine in a largely isolated way, should enhance communications and collaborations with other individual ATC sectors. That is, when an ATC sector is managing the traffic within its own airspace, not only the traffic situation in it own airspace, but also the traffic situations in its neighbouring ATC sectors, or even the global

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traffic situation, should be seriously taken into account before any local decision is made. Simply speaking, air traffic management is a problem of how to best balance between increasing demands and limited supplies. Airspace is the limited supply, and aircrafts flying in the airspace create demands for using the airspace. The duty of ATC sectors is actually to manage to allocate the usage of the airspace, such that the demands of aircraft can be met in a safe and cost-efficient way.

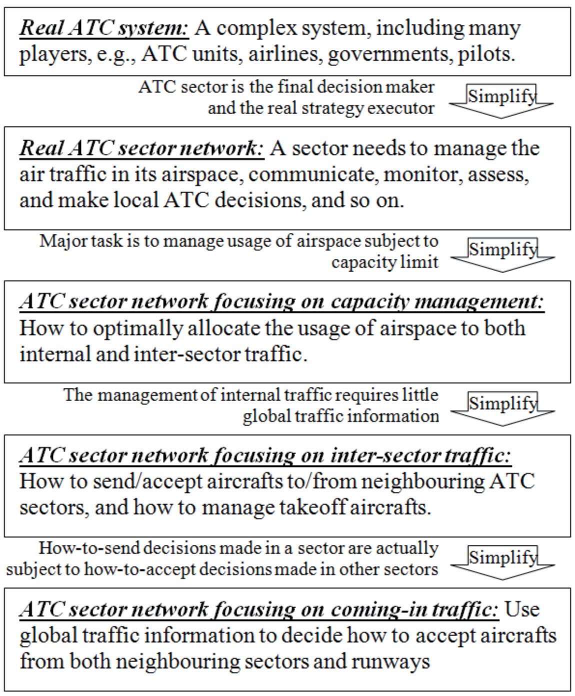

Fig.1. How to simplify ATC system in this study

Based on the procedure of simplification given in Fig.1, this research is concerned with: to achieve a better air traffic control, what is a proper strategy to use the global traffic situation, along with the local traffic situation, to make local decisions on how to accept aircrafts from neighbouring ATC sectors?

III. Modelling Simplificed ATC System

A. Objects in model

Basically, there are three aspects to model an ATC object: parameters, states and basic dynamics. Parameters are used to define static features of an ATC object, e.g., the location of an airport, and they will normally not change during simulation runs/experiments. States are dynamic features of an ATC object, e.g, the usage of capacity in an ATC sector, and they changes during simulation runs/experiments. Basic dynamics is a set of mathematical functions which determine how the states of ATC object changes during simulation runs/experiments.

All ATC sectors together form a spatial network, where nodes are individual ATC sectors, and links are neighbouring relationships between ATC sectors. This network can be simplified and mathematically described by a matrix $M_{Neib} \in R^{N_s \times N_s}$, where N_s is the number of ATC sectors in the network, and the entry $M_{Neib}(i,j) = a_{i,j} \geq 0$ is an integer, and it is the least jumps between node i and j. $a_{i,j} = 0$ means ATC sector i and j are neighbours to each other; otherwise, $M_{Neib}(i,j)$=0 means ATC sector i and j are separated by at least $a_{i,j}$ other ATC sectors. We call this matrix as "neighbouring matrix". Fig.2 illustrates how to use M_{Neib} to describe an ATC sector network. Neighbouring matrix is a very important data structure to introduce spatial global traffic information into local ATC decision-making process, because it is used to define to which global extent the spatial traffic information will be introduced. For instance, assuming the global level is set as $L_G \geq 0$, then when ATC sector i is making local decisions, it only needs to consider the traffic in those ATC sectors with $M_{Neib}(i,j) < L_G$. L_G=0 means no global traffic information will be used to make local ATC decisions.

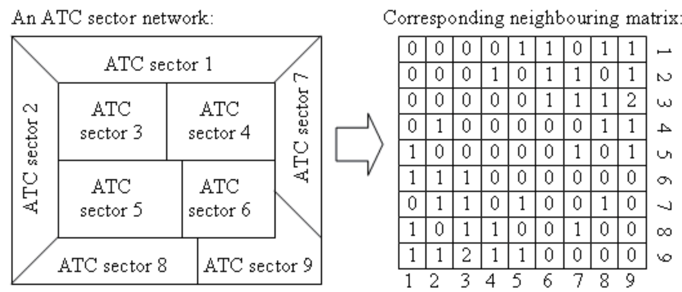

Fig.2. ATC sector network and its neighbouring matrix

Flight route network is also a spatial network composed of waypoints (nodes) and route segments (links) between waypoints. The network itself can be described by a weighted matrix, $M_{FRN} \in R^{N_{wp} \times N_{wp}}$, where N_{wp} is the number of waypoints in the network, and the entry $M_{FRN}(i,j)$=0 means there is no direct link (route segment) between waypoint i and j, otherwise $M_{FRN}(i,j)$>0 means there exists a route segment with a key feature valued as $M_{FRN}(i,j)$, e.g., the length or the capacity limit of the route segment. There is a shadow matrix for M_{FRN}, denoted as $M_{SFRN} \in R^{N_{wp} \times N_{wp}}$, whose entry $M_{SFRN}(i,j)$ is the serial number of route segment between waypoint i and j, and $M_{SFRN}(i,j)$=0 means no route segment. M_{FRN} and M_{SFRN} will be particularly useful to calculate new flight plans for aircrafts.

To increase the complexity of the system, uncertainties and associated behaviours need to be introduced to the above ATC objects, and new ATC objects such as weather factors (e.g., storm and wind) and occasional events (e.g., military practices and terrorism attacks) need to be taken into account as ATC environmental disturbances. These improvement and extension of the system will be crucial to assess the robustness of the ATC strategies under investigated.

B. Dynamics of model

In the simplified ATC system, the dynamics is defined as the behaviours of each individual ATC sector, i.e., how each independent sector handles its arrival traffic. There are some basic ATC rules, e.g., first-come-first-served, to follow when a sector is managing its arrival traffic. We classify ATC sectors into two categories: en-route ATC sectors and airport terminal areas. For different category of ATC sectors, different set of basic rules apply, because the arrival traffic of an en-route ATC sector only considers those coming-in aircrafts which request to enter from the neighbouring ATC sectors, while for an airport terminal area, the arrival traffic includes one more factor: aircrafts which are waiting to take off from the associated airport. Therefore, airport terminal areas need extra rules to make decisions on how to give clearances to aircraft waiting to take off. Fig.3 illustrates an airport terminal sector, where we call the ATC sector under investigation as “Central ATC sector”, those sectors around it as its “Neighbouring ATC sectors”, and squares stand for takeoff aircrafts, while circles for coming-in aircrafts. Without takeoff aircrafts in Fig.3, it becomes an en-route sector.

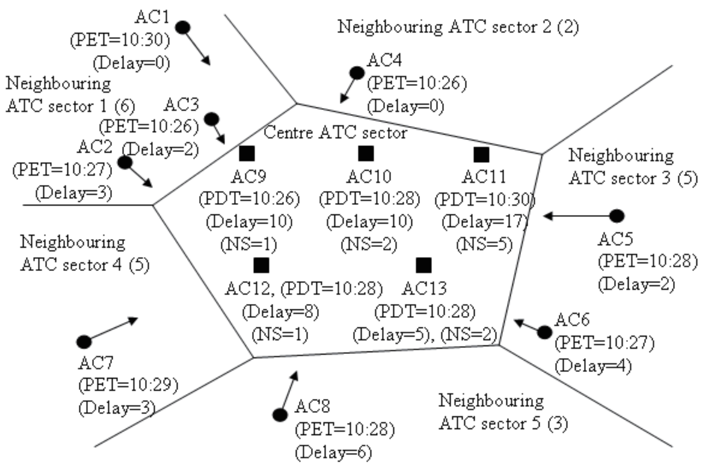

Fig.3. Illustration of Rule 1 to Rule 8

In this study, we discuss 4 basic rules for an en-route ATC sector to accept coming-in aircrafts from neighbouring ATC sectors:

- Rule 1: First come, first served. Each individual aircraft coming from neighbouring ATC sectors has a predicted entry time (PET in Fig.3) to enter the central ATC sector. Under this rule, the central ATC sector will first accept the aircraft which has the earliest PRT at each time instant of decision-making.
- Rule 2: Most congested, first served. Under this rule, the central ATC sector will first accept those aircrafts coming from the most congested neighbouring ATC sector.
- Rule 3: Most delayed, first served. Under this rule, the central ATC sector will first accept the aircraft which has the longest delay time.
- Rule 4: Most potential, first served. Under this rule, a highest priority should be given to those aircrafts which come from those neighbouring ATC sectors that have the most potential to accept traffic from the central ATC sector. This rule is particularly useful when the central sector and its neighbouring sectors have all run out of capacities, or nearly, at the same time.

Rule 1 to Rule 4 are also applicable to airport terminal areas when coming-in aircrafts are concerned. However, we need some more rules for airport terminal areas to clear aircrafts waiting to take off:

- Rule 5: First come, first served. Each individual aircraft has a predicted departure time (PDT in Fig.3) to take off from the airport in the central ATC sector. Under this rule, the central ATC sector will first clear the aircraft which has the earliest PDT at each time instant of decision-making.
- Rule 6: Most delayed, first served. Under this rule, the central ATC sector will first clear the aircraft which has the longest delay time.
- Rule 7: Least congested, first served. Under this rule, the central ATC sector will first clear those aircrafts whose next ATC sector (NS in Fig.3) to go is the least congested neighbouring ATC sector.
- Rule 8: Dynamically balance the usage of arrival capacity and departure capacity. The details of this rule are complicated but it is very useful, and many methods have been reported to address this issue [7], [9].

Besides above 8 basic ATC rules, more other rules may be added. For example, since each aircraft carries limited fuel, it can only continue flying for a certain period of time. Therefore, it must not be delayed in air for unlimited time. To this end, we have the following rule:

- Rule 9: The total air-borne delay of an aircraft must not exceed the maximum allowable air-borne delay of that aircraft; Otherwise, the aircraft must be accepted regardless other traffic situations. This rule should be mandatory rather than optional in order to limit air-borne delay imposed on each individual aircraft for the sake of safety. However, this means the congestion condition of ATC sectors could get worse, which in return could cause safety problem on a larger scale. Therefore, even for this mandatory ATC rule, we also need to have a close look to see whether it is possible to apply it in a more flexible way in order to achieve a better balance between traffic safety, aircraft delays and the congestion condition of ATC sectors.

IV. ATC Strategies

A. *One-rule-at-one-time strategies*

Normally, for a given traffic situation to an ATC sector, each different ATC rule will give different order to accept coming-in aircrafts or clear takeoff aircrafts. For instance, assuming, in Fig.3, the current time interval of decision-making is a 5-minute-long period, from 10:25-10:30, the central ATC sector has the capability to allow 5 aircrafts to come in and 3 aircrafts to take off in the current time interval, and the congestion condition in ATC sectors is scaled from 1 to 6 as it gets worse, then the orders to accept coming-in aircrafts or clear takeoff aircrafts under Rule 1, 3, 6, or 7 are given in Table 1. Some questions are then raised: Which rule should be applied? Is it possible or better to apply more than one rule at one time? If more than one rules are chosen, how to apply them in a mixed way? What is the best way to combine the chosen rules? In this study, an ATC strategy defines a way for an ATC sector to choose and to apply those basic ATC rules to manage coming-in and/or takeoff aircrafts, i.e., to decide which aircrafts to be accepted in which order.

Obviously, "one rule at one time" is a simplest ATC strategy. In this case, we need to define some typical ATC scenarios, and then switch between ATC rules according to the current ATC scenario. That is, for a given ATC scenario in an ATC sector, only one ATC rule will be applied, and when the ATC scenario changes, the ATC sector will switch to other most suitable ATC rule. Key parameters and their critical values need to be identified in order to mathematically define typical ATC scenarios and then to trigger rule-switching. For instance, Rule 1 is preferable when all sectors are far under-congested, Rule 2 should be considered when some neighbouring sector are near congested, and Rule 4 is better when the central sector is congested. Therefore, we need a parameter to describe the congestion condition of an ATC sector, and then we need to decide some critical values to define ATC scenarios according to the congestion condition. Appropriate methods are required to justify and to optimize such parameters and their critical values.

"One rule at one time" is quite similar to the strategy of "focusing on one event at one time" when human controllers are making their decisions manually. Modern computer technology makes it practicable to adopt multi-rules-at-one-time strategies in order to achieve a better ATC performance, particularly when global traffic information needs to be taken into account.

B. *Multi-rules-in-order strategies*

A common case where multi-rules have to be employed is when some aircrafts are given the same priority under a certain single rule but not all of them can be accepted at the moment of decision-making due to the ATC sector capacity limit. Therefore, a secondary rule has to be used to decide which of them should be accepted. It is not rare that it is sometimes necessary to apply the third rule or even more until the orders are finalized subject to the capacity limit for accepting those aircrafts which have the same priority under the primary rule. In this paper we call the above way of applying multi-rules as a "multi-rules-in-order" strategy. Table 1 gives the results of applying some multi-rules-in-order strategies to the ATC scenario in Fig.3. From Table 1 one can see that, under either one-rule-at-one-time strategy, we cannot decide which coming-in aircraft should be accepted as the last aircraft in the current time interval of decision-making, while a multi-rules-in-order strategy can easily solve this problem. However the questions here are: Which rules should be chosen? In which order the chosen rules should be applied? Again, we need to define some typical ATC scenarios, and then for each ATC scenario we decide a multi-rules-in-order strategy which includes a set of basic ATC rules with the order to apply them. For instance, when most ATC sectors are far under-congested, Rule 1 and Rule 3 should be chosen as the primary rule and the secondary rule, respectively, but during a congestion period, Rule 2 and Rule 4 need probably to take over. The definition of ATC scenarios is a strategy-independent process, which involves identifying and tuning some key parameters according to the real ATC environment. Then appropriate methods need to be developed and extensive experiments need to be conducted to decide a most suitable multi-rules-in-order strategy for each ATC scenario, i.e., to apply which rules in which order.

C. *Multi-rules-with-weights strategies*

Another way of applying multi-rules is to assign a weight to each basic ATC rule. We call this as a "multi-rules-with-weights" strategy. In this case, firstly we need to decide the order for accepting coming-in aircrafts (or clearing takeoff aircraft) according to each individual rule. Suppose there are N_{AC} aircraft waiting to enter at the current time instant of decision-making, and they are divided into $N_G(r)$ groups according to their orders to enter under Rule r. As discussed in one-rule-at-one-time strategies, we have $N_G(r) \le N_{AC}$. Assuming aircraft i belongs to the $g(i,r)$th group under Rule r, then each aircraft has a set of orders under different rules: $[g(i,1),\ldots, g(i,N_R)]$, where N_R is the total number of rules used. Suppose the weight assigned to Rule r is $w(r)$. Normally we can have

$$\sum_{r=1}^{N_R} w(r) = 1\,,\ 0 \le w(r) \le 1\,. \qquad (1)$$

Then we can calculate as following the priority of each aircraft to finalize their entry orders:

$$p(i) = \sum_{r}^{N_R} \frac{(N_G(r) - g(i,r) + 1)}{N_G(r)} w(r) \qquad (2)$$

where $p(i)$ is the priority of aircraft i, which will be used to decide the final orders for aircrafts to enter the ATC sector. Apparently, for each ATC scenario we have a set of weights assigned to the basic rules. For instance, when the traffic load is low in most ATC sectors, Rule 1 and Rule 3 may have relatively large weights; as the traffic load is becoming heavier, their weights should be reduced accordingly while the weights of Rule 2 and Rule 4 may go up gradually. Therefore, to study and improve multi-rules-with-weights strategies, properly classifying ATC scenarios is still the first step to go. For a given ATC scenario, different sets of weights will produce different final orders for aircrafts to enter or take off, as illustrated in Table 1. As a result, the main part of finding a suitable multi-rules-with-weights strategy for a given ATC scenario is to develop some effective methods, such as genetic algorithms, to optimize the weights for the basic ATC rules.

Basically, using weights offers a more flexible way to mix different basic ATC rules, particularly when the global traffic information is supposed to play an important role in the local decision-making process. Actually, the multi-rules-with-weights strategy can be considered as a generic framework to study ATC strategies, because both one-rule-at-one-time strategies and multi-rules-in-order strategies are some special cases of it. For instance, if we set

$w(i) = 1$, and $w(r) = 0$, for all $r \in [1,\ldots,N_R]$, but $r \ne i$, (3)

clearly the multi-rules-with-weights strategy become a one-rule-at-one-time strategy. If we set the weights as following

$$v(r) = \begin{cases} \alpha^{r-1}, & r = 1,2,3 \\ 0, & 3 < r \le N_R \end{cases}, \tag{4}$$

$$w(r) = v(r) / \sum_{r=1}^{N_R} v(r), \tag{5}$$

where α is a constant small enough, say α =0.0001, then very likely we will have a multi-rules-in-order strategy: [1,2,3], i.e., Rule 1 is the primary rule, Rule 2 is the secondary one, and Rule 3 is the last rule to apply whenever necessary.

Like a one-rule-at-one-time strategy, there exists a possibility that some aircrafts are given the same priority under a multi-rules-with-weights strategy. This possibility is usually far lower than that of a one-rule-at-one-time strategy. To make the multi-rules-with-weights strategy work effectively, we need a standby multi-rules-in-order strategy, which can normally be designed according to the weights assigned to the rules. If some rules have a same weight, then their orders need to be decided by using the methods discussed in multi-rules-in-order strategies.

A good ATC strategy should be able to take global traffic information into account and combine basic ATC rules for different ATC sectors to make proper local decisions on how to manage coming-in and takeoff aircrafts, such that the global ATC performance can be improved. Global traffic information is mainly used to evaluate numerically the congestion condition of each ATC sector.

V. Preliminary Simulation Results

To study different ATC rules and ATC strategies, we need an ATC simulation platform as illustrated in Fig.4.

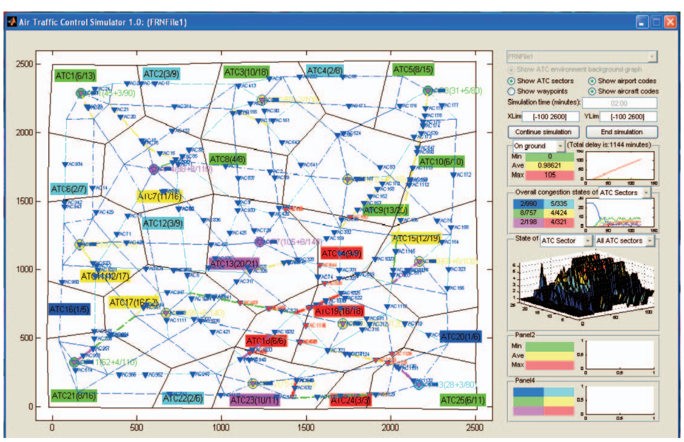

Fig.4. Illustration of ATC simulation platform

Based on the ATC simulation platform, we conducted 8 demonstrative experiments, which all use the same set of ATC data for comparative purposes. For the sake of simplicity, the ATC data are created randomly rather than abstracted from the real ATC world. The ATC sector network has 25 sectors, the route network has 57 normal waypoints plus 13 airports, and 1160 aircrafts are planned in each experiment. To better visualize traffic situation, colour-coding method is used. The background colour of an ATC sector's code changes between marine, light blue, green, yellow, pink, and red as the congestion condition gets worse, e.g., pink means the usage of capacity in an ATC sector is between 90%~100%, while red means the usage exceeds the capacity limit. The same colour pattern is used to indicate the traffic condition at an airport or in a route segment. For aircrafts, blue means normal flight state, pink means delayed on ground, red means delayed in air, and green means landed at a runway. In the experiments, we measure delayed times of aircrafts and congestion conditions in ATC sectors to assess the performance of the ATC system under a certain strategy. The simulation time (an operating day) is 12 hours (720 minutes), and 1 second of CUP time stands for 1 minute of simulation time. In these 8 experiments, different ATC rules are used or combined:

- Experiment 1 (Exp.1): Rule 1 and Rule 5.
- Experiment 2 (Exp.2): Rule 1, Rule 5 and Rule 8. As an initial simple experiment, Rule 8 allocates half of the capacity limit to takeoff flights, while coming-in aircraft can access the whole capacity limit. The same is for other experiments where Rule 8 is employed.
- Experiment 3 (Exp.3): Rule 1, Rule 5 and Rule 9. The maximum allowable air-borne delay for every individual aircraft is 20 minutes under Rule 9. The same is for other experiments where Rule 9 is applied.
- Experiment 4 (Exp.4): Rule 1, Rule 5, Rule 8 and Rule 9.
- Experiment 5 (Exp.5): Rule 2 and Rule 5.
- Experiment 6 (Exp.6): Rule 2, Rule 5, Rule 8 and Rule 9.
- Experiment 7 (Exp.7): Rule 1, Rule 4 and Rule 5.
- Experiment 8 (Exp.8): Rule 1, Rule 4, Rule 5, Rule 8 and Rule 9.

The main results of these 8 experiments are given in Table 2, and Fig.5 to Fig.12 show the final state of each experiment, i.e., after the operating day ends (12 simulated hours, or 720 simulated minutes), what the traffic situation looks like in each experiment. In Table 2, CC*i* means the total minutes of congestion condition level *i*. As is defined before, level 6 means over-congested condition in an ATC sector, and therefore CC6 is one of the indexes we are most interested in.

From Table 2 and Fig.5 to Fig.12, one can see that:

- Exp.1 shows that, only following "first come, first service" (Rule 1 and Rule 5) causes both the heaviest delays (on ground and in air) and the worst over-congestion, and the capacity of airspace is used with the lowest efficiency (647 out of 1160 aircrafts never get chance to take off during the whole operating day). A main reason is, as shown in Fig.5, some over-congested ATC sectors are caught by "dead-lock" problem in the middle of the operating day, and thereafter, the traffic in the whole airspace is completely blocked by the "dead-lock" problem.
- Exp.5 shows that, simply replacing "first come, first service" (Rule 1) by "most congested, first service" (Rule 2) brings a very little improvement, and the overall situation is still very bad. As shown in Fig.9, the "dead-lock" problem still exists.
- Exp.2 is the same as Exp.1, except the introduction of Rule 8. By allocating a small capacity to takeoff flights, the airspace is better reserved to serve coming-in flights.

i.e., aircrafts flying in air have more chance to fly through ATC sectors and eventually land. From Fig.6, it seems "dead-lock" problem is avoided, and smooth traffic flow in air constantly frees airspace for aircrafts on ground to take off. Therefore, the introduction of Rule 8 significant reduces both delays and over-congestion conditions, and the efficiency of using airspace is greatly improved (305 out 1160 aircrafts never take off).

- Exp.3 is the same as Exp.1, except the application of Rule 9. Since Rule 9 pushes aircrafts in air to get through ATC sectors, in a mandatory way, regardless the congestion condition in sectors, it has the highest efficiency of using airspace (only 76 out of 1160 aircrafts never take off), but at a cost of heavy over-congestion condition. The "dead-lock" problem does not exist due to this mandatory rule. Compared with Exp.2, aircrafts on ground have better chance to take off, and therefore total delay on ground is less than that in Exp.2; but due to the heavy over-congestion condition in ATC sectors, most aircrafts in air have to be delayed for 20 minutes before they can fly freely in the airspace, so, the total air-borne delay is much worse than that in Exp.2. The overall situation is still better than that in Exp.1.
- Compared with Exp.1, Exp.3 adds both Rule 8 and Rule 9, which, for the reasons discussed above, results in the best overall situation in the first 4 experiments.
- Exp.6 adds both Rule 8 and Rule 9 based on Exp.5, and the result is that the overall situation is significantly improved when compared with that in Exp.5, and actually, it is quite similar to that in Exp.4.
- Exp.7 is the same as Exp.1, but introduces Rule 4 in order to solve the "dead-lock" problem in Exp.1. From Table 2, it seems the overall situation in Exp.7 is a little worse than that in Exp.3, but according to the recorded historical usages of capacity during the experiments, the capacity limit is exceeded by about 50 percent in some ATC sectors in Exp.3, while in Exp.7, the worst case is just over the capacity limit. From safety point of view, one can see that Exp.7 over-performs Exp.3.
- Exp.8 combines all ATC rules used in other 7 experiments. Although its performance is among the best in all 8 experiments, but is not necessarily the absolutely best. This implies that, for a given ATC scenario, introducing too many ATC rules might not be necessary. In fact, as long as a proper strategy of applying ATC rules is implemented, a few ATC rules could still achieve fairly satisfactory performance.

VI. CONCLUSIONS

In this paper, the Air Traffic Control (ATC) strategy refers to, for each individual ATC sector, how to use global traffic information to make local ATC decisions, such that not only the local air traffic will be safe and efficient, but also the global traffic can be improved. To study the ATC strategies, a software simulation system is developed, which can help to investigate how to apply various local ATC rules, such as first-come-first-served rule, to the coming-in traffic to sectors according to the global traffic information. The simulation results reveal that, even for a same set of ATC rules, a bad strategy of applying them can cause heavy traffic congestion, while a good strategy can significantly reduce delays and increase efficiency of using airspace. It should be noted that the reported work is just the first step of an attempt to study ATC strategies. With this simulation study, further extensive research can be carried out as following: (a) Introduce more ATC rules and study the effect of each of them; (b) Identify and study different real-world traffic scenarios; (c) Based on the understanding of ATC rules and traffic scenarios, design proper ATC strategies, particularly, develop effective and efficient methods to adjust/optimize the ATC strategies; (d) Conduct extensive simulation study based on both randomly generated data and collected real-world ATC data to test the ATC strategies; (e) Collaborate with the ATC industry to modify and improve the simulation systems.

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Table 1 Apply ATC rule(s) to manage coming-in and takeoff aircrafts in Fig.3

	Order/weights to apply ATC rules	Aircrafts to enter/takeoff & order to enter/takeoff in current time interval	Aircrafts to be delayed in current time interval
Coming-in traffic	1	(AC3,AC4), (AC2,AC6), (AC5 or AC8)	AC1, AC7, (AC8 or AC5)
	3	AC8, AC6, (AC2,AC7), (AC3 or AC5)	AC1, AC4, (AC5 or AC3)
	1,2,3	AC3, AC4, AC2, AC6, AC5	AC1, AC7, AC8
	3,1,2	AC8, AC6, AC2, AC7, AC3	AC1, AC4, AC5
	1(0.5)+3(0.5)	(AC6,AC8), (AC2,AC3), AC4	AC1, AC5, AC7
	1(0.4)+2(0.4)+3(0.2)	AC3, AC2, AC6, AC8, AC5	AC1, AC4, AC7
Takeoff aircrafts	6	AC11, (AC9,AC10)	AC12, AC13
	7	(AC10,AC13), AC11	AC9, AC12
	5,6,7	AC9, AC10, AC12	AC11, AC13
	7,6,5	AC10, AC13, AC11	AC9, AC12
	6(0.5)+7(0.5)	AC10, AC11, AC13	AC9, AC12
	5(0.4)+6(0.2)+7(0.4)	AC10, AC13, AC9	AC11, AC12

Table 2. Results of some initial experiments

(Total in minutes)	Delay on ground	Delay in air	CC1	CC2	CC3	CC4	CC5	CC6	Num. of ACs never take off
Exp.1	8015	140058	3710	953	530	516	2543	9773	647
Exp.2	6847	2911	4760	3191	5372	2635	1039	1028	305
Exp.3	4605	12972	4493	3022	1746	1425	2330	5009	76
Exp.4	6785	1712	4835	3271	5367	2712	998	842	303
Exp.5	7346	120130	4241	941	665	647	2804	8727	542
Exp.6	6763	1519	4726	3404	5247	2779	1102	767	299
Exp.7	5581	26817	3893	2382	1633	1637	2819	5661	112
Exp.8	6750	1144	4778	3229	5419	2820	992	787	299

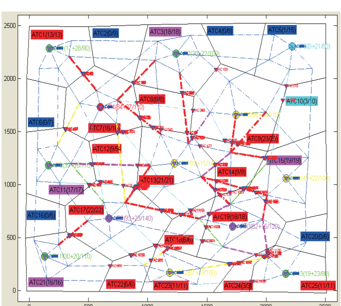
Fig.5. Experiment 1

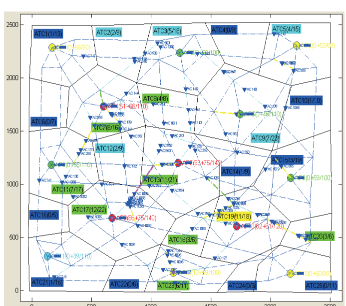
Fig.6. Experiment 2

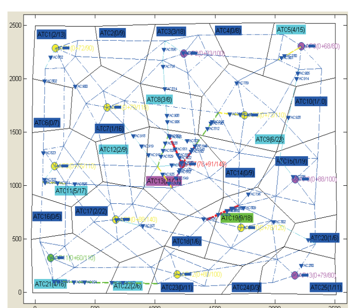
Fig.7. Experiment 3

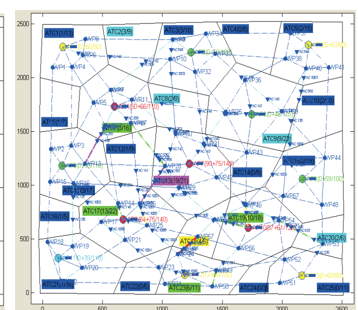
Fig.8. Experiment 4

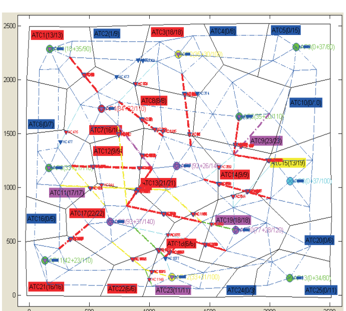
Fig.9. Experiment 5

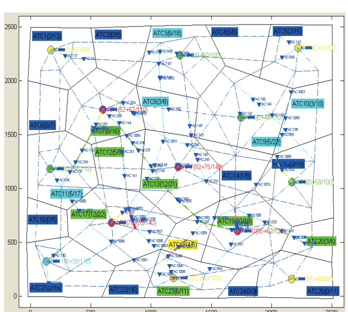
Fig.10. Experiment 6

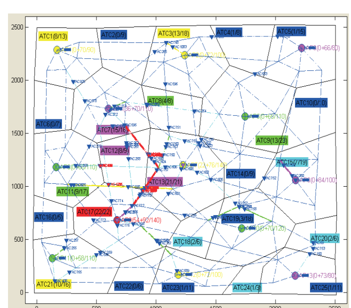
Fig.11. Experiment 7

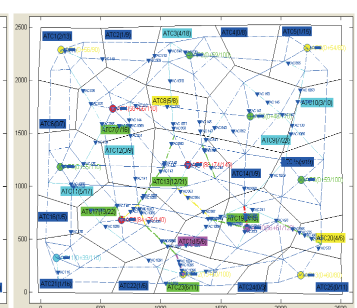
Fig.12. Experiment 8