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Knowledge-based system for air traffic flow management: timetable rescheduling and centralized flow control

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ABSTRACT

A Knowledge-Based System (KBS) has been designed for the Air Traffic Flow Management (ATFM) problem. For *timetable rescheduling*, the system tends to modify airlines timetable to smooth traffic peaks at airports during rush-hours. For *centralized flow control*, the system works on-line to forecast the place, time and magnitude of the congestions and to take some actions to prevent these congestions. As an Artificial Intelligence language, Prolog was chosen to develop the prototype of the Knowledge-Based ATFM System. By using this system, Brazilian ATFM, which includes the principal airports of this country, has been studied.

INTRODUCTION

Air Traffic Flow Management (ATFM)

Future air traffic management (ATM) systems have been recognized as the main significance for the evolution of future air navigation systems (FANS)[21,23]. The means for the development of the ATM system of the 21st century is to make more efficient use of airport and airspace capacity and to permit the harmonious treatment of flights transiting all airspace[22].

As one function of ATM, air traffic flow management (ATFM) provides a service complementary to Air Traffic Control (ATC). Its objective is to ensure an optimum flow of air traffic to or through areas within which traffic demand at times exceeds the available capacity in the ATC systems. Thus ATFM protects ATC from overload situations which are potentially dangerous to the safety of air traffic. As a general description, ATFM may be subdivided into two basic levels: Air Traffic Flow Planning (ATFP) and Air Traffic Flow Control (ATFC)[7]. The former has the objective of managing the air traffic through off-line long and medium term action. The latter is mainly an operational tool, aimed at solving traffic congestion already present or forecast in the near future.

The use of ATM automation tools tends to help air traffic managers and the ATM system sort, process and manage the mass of information. As one of these tools, the automated air traffic flow management system has been developed in order to meet the needs of flow management. This system tends to be large-scale and rather complex, which highly depends on the development of the computer software and hardware techniques, the updating of ATC/ATM facilities and so on. However, the level of automation is still limited and the research direction mostly follows the application of Operation Research techniques. More powerful automation ATFM systems and the suitable tool series are needed to permit controllers to handle more traffic.

Operation Research in ATFM

In many cases in the past, OR (Operation Research) was generally used to cope with various *combination problems* such as scheduling, controlling, etc. In air transportation, 30 years works of AGIFORS[13] and the various generations of the automation ATC system in U.S.A.[2] may be good examples. In the case of Air Traffic Flow Management (ATFM), attempts had been made several times in the past to develop the automated ATFM system. Perie et al[12] gave the description of the major operational problems in controlling the general flow of the nation's air traffic from a central facility and the outline of the OR approaches that can be taken to help to automate their solutions. The work of EUROCONTROL[5], and the series optimization models of air traffic management[6,7] are more successful. By means of the OR technique, the problem of flow planning, flow control, on-line strategic control of flights and aircraft sequencing in the terminal area have been well resolved. However, as the automation level rises, the complexity of system increases, and the difficulties in formulating problems and in maintaining and managing software did not make it easy to achieve satisfactory results. For example, Bianco[6] used a linear constrained optimization program for multi commodity flow network to model the flow control problem. To solve this program, a decomposition approach has been used. The work is difficult even by using modern computers to get the results of a middle

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scale air transportation system.

In Brazil, Alves and Mora-Camino[20] have made a conceptual simulation model to study the flow control problem. The model gave an initial analysis within three principal airports of Brazil.

Artificial Intelligence in Air Traffic Control

Artificial Intelligence (AI) includes many sub disciplines, each intended to imitate some aspect of human thinking. As the products of AI, Knowledge-based System (KBS) and Expert System have been widely used. Some pioneer researches of the application of AI in ATC/ATM system have been done. In Frankfurt Airport, there is a 4D-Planner: A Ground Based Planning System[8,16] which uses a user-friendly man-machine-interface to help the human controller to make best use of the planning data. As part of the work for this system, Võlckers[18] made a rule-based system for arrival sequencing and scheduling in air traffic control. He and others [19] have started to develop a new planning software that will assist the ground controllers to establish a safe and expeditious traffic flow on the ground with full consideration of ATC/ATM and Airline requirements. For that, they have begun to work out the new Man-Machine-Interface and operation procedures.

Gosling[9,10] pointed the potential of the application of Artificial Intelligence in Air Traffic Control in order to improve the interface between the man and computer. He made an expert system to assign appropriate flight departure delay to a sequence of scheduled arrivals at a capacity constrained airport. In 1990, he[11] made another expert system for aircraft gate assignment.

Towhidnejad and Kornecki[24] presented the description of the air traffic control expert system under development at the Airway Science Simulation Laboratory at Embry-Riddle Aeronautical University (ERAU). As conclusion, they mentioned: *Air Traffic Expert Controller is a dynamically driven Expert System with its knowledge base consisting of rules and facts. The rules reflect ATC operational procedures and regulations enhanced by the experience of the domain experts (air traffic controllers). The facts represent the ATC situations and/or required course of action.*

METHODOLOGY OF THE KNOWLEDGE-BASED ATFM SYSTEM

ATFM Problem Identification

In order to situate and illustrate the relative position of flow planning and flow control components in the overall set of ATFM actions, Bielli[7] represented the system as a hierarchical structure of more specific actions, each one relative to given portions of the controlled airspace and time horizons(figure 1). In this research, we focused on the *timetable rescheduling*

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and *centralized flow control* problems.

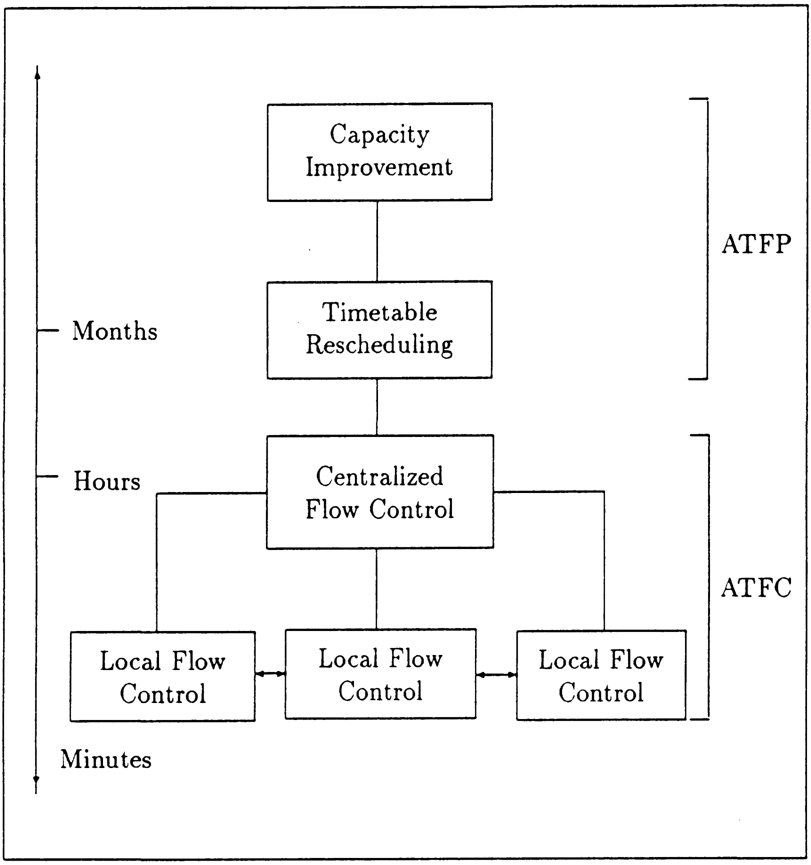

Figure 1: Hierarchical Structure of ATFM

Timetable rescheduling tends to modify airlines timetables, attempting to *a priori* smooth traffic peaks on routes and airports during rush-hours. It ranges from demand-scheduling management (3-8 months) to short-notice constraints (2-24 hours).

Centralized flow control comes into action only when a congestion is forecast. An accurate forecast of the place, time and magnitude of the congestion, with a sufficient lead time to take effective control actions and a centralized information system are necessary. Centralized flow control can be, conceptually, decomposed in to two different phases:

1) Congestion forecast: The accurate evaluation of air traffic capacity and demand in order to see where and when a congestion is likely to arise and the corresponding overload order of magnitude. Capacity varies for air-

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port and airspace structure, navigation aids and control facilities, controller workload, weather etc. Demand relies on time-varying characteristics of air transport. In this research, the runway capacity of an airport was considered and real air transport frequency in airport network is introduced for the traffic demand needs.

2) Congestion prevention: Whenever an overload is forecast, a control action, possibly optimal, must follow so as to prevent congestion development. The action can be performed by means of certain typical control procedures: take-off delay, holding and re-routing etc. The relevant timescale depends on the extent of the air transport. In Brazil, an adequate estimate would be in the range of from 30-60 minutes to 1-3 hours. Take-off delay and holding are considered the main prevention of congestion in this research.

Knowledge-Based ATFM System Design

Knowledge-Based ATFM System is designed to provide the level of performance of a human expert in the ATC/ATM professional domain and enables a computer to assist people to analyze problems (ATFM problem) using that expertise. Like the general KBS system, the Knowledge-Based ATFM System includes four parts: user interface, knowledge base, data bases and inference engine. Figure 2 illustrates this framework.

1) User interface is the part that the user sees and *talks* to the computer. The input and output information is transmitted through this interface. For Knowledge-Based ATFM System, the user should be the ATFM center controller or the terminal in every airport of the network. Through the interface, on-line traffic information and action to prevent congestion will be input/output in the necessary time.

2) Knowledge Base contains both domain knowledge (facts and rules) and process of structuring knowledge (Knowledge representation). For Knowledge Based ATFM System, domain knowledge consists of two parts: Timetable rescheduling predicates and Centralized flow control predicates.

Knowledge representation is the process of organizing knowledge. In Knowledge-Based ATFM System, the rule-based knowledge representation method was used.

3) Data Bases consists of three parts: Flight timetable database, on-line traffic information database and Database administration.

The flight timetable database is the product of Timetable Scheduling Predicates. It includes aircraft type, departure time, arrival time, frequency and other flight information. This database is made as an external database which includes chained database, supports B^+tree references etc.

The on-line traffic information database is a dynamic information store. At run time, it receives the results from the reference engine and gets on-line

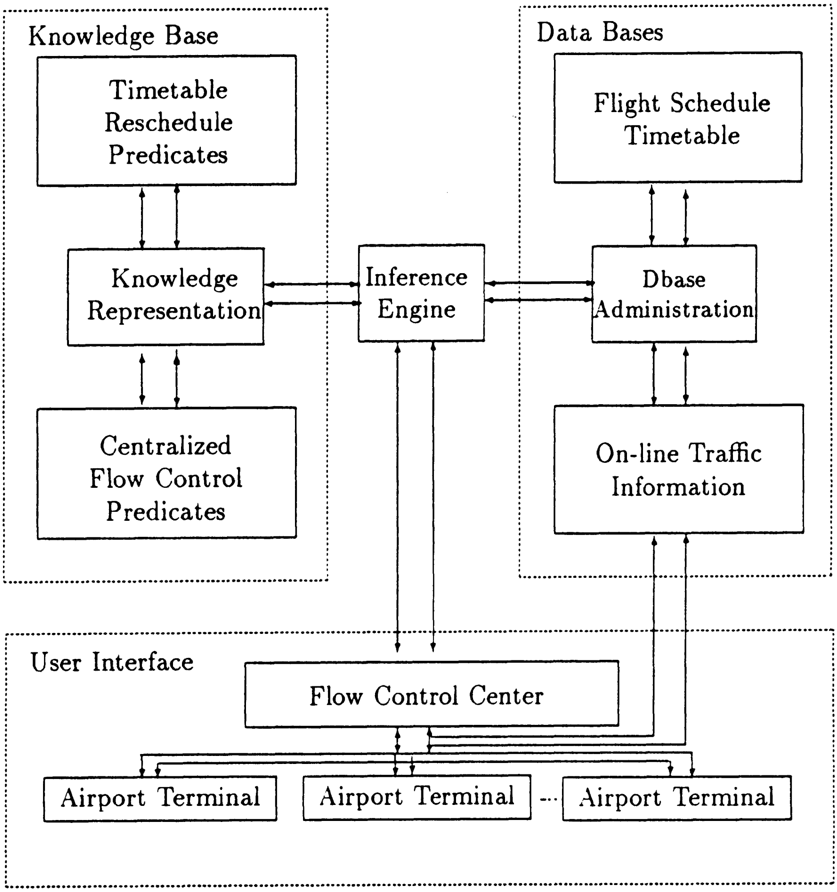

Figure 2: Structure of the Knowledge-Based ATFM System

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traffic data from external terminals (airport and airlines), these data will be input to the reference engine again.

There is an information process center, database administration to control the active databases. The function contains generate, add, list, erase, update, statistic etc.

4) The inference engine contains an interpreter that decides how to apply the rules to infer new knowledge and a scheduler that decides the order in which the rules should be applied. In the following section, we will give the detail description of the inference process of Knowledge-Based ATFM System.

ATFM in Prolog

Knowledge-Based ATFM System is developed using a AI language Prolog. PDC Prolog (3.21)[3,4] has especially been selected. It can provide:

- a fast highly optimizing compiler that generates light native code that can compete with the code generated by Pascal and C compilers;
- a powerful external database system, with over 50 predicates for developing and maintaining multiple large databases, that supports B^+tree and multiuser access to the same file;
- graphics, windows and pop-up menus, etc.

Knowledge-Based ATFM system may be also developed by the use of some tools such as ART-IM, CLIPS, OPs 5, Leve 5, and M.1 etc. These tools contain specific strategies for knowledge representation, inference and control. Elementary structures for modeling specific types of domains are often included, as well as user interface structures and editors. However, the knowledge representation and reasoning structure in many tools are specific or fixed. This inflexibility may limit the representation of a particular problem and its domain knowledge. A programming language such as Prolog, in contract, can support many features. It is up to the developer to write the code for the specific feature desired. Prolog, as one of the highest-level programming languages, allows greater flexibility and power in developing a Knowledge-Based System for Air Traffic Flow Management.

Inference Process

In terms of time conception, Timetable Rescheduling is an off-line process and Centralized Flow Control is an on-line process. When Knowledge-Based ATFM System is used for Centralized Flow Control, the adequate estimate timescale may range from 1 – 3 hours to 15 – 30 minutes. As an example[25], the centralized flow control inference process is described in following steps (which are shown in figure 3):

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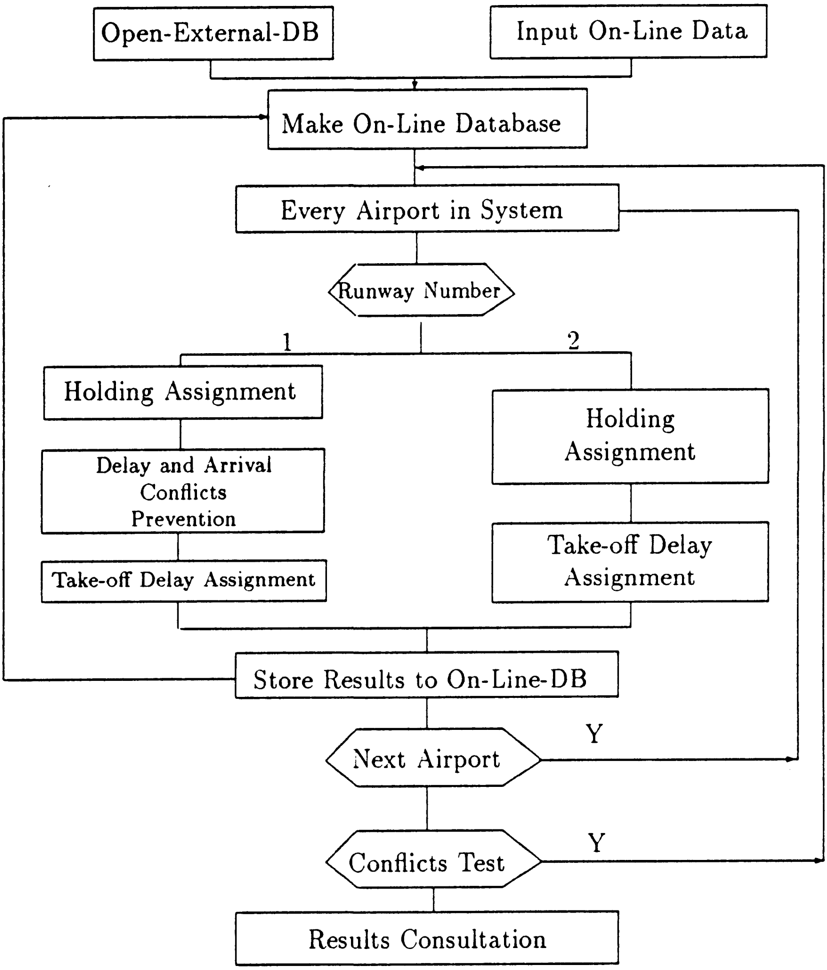

Figure 3: Main Inference Process of KB ATFM System

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System Implementation

Knowledge-Based ATFM System was developed with the following prototypes:

1. Integration Prototype
   (a) Menu Sub Prototype
   (b) System Predicates Sub Prototype
2. Timetable Rescheduling Prototype
   (a) Result Analysis Sub Prototype
   (b) Graph Sub Prototype
3. Centralized Flow Control Prototype
4. Flight Information Consultation Prototype
5. Data Base Prototype

BACKGROUND OF AIRPORT NETWORK AND ATC/ATM SYSTEM

Flight Schedule

In *Guia Aeronautico* [1], there is a complete flight schedule which includes the international, national and regional flights in Brazil. We can get the following information (the data are an example):

Flight	Aircraft	Stop number	Class	Route	Frequency
RG314	733	0	Y	650	1234567
From city	Airport	Depar. time	To city	Airport	Arrival time
SAO	GRU	8:00	RIO	GIG	9:00

Airport Network

The aim of our work is to analyze the Brazilian national airport network. At the beginning, there are 14 principal airports to be considered. These airports are located in following cities: Belem (BEL), Belo Horizonte (CNF), Brasilia (BSB), Curitiba (CWB), Fortaleza (FOR), Goiania (GYN), Manaus (MAO), Natal (NAT), Porto Alegre (POA), Recife (REC), Rio de Janeiro (GIG), Salvador (SSA), Sao Paulo (GRU).

There are about 1000 regular flights per week which fly between these fourteen airports.

Basic Constraints in Airport Terminal Area

There are the following basic constraints in an airport terminal area:

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1. Arrivals have absolute priority over departure;
2. Aircraft are served on a FIFO basis (first in, first out), which also applies to landing operations and for take-off;
3. No two aircraft are permitted on the same runway at the same time;
4. A departure may not be released if the subsequent arrival is less than a specified distance from the runway threshold, usually 2 nmi in IFR conditions;
5. Successive departures are spaced at a minimum time separation equal to the departure service time.

Aircraft Classification

As in Table 1, with little loss in accuracy and to make more simple computations, airline aircraft are divided into three speed classes.

Table 1

Aircraft Classification

Class	Aircraft wake Turbulence class	Max. Certified Take-off weight	A. Landing Speed.knt	Aircraft
1	Heavy	> 300,000 lb	150	B-747...
2	Large	> 12,500 lb	135	B-737...
3	Small	<= 12,500 lb	120	EMB-110...

Ref. Horonjeff[2]

Minimum Time Separation at Runway

1) Minimum interarrival time separation The minimum horizontal separation depends on a number of factors. Among the most importances are: aircraft size, aircraft speed, and the availability of ATC facilities. Current FAA standards were shown in Table 2[2].

Table 2

Minimum Horizontal Separation Criteria for Arrival-Arrival Spacing of Aircraft in IFR Conditions, nmi

Lead aircraft	Trail aircraft type		
type	Heavy	Light	Small
Heavy	4	5	6
Light	3	3	4
Small	3	3	3

In accordance with Horonjeff (1985) and Roger(1976), the minimum interarrival time separation at the runway threshold between two Minimum Horizontal Separation Criteria for Arrival-Arrival successively landing aircraft is analytically determined as a function of the final approach length, the particular landing velocities and the minimum horizontal separation distance etc.

2) Minimum time separation between successive operations Departures are assumed to transit the terminal area on a Standard Instrument Departure (SID) route. According to current FAA rules, successive departures are required to maintain a two minutes take-off separation when traveling on the same SID, and a one minute separation when taking separate SIDs. In other cases, the arrival - departure pair must not violate the restriction prohibiting the simultaneous occupation of the runway. As a consequence, any departure which follows an arrival must wait to begin its roll-out until the arrival exists the runway, which, in this instance, is assumed to equal 60 seconds. The time separation between a departure - arrival pair is determined in a somewhat reverse manner, due to the commitment made by arrivals while on final approach. Specifically, a departure may begin its roll-out if an arrival is with a prespecified distance from the runway threshold. Thus an arrival will cross the threshold following a departure no less than the time it takes for the arrival to fly this prespecified distance. This distance was assumed as 3 nm.

3) Minimum Time Separation at runway Table 3 presents a Minimum Time Separation matrix at runway. There are three aircraft classes. The final approach equal to 5 nm. The runway occupancy time equals 60 seconds. Minimum interarrival time separation is used from Table 2. And for departures, it is assumed there are one to three SIDs.

Table 3

Minimum Time Separation (Sec.) at Runway

	Second operation					
	Departure (SID)			Arrival(Landing speed)		
First operation	1	2	3	120 kt	135 kt	150 kt
Departure 1	120	60	60	90	80	72
(SID) 2	60	120	60	90	80	72
3	60	60	120	90	80	72
Arrival 120 kt	60	60	60	90	80	72
(Landing 135 kt	60	60	60	136.7	80	72
speed) 150 kt	60	60	60	210	146.7	96

Ref. Roger[15]

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APPLICATION AND RESULTS ANALYSIS

Introduction

The initial application of Knowledge-Based ATFM System and the results analysis have been done[25]. We focussed on the following subjects:

- Brazilian ATFM system analysis;
- Knowledge-Based ATFM System for Timetables Rescheduling;
- Knowledge-Based ATFM System for Centralized Flow Control;
- Analysis of aircraft delay in airport.

Due to the space limitation of this paper, we used the Centralized Flow Control case study as the example to illustrate the operation of the Knowledge-Based ATFM System.

Centralized Flow Control Case Study

The application has been developed by means of the actual data from Brasilia and Guarulhos/SP airport. There are three activities: holding assignment, departure and arrival conflict prevention and take-off delay assignment in the centralized flow control procedure. The flight schedule among the fourteen airports for a 12 hour period at Friday is discussed in the following cases.

Holding assignment case During centralized flow control, holding assignment results at Guarulhos airport from 9:00 to 9:40 in the morning of Friday are shown in the Table 4. Four flights are scheduled to arrive at Guarulhos airport at 9:25. They are RG871, VP142, RG733 and RG920. We need to make some holding assignments for them. In terms of the aircraft type, RG871 (B767) has higher priority than VP142 (B737), then, VP142 needs to hold 1 minute (landing at 9:26). For VP142 and RG733, RG733 (B747) has higher priority than VP142. But, due to a departure delay in Rio de Janeiro airport, it arrives at Gaurulhos at 9:26 which is later than VP142. Then, RG733 needs to hold 1 minute (landing at 9:27). RG920 arrives at 9:28, and needs to hold 1 minute (landing at 9:29).

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Table 4

Centralized Flow Control: Guarulhos, 9:00 - 9:40, Friday

Flight	Type	Stop	Depar. Airport	Departure Time Plan	Esti.	Del.	Arrival Time Plan	Esti.	Del.
RG871	763	1	GIG	815	815	0	925	925	0
RG291	73S	3	BSB	645	645	0	920	920	0
TR475	733	1	BSB	650	650	0	915	915	0
RG291	73S	3	FOR	235	235	0	920	920	0
RG871	763	1	MAO	145	145	0	925	925	0
SC880	733	2	GIG	800	801	1	910	911	1
VP142	73S	1	POA	800	800	0	925	926	1
TR508	733	0	POA	730	730	0	900	901	1
RG733	747	1	GIG	815	816	1	925	927	2
RG920	767	0	GIG	815	818	3	925	929	4
VP235	733	0	BSB	800	801	1	930	932	2
RG353	733	0	SSA	700	701	1	930	933	3
VP143	73S	1	CNF	800	802	2	900	902	2
TR475	733	1	CNF	815	816	1	915	916	1

Departure and Arrival Conflict Prevention Case At Brasilia airport, there is only one runway. During centralized flow control, departure and arrival conflict prevention results at Brasilia airport from 9:30 to 10:30 in the morning of Friday are show in Tables 5 and 6. There are three flights: one arrival (VP263) and two departures (SC476 and SC271) at 10:00. For prevention of a conflict between arrival and departures, the departures need to be assigned a delay. In this Table, SC476 will delay 1 minute (take-off at 10:16), SC271 will delay 2 minutes (take-off at 10:17).

Table 5

Centralized Flow Control: Brasilia, 9:30 - 10:30, Friday

Flight	Type	Stop	Depar. Airport	Departure Time Plan	Esti.	Del.	Arrival Time Plan	Esti.	Del.
VP288	73S	1	GRU	715	715	0	930	930	0
VP253	733	2	SSA	840	840	0	1030	1030	0
VP263	733	2	FOR	645	645	0	1015	1015	0
VP253	733	2	REC	700	700	0	1030	1030	0
VP282	73S	0	GIG	800	802	2	940	942	2
SC271	73S	2	SSA	730	730	0	930	931	1
SC271	73S	1	REC	545	545	0	930	931	1
SC476	73S	3	CNF	815	815	0	930	932	2
SC476	73S	4	GIG	645	645	0	930	932	2
SC273	73S	0	REC	715	716	1	1000	1001	1

Table 6

Centralized Flow Control: Brasilia, 9:30 - 10:30, Friday

Flight	Type	Stop	Departure Time Plan	Departure Time Esti.	Departure Time Del.	Arival Airport	Arrival Time Plan	Arrival Time Esti.	Arrival Time Del.
SC476	73S	2	1015	1016	1	GRU	1535	1536	1
SC271	73S	1	1015	1017	2	GRU	1255	1257	3
TR423	T34	0	1000	1002	2	GIG	1130	1133	3

Take-off assignment Case Table 7 gives the results of take-off assignments during centralized flow control at Guarulhos airport from 12:00 to 13:00. There are four flight departures from this airport at 12:45. The take-off assignment depends on the aircraft type, number of stops, route etc. For SC354 and VP370, because of the aircraft type, SC354 (DC-10) has higher priority than VP370 (B73S). Then, VP370 needs to delay 1 minute (Take-off at 12:46). For VP370 and VP161, because of the number of stops for the Flight, VP370 (Stop Number = 5) has higher priority than VP161 (Stop Number = 0). Then VP161 needs to delay 2 minutes (12:47). For VP161 and VP236, they have the same priority and were scheduled to take-off at 12:45. Then, VP236 should be rescheduled to delay 3 minutes (take-off at 12:48).

Table 7

Centralized Flow Control: Guarulhos, 12:00 - 13:00, Friday

Flight	Type	Stop	Departure Time Plan	Departure Time Esti.	Departure Time Del.	Arival Airport	Arrival Time Plan	Arrival Time Esti.	Arrival Time Del.
SC477	73S	4	1300	1300	0	BSB	1825	1825	0
VP114	73S	0	1200	1200	0	GIG	1300	1300	0
VP158	AB3	1	1215	1215	0	REC	1625	1625	0
VP158	AB3	1	1215	1215	0	SSA	1430	1430	0
SC354	D10	0	1245	1245	0	SSA	1455	1455	0
SC931	767	0	1215	1216	1	GIG	1315	1316	1
VP370	73S	5	1245	1246	1	CNF	2140	2141	1
SC782	EM2	2	1200	1201	1	CNF	2140	2141	1
VP370	73S	5	1245	1246	1	BSB	2000	2001	1
VP161	733	0	1245	1247	2	POA	1415	1417	2
VP236	733	0	1245	1248	3	BSB	1415	1418	3

CONCLUSIONS

We just have done the initial research of Knowledge-Based System in ATFM domain. As an auxiliary tool, Knowledge-Based System can efficiently resolve *timetable rescheduling* and *centralized flow control* problem. Delay

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analysis gave interesting results for improving the flight scheduling. Our further work may be to apply Knowledge-Based ATFM System to the real situation. The complexity level of the system needs further development.

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