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Continuous Flight Rescheduling Problem Resolution Based on Genetic Algorithms

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***Abstract*—This present paper deals with air traffic management problem for the continuous flights with stopover and returning at initial airport. The initial scheduling is disrupted by poor weather conditions, which may change over time. For this problem, we consider the air traffic as a discrete event system where the rescheduled flights are modelled by time Petri net tool. As a resolution approach for this problem, a genetic algorithm is introduced where a new encoding of flight plans is proposed. The feasibility of generated solutions, by genetic algorithm, is checked by means of our recently approach so-called Time Reduced Ordered Binary Decision Diagrams (TROBDDs). A numerical example is provided to show that the proposed genetic algorithm exhibits a much better quality of routing solution and a much higher rate of convergence than other algorithms.**

Keywords-continuos aircraft; optimization;genetic algorithm Time Petri net;Time reduced ordered binary decision diagram

I. INTRODUCTION

On account of air capacity limitation, the flights scheduling is always confronted with flight delays either on the ground or in the airborne due to permanent congestion in air traffic. This delay has a direct impact on aviation safety and indirectly on the airlines reputation. Moreover, the airborne delay decision generates a very high cost for airlines by effect that the cost of kerosene represents the high percentage of the total cost of flight [5]. To overcome this problem, three policies are envisaged to deal with air traffic congestion. The first one consists to build more airports and airways or to expand the capacity of the existing airports\airways. The second way consists to give the pilots the opportunity to freely choose their airways (free-flight) [6,7,11], and manage the induced conflicts by using an embedded system. The third way aims to balance as much as possible between the air demand and the available capacity while respecting the initial flight scheduling. Certainly, the first two policies allow resolving the congestion problem, but they are nevertheless difficult to implement in real-case and they generate huge costs. The third policy can be applied at short-term and it allows taking different strategies such as ground holding. This policy is considered in this paper where the ground holding strategy is adopted for the needs of the problem.

The ground holding strategy aims to maintain aircrafts on ground in the case where the initial scheduling is disturbed. Furthermore, the air traffic management problem that is based on the ground holding strategy aims to minimize the total cost of the rescheduled flights plans submitted to the capacity constraints, by affecting the appropriate ground delays.

The air traffic management problem can be divided into two categories namely the Ground Holding Problem (GHP) for the direct flights and multi-Ground Holding Problem (MGHP) for the flights more than one stop-over. The first category means that aircrafts perform only flight where the ground delay is taken once at departure airport. This problem has been firstly introduced by [16], and then addressed by several works [2,18]. These studies are based on mathematical programming techniques using exact and approximate methods. Other techniques are also used to solve the GHP such as TPN based approach. Recently, [12,13] proposed two new approaches named Timed Discrete Reachability Graph (TD-RG) and Time Reduced Ordered Binary Decision Diagrams (TROBDDs) as suitable approaches to resolve the studied problem. The second category referred as MGHP was initially solved by [22,23] using an integer programming formulation, respectively, for the deterministic and stochastic version that was related to the knowledge of the air capacity. [3] proposed a new integer programming formulation by defining new decision variables. This study was evaluated by [3]. They proved that the model of [3] is more efficient. Additionally, for the deterministic and the stochastic versions [1] developed 0–1mixed integer programming models for MGHP including airborne delay, rerouting of flights in air and cancelation decisions. This paper consider the case where the aircrafts return to original airports that is called Continuous Flight Rescheduling Problem (CFRP), in order to optimize the use aircraft fleet and reduce the delay time toward increasing profits of Airline companies.

On the other hand, new methods based on TROBDDs can be used to represent at each time slice the reachable states of a given system with relatively small structure, [13]. The TROBDDs has proved its usefulness for highly competitive systems, in particular in the air traffic flow management [10]. In this paper we use the TROBDDs to check the feasibility of solution subject to constraints.

Evolutionary algorithms are the population-based algorithms that are the most processed among the metaheuristic approach. They have proved their effectiveness in practice to solve combinatorial optimization problems for any application field [10,15,20,21]. For the continuous flight rescheduling problem, we use the genetic algorithm with a new encoding [24].

In this paper, due to the high complexity (highly constraints problem) we propose a novel approach which is based on Time Petri Net (TPN) tool where the path set for

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each aircraft is modeled by one TPN with binary marking. Furthermore, a genetic algorithm is presented to determine the sub-optimal solution, respecting the capacity restriction that is variable through time. In this context, the TROBDDs tool is introduced to explore the generated solution (by genetic algorithm) for purpose to verify the respect of capacity constraint.

The rest of the paper is organized as follows: Section 2 depicts the background of time Petri net and time reduced ordered binary decision diagrams. Section 3 presents the problem statement. The CFRP modeling approach using TPN is presented in Section 4. Section 5 introduces the approach to resolve the CFRP solving using genetic algorithm. The numerical application and discussion are presented in section 6. Finally, we concluded this paper by some perspectives.

II. BACHGROUND

A. Time Petri Net

A time Petri net [12] is known as a robust modeling approach for systems taking into account the temporal aspect of events. Formally, TPN is a five-uplet $(P, T, Pre, Post, I_s)$, where P is a set of places and T is a set of transitions, which are disjoint sets, i.e, $P \cap T = \emptyset$. $Pre: P \times T \rightarrow \mathbb{N}$ models weighted arcs from places to transitions whereas $Post: T \times P \rightarrow \mathbb{N}$ designs weighted arcs from transitions to places. Each transition of TPN is related with time interval $[a, b]$, where $a \leq b$. For this, $I_s: T \rightarrow \mathbb{N} \times \mathbb{N}$ is a function associated with a given transition $t \in T$.

A marked TPN is defined by the couple (G, M_0^τ), where M_0^τ is the initial marking at time sliceτ. A state is a couple $s = (M_i^\tau, I_T)$, where M_i^τ is the marking and I_T is the firing interval function of transitions enabled at M_i^τ. Moreover, the state $s^* = \left(M_{i^*}^{\tau^*}, I_T^*\right)$ can be reached from the state $s = (M_i^\tau, I_T)$by firing a sequenceσ, this process is written by $s \overset{\sigma}{\rightarrow} s^*$.

B. Time Reduced Ordered Binary Decision Diagrams

In our previous work [4,9,13], a new class of Binary Decision Diagram (BDD) so-called Time Reduced Ordered Binary Decision Diagrams (TROBDD_s) is developed, which allows to represent at each time the states space of STBPNs using a small data structure. The $\mathrm{TROBDD_s}$ are consisted of TROBDD_τ set that each one models the reachable sates at $\tau$with a size proportional to the number of marked places. For the same purpose, our contribution in this is to provide new construction method with a reduced time by exploiting the TPN property. In this issue, the developed exploration method of TROBDD_s is adopted to verify the generated solution by the proposed genetic algorithm.

TROBDD_s are composed of a set of TROBDD_τ that each one models compactly the markings at time slice τ. The TROBDD_τ number is equal to time window of system operating time. The determined TROBDD_τ is made up of $1 - terminal$ and non-terminal nodes. $1 - terminal$ nodes that model the reachable state of symbolically Boolean function equals to '1', [17,19]. The non-terminal nodes are indexed by binary variable y_i encoded the place p_i . Each non-terminal node has two children defined as follows:

- right children denoted by $RightC(y_i)$ where y_i has '1' as value in Boolean function.
- left children denoted by $LeftC(y_i)$ where y_i has '0' as value in Boolean function.

A Depth-First Search (DFS) of $TROBDD_\tau$ determines the reachable markings at time slice τ . We denote by $E^\tau = \{(y_k(\tau), I_x) \mid k = 1 \dots K\}$ a state generated from $TROBDD_\tau$ with I_y the local time interval to decide crossing the next of $y_k(\tau)$. For a simple notation the $E^\tau = \{y_k(\tau) \mid k = 1 \dots K\}$ present the state generated from $TROBDD_\tau$. A node contains the binary variable, this local time interval and the successor nodes. To determine the reachable markings through $TROBDD_s$ from a current state E^τ, we update the local time interval of each visited $y_k(\tau)$. Then, in according to the I_x value the next state of E^τ is determining in $TROBDD_\tau$ or $TROBDD_{\tau+1}$.

III. THE CONTINUOUS FLIGHT RESCHEDULING PROBLEM FORMULATION

A. Problem Setting

Consider an airspace consisting of a set of airports A and a set of sectors S. A set of continuous flights F uses the airspace where each aircraft q performs more than one flight. Each aircraft has a set of path, J_f, which each one is related to two airports. For two consecutive flights $\left(f_i, \ddot{f_{i'}}\right)$ execute by the same aircraft, the stop-over time is necessary to prepare the flight $\ddot{f_{i'}}$ (filling kerosene, the landing of some or all of the travelers f_i ... etc.). The stop-over time is supposed to be known and it elapses at airport a_k.

The planning horizon $\mathcal{H}$ is the time between the opening time and the closing time of airports. It is partitioned into Δt equal time slice and is presented as an ordered set of global time slice $\mathfrak{J} = \{1, \dots, N\}$. For each flight $f_i \in F$, the scheduled departure time is assumed to be known. The time slice number to fly over a sector through an airway j is fixed and independent of the other aircrafts occupying the same sector. The capacity $\mathrm{C}_{e_j}^\tau$ of an air traffic element $e \in A \cup S$ is assumed to be known at each $\tau \in \mathfrak{J}$.

However, in the course of day an adverse weather condition reaches certain air traffic element at specific time slice, and reduce its capacity. This unforeseen event makes the scheduled flight plan affected unfeasible. In that situation, the ground delay and cancelation are the option adopted to rescheduled flights. In the case of rescheduling decision using the ground delay, the time slice number of ground delay shall not exceed the maximal tolerated delay.

The Continuous Flight Rescheduling Problem (CFRP) that we propose consists of minimizing the flight plan cost through determining the minimal ground delay to reduce the effect of climatic perturbation on the air capacity. Indeed, the CFRP is subject to capacity constraint where the aircraft number used a given air element must not overtake its available capacity.

B. Notations

The continuous flight rescheduling problem is defined by the following notations:

- A : set of airport;
- S : set of sector;
- a_k : airport number k;
- F : set of continuous flights;
- f : flight number;
- j : path relating two airport;
- J_f : set of paths reserved for flight f between two airports;
- $\mathcal{H}$: planning horizon;
- Δt : length of time slice;
- τ : time slice number;
- $C(\tau, e)$: capacity of air traffic element e at time slice τ;
- $y^j_{f,e}(\tau)$: coded variable of marked place models the flight f in e through j at τ

C. Constraints

As explained in above section, the continuous flight rescheduling problem is submitted on capacity constraint that related to the limitation of air traffic element which floats at time. By using the time flow mutual exclusion constraint, the formulation of capacity constraint is presented by equation 1.

$$\sum_{f_i \in F} \left(y^{j_{f_i}}_{f_i,e}(\tau) \right)_{\left[T^{e_k}_{min}, T^{e_k}_{max}\right]} \leq C(\tau, e_k)$$

$$\forall\ j_{f_i} \in J_{f_i}, e_k \in A \cup S \qquad (1)$$

where $\left[T^{e_k}_{min}, T^{e_k}_{max}\right]$ is the time interval in which the capacity of air traffic element e_k reduced.

IV. Modelling Method and Illustrative Example

In this part, we present the new approach modeling of path set for a given aircraft by one time Petri net. One can generalize the proposed approach modeling for any transport scheduling problem which has less or more CFRP property.

The notations of places and transitions are presented in table I. Two notations of places: the first one when the aircraft is at airport (departure or arrival) and the second one when the aircraft in air following a chosen path j. For transitions notation, they are differentiated by the air traffic element used where the aircraft leaves as shown in Table I.

TABLE I. Places and Tranitions Notations

p_{f,a_k}	: flight f at airport a_k;
$p^j_{f,s}$	: flight f in sector s through j;
t_{f,a_k}	: flight f leaves airport a_k;
$t^j_{f,s}$	: flight f leaves sector s throught j.

For more details, we can note that sector place may be doubled to differentiate the path number used by aircraft; one can have several paths passes through a sector. As a ground delay is only adopted for rescheduling, only the airport-transitions, t_{f,a_k}, are controllable whereas the sector transitions are uncontrollable. In other words, the take-off-time is controllable, and once aircraft leaves the air traffic controller assures its arrival at destination airport.

A. Examples

In order to assess the efficiency of the proposed modelling, an example is provided. We consider an aircraft q_1 performs two continuous flights f_1 and f_2. The last flight, f_2, returned at initial departure airport as shown in Fig.1.

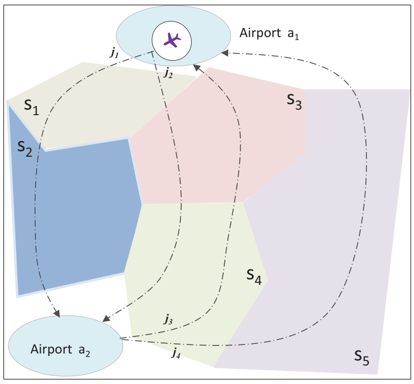

Figure 1. CFRP example.

The first flight executed by q_1 is disposed of two paths j_1 and j_2, which related the two airports a_1 and a_2. For the second flight it has the paths j_3 and j_4, which related a_1 and a_1. For instance, the path j_1 passes successively through sectors s_1 and s_2.

The modeling approach of CFRP presented in Fig 1 is illustrated by Fig 2.

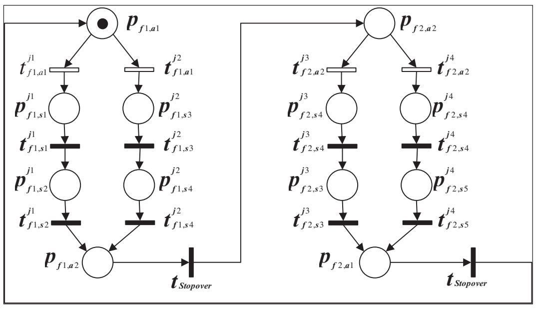

Figure 2. TPN model of Fig. 1.

V. Proposed Methedology Resolution

The proposed approach to resolve the continuous flight rescheduling problem can be summarized by Fig 3. As a first step, the path set is modeled by one time Petri net with binary marking as explained in above section. A metaheuristic method using genetic algorithm is proposed to explore the routing solution of aircrafts. For this, a new coding solution is proposed for CFRP that will explained in the next section. As a final step, each generated solution by genetic algorithm will be checked related to capacity constraint using our recently approach time reduced ordered binary decision diagrams. Each feasible solution is conserved to the next population.

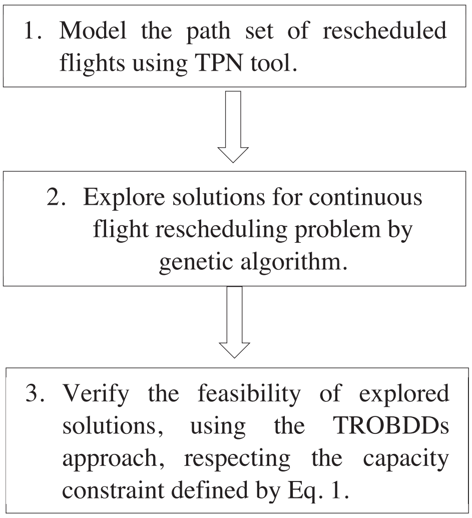

Figure 3. The steps of resolution approach.

A. *Proposed Encoding*

For the continuous flight rescheduling problem, the new encoding of proposed genetic algorithm consists of series of positive integers that designate the time assigned for each air traffic element. The first genes saved the time ground delay at departure airports, and the next genes for the time slice number needed for each aircraft to reach the destination airport and so forth until the aircrafts conclude the cycle of flights. Indeed, the length of chromosome is finite and equal to twice the flight number.

An example of new encoding is presented in Fig 4, which models the aircraft routing presented in Fig 1. For this solution, we assume that the aircraft is delayed by 2 $t.s$ at departure airport a_1, and it needs 5 $t.s$ to reach the airport a_2. However, for the flight f_2 the aircraft q_1 remains 3 $t.s$ on the ground and complete its mission after 6 $t.s$. Since the encoding solution, the aircraft routing needs to 16 $t.s$.

2	**5**	**3**	**6**

Figure 4. Chromosome example.

B. *Proposed Encoding*

The operator of selection aims to enhance the quality of generated population by selecting the best individuals [8,14]. The selected individuals, called parents, are then available for the next phase, called reproduction. It involves applying variation operators on copies selected individuals to generate new ones. Among the existing selection methods, the elitism selection is adopted.

C. *Proposed Crossover*

Crossover is the first operator involved in creation process. It is vital, in the sense, which it is through the exchange of information among the population. In CFRP, the crossover operator consists of modifying the holding time of an aircraft at airport and/or the traveled path. Several crossover operators are developed and among them we choose the uniform crossover, which has as interesting advantage is to avoid an additional step of verifying the feasibility of the generated descendants.

D. *Proposed Mutation*

After crossover, a mutation operator is applied within the children's population. This operator acts as a disruptive element. It allows to maintain the diversity of the children's population and to explore the research space by avoiding the algorithm converging too quickly towards a local optimum. Small mutation rates are recommended because a large rate can cause destruction of the useful information contained in solutions and be considered probably a random search. For our studied case, two possible cases for mutation operator: change randomly the time holding that must not exceed the maximum time allowed or arbitrarily select a path among the set of paths J_f.

E. *Proposed Insertion*

Several methodologies of insertion exist in the literature, the best individuals and parent's replacement are adopted for the continuous flight rescheduling problem. We retain the best individuals

VI. Numirical Application and Discussion

In this part, we present the numerical application of the proposed genetic algorithm for the CFRP with elitism selection and best individual insertion steps. The fitness function is proposed in [10]. The following parameters are used:

- The population size is with 100 individuals.
- The maximum generation is 100.
- The crossover rate is 0.95.
- The mutation rate is 0.05.

All the numerical application are performed with C, 2.1 GHz processor speed and 8Go of RAM. CFRP instances are selected with randomly chosen capacities. Table II illustrates the obtained results of genetic algorithms with 100 generations. The second column presents the path number that is fixed to 10 for all instances. The number of flights increases by 200 from instance to another as described in third column.

TABLE II. Numirical Application Results

Instances	$\|J_f\|$	$\|F\|$	*Cost (monetary cost)*	*CPU time (second)*
1	10	200	106130	0,62

2	10	400	203000	1,41
3	10	600	286540	1,51
4	10	800	545210	2,05
5	10	1000	645940	2,98

The CPU time that is consumed are presented in last column for 100 generations. We can see for elitism selection and best individual insertion, the genetic algorithm takes a reasonable amount of time to resolve the CFRP comparing to the huge number of flight and important number of paths.

VII. Conclusion

In this paper we presented a novel approach based on genetic algorithm embedded with time Petri net to resolve the continuous flight rescheduling problem. Firstly, we considered the air traffic system as a discrete event system, where the set of path for a given rescheduled flight are modeled by a time Petri net. Then, genetic algorithm was introduced to generate a possible solution with selection using elitism and insertion based on best individual.

On other hand, we took advantage of the robustness of our recent approach modeling that named time reduced ordered binary decision diagrams to test the feasibility of generated solutions. The numerical application has shown the efficiency of proposed algorithm that can search the sub optimal solution effectively and speedily.

In future research, we will study the continuous flight rescheduling problem in real time in case where the capacity of air element varied when aircraft in cruising.

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