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STABILITY EVALUATION OF A RAILWAY TIMETABLE AT STATION LEVEL

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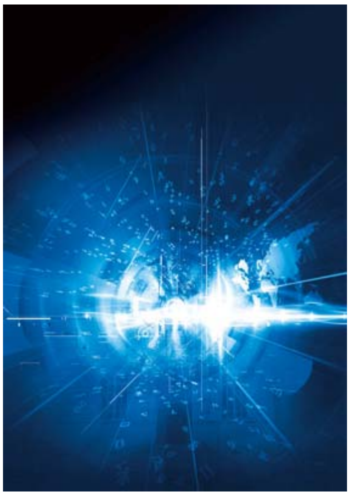

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Stability evaluation of a railway timetable at station level

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Abstract: This research deals with a real-world planning problem in railroad infrastructure operations. It belongs to a project, named RECIFE, aiming at proposing a decision support software dedicated to the evaluation of the capacity of a junction or a station. The aim of this project is to develop a timetable optimization model along with timetable evaluation modules. A module dealing with the evaluation of the timetable stability is presented here. It considers an original method based on delay propagation and using shortest path problems resolution. A didactic example and a complete case-study, using the Pierrefitte-Gonesse junction, are also presented.

Keywords: Railroad infrastructure capacity, Timetable stability, Shortest path, Multiobjective optimization

1 Introduction

This paper is an extended version of [8]. It focuses on railroad infrastructure operations planning at the level of a junction or a station (also called node). In order to determine a strategy of commercial offer, it is important to have tools for evaluating infrastructure capacity. Such tools allow a decision-maker to evaluate the network limits, and to study the impact of proposed modifications. This kind of careful analysis is crucial given the extremely high costs and the long-term implications of system modifications. It is especially important in certain complex junction or stations where bottlenecks develop due to increasing traffic.

Usually, assessing the capacity of a component of a rail system is carried out by measuring the maximum number of trains that can be operated on it within a certain unit of time. For measuring the capacity of lines, analytical models can be applied. The theoretical expression of the capacity of a railway line in a given direction, denoted C, can be defined as:

$$C = \frac{u}{h} \tag{1}$$

where h is the minimum headway time between two successive trains and u is the considered unit of time. The minimum headway time depends on the signaling system installed on the line considered. Expressions which are more accurate can be used to include more features of the rail system [19].

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However, in the case of junctions or stations the analytical models alone can't be applied. The capacity of a junction is not the sum of the capacity of the converging lines. In [11] an analytical method is proposed for junctions and stations, but the authors concluded on the need of search tools to find good or optimal solutions of a problem. The capacity of junctions is therefore determined by the solution of an optimization problem called the "Railway Infrastructure Saturation Problem" (RISP). The Railway Infrastructure Saturation Problem of a junction can be stated as follows:

> Given the layout of a junction and a set of trains T, how many trains of T can be routed through the junction within a certain unit of time such, that all safety constraints are satisfied, and with respect of the practical operations conditions ?

Moreover, if defining a saturated timetable is the main part of a capacity evaluation, some other questions have often to be considered as the feasibility of a given combination of trains and its optimization for criteria such as specific pre-defined preferences associated with each train. In addition, when choosing between the timetables obtained, their stability, i.e. their ability to absorb train delays, is also an important aspect to consider.

A project, named RECIFE, has been designed for integrating research work into a complete decision support software dedicated to the evaluation of railroad infrastructure capacity. This project is part of a collaborative project involving the French National Institute for Transport and Safety Research (INRETS), the University of Valenciennes (until the end of 2004), the École des Mines of Saint-Etienne, the University of Nantes and the French National Railroad Company (SNCF). Thus, an optimization model and some resolution algorithms have been proposed to solve this problem [6], and are included in the proposed software. But this software will also include several analysis and vizualization modules. These analysis modules will permit decision-makers to evaluate the stability of the generated timetables and determine the critical elements when no complete solution can be found; the vizualization modules will allow the timetables to be displayed with either classic railway representations (Gantt chart, tracks map, . . . , see figures 1 and 2). Moreover, the decision-maker will be able to use the graphic interface of the software to change the infrastructure in order to determine the impact of such modifications on the capacity (see figure 3).

The aim of this paper is to describe the original method proposed to evaluate the stability of the generated timetables, dealing with the variables defined in the optimization model and with the same assumptions. This method is inspirated from the know-how and the practice of some railroad managers. It is based on a propagation model of potential delays, these delays are computed solving several shortest path problems. Its objective is to determine the overall delay that results from the initial delay of any single train and its direct or indirect effect on the other trains on the timetable.

The paper is organised as follows: the next section introduces the optimization model. The stability evaluation model is presented in section 3. Sections 4 and 5 presents respectively a didactic example and a case-study of this model on a real infrastructure. Finally, some discussions and issues are provided in section 6.

2 The railroad infrastructure operation model

This section briefly describes the optimization model considered in the RECIFE project to assess the capacity. The complete version of this model has been proposed by [6] (see also [9] for a first version). Using optimization for railroad problems is usual: as stated by [1] and [3], various models have been proposed to solve many routing and scheduling problems in railway. However, few researches or softwares concern the capacity analysis of infrastructures. Actually, only three works have been published, and mainly considered the capacity of global networks instead of a junction or a station:

- the project DONS (Design Of Network Schedules) was developped by the Nederlandse Spoorwegen and was initialy presented by [20]. Within DONS, the subproject CADANS [18] deals with

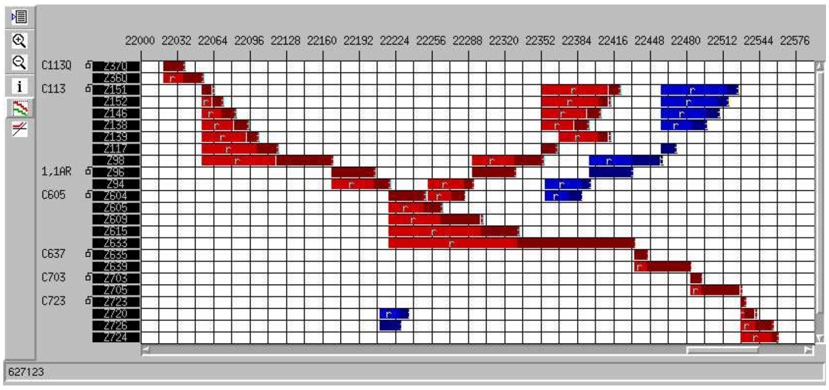

Figure 1: Gantt chart vizualization of a timetable in RECIFE

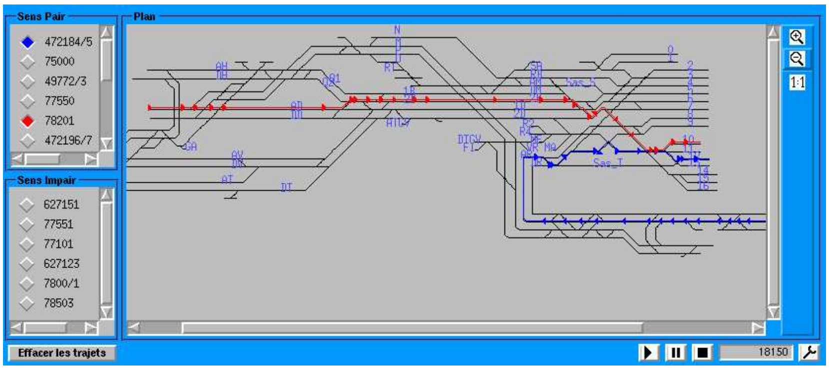

Figure 2: Tracks map vizualization of a timetable in RECIFE

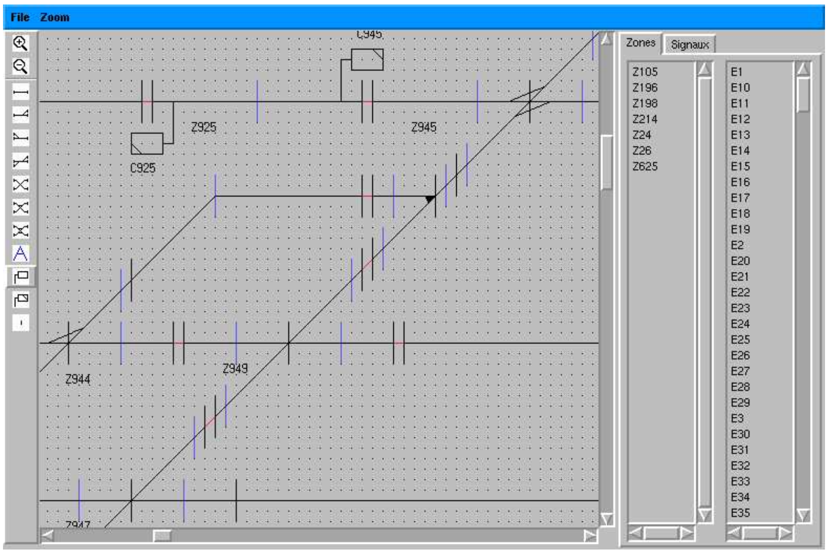

Figure 3: Infrastructure layout editor of RECIFE

$$\left[\begin{array}{lll}
lex\ max(z_{Feas}|z^q_{Sat}, z_{Pref}) & & \\
sc \quad z_{Feas} = \sum_{t\in T_{Feas}, r\in R_t, \delta\in\Delta_t} x_{t,r,\delta} & & \\
\quad z^q_{Sat} = \sum_{t\in T^q_{Sat}, r\in R_t, \delta\in\Delta_t} x_{t,r,\delta} & , \forall q \in Types & \\
\quad z_{Pref} = \sum_{t\in T, r\in R_t, \delta\in\Delta_t} w_{t,r,\delta} x_{t,r,\delta} & & \\
\quad \sum_{r\in R_t, \delta\in\Delta_t} x_{t,r,\delta} \leq 1 & , \forall t \in T & \\
\quad x_{t,r,\delta} + x_{t',r',\delta'} \leq 1 & , \forall t, t' \in T^2 & \\
 & , \forall r, r' \in R_t \times R_{t'} & \\
 & , \forall \delta, \delta' \in \Delta_t \times \Delta_{t'} & \\
 & , ((t, r, \delta), (t', r', \delta')) \in Inc & \\
\quad x_{t,r,\delta} \in \{0, 1\} & , \forall t \in T, \forall r \in R_t, \delta \in \Delta_t &
\end{array}\right] \tag{2}$$

the global network whereas the subproject STATIONS [23, 22, 16, 24] focuses on the station level.

- The project CAPRES in Switzerland was based on the research of [15], and has been finalized in a commercial software [4].
- The project DEMIURGE is currently developped in France by the SNCF [17].

Like these three approaches, the work presented in this paper considers a timetable saturation approach to evaluate the capacity. Thus, a constructive method is applied that involves building a timetable capable of running a maximum number of trains. This model is based on a list of trains, represented by boolean variables, whose possible routes and arrival times have been pre-defined. This approach makes sense because, in the problem under consideration, only the trains and times that are compatible both with the traffic demands and with the extra-node requirements are relevant. The model seeks to optimize the feasability and saturation criteria of the timetable, as well as the criteria representing the decision-maker's pre-defined preferences. The model's constraints formulation is capable of taking a variety of situations into account: simultaneous stop of several trains on one platform, connecting trains, train coupling or uncoupling, and cyclic timetables for example. This new model is based on an incompatibility graph of the route assignments to trains, and is accurate enough to produce practicable timetables for the infrastructures studied. It is structured primarily as a classic multiobjective combinatorial optimization set packing problem, a well known NP-hard problem.

The following notations are used in the model:

T: set of trains

T_{Feas}: subset of trains considered for the feasibility ($T_{Feas} \subseteq T$)

T_{Sat}: subset of trains considered for the saturation ($T_{Sat} = T \setminus T_{Feas}$), these subset can also be divided in q subsets T^q_{Sat} considering different types of trains (for example passenger and freight)

R_t: set of possible routes for a train $t \in T$

Δ_t: set of possible arrival times for a train $t \in T$

Inc: set of incompatibility between all potential pair of train for each possible combination of route and arrival date such that if both trains were selected in a timetable, a conflict would occur and delay one of them.

Considering binary decision variables $x_{t,r,\delta}$ with a value of 1 if the train t is routed on the route r at an arrival date δ, 0 otherwise, the problem can be defined by the lexicographic model (2). The first objective (z_{Feas}) corresponding to the feasibility problem is considered with top priority, and then the other objectives (z^q_{Sat}, z_{Pref}) are considered with equal priority. The first constraint ensures that at most one route and one arrival date is chosen for each train. The second constraint prevents to select a couple of incompatible trains in the timetable.

3 The stability evaluation model

This section describes the approach considered to analyze the stability of the timetable(s) obtained with the optimization model. Several methods have already been proposed to compute such an analysis, mainly for cyclic timetable. Many of these methods are based on Petri nets and Max-plus algebra (see [13, 14] for recent works) and consider three types of stability evaluation:

1. the time needed to recover the decided cyclic timetable when a delay occur,
2. the time margin of the different trains before they delay any other trains, and
3. delay propagation statistics considering initial delay scenarios.

However the first two types of evaluation are not adapted to the problem we consider. The first one because the timetable considered can be non cyclic, and the second one because, as the timetable is saturated, the time margin of the trains is nearly null.

Alternatively, the delay propagation statistics can also be provided by other methods such as simulation (e.g. see [2]).

Besides these works on stability evaluation of existing timetables, [5] has proposed to include stability within a probabilistic capacity evaluation model: they search to process the maximum number of trains coming from unspecific timetables with a predefined stability threshold to respect. Also, [21] has recently considered the stability optimization at a network level using a stochastic optimization model, which is a large linear programming model, to optimize the average propagated delay of cyclic timetable given set of disturbances. Finally, [10] has presented a biobjective genetic algorithm yielding a compromise between investment cost and passenger waiting time taking into account the propagation of random delays. However, it works only at the network level and without considering safety distances or capacity restrictions.

In this paper, we focus on the stability evaluation of timetables based on delay propagation. As stated in [13], two types of delay can actually be distinguished in railways. First, delays can result from a disruption within the process (time fluctuations due to technical or environmental conditions, . . .). Such delays are called primary delays or initial delays and do not depend on the timetable. Second, some trains can be delayed by the primary delay of an other train due to the interaction between trains (conflicting ressources, passenger connections, train coupling, . . .). Such delays are called secondary delays or knock-on delays and some timetables can eventually permit to avoid or limit them.

So the evaluation our evaluation is determined by the secondary delays on all the other trains of the timetable caused by a primary delay of one of the routed trains. These secondary delays are computed without changing the routes selected for each train and their scheduling: only their arrival date is updated to avoid a conflict to occur. This assumption is justified by the practical difficulty to re-optimize the timetable in real-time. Obviously, it only makes sense with short primary delay that should not exceed the time needed by any train to go through the node. The evaluation corresponds then to the sum of all the generated secondary delays for each train of the timetable being delayed of a primary delay. Such stability evaluation was already considered by the SNCF, but computed by simulation. Since this evaluation strongly depends of the value considered for the primary delay, several values should be considered: this indeed a multiobjective problem.

The following notations are used:

X^*: set of selected variables in the timetable to evaluate:

$$X^* = \{(t, r, \delta), t \in T, r \in R_t, \delta \in \Delta_t, x_{t,r,\delta} = 1\}$$

primaryDelay: the value considered for the primary delay successively applied to each train $x \in X^*$.

P: set of potential direct conflicts between any pairs of train $x \in X^*$:

$$P = \{((t, r, \delta), (t', r', \delta')) \in X^{*2}, t \neq t',$$

$$\exists d > 0, ((t, r, \delta + d), (t', r', \delta')) \in Inc\}$$

$w : P \rightarrow I\!N$: larger possible delay value for the first train before directly generating a conflict with the second train (i.e. time slack between the two trains).

$$w_e = min\ d \geq 0, ((t, r, \delta + d), (t', r', \delta')) \in Inc,$$

$$\forall((t, r, \delta), (t', r', \delta')) \in X^{*2}, t \neq t'$$

The whole set of secondary delays generated by the primary delay of any train of the timetable on the other trains can be computed with the oriented valued graph $G(X^*, P, w)$. In this graph, each node represents one variable selected in the timetable. Each pair of node is linked by an oriented edge when a delay associated to the first node can delay the second, the minimal value of such a delay corresponding to the valuation of the edge.

The time margin $margin_{x1,x2}$ available between two trains associated to two nodes $x1 = (t1, r1, \delta 1)$ and $x2 = (t2, r2, \delta 2)$ of the graph correspond to the maximal possible delay for the variable $x1$ without generating, directly or indirectly, any delay on the variable $x2$. It can be obtain by computing the shortest path between these two nodes (which can be easily done in polynomial time). Such an approach could be connected with that proposed recently by [14] which is based on critical path searchs in the timed event graph associated with the max-plus model considered. Knowing this margin, the secondary delay generated by a primary delay of the variable $x1$ on the variable $x2$ can be computed.

Finally, the stability evaluation can be deduced from all these secondary delays (see equation 3).

$$\begin{bmatrix} z_{Stab}^{primaryDelay} = \sum_{x1 \in X^*} (\sum_{x2 \in X^* \setminus \{x1\}} \max(0, primaryDelay - margin_{x1,x2})) \\ \\ \text{with } margin_{x1,x2} = \text{ shortest path between } x1 \text{ and } x2 \text{ in } G(X^*, P, w) \end{bmatrix} \quad (3)$$

It should also be noted that, even if this stability evaluation was developped within the RECIFE project and so was designed to deal with the same variables and assumptions as the corresponding optimization model, it can be used independently to evaluate the stability of timetables provided by any methods.

4 An example of stability evaluation

This section presents a didactic example of such an evaluation. The Pierrefitte-Gonesse node (Figure 4), which is located north of Paris, is considered. Three main kinds of trains travel through this node in both directions:

- TGV between Paris and the High Speed Line (HSL)
- Inter City trains between Paris and Chantilly
- Freight trains between Chantilly and the Grande Ceinture which cut-across the TGV routes

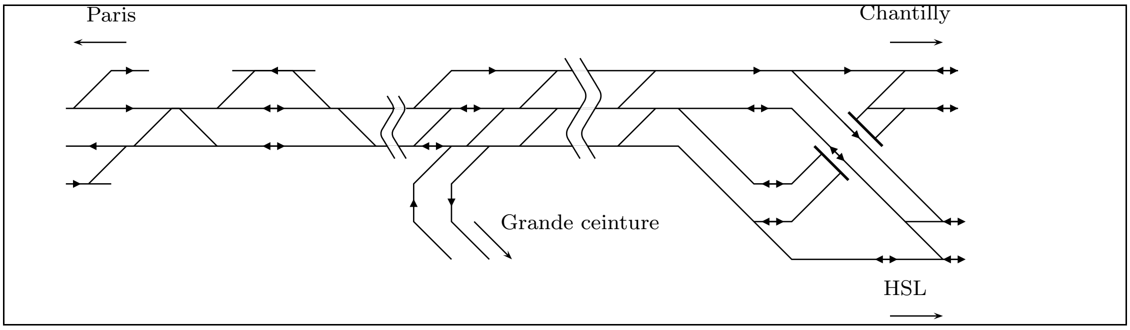

Figure 4: Railway track map of Pierrefitte-Gonesse node

The instance corresponds to a problem with six trains (two TGV, two Inter City trains, and two Freight trains). Each train has only one possible arrival date and the interval between the first and the last arrival date is equal to 450 seconds. The set Inc has been computed using the data provided by the SISYFE simulator [12].

The resulting optimization model for this problem is a set packing with 36 variables. Using an heuristic proposed by [7] and based on the GRASP metaheuristic, the best solutions obtained contains five trains which actually corresponds to the optimal solution for this problem, no solution with six trains being feasible considering the possible arrival time of each train (either an inter city train or a freight train is not in the timetable generated). Such a case frequently occurs when some trains belong to a saturation list. Fifteen different timetables with five trains have been generated by the heuristic: the stability evaluation can permit to help choosing between these timetables.

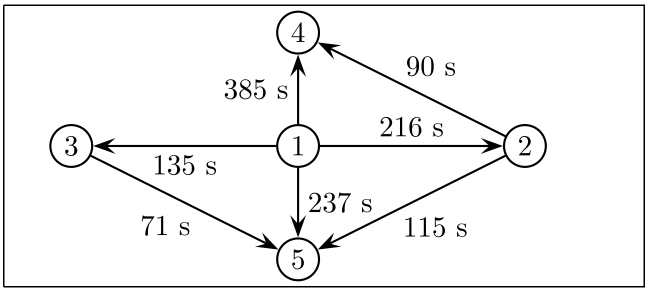

Figure 5: Example of graph $G(X^*, P, w)$

Thus, to compute their stability evaluation, the graph $G(X^*, P, w)$ associated with each timetable have to be generated. For example, the figure 5 represents the graph obtained for one of the solution. The five nodes correspond to the five trains routed, and the edges to the maximal delay before a conflict occur: thus a delay longer than 216 seconds of the train 1 would delay the train 2, but any delay of the train 4 would not delay the train 3 since there is none edge from node 4 to 3.

With these graphs, the time margin can be deduced by computing the shortest path between all pairs of nodes for each graph. The figure 6 gives the shortest paths computed for the graph margin of the figure 5: the new valuation for the edge $(1, 4)$ (resp. $(1, 5)$) is due to the delay propagated via the train 2 (resp. 3).

Finally, the secondary delay generated on the other trains by a primary delay of a train can be computed. For the example considered, the figure 7 presents the secondary delays generated by a primary delay of 180 seconds: the edge from the node 1 to 3 indicates that an primary delay of 180 seconds for the train 1 would result in a delay of 45 seconds for the train 3. The stability evaluation of this timetable for a primary delay of 180 seconds is equal to the sum of these secondary delay, ie. 309 seconds.

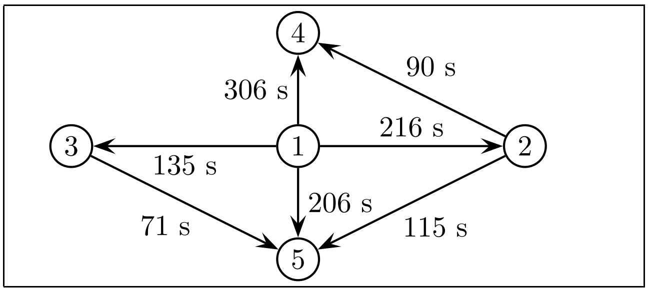

Figure 6: Shortest paths for the example

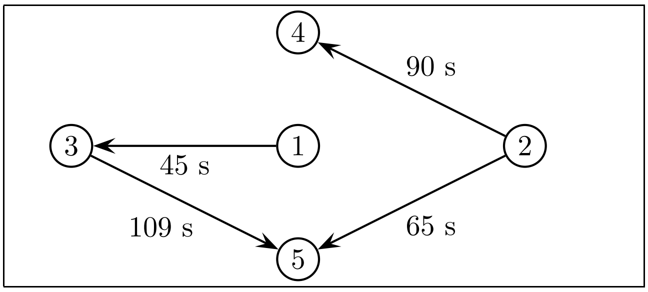

Figure 7: Secondary delays generated for the example by a primary delay of 180 s

Thus, the stability evaluation of the fifteen timetables have been computed for a primary delay of 180 seconds and 300 seconds. The results are reported in the figure 9. In this figure, each timetable is represented by a point with an abscissa equal to its stability evaluation for a primary delay of 180 seconds, and an ordinate equal to its stability evaluation for a primary delay of 300 seconds (the example corresponds to the solution 15). So here the solution 10 seems clearly to be the better timetable produced in terms of stability since it is the better on the two evaluations. However, choosing between two timetables could be more difficult, for example between the solution 1 and 11 because the two evaluations provide opposite results.

5 Case study

This section presents a case study of our stability evaluation. As indicated in section 3, this is a multiobjective evaluation. We will now introduce the main definitions we considered. Let y_1 and y_1 be two timetables. We can note $z^k_{Stab}(y_1)$ the stability evaluation for all primary delays $k \in PrimaryDelaySet$ considered. y_1 dominates y_2 in the sense of Pareto dominance if and only if $z^k_{Stab}(y_1) \leq z^k_{Stab}(y_2), \forall k \in PrimaryDelaySet$ with $z^k_{Stab}(y_1) < z^k_{Stab}(y_2)$ for some k. Considering the set Y containing all the feasible timetables with the same number of trains, a timetable is considered as efficient if there is no $y' \in Y$ such that y' dominates y. This means that no timetable is at least as good as y for all primary delays, and none is strictly better for at least one primary delay. The set of efficient solutions is $Y_E \subseteq Y$ represents a frontier or trade-off surface. However, as we do not evaluate the whole Y set but only a subset $Y' \subseteq Y$, we can't determine the efficient set Y_E. Instead, we consider the set of potentially efficient timetables $Y_{PE} \subseteq Y'$ such that no timetable of Y_{PE} is dominated by a timetable of Y'. For example with the didactic instance of section 4, the solution 10 was the only potentially efficient timetable. Usually, decision-maker can reduce his study to the potentially efficient timetables and search for the best compromise among them.

The main characteristics of the six instances of the capacity problem considered are presented in

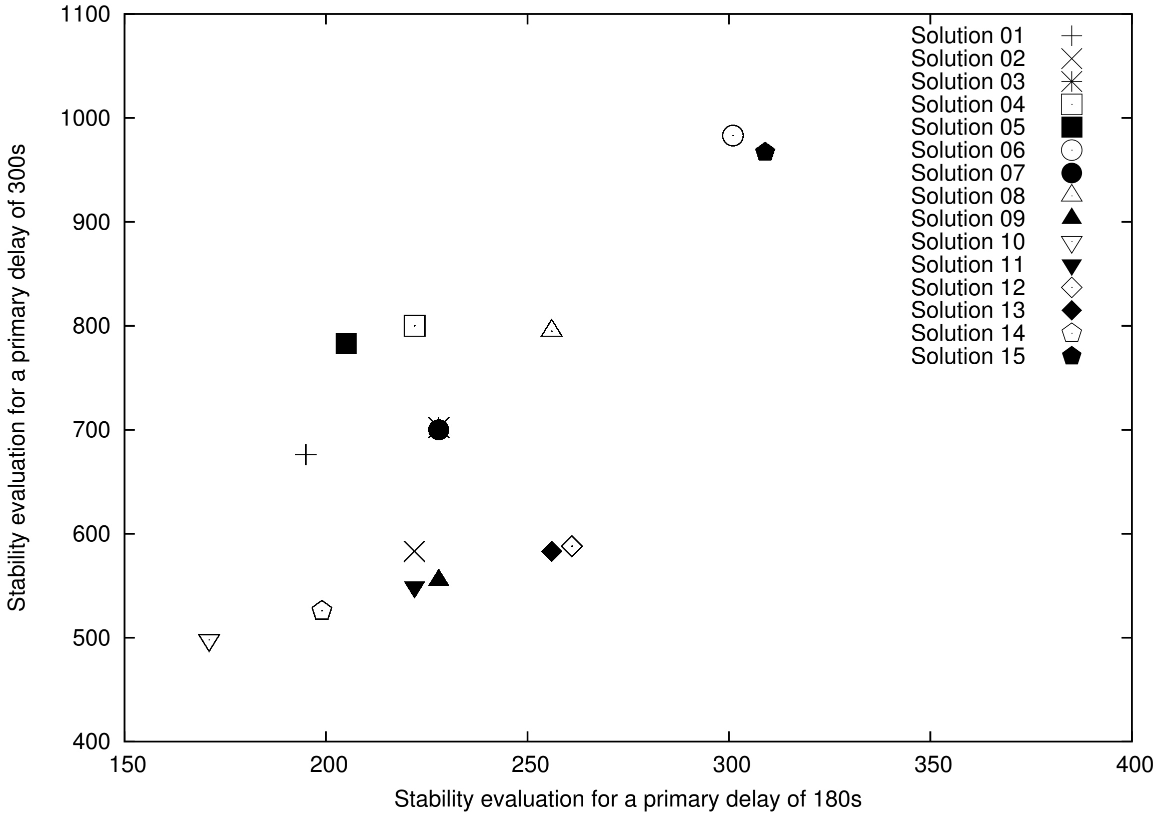

Figure 8: Stability evaluation of the solutions of the example for two primary delays

table 1. They correspond to six different sets of trains to route on the Pierrefitte-Gonesse junction. Again the set *Inc* has been computed using the data provided by the SISYFE simulator, and the resulting optimization models have been solved by the same GRASP algorithm as in section 4. Obviously, the optimization model could also be solved with an other heuristic or an exact algorithm, or the timetables could even result from an other method. In order to keep a graphical display in the objective space of the stability evaluations, we consider two primary delays (60s and 300s), but similar results have been obtained with more primary delays.

Depending on the instance considered, the number of different timetables with the same number of trains (i.e. the maximum number of trains found by GRASP) can be quite different. It can yield to a large number of timetables to evaluate, as for instances 3 and 4, and thus a large number of shortest path problem to solve. However, the graphs are small (around 100 nodes) and there are very efficient existing algorithms to solve them. Actually only less than two minutes were necessary on an Pentium M with 1.8 GHz to compute the whole set of stability evaluations presented in this section.

For all the instances considered, there is a very low number of potentially efficient timetables, so decision-makers can really focus on each of them. All the stability evaluations for each instance are displayed in figure 9. In this figure, each timetable is represented by a point with an abscissa equal to its stability evaluation for a primary delay of 60 seconds, and an ordinate equal to its stability evaluation for a primary delay of 300 seconds. It should be noted that the number of points can be lower than the number of timetables since several timetables can have the same value considering both stability evaluations.

Looking at the stability values involved, they can be quite large since the timetables evaluated were saturated: for the instance 6 the largest value obtained is 702,838s, i.e. the average value of the

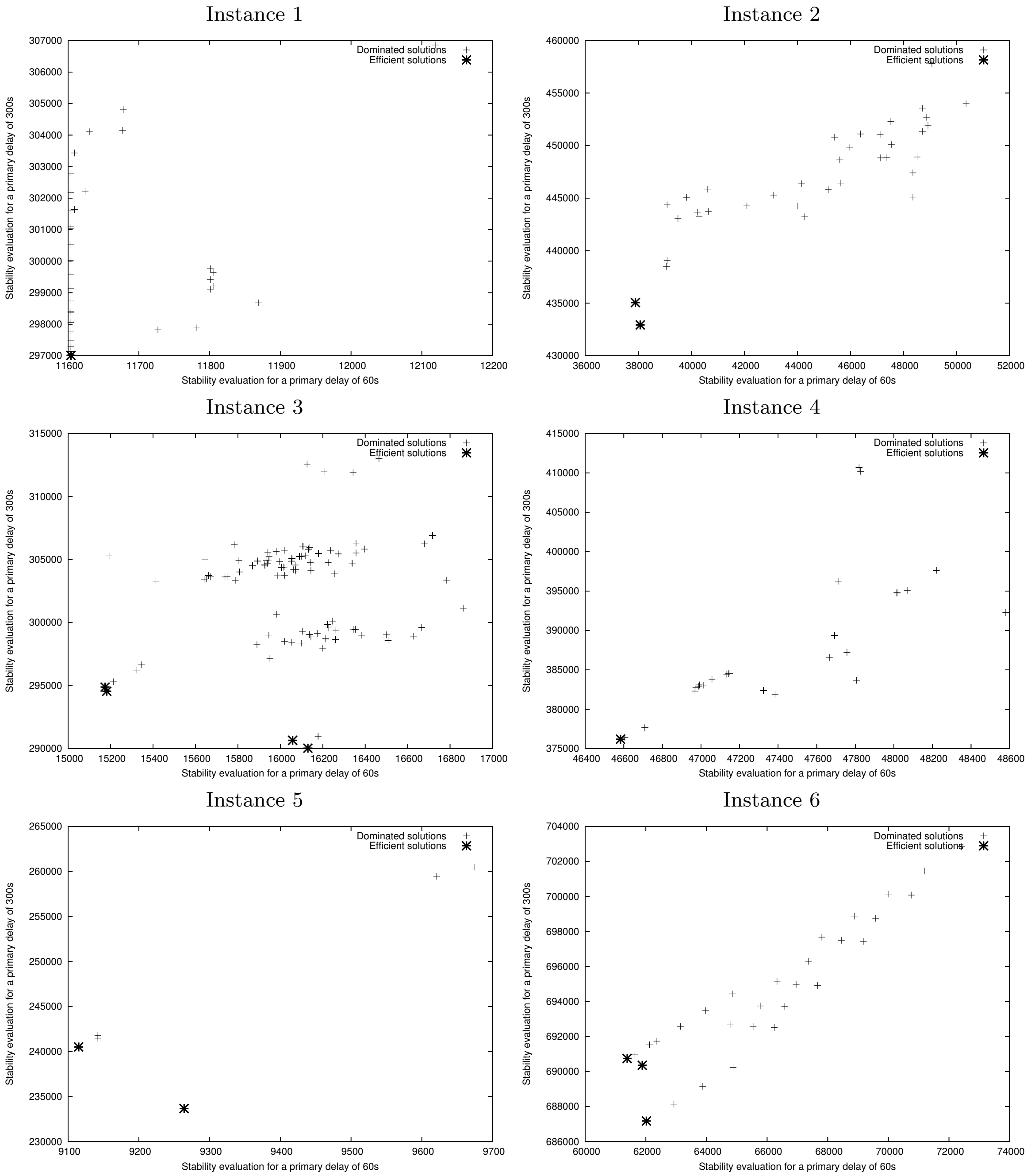

Figure 9: Stability evaluation of the solutions for two primary delays

Instance	$\|T\|$	SPP Variables	$\|X^*\|$	Number of timetables with $\|X^*\|$ trains	Number of potentially efficient timetables
1	150	2,400	83	38	1
2	125	2,683	87	36	2
3	200	2,880	87	353	4
4	157	3,210	86	500	1
5	150	2,160	86	6	2
6	130	2,503	102	30	3

Table 1: Numerical characteristics of the instances

total secondary delays generated by a primary delay of 300s for a single train is 6,890s.

Finally, it is interesting to observe that the stability evaluation gap between the best and worst timetables can be important (up to 33.9%, the mean and maximal gap are reported in table 2 for each instance and primary delay). Actually, only the instance 1 presents small gap on both stability evaluations (less than 1%). However, there is only one potentially efficient timetable for this instance so the gap on both stability evaluations concerns the same timetable. Choosing one of the potentially efficient timetables instead of a random one can thus permit to obtain significant gains in terms of stability. This is a very promising result since these gains were obtained without optimizing the stability, but just evaluating the available timetables.

Instance	Stability evaluation gap for a primary delay of 60s		Stability evaluation gap for a primary delay of 300s	
	Mean	Maximal	Mean	Maximal
1	0.52%	4.44%	0.95%	3.32%
2	17.48%	32.90%	3.20%	5.75%
3	5.94%	11.12%	4.68%	7.92%
4	2.02%	4.29%	3.21%	9.17%
5	2.32%	6.13%	5.38%	11.48%
6	7.55%	17.96%	1.05%	2.28%

Table 2: Stability evaluation gap

6 Conclusion

In this paper, a new model to evaluate the stability of railway timetables have been presented. This evaluation is based on a delay propagation method, and is obtained by computing shortest path in a graph. To the best of our knowledge, this is the first method based on a multiobjective evaluation.

The analysis of stability can thus permit to assist the choice between several timetables in a decision system software assessing the capacity of a junction or a station. For a particular timetable, studying the repartition of the secondary delays among the trains of the timetable allows the decision-maker to determine the critical trains and/or the blocking ressources.

Obviously, other delay propagation indicators could be generated with this model. The next step of this work would be to propose a model optimizing the stability instead of only evaluating it, or to integrate this evaluation in a multiobjective heuristic scheme as in [10].

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