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RESEARCH ARTICLE

Robust control strategies facing disturbances in Railway Transport Networks

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Abstract

Objectives: The key objective of this present article is the presentation of a control strategy which consists to compensate the disturbance as soon as it is observed. The main purpose of the proposed control strategy is to guarantee the respect of railway scheduling. The novel strategy allows compensating temporal disruption as soon as it is observed in order to avoid the time constraint violation and to respect planned scheduling. **Methods:** An algorithm that amends the measured disturbances by compensating the disruption along the mono-synchronized paths is presented. The proposed algorithm allows computing the available control margin for every controllable place. **Findings:** The main impartial is to compensate partially or totally the disturbance so as to avoid time constraint violation in railway transport networks. In these networks, time may be a significant parameter because it encompasses constraints to avoid adverse events. The temporal constraints which will arise on the railway network may degrade the planed schedules and consequently affect the availability of transportation systems. This leads to many problems in the decision and optimization of the studied transport systems. **Novelty/Applications**: This paper is devoted to the modeling and robust control of the Tunisian railway network. In this context, a novel robustness strategy is developed to compensate the time disruption in railway networks and to preserve the planned schedule.

Keywords: robustness; control; temporal disturbances; railway networks; Ptime Petri Nets

1 Introduction

Manufacturing workshops, rail or road transport networks and computer networks can be considered as Discrete Events Systems (DES). However, the discrete nature of flows run does not exclude the existence of schedules to respect, delivery and expiry dates. All these temporal constraints are generally characterized by a minimum and a maximum time constraints assigned to an operation or a state.

In rail transport networks, the processes control must guarantee the travel durations specifications in order to ensure the traffic stability. Each system has a robustness property in order to maintain product quality when there are time disturbances. The robustness is defined as the ability of the system to preserve

the specifications facing some expected or unexpected variations. So, the robustness characterizes the capacity to deal with disturbances. In this context, the work presented attempt to build a robust control approach facing traffic disturbances. These disruptions were no longer acceptable due to the growing demand.

In railway transport networks traffic disturbance cannot be avoided. Keeping traffic stability is of importance to researchers and manufacturers. The railway system is subject to different constraints, whether at the level of the equipment or of service. In addition, the increase in the traveler's number causes remarkable delays and the unavailability of the transport systems. In these transport systems, a temporal disturbance cannot be predicted or prevented. Our research focuses on the elimination and compensation of these disturbances by an application of robustness control techniques. The system that motivated this study is a real railway transport network. In the system under consideration, the processing times are interval-valued. Otherwise, a processing time is selected between two bounds which depend on the operation to be performed. Any deviations (occurrence of a temporal disturbance) from the allowed lower (resp., upper) bounds will lead to a low service quality. Thus, the study of robustness of these systems is needed to be carried out. The main objective of this paper is the presentation of a control strategy which consists to compensate the disturbance as soon as it is observed. The established strategy allows averting catastrophic scenarios, avoiding the violation of time constraints and guarantees the stability and safety of railway traffic.

Most of the existing research focuses on short delays and small disturbances. In our study, the focus is on all types of disturbances, such as major disturbances (like the accumulation of delays). Moreover, no systematic study was conducted in the Sahel railway network. These are the main motivation for our research. The main contribution is to supervise by simulation the railway traffic and to rate the impact of temporal disruption on the railway network modeled by a SP-TPN.

Railway transport systems must be supervised online in order to avert critical situations. The time disruptions can affect the railway scheduling and can lead to a transport service degradation. The general objective is to preserve the railway network stability and make it more efficient and secure. In this context; various research were conducted on the robustness and control of transportation systems in order to improve railway quality service.

On the one hand, in [1] an evaluation of the railway network robustness with regard to operational delays is proposed. The author proposes, a stochastic model of delayed propagation to identify imposed delays and to calculate the resultant secondary delays. Individual robustness measures the ability of trains to limit and reduce the adverse effects of their own primary delays.

The authors in [2] study the impact of the robustness on the railway scheduling. The impartial is to maintain travelling task while there is a disturbance such as a delay or a failure.

Other authors [3,4], use Colored Petri Nets (CPN) as a modeling tool for transportation systems The same formalism served as a support for a comparative analysis of the performances of the BAL (Automatic Light Block) / KVB (Speed Control by Beacons) systems and ETCS on a European freight corridor project [5]. Numerous other works use Petri nets to model and analyze railway systems [6–8].

Some works are interested in the rescheduling of railway traffic in presence of unpredictable events. They are based either on simulation [9], heuristic procedures [10] or mathematical optimization [11]. Other approaches use Integer Programming (IP), Linear Mixed

Programming (MLP) [12], Linear Programming (LP) or Nonlinear Programming (NLP) [13]. To our best knowledge, no paper in this category considers the study of disturbances impacts on railway traffic.

All previous works are different from our work. In our article a new control strategy allowing to compensate unpredictable events as small disruptions. The main impartial is to guarantee strict compliance with the planned scheduling. This is done by updating, the token sojourn times in the places affected by the disturbances. To the best of our knowledge, such control approach has been never formalized for railway transport networks.

The contributions of the present paper are

(i) The improvement of the time semantic of the railway network model with the introduction of the Stochastic P-timed Petri Nets (SP-TPNs)

(ii) A new control strategy approach, based **o**n the study of effective sojourn time of the token in places. This approach is used to evaluate the influence of different types of disturbances on the expected schedule.

This paper is organized as follows. Section 2 introduces the studied Tunisia railway system. Section 3 recapitulates the approach for model identification through real measurements. Section 4 present the robust control strategy facing disturbances and illustrates by simulation the effectiveness of the proposed approach. Finally the conclusions and extensions may be read in the last Section.

2 Problem statement

2.1 Presentation of Tunisian Railway Network

Tunisian National Railways Company (TNRC) is a state owned company, which is responsible for operation, maintenance and management of national rail network. The TNRC operates 11 lines linking major cities of Tunisia including the Sahel rail network. This line linking mainly the cities and agglomerations of the Sahel from Mahdia to Monastir. It begins from the Mahdia station crosses, Tebouloba until Monastir station by serving the agglomerations of Ksar Hellel, Bouhjar, [Figure 1]. With a mean of 50 minutes frequency, Sahel Metro guarantees a daily scheduled traffic between 5:00. To 9:00 P. M.

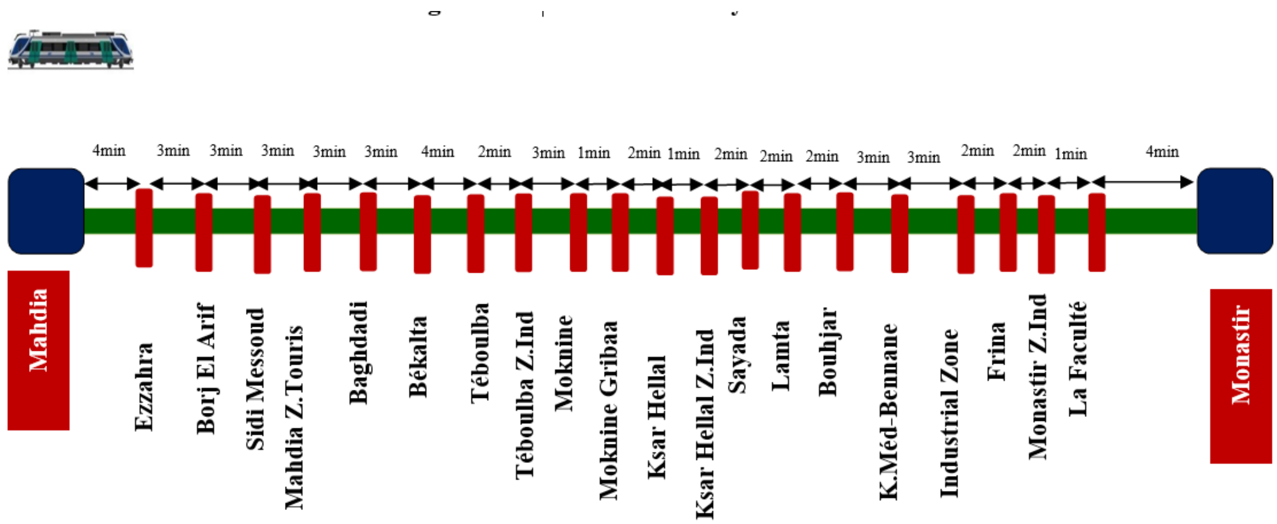

Fig 1. The Sahel Railway line

2.2 Modelling of the railway transport system

In the transport system under consideration, the travelling and staying time, are interval- valued. So, any deviations from the allowed lower and upper bounds will cause the defective traffic disturbances. Stochastic P-time Petri Nets (SP-TPNs) are practical tools for modeling the studied railway system whose travelling times aren't precisely given.

3 Parameter identification of the Tunisia railway network model

In this part, we sum up the different parts of the identification approach discussed in [14]. This approach is based on experimental measurements observed during travel operation in the the studied Railway Network. Based on measurements reported by the SCADA of the TNRC company, dynamic intervals and sojourn times for each place of the SP-TPN are determined. The main impartial is to built SP-TPN model able to reproduce the railway traffic behavior.

3.1 Collected data from TNRC company

The approach proposed in this paper is based on a statistical analysis of the real measurements, collected by the Supervisory Control And Data Acquisition (SCADA) system of the Tunisian National Railway Company (TNRC), to identify the time parameters of the Stochastic P-timed Petri Net (SP-TPN) model.

[Figure 2], shows a SP-time Petri net (S) modelling the studied transport system. The acquired S is used to study the robustness facing time disturbances of the Tunisian Railway system.

For each place of S, we denote [L_{ij}, q_{ij}^{e} , H_{ij}] the lower bound of the time window, the expected sojourn time of tokens, and the upper bound of the time window, respectively.

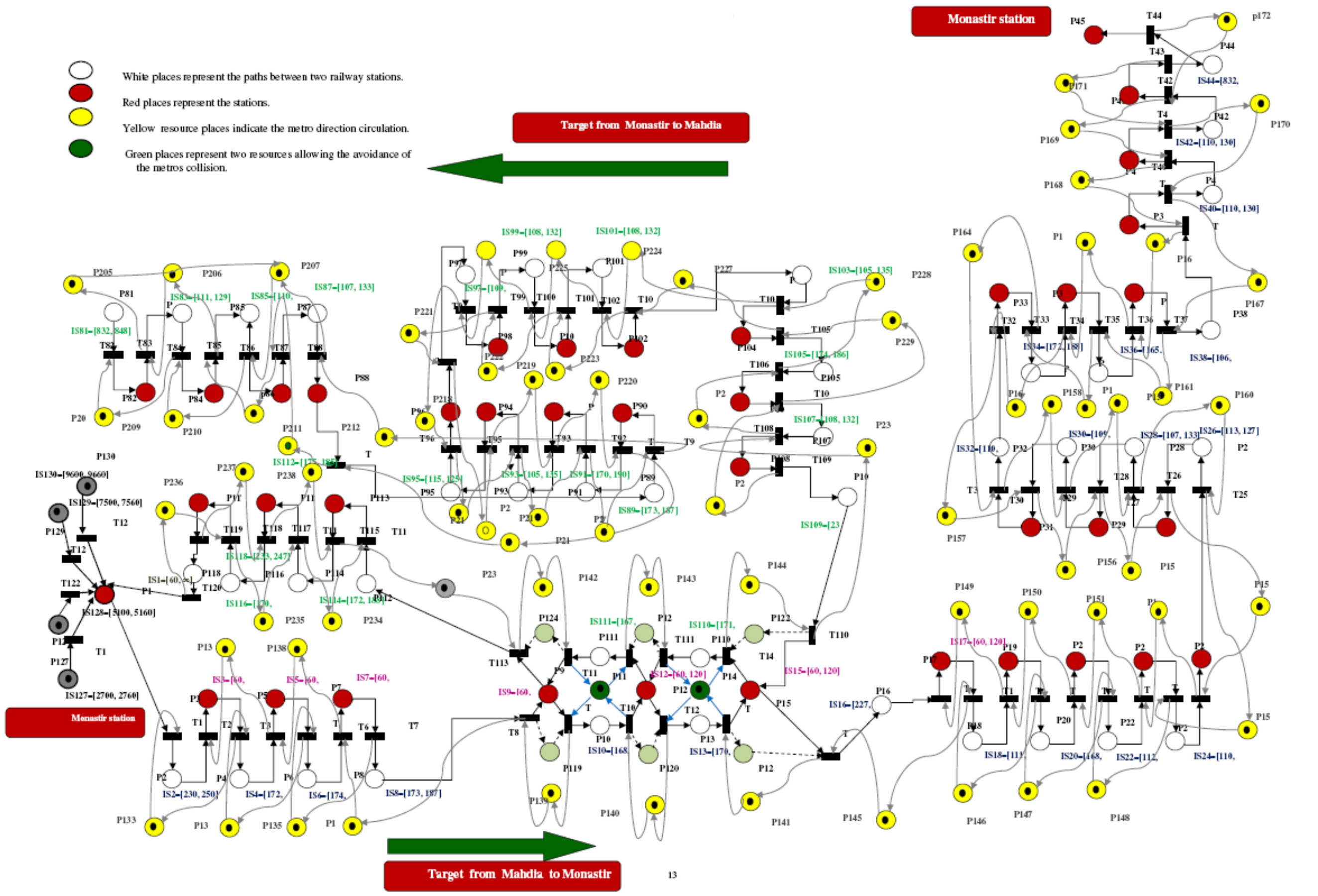

Fig 2. SP-TPN model of the Tunidsian Sahel Railway network

4 Robust control Strategy facing Distrubances

Unpredictable events as small disruptions (such as malfunctions or absence of personnel) and significant disruptions (such as significant and particularly damaging external accidents; train and infrastructure failures) are considered in [15] and [16–19]. Both types of events necessarily result in the invalidity of the train time table. In general, for small disruptions, the train dispatchers manage the disturbances manually according to their knowledge especially when the metro is not operated. But this process becomes more complex when major disruptions occur during the metro circulation. Moreover, manual interventions often leads to degraded performance, where as robust approaches allow to determine the most appropriate control actions and to schedule updating.

In this section, we propose a robust control approach allowing to detect temporal disturbances on the railway network and to compensate these disruptions in order to guarantee strict compliance with the planned scheduling. This is done by updating, the token sojourn times in the places affected by the disturbances. For this purpose, some definitions are introduced:

Definition 1: A place p_k is observable if the firings of the input and output transitions of p_k are computed. Based on these measurements, the effective sojourn time of a mark is observed. $P_O \subset P$ is the set of observable places.

Definition 2: A place p_k is controllable if the expected sojourn duration qe_k of the tokens can be modified by a control action. $P_c \subset P$ is the set of controllable places.

Definition 3: A path $pth(y_1, y_K) = y_1\ y_2 \ldots y_K$ in a SP-TPN is defined as an orderly and oriented succession of K nodes with $y_k \in T \cup P$ such as $y_{k+1} \in (y_k)^{\circ}$ for $k = 1, \ldots, K-1$.

In the proposed robust control approach, synchronization transitions play an important role due to the possibility of death of marks in the input places of such transitions since it allows synchronization between events. Let us take the example of the places p_x and p_y which represent the input places associated to the synchronization transition t_s, [Figure 3]. The unavaibility of a token in the place p_y can cause a death of mark in p_x. The death of mark means the time constraints violation, which means in railway transport the infraction of the time constraints imposed by the scheduled layer.

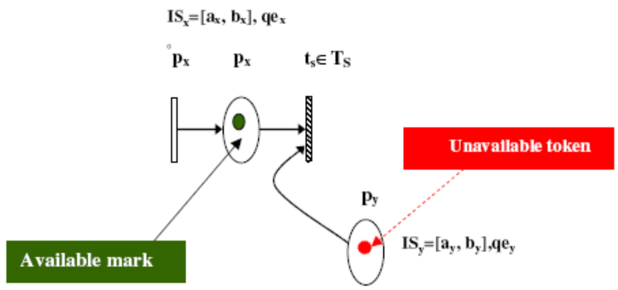

Fig 3. Possibility of death of token on the level ofthe synchronization transition ts

Definition 4: A disturbances Ω is defined as unforeseen event affecting the scheduling performances. Formally, Ω is defined as: $\Omega = q_{ie} - q_i$. The disturbance is considered as a delay if Ω>0, otherwise it is an advance.

Definition 5: The robustness is defined as the ability of the system to conserve its specified properties against unpredicting and predicting events. A SP-TPN is robust against disturbances Ω if there is not a death of mark at the level of synchronization transitions.

Definition 6: The temporal Compensation Capacities "CC" of a mono-synchronized path $L_{pth}(p, t_s)$ are defined by the following formulas respectively for advances and delays:

$$CCa\left(L_{pth}\left(p,t_s\right)\right) = \sum_{\left(p_r \in L_{pth} \cap P_C\right)} CMa\left(p_i\right) = \sum_{\left(p_i \in L_{pth} \cap P_O\right)} \left(b_i - \beta_i\right)$$

$$CCd\left(L_{pth}\left(p,t_s\right)\right) = \sum_{\left(p_i \in L_{pth}\left(p,t_s\right) \cap P_c\right)} CMd\left(p_i\right) = \sum_{\left(p_i \in L_{pth}\left(p,t_s\right) \cap P_c\right)} \left(a_i - \alpha_i\right)$$

4.1 Tenet of robust control strategy

The main purpose of the robust control strategy is to guarantee the respect of the travel duration, which must imperatively belong to a very strict time interval. The novel strategy allows compensating temporal disruption as soon as it is observed in order to avoid the time constraint violation and to respect planned scheduling.

4.2 Study of path robustness

The proposed algorithm amends the measured disturbances by compensating the disruption along the mono-synchronized paths. The proposed algorithm allows computing the available control margin for every controllable place. The main impartial is to compensate partially or totally the disturbance so as to avoid time constraint violation.

Let us take an example a temporal disruption occurred in a place p belonging to the mono- synchronized path $L_{pth}(p, t_s)$, [Figure 4]. The proposed algorithm allow to compensate the time disruption ,if the robust indicator will be equal to 1 and equals 0 otherwise, by computing the available control margin of the path $L_{pth}(p, t_s)$,

Algorithm 1: disturbance compensation
Inputs: Ω, p, t_s;
Outputs : robust, Sqe^c)

1. $\Omega r \leftarrow \Omega$
2. $t_{next} \leftarrow (p^\circ) \cap L_{pth}\ (p,t_s)$
3. $Sqe^c \leftarrow [\varnothing]$
4. while $(\Omega r \neq 0) \wedge (t_{next} \neq t_s)$
5. $p_{next} \leftarrow (t_{next}{}^\circ) \cap L_{pth}\,(p,t_s)$
6. if $p_{next} \in P_C$

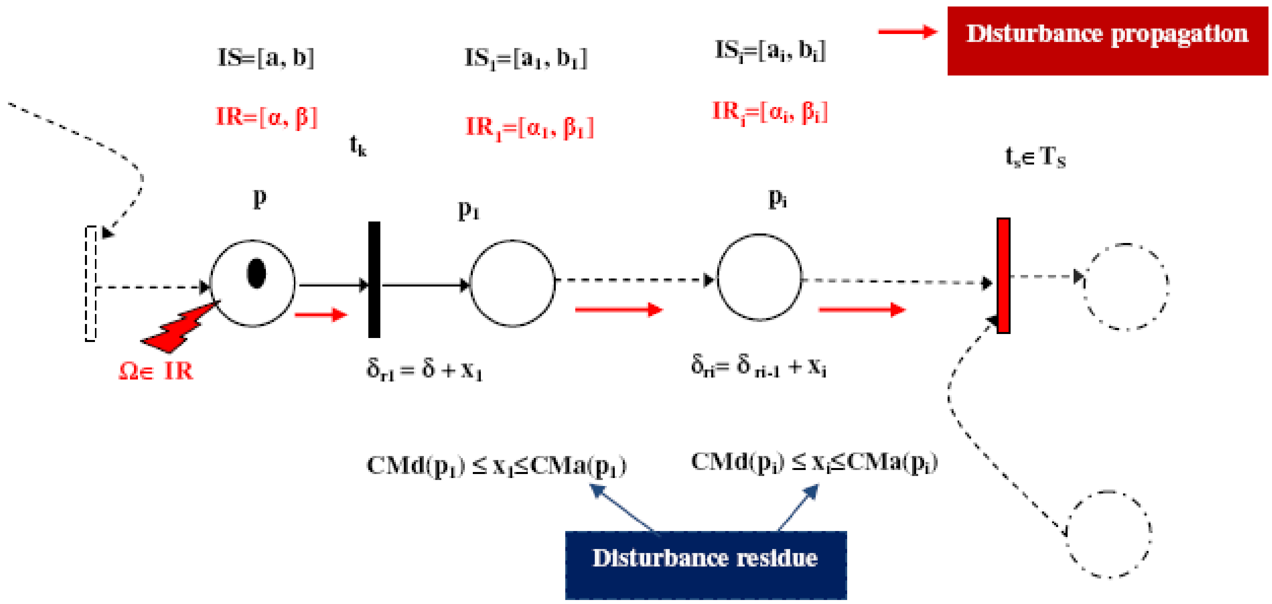

Fig 4. Propoagation of the disturbance in thesubpath Lpth(p, ts)

7. if $\Omega r > 0$
8. $qe_{next}{}^{c} = qe_{\text{next}} - \min\left(\Omega r, -CMd\left(p_{\text{next}}\right)\right)$
9. $\delta r \leftarrow \max\left(0, \Omega r + CMd\left(p_{\text{next}}\right)\right)$
10. *end*
11. if $\Omega\text{a} < 0$
12. $\text{qe}_{\text{next}}\,\text{c} = \text{qe}_{\text{next}} + \min\left(-\Omega\text{a}, \text{CMa}\left(\text{p}_{\text{next}}\right)\right)$
13. $\delta r \leftarrow \min\left(0, \Omega a + CMa\left(p_{next}\right)\right)$
14. end
15. $\text{t}_{\text{next}} \leftarrow \left(\text{p}^{\circ}_{\text{next}}\right) \cap \text{L}_{\text{pth}}\left(\text{p}, \text{t}_{\text{s}}\right)$
16. $\text{Sqe}^{\text{c}} \leftarrow \left[\text{Sqe}^{\text{c}}\text{qe}^{\text{c}}_{\text{next}}\right]$
17. *else*
18. $\text{Sqe}^{\text{c}} \leftarrow \left[\text{Sqe}^{\text{c}}\text{qe}_{\text{next}}\right]$
19. *end*
20. *end*
21. if $\Omega\text{a} = 0$, robust $\leftarrow 1$ else robust $\leftarrow 0$
22. *end*

The proposed iterative algorithm is able to compute the available control margins for each place p $\in$Pc. These margins are explored to compensate the disturbance along a mono- synchronized paths from the place where the disturbance was observed.

The lines 4-5 select the mono-synchronized path $L_{pth}(p, t_s)$ on which the disturbance Ω is occurred and and which contains, as last node, a synchronization transition t_s.

In the delay case (disturbance $\Omega r \leftarrow \Omega_n, \Omega r > 0$), the effective sojourn time is computed, in the observable place p_{next} as follows q_{next} = qe_{next} + Ω. In this case the time disturbance is compensated in the controllable places belonging to the path $L_{pth}(p, t_s)$ admitting p_{next} as a starting place.

In this case, the expected sojourn times associated to the controllable places "$qe_{next}{}^{c}$ " is computed by lines 8-9. The CMd(p_{next}) associated to the controllable place p_{next} is calculated as follows $\text{CMd}\left(\text{p}_{\text{next}}\right) = L_{\text{next}} - \alpha_{\text{next}} \leq 0$. The $\text{qe}^{\,c}_{\text{next}}$ satisfy $\text{qe}_{\text{next}}{}^{c} = \text{qe}_{\text{next}} + \text{x}$ with $\text{CMd}\left(\text{p}_{\text{next}}\right) \leq \text{x} \leq 0$.

The calculation procedure for the expected sojourn times of the controllable places along mono-synchronized paths $L_{pth}(p, t_s)$ proceeds until the delay compensation.

Otherwise (the disturbance is an advance) $\Omega a \leftarrow \Omega, \Omega a < 0$ then q_{next} = qe_{next} + Ω< qe_{next} in the observable place p_{next} . In this case the disturbance is compensated on the level of controllable places belonging to the $L_{pth}(p, t_s)$ by generating an advancement on their expected duration.

Algorithm 1 stops as soon as the condition in line 21 is satisfied.

5 Simulations and validation

5.1 Simulations and validation of the identification approach

The main objective of this section is to illustrate how the SP-TPN model, after identification, simulates the Sahel Tunisian railway network in nominal and degraded modes (with and without disturbances). Thus a temporal study based on simulation is intended. In this study, marks represent the metro position and the transitions firing correspond to metro passage times. This study is spread over a period of 30 days and the main results have been reported in [figure 5]. This figure shows the position of the metro in the Sahel railway network (Y axis) over time (X-axis).

The [Figure 5] shows the tokens evolution (the metros traffic of the studied railway network) according to SP-TPN model, figure 2. Let us take the case of a trip made by a metro M1 (represented by red ellipse): This metro leaves from Mahdia station (place P1). Arriving at Monastir station (place P45), M1 parks for a period T1 (level 1), then continues his journey to Sousse station (Place 63) where he stays for a period T2. From Sousse station (return trip) the metro M1, parks at Monastir station (level 2, place P80) before returning to Mahdia station (level 3, place P120).This simulation shows that a metro, during its circulation, can have delays which result in temporal disturbances in the operating times. These delays are shown by a tokens scattering, Figure 5.

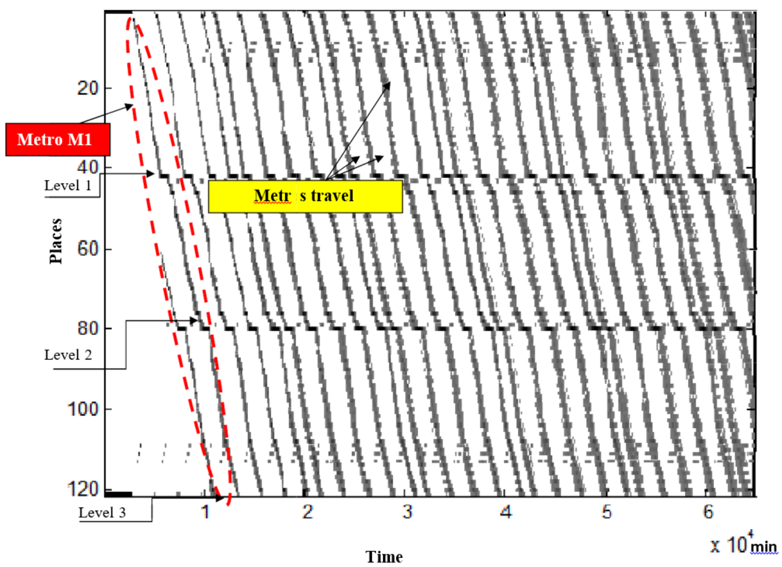

Fig 5. Position of the metro in the sahel railway network (Y axis) over time (period of 16 hours

[Figure 6], reports the distribution of the trains departure times in various railway stations, for February month simulated period, without control action. One can notice that the passage times dispersion corresponds to successive disturbances that have an impact on the metro traffic.

According to the Figure 6, The dispersion increases over time: The dispersion is weak in the morning since the traffic stops at night and a new network scheduling is proposed for the subsequent day. The main impartial is to ensure that metro leave on time in the morning. The dispersion increases during the day due to cumulative delays and various disturbances (see for instance the histogram of the metro passage times at Monastir station, transitions t45, Figure 6, up, right).

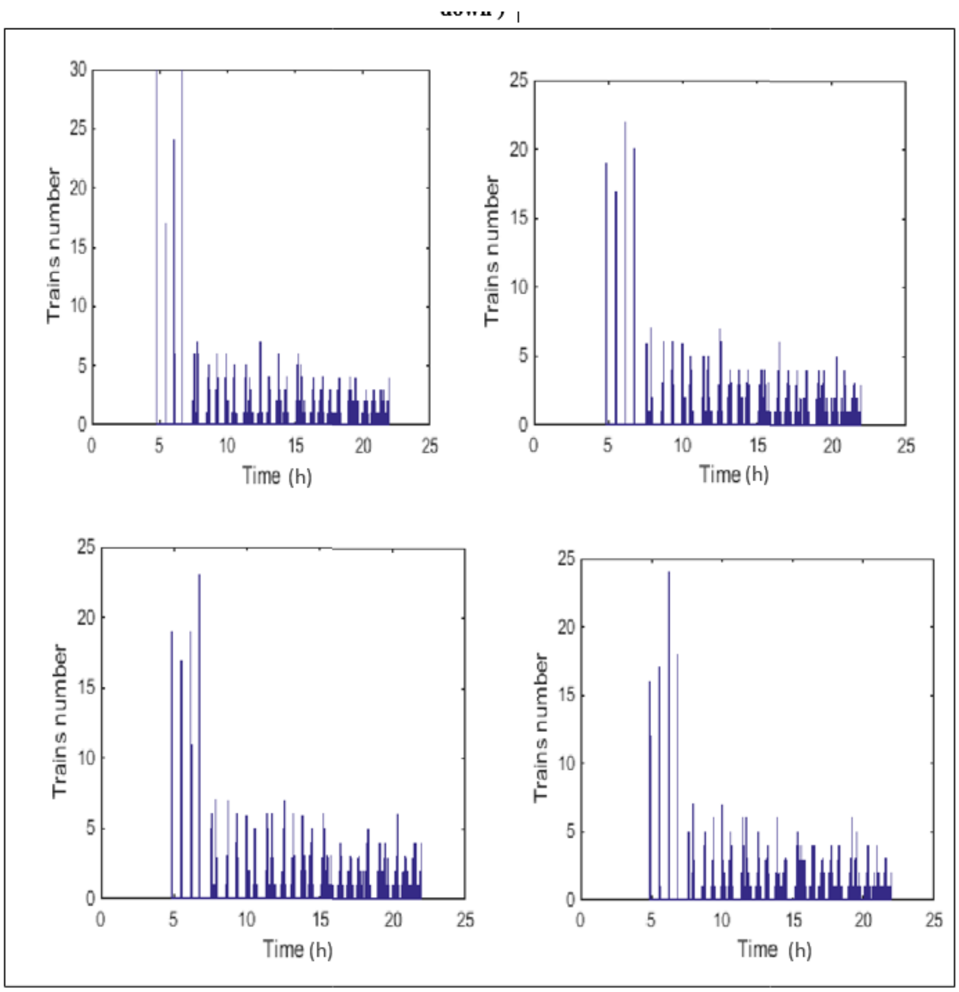

Fig 6. Passage times of metro at transitions t1 (up right), t45 (up left), t63(left down), t81(right down)

5.2 Simulations and validation of control strategy

A/ Application of the robust control approach to the railway transport network: temporal disturbance on the railway (Mahdia - Monastir)

In SP-time PNs, if the upper limit is exceeded, there is a death of mark. The "death" of a token has to be seen as a time constraint violation. In the studied railway network, a death of token corresponds to illegal behavior. Thus, some disturbance can lead to a degraded service (traffic perturbation, cumulative delay, travelers claims, …) and influence the stability and the security of the networks.

In order to avoid the traffic delay (occurrence of time disturbance δ in p_{127}), Figure 7, it is possible to catch up the late departure of the metro from Mahdia station by minimizing the staying time of the metro in the stations (generating advances on the controlled transitions t_5, t_7, t_9 and t_{12}). This delay compensation makes it possible to avert catastrophic scenarios since it allows to avoid the collision with the metro arriving from the station of Bekalta (single railway lane shared between the two metros).

A series of simulations during the February month was collected taking into account the application of novel control strategy. The results are shown in the [Figure 8]. The impact of the perturbation on the railway line has been attenuated, so as so the planned schedule is respected. Therefore according to [Figure 9], it is easy to take into account that the control strategy leads to satisfactory results in the disturbances compensation.

This control approach can be applied to any Discrete Event System integrating time constraints (urban, maritime, rail transport networks, manufacturing system with time constraints, etc.). Certainly the proposed approach can be applied to

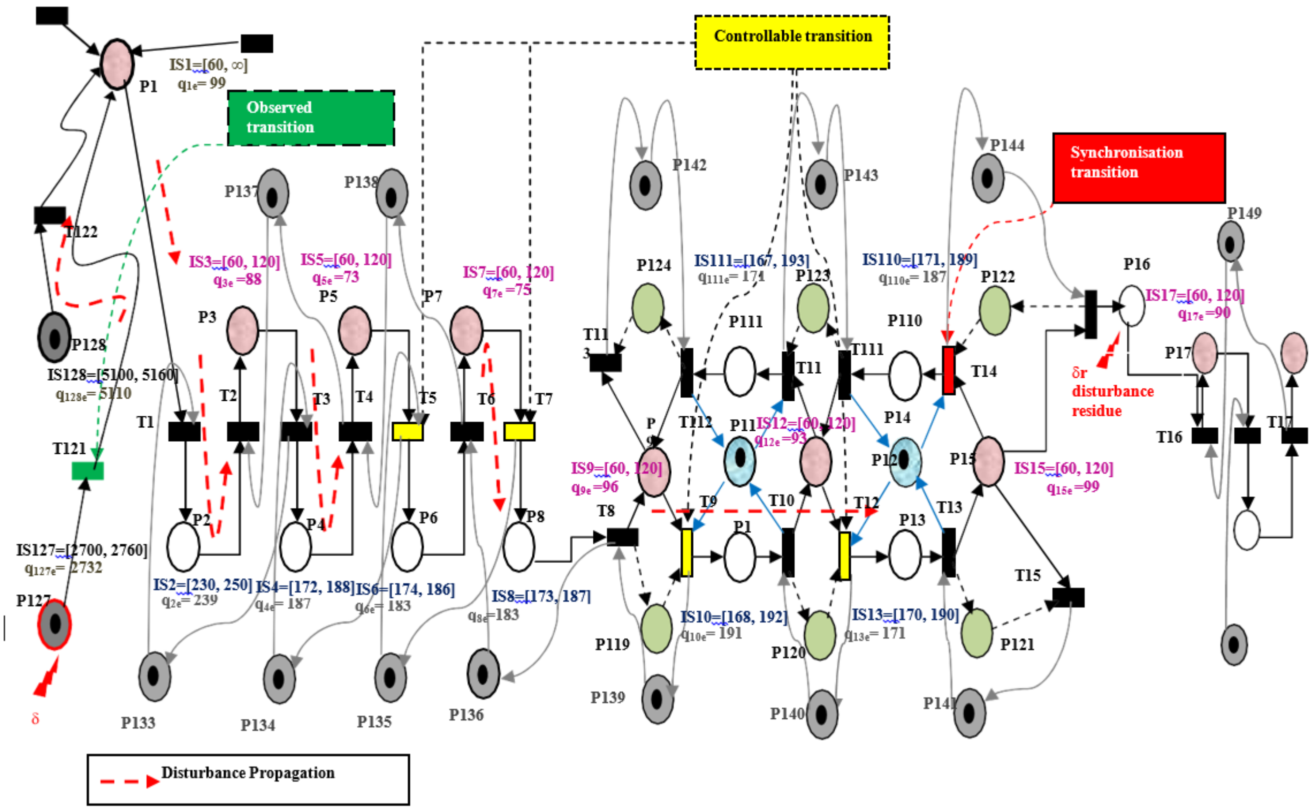

Fig 7. Example of disturbance propagation on railway network Mahdia-Monastir

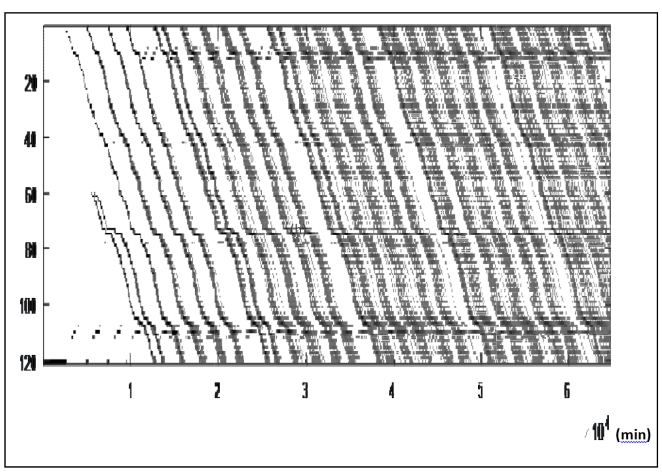

Fig 8. Impact of the control strategy on the metro circulation

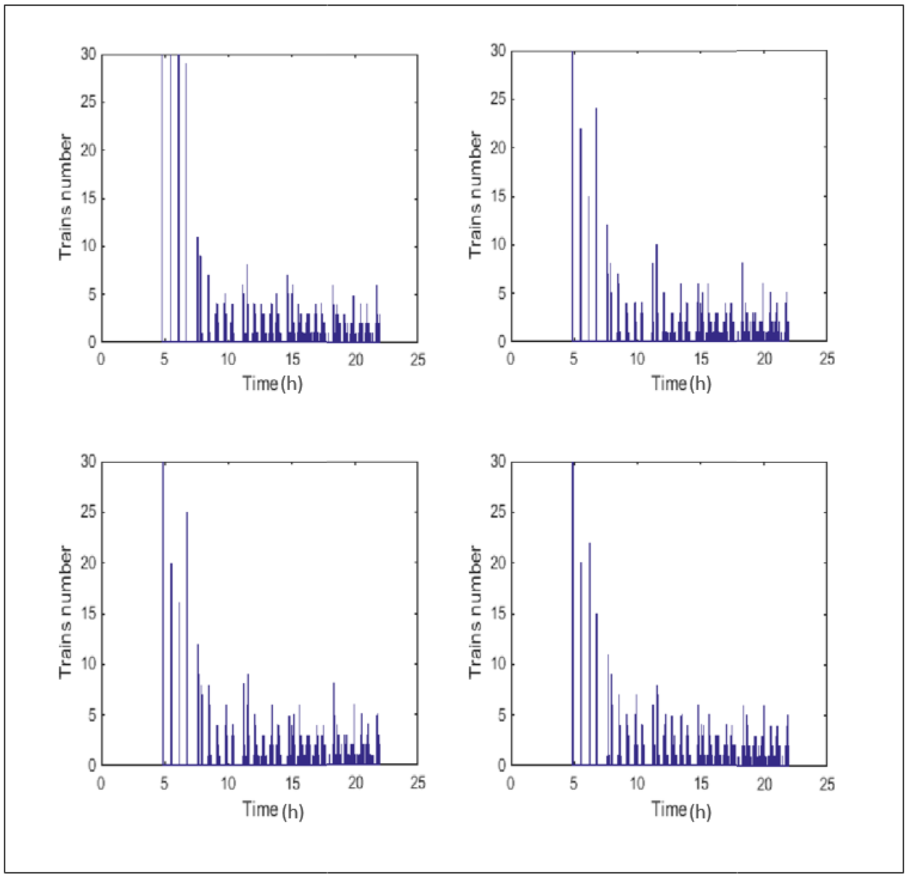

Fig 9. Passage times of metro at transitionst1 (up right), t45 (up left), t63 (left down), t81 (right down) with control action

other networks but it does not cover two aspects:

- The first is the progression of faults: it is not easy to define, extract or 'quantity' damage; but it may be worthwhile to consider the history of maintenance on a point, and other relevant facts.
- The second aspect is the deterioration process. It is not possible to wait until the component deteriorates to an unrepairable status because it may be very unsafe when it is working in this condition. Hence, it would be better to repair or replace the components before its deterioration.

6 Conclusion

The planned schedule in railway network is frequently disrupted by disturbances that can lead to significant delays that degrade the traffic or even lead to serious incidents on the railway line. In order to attenuate the disruptions impact on traffic, a novel control strategy has been applied to a realistic railway network. This control strategy consists to compensate the disturbance as soon as it is observed. The control approach have been approved and verified based on real data provided by TNRC which manages the Sahel railway networks.

An algorithm has been designed to compute a new calendar each time a disturbance occurs. This algorithm updates the expected sojourn times in the places affected by the disturbance. The method has been validated by simulation on the studied railway network. The results are promising in terms of disturbance compensation. This leads to an optimization of the railway network performance and thus the improvement of the transport service of this network.

From a methodological point of view, it would be interesting to improve the efficiency of the control strategy proposed in this manuscript. Extension to partial will extend the range of applications for the proposed control approach.

In the railway networks, the travelling times should be within two bounds. Any deviations (occurrence of a temporal disturbance) from the allowed lower (resp. upper) bounds will lead to a low service quality and can lead to disaster scenarios.

The proposed control approach have been validated and verified by the real data provided by TNRC. In this context, we are in the process of developing with the engineers of the railway company a platform (dashboard) allowing the control and supervise in real time the studied railway network. The developed dashboard permit real-time data display and allows the supervisor to control the train locomotive through a graphical interface. The first tests demonstrate that the surveillance approach has the potential to react in real time in order to avoid catastrophic scenarios and to further rail safety.

References

1) Khadilkar H. Data-Enabled Stochastic Modeling for Evaluating Schedule Robustness of Railway Networks. *Transportation Science*. 2017;51(4):1161–1176. Available from: https://dx.doi.org/10.1287/trsc.2016.0703.
2) Lusby RM, Larsen J, Bull S. A survey on robustness in railway planning. *European Journal of Operational Research*. 2018;266(1):1–15. Available from: https://dx.doi.org/10.1016/j.ejor.2017.07.044.
3) Labadi K. Contribution a la modélisation et à l'évaluation de performances des systèmes logistiques à l'aide d'un nouveau modèle de réseaux de Petri stochastiques. 2005. Available from: https://tel.archives-ouvertes.fr/tel-00389432/.
4) Barger P, Schön W, Bouali M. A study of railway ERTMS safety with colored Petri nets. In: The European Safety and Reliability Conference ESREL. 2009;p. 1303–1309. Available from: https://hal.archives-ouvertes.fr/hal-00447528.
5) Lalouette J, Brinzei N, Malassé O. Evaluation des performances du système de signalisation ferroviaire européen superposé au système français. *Congrès Lambda- Mu*. 2010;17. Available from: https://hal.archives-ouvertes.fr/hal-00530353/document.
6) Hagalisletto AM, Bjork J, Yu IC, Enger P. Constructing and Refining Large-Scale Railway Models Represented by Petri Nets. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)*. 2007;37(4):444–460. Available from: https://dx.doi.org/10.1109/tsmcc.2007.897323.
7) Sarkar S, Dutta A. Petri Net based modelling of railway intersection collision avoidance system. *2016 IEEE International Conference on Intelligent Rail Transportation (ICIRT)*. 2016;p. 356–361.
8) Venkatarangan MJ, Yam Y. Modelling and Simulation of Two Way Railway Traffic Using Extensions to Petri Nets. *2014 8th Asia Modelling Symposium*. 2014;p. 97–103.
9) Jacobs J. Reducing delays by means of computer-aided 'on-the-spot'rescheduling. *WIT Transactions on The Built Environment*. 2004;74:603–612.
10) Pellegrini P, Marliere G, Pesenti R, Rodriguez J. RECIFE-MILP: An Effective MILP-Based Heuristic for the Real-Time Railway Traffic Management Problem. *IEEE Transactions on Intelligent Transportation Systems*. 2015;16(5):2609–2619. Available from: https://dx.doi.org/10.1109/tits.2015.2414294.
11) Pellegrini P, Marlière G, Rodriguez J. Real time railway traffic management modeling track-circuits. *OpenAccess Ser Informatics*. 2012;25:23–34.
12) Johanna T. Computer-based decision support for railway traffic scheduling and dispatching: A review of models and algorithms. *Algorithmic MeThods Model Optim Railways*. 2006;2. doi:10.4230/OASIcs.ATMOS.2005.659.
13) Cavone G, Blenkers L, Boom TVD, Dotoli M, Seatzu C, Schutter BD. Railway disruption: a bi-level rescheduling algorithm. In: 2019 6th International Conference on Control, Decision and Information Technologies (CoDIT). IEEE. 2019.
14) M'halla A, Lefebvre D, Gaied M. Distributed Monitoring Based on P-Time Petri Nets and Chronicle Recognition of the Tunisian Railway Network. *Journal of Electrical and Computer Engineering*. 2020;2020:1–12. Available from: https://dx.doi.org/10.1155/2020/6265379.
15) Li X, Shou B, Ralescu D. Train Rescheduling With Stochastic Recovery Time: A New Track-Backup Approach. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*. 2014;44(9):1216–1233. Available from: https://dx.doi.org/10.1109/tsmc.2014.2301140.
16) Dollevoet T, Huisman D, Kroon LG, Veelenturf LP, Wagenaar JC. Application of an iterative framework for real-time railway rescheduling. *Computers & Operations Research*. 2017;78:203–217. Available from: https://dx.doi.org/10.1016/j.cor.2016.08.011.
17) Robey A, Lindemann L, Tu S, Matni N. Learning Robust Hybrid Control Barrier Functions for Uncertain Systems. *IFAC-PapersOnLine*. 2021;54(5):1–6. Available from: https://dx.doi.org/10.1016/j.ifacol.2021.08.465.
18) Modica G, Praticò S, Laudari L, Ledda A, Fazio SD, Montis AD. Implementation of multispecies ecological networks at the regional scale: analysis and multi-temporal assessment. *Journal of Environmental Management*. 2021;289:112494. Available from: https://dx.doi.org/10.1016/j.jenvman.2021.112494.
19) Lu H, Ge Z, Song Y, Jiang D, Zhou T, Qin J. A temporal-aware LSTM enhanced by loss-switch mechanism for traffic flow forecasting. *Neurocomputing*. 2021;427:169–178. Available from: https://dx.doi.org/10.1016/j.neucom.2020.11.026.