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Comparative study of the unreliability of a Moroccan Level Crossing using stochastic Petri Nets approach and fault tree analysis

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Résumé **– Les passages à niveau (lieu du franchissement d'une voie ferrée par une route) constituent l'une des sources les plus importantes d'accidents dans le domaine ferroviaire au Maroc. Pour cette raison, l'Office National du Chemin de Fer (ONCF) Marocain a lancé un programme qui vise à supprimer plusieurs passages à niveau à cause de leur dangerosité. Ce travail propose une description du système de signalisation ferroviaire Marocain et une modélisation par deux méthodes afin de faire une étude comparative entre l'approche des Réseaux de Pétri stochastiques et l'analyse par Arbres de Défaillance et d'évaluer la probabilité d'occurrence de l'événement redouté (collision entre un train et un véhicule) en fonction du temps des Passages à Niveau Marocains en intégrant le facteur Humain et les données de défaillances des composants . En effet, les Réseaux de Pétri stochastiques et les arbres de défaillance sont des méthodologies adéquates pour la modélisation des systèmes complexes pour évaluer les performances liées à la sûreté de fonctionnement. Les méthodes proposées et les outils associés permettent l'évaluation des performances du système de passages à niveau marocains en termes de la probabilité de l'occurrence de l'événement redouté en fonction du temps afin de valider les résultats**

Abstract**-The Level Crossings (place of crossing of a railway by a road) constitute one of the most important sources of accidents in the railroad domain in Morocco. For this reason, the National Office of the Moroccan Railroads launched a program which aims at deleting several level crossings because of their dangerousness. This work proposes a description of the Moroccan railway signalling system and a modelling by two methods in order to do a comparative study between the Stochastic Petri Nets approach and the Fault Tree analysis and to evaluate the occurrence probability of the feared event (collision between a train and a vehicle) over the time of the Moroccan Level Crossings by integrating human factor and components failures data. Indeed, Stochastic Petri Nets and Fault Tree are adequate methodologies for modelling complex systems so as to evaluate the performances related to the dependability. The proposed methods and associated tools allow the evaluation of the performances of the Moroccan level crossings systems in terms of the occurrence probability of the feared event over the time so as to validate the results.**

Mots clés-Passage à niveau ; Réseaux de Pétri stochastiques, Arbres de défaillances ; Evènement redoute ; Facteur Humain.

Keywords- Level Crossing; Stochastic Petri Nets;Fault Tree; Feared Event ;Human Factor.

1 INTRODUCTION

The railway safety is one of the most complex problems which are necessary to approach in order to estimate better and improve the performances of the railway systems. Indeed, the level crossings constitute the major source of the risks of accidents in the railway domain in Morocco.

Several works related to this problem were presented in the literature. In the paper (Paul M, et al., 2013), the authors examine driver situation awareness at rail level crossings using a network analysis-based approach and analyze revealed key differences between novice and experienced drivers situation awareness by proposing a series of wider driver behaviour applications. In the paper (Joe , et al., 2010) , the authors analyze the functional interactions between the existing level crossing functions and any new technological system in terms of reliability, so as to choose asset owners wishing to upgrade and improve the existing systems reliability. The study presented in (Samantha G, et al., 2014) shows an overview of the challenges of level crossings to shared high-speed rail passenger and heavy-axle-load freight operations in the U.S. This study is expected to identify and evaluate the principal technical challenges related to level crossings in developing high-speed rail systems so as to

facilitate the planning, development, construction, and operation of new systems. The purpose of the work discussed in (Bahloul, et al., 2012) is to improve safety of level crossing by analyzing accident/incident data bases and integrating human behaviour using UML diagrams, in order to bring out the main functions of level crossing protection system which are concerned by different actors of the project. The paper (M.EASA, 1994) presents a probabilistic method that accounts for the variations of the component design variables of sight distance at level crossings so as to evaluate system reliability. The method is validated using Monte Carlo simulation. The proposed method should result in safer operations at railroad grade crossings. The paper (Rizati , Hamiduna; Siti, Zaharah Ishaka; b, Intan Roh, 2014) gives an insight view of translating the sequence of event to model pedestrian level crossing scenarios using Petri Nets approach. The developed model gives an understanding of the risky situation when pedestrian and vehicle are interacted at signalized intersections. Further analysis of this model is expected to give a potential risk value of pedestrian level crossing. In (Collart, et al., 2006), level crossings are modelled by p-time Petri Nets in order to satisfy time specifications defined in safety requirements of railway systems. In (Ghazel, 2009) the authors propose a global model of the level crossing implying at the same time the rail and road traffic by using stochastic Petri Nets. This model is obtained by a progressive integration of the developed elementary models; each of them describes the behaviour of a section. It allows the follow-up and the qualitative and quantitative evaluation of the effect of various factors on the level of the risk.
In this paper, we evaluate the occurrence probability of the feared event of the Moroccan level crossing by comparing the results of two approaches: Stochastic Petri Nets and Fault Tree Analysis.
The proposed paper is structured as follows: section 2 introduces the Moroccan rail network and the railway level crossing definition, types, evolution and density in Morocco. In Section 3, Petri Nets approach is introduced. Section 4 presents the basic notions of the Fault Tree Analysis. In Section 5; we present the methodology of transformation from Fault Tree gates to Petri Net. Section 6 illustrates the study of the human factor. In sections 7 and 8, we proposed the modelling of the Moroccan Level Crossing system by the two presented methods as well as the results comparison. Finally, Section 9 concludes the paper.

2 The level crossings in Morocco

2.1 Rail network in Morocco

Railway transport is a strategic element in the development of the Moroccan economy. This justifies the necessity to develop adequate infrastructure, enabling the sector to play its role in providing a service increasingly perform ensuring the necessary safety for driving under the best conditions.
The Moroccan railway network presented in figure 1 consists of 2110 km of lines including 600 km of double track (ONCF, 2013).

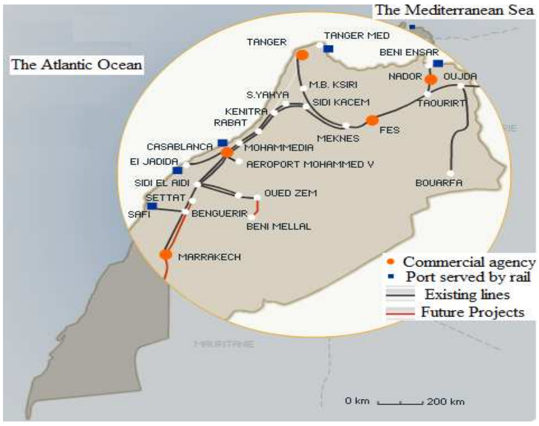

Figure 1. Moroccan railway map

2.2 The level crossings

2.2.1 Definition

Level crossings are crossings at the level of a railway with a highway or pedestrian path. They constitute one of the most important sources of accidents in the railway domain in Morocco. This led early in the railway to choose a radical solution: temporarily prohibiting the road crossing, often physically by barriers. This barrier can be operated manually or automatically.

2.2.2 Types of level crossings

We can easily classify crossings into two main categories:

- Level Crossings with manual barrier:

The guarded level crossings are managed by guards. They must ensure their safety, either by closing the barriers from the approach of a train or stopping trains in case of problems in the level, this type of level crossing has a tendency to disappear.

- The automated level crossings:

The principle of safety of the level crossing not guarded is as follows (ONCF, 2013) (cf.Figure 2):
-Rest situation (Level crossing open): the road fires and the bell switched off, and barriers lifted.
-Activation of the system: a device of detection (pedal of announcement) is placed at a distance of the level crossing, when the train attacks this device, the road fires ignite in red and the bell rings (announcement of the train).
-Closure of barriers: after approximately 7 seconds of the release of the announcement, the barriers begin to fall. The low position of the barriers is reached after 10 seconds.
-Reopening of the level crossing: when the train arrives at the level crossing (35 seconds after the announcement), it attacks the device of rearmament (pedal of surrender). After the complete release of the train, the barriers go up, the road fires and the bell stop ringing.

Figure 2. Principle of functioning of the automated level crossing

2.2.3 *Prototype* of the Moroccan Level Crossing

Within the framework of the global program of the safety of the level crossing of the Moroccan railway, it was decided in July, 2012 to strengthen the safety of the level crossings not guarded and situated on lines with high traffic (approximately 260 level crossings) by a program that extends through 2015. New equipments will be installed on the unguarded level crossing and will allow announcing to the road users the approach of the train. For instance, Figure 3 represents the first prototype which is put in the level crossing N_3080 situated at km 168+088 between Tangier and Sidi Kacem, on May 7th 2013. (ONCF, 2013).

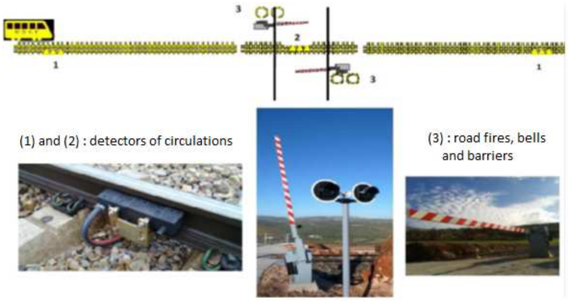

Figure 3. Prototype of the Moroccan Level crossing

3 THE PETRI NETS

3.1 Definition

A Petri Net is a quintuple: PN = (T, P, A, M0)
T: Set of transitions T = {t1, t2, tl}
P: Set of places P = {p1, p2, pm}
A: Set of arcs A = {a1, a2, an}
M0: initial marking: {m (pi)} (integer >=0 = numbers of tokens in the place Pi).(Ould El Mehdi, et al., 2008).

- **Example:**

Figure 4 shows an example of a Petri Net. Places, transitions, arcs and marking of the present example are given below:

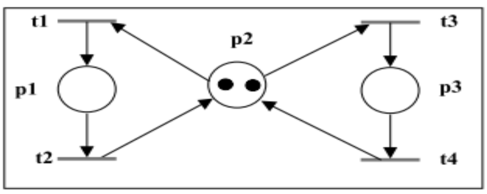

Figure 4. Example of a PN

T = {t1, t2, t3, t4}

P = {p1, p2, p3}

Arcs = {(p2, t1), (t1, p1), (p1, t2), (t2, p2), (p2, t3), (t3, p3), (p3, t4), (t4, p2)}

M0 = [0 2 0]

1 2 3

3.2 The Stochastic Petri Nets

An ordinary Stochastic Petri Net in exponential laws SPN=< PN, (µ1, µ2, µq) > is an ordinary time Petri Net whose durations of sensitization of every transition Tj are random variables pulled in exponential distributions of parameters (µ1, µ2, µq) (Ould El Mehdi, et al., 2008) .The Stochastic Petri Nets were introduced by Guilder since1978 to answer certain problems of evaluation bound to the safety of the computer systems. These problems are bringing in random phenomena; the transitions of the Petri Net contained random time of crossing, distributed by an exponential law. This exponential distribution allows exploiting the mathematical properties of a process of Markov. Well extended, this concept was widely developed from the beginning of the 80s to fulfil the requirements of the more complex modelling such as the modelling of the systems of production (LABADI, 2005) .
The basic notions as well as the main properties are found in numerous works (J. Haas, 2002), (Lindemann, et al., 1996).
Numerous classes of Stochastic Petri Nets are proposed for the analysis of the performances of the systems of production. The characteristics of the various classes of Stochastic Petri Nets are essentially situated in the nature of the transitions used. Initially, a Stochastic Petri Net has all its transitions timed by a random time which is distributed with an exponential law, but we find other types of transition. (LABADI, 2005).

- Generalized stochastic Petri Nets (GSPN)

The network consists of transition with a no temporization called immediate transition and of transition with a random temporization distributed exponentially said stochastic transitions.

- Deterministic stochastic Petri Nets (DSPN)

It is an extension of the generalized Stochastic Petri Nets. The network contains immediate transitions (lasted sensitization zero), transitions with deterministic delays (lasted sensitization constant) and transitions with stochastic delays distributed following exponential laws (LABADI, 2005).

4 THE FAULT TREE ANALYSIS

4.1 Generalities

The fault tree method is very widely used in the field of the dependability of systems. It offers a privileged setting to the deductive analysis which consists in looking for the diverse possible combinations of events leading to the realization of a Feared Event, and allows representing simply these combinations under graphic shape by means of a tree structure of logical gates (cf. Figure 5).

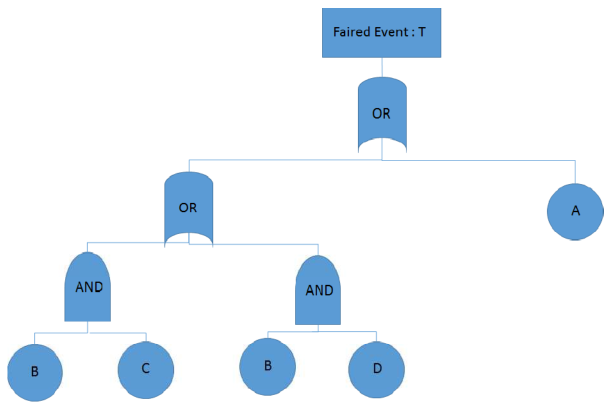

Figure 5. Example of Fault Tree

4.2 Probability calculation

The main treatments made on the fault trees are the research for the minimal cuts (the smallest combinations of events which the simultaneous realization of which leads to the Feared Event) which are used for quantitative evaluation of the probability of occurrence of the Feared event from the probability of occurrence of basic events using the following theorem:

Given a probability space (Ω, Θ, P) and a collection A = {A1,A2,. . .,AN} of measurable subsets of Θ , Sylvester-Poincare equality says that:

$$P\left(\bigcup_{j=1}^{N} A_j\right) = \sum_{I \subseteq A} (-1)^{|I|+1} P(\bigcap_{A_j \in I} A_j) \quad (1)$$

This equality is particularly useful in Fault Tree analysis in which its use in conjunction with the notion of minimal cuts facilitates the computation of the probability of occurrence of the Faired event.

For example, let us consider the Fault Tree presented in Figure 5. The minimal cuts of the Fault Tree are :{A},{BC}, and {BD}. Then, applying the Sylvester-Poincare equality, the probability of occurrence of the Feared Event T is given by (all the basic events are considered to be independent in this work):

$$P(T) = P(A \cup BC \cup BD)$$
$$= P(A) + P(BC) + P(BD) - P(ABC)$$
$$- P(ABD) - P(BCD) + P(ABCD)$$

We say that a model of Fault Tree is solved exactly when the full Sylvester-Poincare development is applied. Unfortunately, applying this development fully is exponential in the number of products. Due to algorithmic limitations, most quantification engines approximate it by computing only the first term of this development (rare event approximation).

5 TRANSFORMATION FROM FAULT TREE GATES TO PETRI NET TRANSITIONS

Logic gates in fault trees can be transformed to corresponding Petri Nets. Figure 6 show the Petri Net representation of AND, and OR gates. (Wu, et al., 2011).

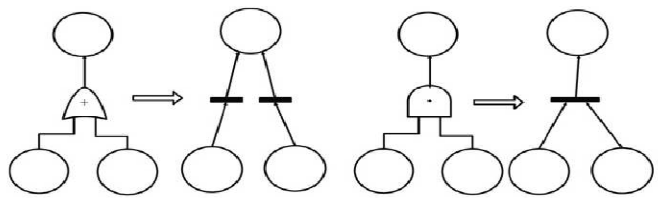

Figure 6. Transformation of the AND gate and the OR gate.

6 INTEGRATING OF THE HUMAN FACTOR

The human error can be defined as a fault of the operator which leads to an accident or a railway incident. In the literature, several works taking into account human factors were proposed. In (LABADI, 2005), the human reliability is defined as the probability that a task or a work is successfully achieved by a person at a required time if a temporal requirement is necessary.

In our study, we use the methodology presented in our previous works (Boudnaya, et al., 2014) to compute the rate of error of the operator which we suppose that is constant.

The distribution appropriate for the model of rate constant is the exponential distribution. Thus, the rate of transition of the state of functioning to the state of failure is $\lambda_{HF} \cdot \Delta t$.

To obtain a significant value of the rate of error, we considered the statistics presented in (ONCF, 2013) in Morocco from 2000 till 2008. The numbers of accidents on 10 busiest lines are given in the **Table 1**.

Table 1. Statistics of the railway accidents in Morocco

Years	Numbers of accidents
2000	11
2001	6
2002	18
2003	13
2004	15
2005	21
2006	12
2007	7
2008	15
Total	118

The safety experts at the National Office of the Moroccan Railroad confirmed that about 90% of railway accidents are caused by human error. Thus the error rate of the operator on every line is:

$$\lambda_{HF} = \frac{a.p}{y.r} = \frac{118 \quad * 0.9}{9 \; years \quad * 10} = 1.347 \quad * 10^{-4} h^{-1} (2)$$

Where:

a: number of accidents.

p: human error percentage

y: number of years

r: number of railway

7 MODELING OF THE LEVEL CROSSING

7.1 *Description* of the system

The Moroccan railway signalling system consists of three parts:

- Rail part: it consists of a material part (train and rail-road) and of a human part (the operator of the train).
- Road part: it contains a material part (vehicle and road) and a human part (the driver of the vehicle).
- Level crossing: it consists of three main parts:
  -Power network and communication network between the components of the railway signalling system.
  -Control part: it consists of Programmable Logic Controller and its program.
  -Operative part: it consists of sensors (Sensor of Ad and Sensor of Surrender) and actuators (the road lights, the alarms and the barriers).

7.2 Level Crossing Fault Tree model

From the description of the Moroccan railway signalling system in the previous section, we were able to model the Feared Event (Collision between train and vehicle) by a Fault Tree (Boudnaya, et al., 2014).(cf. figure 7)

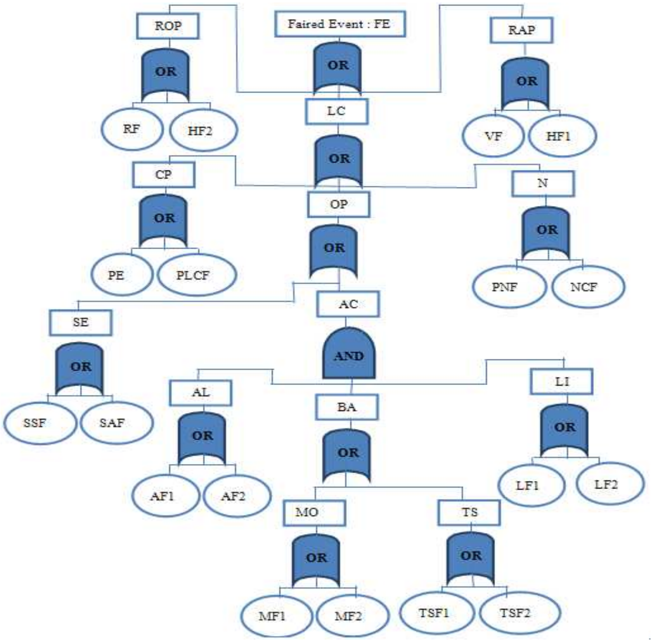

Figure 7. Fault tree of the Moroccan Level Crossing

The basic events which produce the feared event are given in the table 2.

We suppose that these events follow exponential laws with an approached failure rates given in the same table 2.

The failure data are taken from the following sources (Brissaud, et al., 2007),(Cabau, 1999),(HOUASNIA, 1999).

Table 2. BASIC EVENTS

Symbol	Basic Events	Failure Rates : $\lambda(h^{-1})$
HF	Human Failure	$1.347*10^{-4}$
VF	Vehicle Failure	$18*10^{-3}$
RF	Rail Failure	$2.85*10^{-6}$
PLCF	Programmable Logic Controller Failure	4*10-^{6}
PE	Program Error	$5*10^{-8}$
NCF	Network Communication Failure	$5*10^{-6}$
PNF	Power Network Failure	$5*10^{-6}$
SAF	Sensor Ad Failure	$2*10^{-4}$
SSF	Sensor Surrender Failure	$2*10^{-4}$
AF	Alarm Failure	$4*10^{-4}$
LF	Light Failure	$4*10^{-4}$
MF	Motor Failure	$3*10^{-6}$
TSF	Transmission System Failure	$5*10^{-5}$

The symbols of intermediate events of the fault tree are given in table 3.

Table 3. Symbols of intermediate events

Symbol	Intermediate Event
FE	Feared Event
ROP	Road Part
RAP	Rail Part
LC	Level Crossing
N	Network
CP	Control Part
OP	Operative Part
SE	Sensors
AC	Actuators
BA	Barriers
AL	Alarms
LI	Lights
MO	Motors
TS	Transmission Systems

7.3 Level Crossing Stochastic Petri Net model

From the description of the Moroccan railway signalling system and the results of our paper (Boudnaya, et al., 2014), we model the Moroccan Level Crossing system by a Stochastic Petri Net (cf. figure 8).

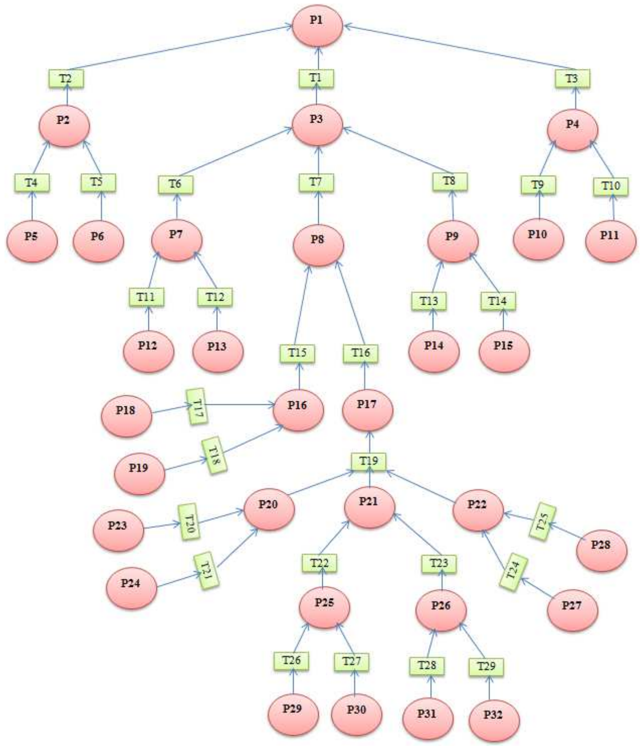

Figure 8.Stochastic Petri Net of the Moroccan Level Crossing

The meanings of the places are given in table.4, and the rates of transition in table.5.

Table 4. MEANINGS OF THE PLACES OF THE STOCHASTIC PETRI NET MODEL.

Place	Symbol	Meaning
P1	FE	Feared Event
P2	ROP	Road Part
P3	LC	Level Crossing
P4	RAP	Rail Part
P5	RF	Rail Failure
P6	HF2	Human Failure 2
P7	CP	Control Part
P8	OP	Operative Part
P9	N	Network
P10	VF	Vehicle Failure
P11	HF1	Human Failure 1
P12	PE	Program Error
P13	PLCF	Programmable Logic Controller Failure
P14	PNF	Power Network Failure
P15	NCF	Network Communication Failure
P16	SE	Sensors
P17	AC	Actuators
P18	SSF	Sensor Surrender Failure
P19	SAF	Sensor Ad Failure
P20	AL	Alarms
P21	BA	Barriers
P22	LI	Lights
P23	AF1	Alarm Failure 1
P24	AF2	Alarm Failure 2
P25	MO	Motors
P26	TS	Transmission Systems
P27	LF1	Light Failure 1
P28	LF2	Light Failure 2
P29	MF1	Motor Failure 1
P30	MF2	Motor Failure 2
P31	TSF1	Transmission System Failure 1
P32	TSF2	Transmission System Failure 2

We suppose that all the transitions follow exponential laws, the rates of transitions which are associated with the basic events have the same data of the previous failure rates of the fault tree.
The others rates of transitions which are associated with intermediate events are computed by the sum of the elementary rates: $\lambda_s = \sum_i^n \lambda_i$ (3)
Except, the rate of transition T19, which represent a parallel system, so it is calculated by the formula:

$$MTTF = \sum_{i=1}^{n} \frac{1}{\lambda_i} - \sum_i \sum_{j \neq i} \frac{1}{\lambda_i + \lambda_j} + \sum_i \sum_{j \neq i} \sum_{k \neq j \neq i} \frac{1}{\lambda_i + \lambda_j + \lambda_k} + \ldots + (-1)^{n+1} \frac{1}{\sum_i \lambda_i} \quad (4)$$

With $\lambda_s = \frac{1}{MTTF}$ (5)
Where: MTTF represent the mean time to failure.

Table 5. RATES OF TRANSITION O OF THE STOCHASTIC PETRI NET.

Transition	**Type of associated events**	**Rate of Transition (h^{-1})**
T2	Intermediate	$137.55*10^{-6}$
T1	Intermediate	$5.23923*10^{-4}$
T3	Intermediate	$181.347*10^{-4}$
T4	Basic	$2.85*10^{-6}$
T5	Basic	$1.347*10^{-4}$
T6	Intermediate	$405*10^{-8}$
T7	Basic	$5.09873*10^{-4}$
T8	Intermediate	10^{-5}
T9	Basic	$18*10^{-3}$
T10	Basic	$1.347*10^{-4}$
T11	Basic	$5*10^{-8}$
T12	Basic	$4*10\text{-}^{6}$
T13	Basic	$5*10^{-6}$
T14	Basic	$5*10^{-6}$
T15	Intermediate	$4*10^{-4}$
T16	Intermediate	$1.09873*10^{-4}$
T17	Basic	$2*10^{-4}$
T18	Basic	$2*10^{-4}$
T19	Intermediate	$1.09873*10^{-4}$
T20	Basic	$4*10^{-4}$
T21	Basic	$4*10^{-4}$
T22	Intermediate	$6*10^{-6}$
T23	Intermediate	10^{-4}
T24	Basic	$4*10^{-4}$
T25	Basic	$4*10^{-4}$
T26	Basic	$3*10^{-6}$
T27	Basic	$3*10^{-6}$
T28	Intermediate	$5*10^{-5}$
T29	Basic	$5*10^{-5}$

8 RESULTS AND DISCUSSIONS

8.1 Presentation of the software "GRIF"

The results presented in this paper are generated by the GRIF software. It is a platform of analysis of the systems which allows determining the indicators of dependability- Availability - Performance – Security.
GRIF lets the choice to the user opt for the technique of modelling the most adequate to the resolution of the studied system: block diagrams, Fault trees, graphs of Markov, Petri Nets. Architectures already integrated into the software facilitate this modelling. Developed within Total, GRIF benefits from more than 25 years of Research and development. This platform has very success full engines of calculation in the capacities of modelling answered to the needs of all the fabulists studies (htt).

8.2 Fault Tree results

The results of this section are presented in our previous work (Boudnaya, et al., 2014).
We launched the calculation in the interval [0,300h] with a step Δt=1h. Then we plot the unreliability of the railway signalling systems as a function of time (cf.figure 9).

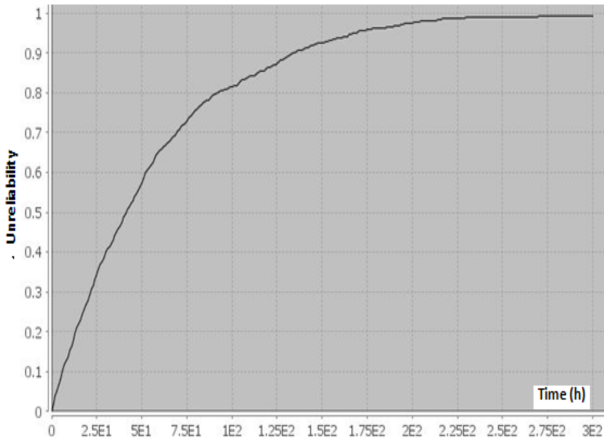

Figure 9.Level Crossing Unreliability using the fault tree analysis

As we can see, the level crossing system become unreliable at time t=300h. This is due to the fact that no maintenance policies are done on the system in this study.

8.3 Stochastic Petri Net results

So as to evaluate the unreliability of the Moroccan Level Crossing, we use the software "GRIF".
We took a number of history equal to 1000 and we launched the calculation in the interval [0, 300 h] with a step Δt=50h.
The results of thr unreliability which is represented by the number of token in the place P1 , are given in the table.6.

Table 6. Average number of token in the place P1 as a function of time

Time (h)	Average number of token in the place P1
0	0
50	0,216
100	0,547
150	0,766
200	0,894
250	0,962
300	1,01

Then we plot the unreliability of the railway signalling systems as a function of time, it is represented in the figure 10.

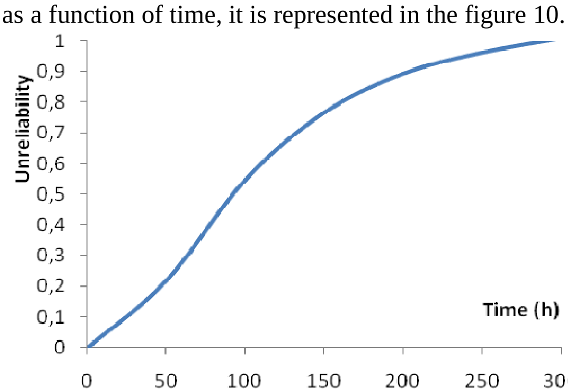

Figure 10.Level Crossing Unreliability using the Petri Net approach

From the previous curve, we can see that the occurrence probability of the Feared Event (Collision between train and vehicle) of the Moroccan level crossing system become equal to one at time t=300h.

8.4 Discussion of the results

As we can see, the two curves of the unreliability using the two approaches (fault tree analysis and Stochastic Petri Net) are almost the same allure, and the system becomes unreliable also at the same time t=300h.
So, the unreliability results of the Moroccan level crossing are validated.
These results can help engineers of maintenance and specialists in railway safety for the development of plans of maintenance and revisions of level crossings systems.

9 CONCLUSION

The Stochastic Petri Nets approach and the Fault Tree Analysis are methodologies for modelling and evaluating dependability of complex systems.
In this paper, we have proposed a comparative study of the unreliability of the Moroccan Level Crossing using the Stochastic Petri Nets approach and the Fault Tree Analysis.
It is a methodology to estimate the unreliability of the Moroccan railway signalling system over the time by integrating human factor and components failures rates data in order to validate these results.
In our future works, we will complete our study, by considering dependency between components and taking into account different types of data uncertainty (aleatory and epistemic uncertainty) using other methods like fuzzy logic analysis.

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