A reliability evaluation of the Moroccan level crossing system using fault tree modelling and importance measures

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ABSTRACT. *In this paper, we model the Feared Event (Collision between train and vehicle) of the Moroccan level crossing system using Fault Trees, in order to evaluate the unreliability of the system and to identify the critical components. First, a fault tree analysis to evaluate the system unreliability over the time is proposed. The human factors and components failure rates are taken into account. Then, an importance measures study is proposed to identify the critical components in the level crossing system.*

RÉSUMÉ. *Dans ce papier, nous modélisons l'événement redouté (Collision entre un train et un véhicule) du système de passage à niveau Marocain en utilisant les arbres de défaillance, afin d'évaluer la défiabilité du système et d'identifier les composants critiques. Tout d'abord, une analyse d'arbre de défaillance pour évaluer la défiabilité du système en fonction du temps est proposée. Les facteurs humains et les taux de défaillance des composants sont pris en compte. Ensuite, une étude de facteurs d'importance est proposée pour identifier les composants critiques dans le système de passage à niveau.*

KEYWORDS: *railway signalling system, level crossing, minimal cuts, fault tree, importance measures.*

MOTS-CLÉS : *système de signalisation ferroviaire, passage à niveau, coupe minimale, arbre de défaillance, facteurs d'importance.*

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1. Introduction

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

Several works related to this problem were presented in the literature. In (Paul *et al.*, 2013) , the authors examined driver situation awareness at rail level crossings using a network analysis-based approach and analyse revealed key differences between novice and experienced drivers situation awareness by proposing a series of wider driver behaviour applications. In (Joe & Clive , 2010) , the authors analysed the functional interactions between the existing level crossing functions and new technological systems in terms of reliability in order to upgrade and improve the existing systems reliability. The study presented in (Samantha *et al.*, 2014) showed 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 has identified 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) was 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. In (M.EASA, 1994), the authors presented a probabilistic method that accounted for the variations of the component design variables of sight distance at level crossings when computing system reliability. The method was validated using a Monte-Carlo simulation approach and has led to safer operations at railroad grade crossings. The paper (Rizati *et al.*, 2014) presented an insight view of translating the sequence of events to model pedestrian level crossing scenarios using Petri Nets approach. The developed model provided an understanding of the risky situation when pedestrian and vehicle are interacted at signalized intersections. In (Collart *et al.*, 2006) , level crossings were modelled by p-time Petri Nets in order to satisfy time specifications defined in safety requirements of railway systems. In (Ghazel, 2009) the authors proposed a global model of the level crossing implying at the same time the rail and road traffic by using stochastic Petri Nets. This model was obtained by a progressive integration of the developed elementary models; each of them described the behaviour of a section. It allowed 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 model the Moroccan level crossing using Fault Trees. It is an adequate approach to model the Feared Event (Collision between train and vehicle). We also have taken into account human factors. The failure data used in this approach are based on the Moroccan statistics of railway accidents (Bouchiba, 2013). Then, we compute the unreliability of the level crossing system as a function of the time. Furthermore, we identify the components within the level crossing system that more significantly influence the level crossing's behaviour with respect to its unreliability. As we cannot replace all components at one time to improve the level crossing's reliability, priority should be given to components that are more important.

2. The levels crossing 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 security for driving under the best conditions. The Moroccan railway network consists of 2110 km of lines including 600 km of double track (cf. figure 1).

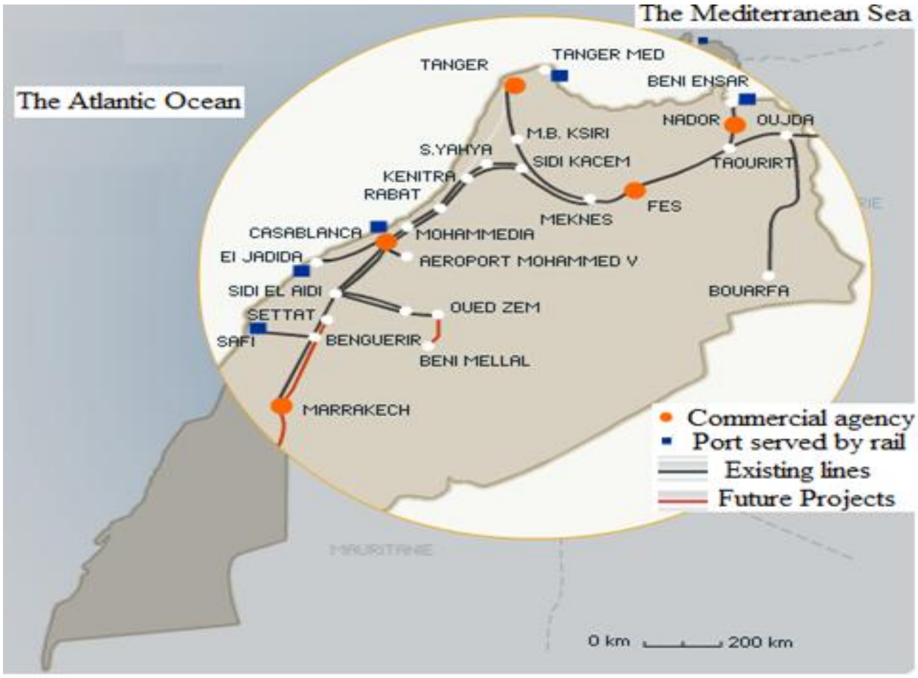

Figure 1. Moroccan railway map

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 guards manage the guarded level crossings. 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 security 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 rose.

*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), 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 in Morocco

2.3. Evolution of level crossings in Morocco

To enhance railway safety particularly at level crossings, the National Office of the Moroccan Railroad (ONCF) decided to delete several level crossings by building bridges, or install automatic level crossings. The curve in figure 3 shows the variation of level crossings number over years (ONCF, 2013). (A total of 77 LC deleted in 5 years).

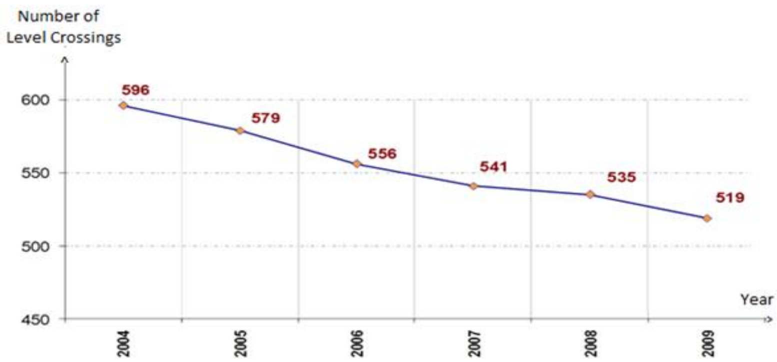

Figure 3. Variation of Moroccan level crossings number

Within the framework of the global program of the security 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 equipment will be installed on the unguarded level crossing and will allow announcing to the road users the approach of the train. For instance, figure 4 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).

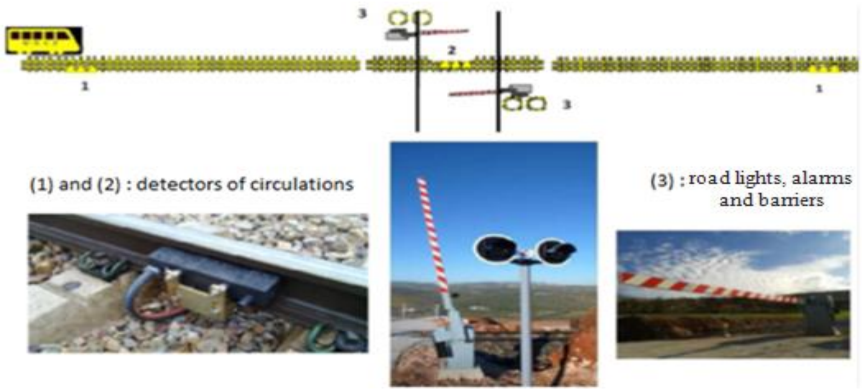

Figure 4. Prototype of the Moroccan Level crossing

2.4. Density of level crossings in Morocco

Currently, the Moroccan rail network has around 490 level crossings, 44 of them are guarded. On average, there are 23 crossings every 100 km. Table 1 shows the number of level crossing into each railway in Morocco at the end of 2011 (ONCF, 2013).

Table 1. The number of level crossing systems in each railway lines in Morocco at the end of 2011

Railway	Number of level Crossing systems
TANGER / S.KACEM	78
FES / OUJDA	73
S.EL AIDI / O.ZEM	72
S.EL AIDI / MARRAKECH	67
BENGUERIR / SAFI	50
NOUACEUR / EL JORF	16
CASA / S.EL AIDI	14
CASA / S.KACEM	13
S.YAHIA / M.B.KSIRI	9
S.KACEM / FES	7
Total	399
Other uncrowded railway: Beni Oukil/ Bouarfa, Oujda/Algerian border Benguerir/ Sidi azzouz	91

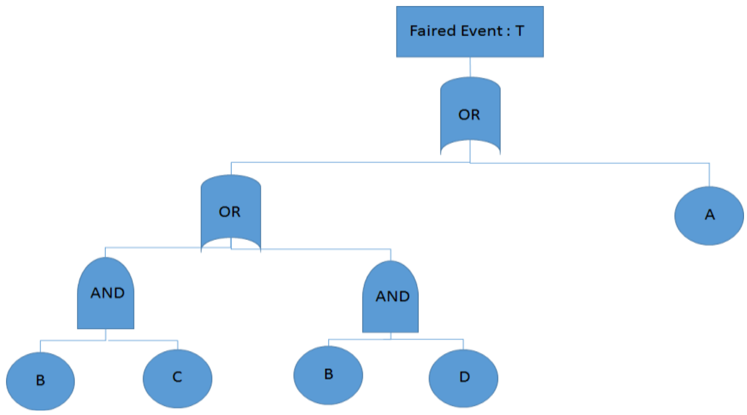

Figure 5. Example of fault tree

3. Fault tree analysis

3.1. Introduction

The fault tree (FT) 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). The FT displays information in a structured, graphic way that makes it easy to interpret and communicate. However, FTs require detailed knowledge of the design, construction and operation of the system.

FTs may fail if the technique is not implemented in a disciplined fashion or if the system problem is so complex that multiple levels of potential causes exist for each problem type.

3.2. Failure probability computations

In this work, the following key assumptions are taken into account:

– System and components are allowed to take only two possible states: either working, or failed.

– Component failures are stochastically independent. Failure of one component does not impact the failures of the other components.

– The system is coherent. That is, improvement of component states cannot damage the system.

– The components are not repairable.

The main treatments made on the fault trees are the research for the minimal cuts (the smallest realization combinations of events which lead 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 $\left(\Omega, \Theta, P\right)$ and a collection A = {A_1, A_2,. . .,A_N} of measurable subsets of Θ , Sylvester-Poincare equality says that:

$$P\left(\bigcup_{j=1}^{N} A_j\right) = \sum_{j=1}^{N} P(A_j) - \sum_{(j,k)/1\leq j\leq k\leq N} P(A_j \cap A_k) + \sum_{(j,k,l)/1\leq j\leq k\leq l\leq N} P(A_j \cap A_k \cap A_l) - ... \quad (1)$$
$$+(-1)^{N+1} P(A_1 \cap ... \cap A_N)$$

Or as a short form as follow:

$$P\left(\bigcup_{j=1}^{N} A_j\right) = \sum_{I \subseteq A} (-1)^{|I|+1} P(\bigcap_{A_j \in I} A_j) \quad (2)$$

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 7. The three 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):

$$\begin{aligned} P(T) &= P(A \cup BC \cup BD) \\ &= P(A) + P(BC) + P(BD) - P(ABC) - P(BCD) + P(ABCD) \end{aligned} \quad (3)$$

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 terms of this development (rare event approximation).

4. Study 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 person successfully achieves a task or a work at a required time if a temporal requirement is necessary. In the latter, several models were proposed to estimate and study the human factor, among these models:

– Models stemming from the psychology and from the ergonomics of the work: Among these models, the model SRK of Rasmusen (North-Holland, 1986), supposes that the cognitive control and the human cognition are made at several levels of abstraction. The highest layers correspond to a more and more complex data processing.

– Models stemming from engineering sciences: The method THERP (Techniques for Human Error Rate Prediction) (Swain & G, 1983), which is a method centred on the operator (individual level), is said first generation because of the sequential model of accident on which it is based.

– Models stemming from human and social sciences: By taking for example the method MERMOS (Magne & Vasseur, 2006) which is developed to update the approach of evaluation of the missions of the operators in accidental conduct, the failure of the mission can arise by several independent scenarios of failures (that will be necessary to quantify).

In our study, we suppose that the rate of error of the operator 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 $\lambda_{HF}.\Delta t$.

To obtain a significant value of the rate of error, we considered the statistics presented in (Bouchiba, 2013) in Morocco from 2000 till 2008.The numbers of accidents on 10 busiest lines are given in the Table 2.

Table 2. 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 different types of human error related to road part or rail part cause about 90% of railway accidents. Thus the error rate of the operator on every line is:

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

Where:

a: number of accidents.

p: human error percentage

y: number of years

r: number of railway

5. Importance measures of basic events of fault tree

In 1969, Birnbaum first introduced the concept of components' reliability importance (Birnbaum, 1969). This measure was defined as the probability that a component *i* is critical to system failure, i.e. when component *i* fails it causes the system to move from a working to a failed state. The Birnbaum's importance measure of a component *i* can be interpreted as the rate at which the system's reliability improves as the reliability of component *i* is improved. Analytically, Birnbaum's importance interval measure of a component *i* is defined by (Birnbaum, 1969).

$$I^B(i) = R_S|\{R_i = 1\} - R_S|\{R_i = 0\} \tag{5}$$

Where $R_S|\{R_i = 1\}$ and $R_S|\{R_i = 0\}$ denote respectively the reliability of the system when it is known that component *i* is in a working state and when component *i* is in a failed state.

In this study, we propose to define the importance measure of an event i which represents the failure occurrence of a component *i* as follows:

$$I(i) = P_S|\{P_i = 1\} - P_S|\{P_i = 0\} \tag{6}$$

Where $P_S|\{P_i = 1\}$ and $P_S|\{P_i = 0\}$ denote respectively the probability of top event occurrence when it is known that event *i* is occurring (i.e., $P_i = 1$) and when it is known that event *i* is not occurring (i.e., $P_i = 0$).

6. Case study

6.1. Description of the system

The Moroccan railway signalling system consists of three parts (figure 6) :

*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).

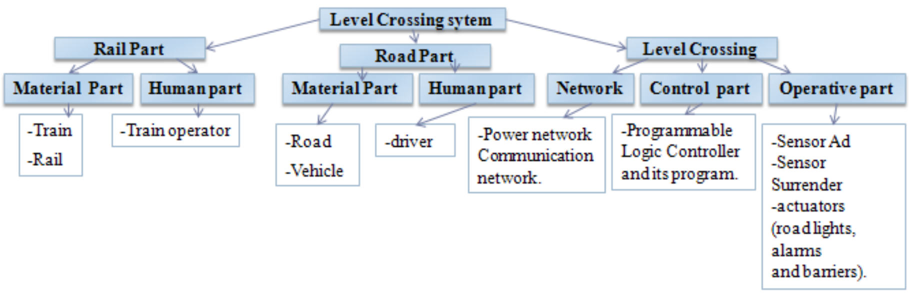

Figure 6. Moroccan Level crossing components

*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 Ad and Sensor Surrender) and actuators (the road lights, the alarms and the barriers).

Note that in this case study, since the components are not repairable, the system availability is equal to its reliability.

6.2 Fault Tree analysis

From the description of the railway signalling system, we were able to model the Feared Event (Collision between train and vehicle) by a Fault Tree. It is a model consisting of 14 logic gates (1 AND gate and 13 OR gates). The AND gate models the redundancy in the railway system which is represented by the three actuators (alarms, road lights and barriers).The basic events which produce the Feared event are given in the Table 3 (Brissaud *et al.*, 2007 ; Houasnia, 1999 ; Cabau, 1999). The system is composed by electronic, electric or electromechanically components so, we suppose that theses events follow exponential laws with an approached failure rates (cf. Table 3). Thus, the occurrence probability of each basic event *i* at time *t* is given by $P_i(t)=1-\exp(-\lambda_i t)$. The symbols of intermediate events of the fault tree are given in Table 4.

Table 3. Failure rates of components

Symbol	Basic Events	Failure Rates : λ (h^{-1})
HF	Human Failure	$1,347*10^{-4}$
VF	Vehicle Failure	$1,800*10^{-2}$
RF	Rail Failure	$2.850*10^{-6}$
PLCF	Programmable Logic Controller Failure	$4,000*10\text{-}^{6}$
PE	Program Error	$5,000*10^{-8}$
NCF	Network Communication Failure	$5,000*10^{-6}$
PNF	Power Network Failure	$5,000*10^{-6}$
SAF	Sensor Ad Failure	$2,000*10^{-4}$
SSF	Sensor Surrender Failure	$2,000*10^{-4}$
AF	Alarm Failure	$4,000*10^{-4}$
LF	Light Failure	$4,000*10^{-4}$
MF	Motor Failure	$3,000*10^{-6}$
TSF	Transmission System Failure	$5,000*10^{-5}$

The Fault Tree which describes the Feared event (Collision between train and vehicle) is given in Figure 7.

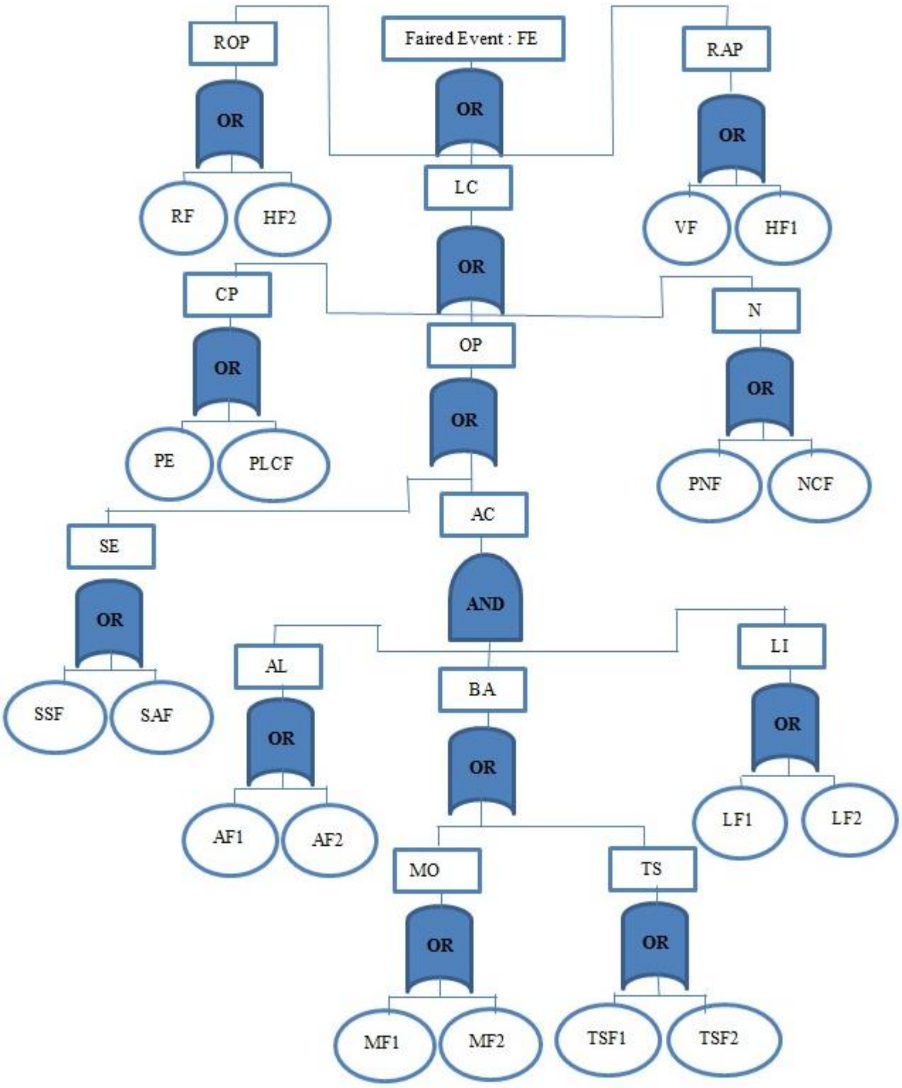

Figure 7. Fault Tree of Level crossing

The minimal cuts C of the Moroccan Level Crossing model are given in the following expression:

C={[HF2],[RF],[PE],[PLCF],[SAF],[SSF],[PNF],[NCF],[VF],[HF1],[AF1,LF1,MF1],[AF1,LF1,MF2],[AF1,LF1,TSF1],[AF1,LF1,TSF2],[AF1,LF2,MF1],[AF1,LF2,MF2],[AF1,LF2,TSF1],[AF1,LF2,TSF2],[AF2,LF1,MF1],[AF2,LF1,MF2],[AF2,LF1,TSF],[AF2,LF1,TSF2],[AF2,LF2,MF1],[AF2,LF2,MF2],[AF2,LF2,TSF1],[AF2,LF2,TSF} (7)

Table 4. 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
M	Motors
TS	Transmission Systems

6.3 Results and discussion

To evaluate the reliability of the level crossing system, we use Henry-Poincare Formula applied to minimal cuts of the Fault Tree presented in Figure 7. We launched the calculation in the interval [0,350h] with a step $\Delta t=1h$. Then we plot the unreliability of the level crossing system as a function of time (cf. Figure 8). 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.

For example, we consider a Level Crossing at the line FEZ-SIDI KACEM with a density of 42 trains by day, we suppose that for each train the Level Crossing is busy for 2 min, so 84 min=1.4 h by day with a rate of occupation of RO=1.4/24=5.83%.The Level Crossing in this line becomes unreliable at t=300/1.4=214.

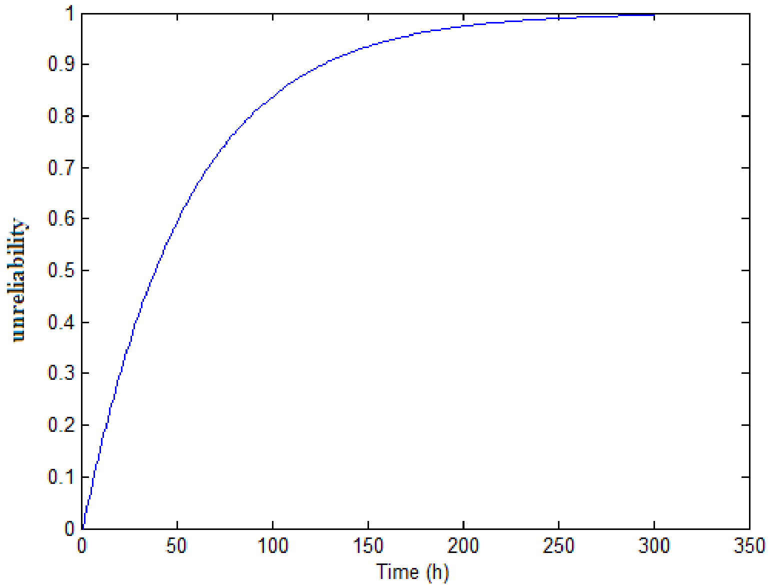

Figure 8. Unreliability of the level crossing system over the time

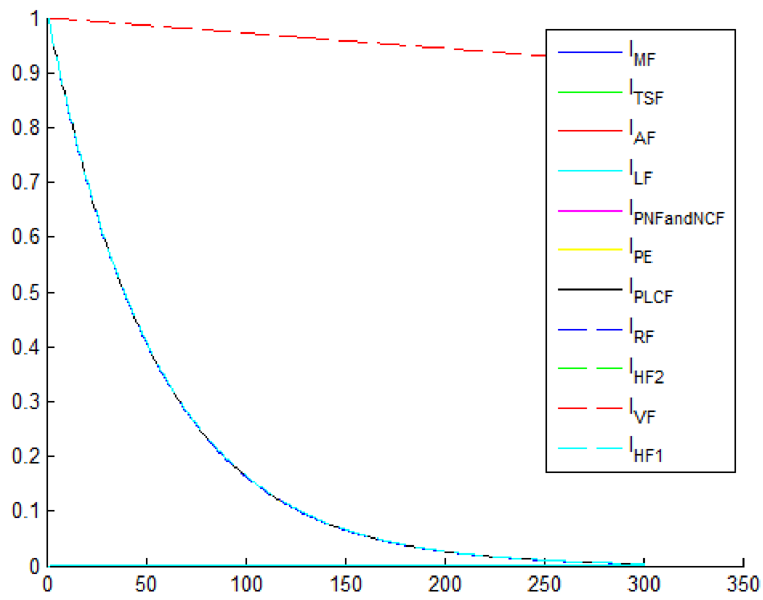

Figure 9. Importance measures of components over the time

In Figure 9, we plot important measures of components as a function of time. As we can see, the most critical components are: VF, HF1, PLCF, PNF and NCF. Even though we can not obviously reduce the vehicle failures (which is the most critical component but it is out of scope of the paper because we are only concerned by the level crossing system), we can focus our efforts on Human Failure (HF), Programmable Logic Controller Failure (PLCF), and Failures Networks (PNF and NCF) in order to reduce efficiently the Faired Event occurrence.

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.

7. Conclusion

In this paper, we have proposed an approach based on Fault Tree Analysis (FTA) to evaluate the occurrence probability of the Feared Event (Collision between train and vehicle) of the Moroccan Level Crossing system by taking into account human factor and components failures data. We have also identified the most critical components of this Level Crossing in terms of criticality.

In our future work, we will complete our study, by considering epistemic uncertainties of components failure rates as well as failure dependencies between components.

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