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A modelling of disruptions cascade effect within a rail transport system facing a flood hazard

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Abstract

The vulnerability of rail transport systems facing flood hazard, increased by the climate change, is a burning issue for the future urban risks management. Analysing the resilience of rail transport systems against flood hazard appears necessary for improving the proper functioning of cities that strongly depend on such critical infrastructures. The critical infrastructures are complex systems in which the components are particularly interdependent. This interdependency implies many failures caused by cascade effect within the system. From dependability methods, this paper provides a global methodology in order to automatically produce the chains of failures caused by cascade effect within a rail transport system facing to a flood hazard.

Keywords: Rail transport system – flood hazard – cascade effect modelling – dependability methods.

1. Introduction

Although the vulnerability of rail network systems facing different events is not theoretically demonstrated, facts and figures on international transport systems reveal empirically it. Indeed, on Netherlands rail infrastructure, between 5 % and 10 % of all failures in 2003 is weather related (Duinmeijer & Bouwknecht, 2004). Besides, nowadays adverse conditions cause 20 % of all unplanned delays on UK railway network (Thornes & Davis, 2002) and if no changes are made to maintenance processes, the total costs of heat-related delays will eventually double to nearly £23M

during extreme summers (Dobney *et al.*, 2010). In 2007, heavy rainfall in New York shut down 19 major segments of the subway system because of flooding issues, affecting two million customers (MTA, 2007). Thus, the continuity of urban rail transport service is necessary to maintain citizens' activities and economic flows. The costs of weather-related incidents can be considerable. In 1996, heavy rains raised the level of Boston's Muddy River, flooding a tunnel entrance to the city's subway system. The damages cost approximately \$75 million (UCS, 2007). The rail transport systems are indubitably vulnerable to many natural hazards of different intensities.

Furthermore, two major facts have a direct impact on the rail transport systems vulnerability. The first fact concerns the climate change, recognized by the international scientific community, which projects the same types of events to become more frequent and more severe in the next years. Without any structural and organisational adaptations, the impacts on rail transport systems, large and small, will increase and affect all regions. The second fact is about the growth of the world population; since 2007, half the world population has lived in urban areas (UN-Habitat, 2012). This established fact implies a greater need of urban mobility and public transport systems operating in increasingly intense meteorological conditions.

Thus, in the long term, the simultaneity between the growing urbanisation and the climate change threaten the modern cities. More specifically, urban technical systems as rail networks will be probably highly disrupted in a natural hazards context. But, the modern cities are dependent on technical systems, considering them as critical infrastructures to ensure their functioning (Lhomme *et al.*, 2011). Reducing the vulnerability of modern cities against natural hazards involves improving the resilience of critical infrastructures, such as transport systems. A study about the resilience of transport systems prove to be necessary to increase urban resilience at a global scale.

Flood risk particularly affects the sub-systems of urban transport systems through the existing functional interdependencies between the components. The assumption made in this paper is that the modelling of disruptions cascade effect of transport system components facing a flood hazard offers an interesting way to assess the resilience of such a system. In a first part, the methodological choices to study the interdependencies between the transport system's components are developed. In a second part, the methods are applied to a typical rail transport system facing to a flood hazard and an informatic tool is implemented in order to determine all the disruptions cascade effect, that is to say the components interdependencies.

2. Methodological choices and working assumptions

2.1. Dependability methods

Some types of natural hazard have a complex impact on transport system. The first characteristic of this complexity is physical. Indeed, the hazard, characterizing by its intensity, disrupts a great number of components putting them potentially out of service. The second characteristic of this complex impact is functional. Indeed, subsequently to the components disruptions, the operating of the transport system may be perturbed in varying degrees: trains slowing down, parts of a rail network segments unavailable... The third characteristic of this complexity, and perhaps the most difficult to characterize, comes from the interrelationships between the

components. Indeed, the interrelations are very numerous in a rail transport system. As a complex system, composed of many elements, the interactions between the components have a non-linear behaviour (Simon, 1991) because most of components needs other ones to properly operate. A single disruption within the system can create many indirect disruptions relatively unknown.

Different types of methods and approaches exist for the risks analysis, usually used in the civil engineering field (Peyras, 2003). The first type of approaches employs technical expertise, essentially for establishing rapid diagnosis or validating specific studies. The second method consists in modelling physically the system in order to study its behaviour. The third type of approaches uses existing data coming from the system itself (monitoring data, visual inspections) to establish statistical models. The fourth risks analysis approach builds a functional modelling. This is a systemic approach identifying the main risks for the system, ordering maintenance activities. The functional modelling is based on dependability and safety methods.

These four approaches are applicable in other contexts, as rail transport systems facing a flood hazard. Indeed, specialists can be mobilized during technical studies, physical models of railway subsystems (tracks, vehicles...) can be built, and monitoring data allow operators to establish behaviour laws of components. But, the global approach of functional modellings seems more relevant in case of a rail transport system facing a flood risk. Indeed, the complexity of the flood risk impacts affecting all the components appears to be approachable only with a systemic approach.

Thus, in this paper, a methodology (**Figure 1**) is provided to establish failure scenarios due to cascade effect between the components of a rail transport system in case of a flood hazard. This methodology is based on dependability methods successively implementing on a rail transport system: the Functional Analysis (FA), the Failure Modes and Effects Analysis (FMEA) and the Fault Tree Analysis (FTA).

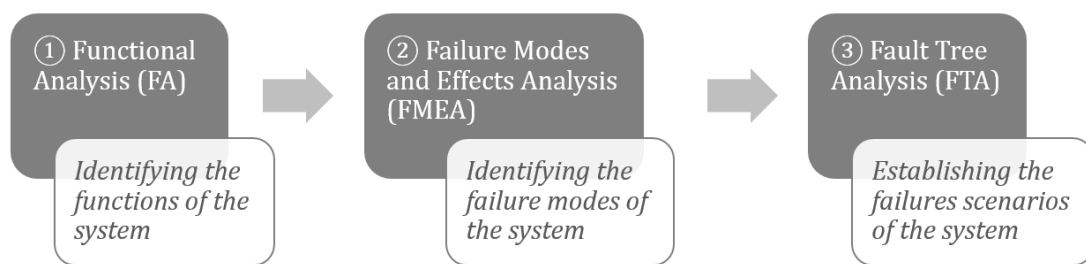


Figure 1. The methodology used to establish failure scenarios due to cascade effect between the components of a rail transport system facing a flood hazard

2.2. Description of the studied system

The initial step is to break down the rail transport system into sub-systems, then to break down each sub-system into components. This double breakdown gives a characterisation of the system vulnerability at a small scale, the component scale. This work has been realized for two types of rail transport system, according to their

level positioning: at ground level and at underground level. Indeed, for a given hazard, the experience shows that the level positioning has an influence on the vulnerability of the system (Gonzva et al., 2014), particularly in the well-known case of the flood risk threatening to underground infrastructures (Duffaut & Labbé, 1995). Eight sub-systems have been identified (**Figure 2**) as relevant to characterize the system, for the two positioning levels studied. Then, nineteen components have been identified for the two types of system, defining the theoretical framework for the functional analysis.

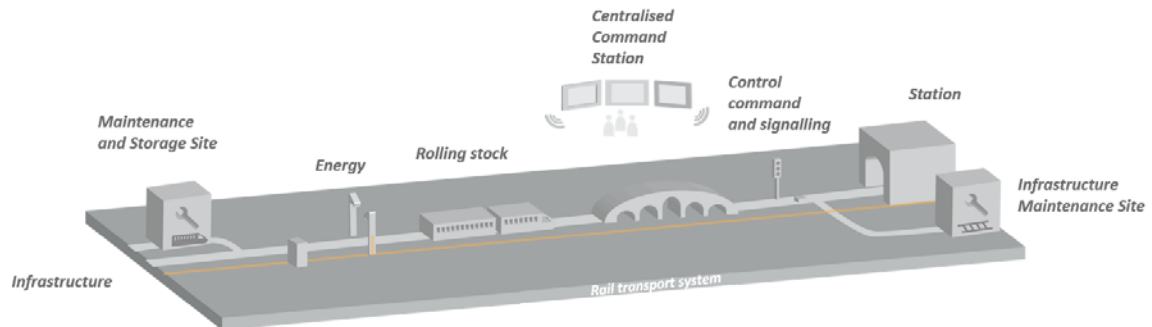


Figure 2. The breakdown of a rail transport system into sub-systems (Gonzva & Gautier, 2014)

3. Application on rail transport systems in case of flood hazard

3.1. Functional Analysis (FA) and Failure Modes and Effects Analysis (FMEA)

From the previous structural analysis, the functional analysis consists in identifying the functional relationships or interactions between all the components. These relationships of different types have been studied to build a functional modelling of the rail transport system, according to the level positioning (ground or underground level) and according to the situation (normal or in an hazard context).

Three types of relationships have been distinguished:

- In a normal functional situation :
 - The contact relationships : highlight the existence of at least one physical connection between two elements of the system;
 - The dependence relationships : highlight the fact that the proper functioning of an element B is determined by the proper functioning of a preceding element A;
- In a flood hazard situation :
 - The vulnerability relationships: highlight a qualitative degree of vulnerability against the flood hazard for each element of the system.

These functional modellings are represented as a synthetic diagrams: the Functional Block Diagrams (FBD) (Zwingelstein, 1996). The FBD are realized at the sub-system

scale, identifying the contact, dependence and vulnerability relationships between the eight sub-systems. The **Figure 3** and the **Figure 4** show respectively the FBD obtained in a normal functional situation and the FBD obtained in a flood hazard situation, for a rail transport system positioned at ground level.

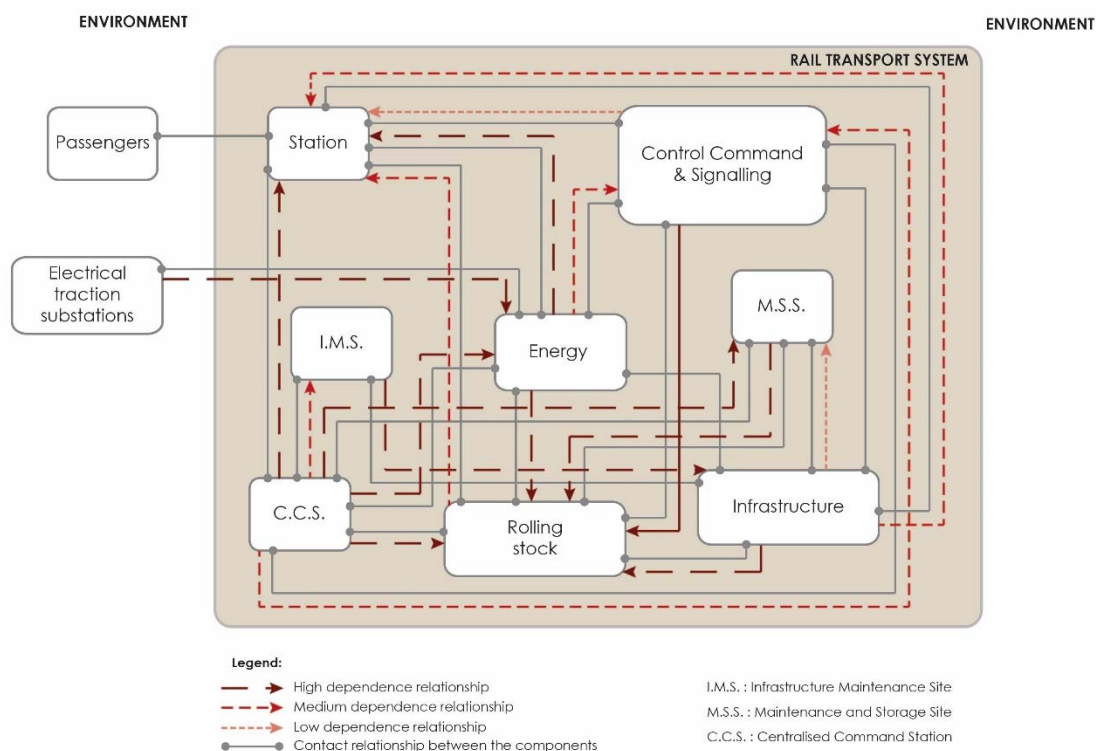


Figure 3. Functional Block Diagram (FBD) of a rail transport system at ground level and in a normal functional situation

The functional relationships highlight different degrees of dependence between components. Indeed, the “rolling stock” subsystem is highly dependent on the “energy” subsystem, the second one providing the traction current for the operating of the first one. The “energy” subsystem is itself dependent on the “electrical traction substation” element, an element of the system’s environment. These examples of dependency relationships imply the existence of vulnerability induced relationships. Indeed, the disruption of an element stricken by a flood hazard induces other disruptions due to the dependency relationships to the initiating element. In fact, all these functional interactions, more or less numerous and complex, between the components of the system lead to cascade effect disruptions.

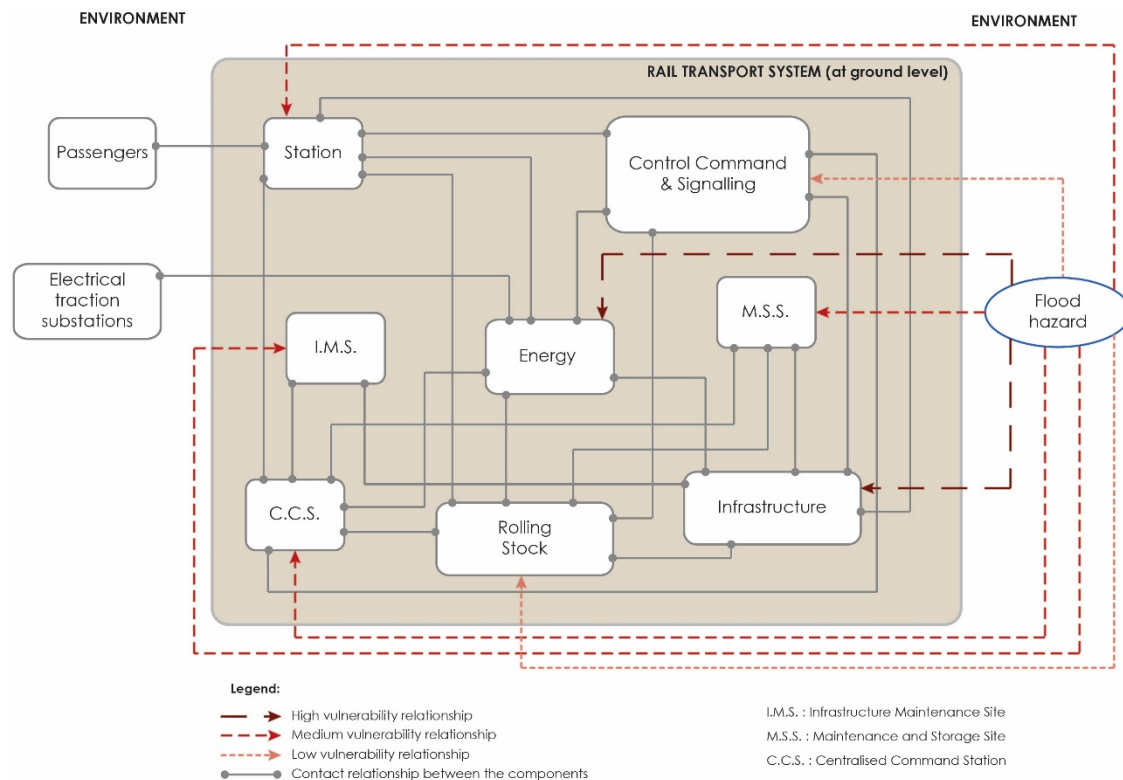


Figure 4. Functional Block Diagram (FBD) of a rail transport system at ground level and in a flood hazard situation

At this stage of the study, the functional analysis is completed. This first analysis, especially in flood hazard situations, provides the sub-systems implied in the system chain of failures. But, to determine more specifically the vulnerability of a rail transport system facing to a flood hazard, it is necessary to:

1. Break the subsystems down in constitutive elements to have a better understanding of how sub-systems disrupt;
2. Explicate the disruptions causes of each component facing to a flood hazard and the induced effects of these disruptions on the system.

The Failure Modes and Effects Analysis (FMEA) is applied to resolve these issues. Indeed, the FMEA is a tool used to analyse component failures and identify the resultant effects on system operations. For each component, the FMEA determines the functions provided, the failure mode meaning the way by which a failure occurs, the failure causes and the failure effects. Thus, two FMEA have been realized: for a rail transport system positioned at ground level and at underground level; around 70 functions and 300 “causes-effects” pairs – the failure of a function may be provoked by several causes and, thus, generate several effects – have been identified. An extract of the FMEA for the “ballast”¹ component is presented in the **Table I**.

¹ Ballast: the crushed stones upon which the railway is laid.

Table I: Extract of the FMEA realized for a rail transport system at ground level.

Compo.	N°	Function	Failure mode	Failure causes	Failure effects
Ballast	47	<ul style="list-style-type: none"> Ensuring the ballasted track stability 	<ul style="list-style-type: none"> No ensuring of the ballasted track stability 	<ul style="list-style-type: none"> Collapsing of the ballasted track 	<ul style="list-style-type: none"> Traffic interruption
	48	<ul style="list-style-type: none"> Bearing the load from the railroad ties Holding the track in place as the trains roll by Facilitating drainage of water 	<ul style="list-style-type: none"> No bearing the load from the railroad ties No holding the track in place as the trains roll by No facilitating drainage of water 	<ul style="list-style-type: none"> Ballast transport Ballast submerged by water 	<ul style="list-style-type: none"> Collapsing of the ballasted track
	49	<ul style="list-style-type: none"> Withstanding water hydro-mechanical pressures Preventing the ballast submersion Preventing ballast transport 	<ul style="list-style-type: none"> No withstanding water hydro-mechanical pressures No preventing the ballast submersion No preventing ballast transport 	<ul style="list-style-type: none"> High flow rate High height of water High immersion time Carrying of solid elements (trees...) by water flow 	<ul style="list-style-type: none"> Ballast transport Ballast submerged by water
	50	<ul style="list-style-type: none"> Ensuring the track bed stability during the flood event 	<ul style="list-style-type: none"> No ensuring the track bed stability during the flood event 	<ul style="list-style-type: none"> High height of water Transport of solid elements (trees...) by water flow 	<ul style="list-style-type: none"> Ballast transport Collapsing of the ballasted track

Thus, the FMEA is a powerful tool to structure the relevant information about the disruptions of each component (Lhomme et al., 2011).

3.2. An informatic tool for the cascade effect modelling

The completeness of the FMEA method allows to determine chains of failures. Indeed, the FMEA identified the interdependent connections between the components permitting to produce many chains of failures due to cascade effect. However, considering that the system is divided into nineteen components and that each component presents several failure causes and failure effects, many chains of failures due to cascade effect can be produced. In these conditions, the production of all the chains of failures is a tedious and complex work. One option to reduce the complexity of the problem would be to identify the most likely chains of failures, in order to reduce the number of relevant chains to produce. This option is not a satisfactory solution because it limits the cascade effect modelling and analysing of the whole rail transport system facing to flood hazards. The main objective, according to the assumption made in this paper that the modelling of disruptions cascade effect offers an interesting way to assess the resilience against flood hazard, is to exhaustively establish the chains of failures.

The idea retained consists in automating the production of the chains of failures, in order to use the completeness of the FMEA realized previously. An informatic tool has been developed. Indeed, the creation of a database using the FMEA as input data has been selected. The database allows to determine automatically the direct causal relationships between all the functions of all the components (**Figure 5**). A direct causal relationship is identified when the “failure effect” of a first component is

exactly the “failure cause” of a second component, and so on. But, a preliminary work of making a typology of the causes and the effects is essential to automate the determination of the direct causal relationships. Indeed, in terms of algorithmic approach, this typology is necessary to identify the direct causal relationships which precisely are the direct chain of failures between the functions and, as a result, between the components.

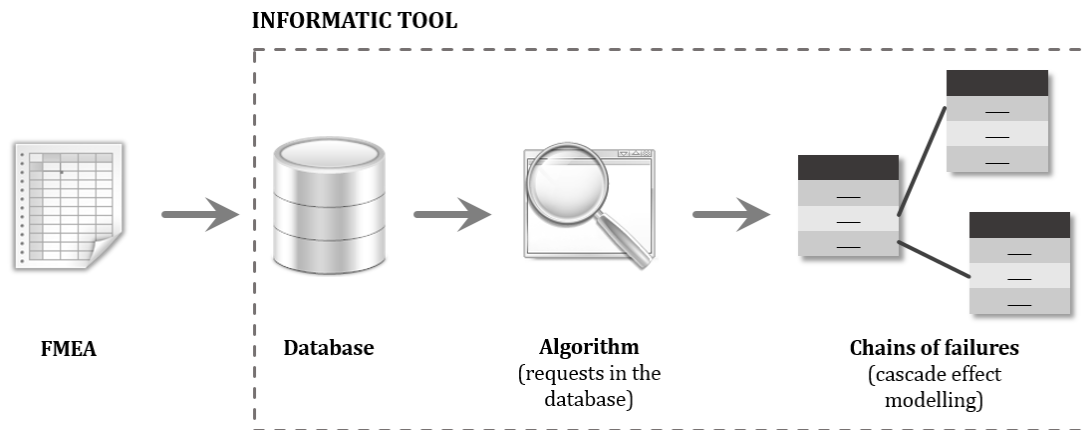


Figure 5. Functioning of the informatic tool developed (inspired by (Lhomme et al., 2011))

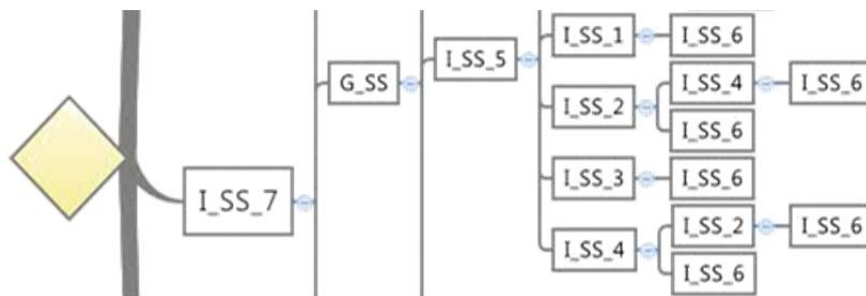


Figure 6. Extract of a chain of components failures presented as a causal graph

4. Discussion

For the two positioning levels studied, hundreds of chains of failures have been produced by the informatic tool. The range of components in the chains of failures due to cascade effect is from two to seven. However, all these chains of failures have been theoretically established. It is necessary to validate these results and the methodology on the basis of experience feedbacks concerning rail transport systems vulnerability against flood risks.

A statistical study has been realized on the chains of failures produced by the tool. The objective is to determine the statistical behaviour of components in terms of failures cascade effect. The typology of components used in (Lhomme et al., 2011) can be adapted to rail transport systems: aggressive, sensitive and intermediary components. The aggressive components are at the beginning of many chains of

failures; on the contrary, the sensitive components are at the end of many chains of failures; the intermediary components are not at the origin or at the conclusion of the chains of failures but they spread the disruption effect on other components (FloodProBE Project, 2013). For example, for the rail transport system at the ground level, the statistical results obtained from the hundreds of chains of failures illustrate that (**Figure 7**):

- The “station” component is the largest number of times at the end of the chains of failures, regarded as a sensitive element;
- The “drainage system” component is the largest number of times at the beginning of the chains of failures, regarded as an aggressive element.

The results obtained from this theoretical methodology seem to be corroborated by experience feedbacks. In 2000, the so-called “Sarry event” occurred around the Sarry city (France) on the high-speed line between Paris and Lyon is an incident caused by a brief and violent rainstorm. During the incident, the ballast removed over a distance of 100 m on both tracks because of the drainage system obstruction (Pams-Capoccioni et al., 2013). More precisely, because of an important water runoff during the rainstorm, the drainage system was obstructed by mudslides and flows of solid materials, resulting in overwhelmed tracks by water. Thus, the disruption of the drainage components (pipes and ditches) generated through a cascade effect the failures of other components like the ballast, until the traffic interruption of the line.

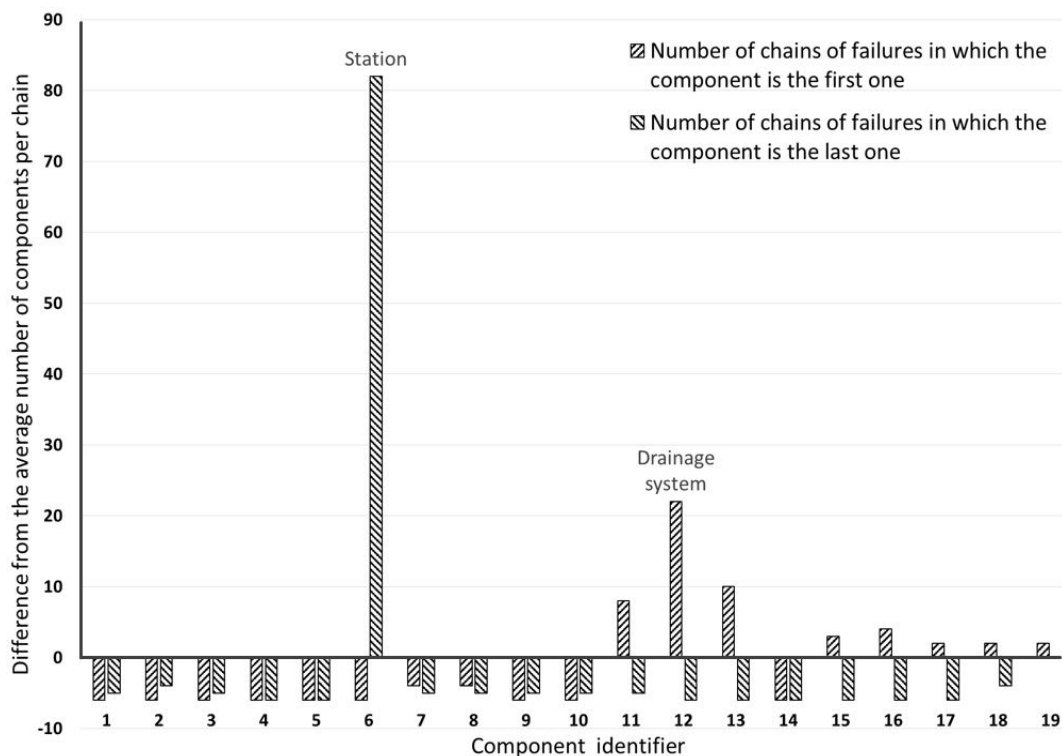


Figure 7. Statistics obtained for the rail transport system at the ground level

5. Conclusion

The assumption made in this paper is validated: modelling the disruptions cascade effect of rail transport system components facing a flood hazard offers an interesting way to assess the resilience of such a system. The interdependencies between the sub-systems and the components are the source of the cascade effect observed. In order to analyse the mechanisms of these interactions within the system, a global methodology has been established and applied to a rail transport system positioned at ground level and underground level. Based on the use of dependability methods, an informatic tool has been developed in order to exhaustively produce the chains of disrupted components due to cascade effect. Thus, the informatic tool highlights all the direct causal relationships between all the components, providing a global cascade effect modelling and identifying the scenarios of disruptions. Although this methodology is theoretical, experience feedbacks from rail transport systems validate some conclusions.

Further research around this methodology may be investigated. Firstly, the methodology can be applied to a rail transport system facing other natural hazards, providing the same type of cascade effect modelling. Secondly, this methodology can be applied at different scales, at multi-systems level, at the subsystems levels and at the component levels. Thirdly, the quality of the FMEA directly influences the relevance of the obtained chains; this is the reason why the FMEA must be realized with the help of experts in each field.

The methodology is suitable for other critical infrastructures (Lhomme et al., 2011) and critical urban services (Toubin et al., 2013). Thus, through the functional modelling, a global analyse of the cities resilience facing natural hazards appears to be relevant and useful in terms of urban risks management.

6. Acknowledgements

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