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A model to quantify the resilience of mass railway transportation systems

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ABSTRACT

Traditional risk management approaches focus on perturbation events' likelihood and their consequences. However, recent events show that not all perturbation events can be foreseen. The concept of resilience has been introduced to measure not only the system's ability to absorb perturbations, but also its ability to rapidly recover from perturbations. In this work, we propose a simulation-based model for quantifying resilience in mass railway transportation systems by quantifying passenger delay and passenger load as the system's performance indicators. We integrate all subsystems that make up mass railway transportation systems (transportation, power, telecommunication and organisation subsystems) and their interdependencies. The model is applied to the Paris mass railway transportation system. The model's results show that since trains continue running within the system even by decreasing their speed, the system remains resilient. During the normal operation of the system as well as during perturbation, the model shows similarities with reality. The perturbation management plan that consists of setting up temporary train services on part of the impacted line while repairing the failed system's component is considered in this work. We also assess the extent to which some resilient system's capacities (i.e. absorption, adaptation and recovery) can increase the resilience of the system.
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1. Introduction

Our societies are becoming increasingly dependent on critical infrastructures. An infrastructure is called critical when its unavailability has serious impact on well-being, health, safety and economy of the region in which this infrastructure is located [1–3]. Today, these infrastructures are increasingly complex and interdependent, so that a perturbation in one of these infrastructures becomes difficult to control and can quickly spread to other facilities because of their interdependencies. Energy, telecommunications and transportation systems are examples of critical infrastructures [2,4,5].

These critical infrastructures can be the target of malicious acts. The terrorist threat to mass transportation systems is high and will remain so for the foreseeable future. Historical evidence, including the recent attacks in Madrid in 2004, London in 2005 and Mumbai in 2008, show that transportation systems are exposed to this kind of threat. The nature of a public transportation system is such that:

- it is a public infrastructure (open to everyone),
- it has many points of entry and exit,
- it is interconnected through a vast range of transportation modes.

These characteristics increase the vulnerability of transportation systems and make them attractive to terrorists. Terrorists are attracted to mass transportation systems not only due to the large number of casualties attacks can cause, but also because of the social, economic and political consequences of these attacks.

In order to protect critical infrastructures from threats, several studies have been conducted on the risk analysis of sociotechnical systems. There are several approaches for analysing risk. They often consist of assessing the probability of occurrence of the threat, the exposure and the vulnerability of the infrastructure relative to the threat. Most approaches found in the literature encompass the evaluation of the likelihood and/or frequency of occurrence of the threat. This creates added difficulties when analysing rare events with serious consequences to the studied system. Because these events are rare, it is difficult to assess their probability. In addition, due to the multitude of threats that exist on critical infrastructures, it is impossible to protect each component against each of these threats and prevent their occurrence.

There is then a real need to understand how, in time of crisis, the system can combine its own resources and the external resources that can be mobilised to ensure business continuity. The concept of resilience has been introduced to measure the system's

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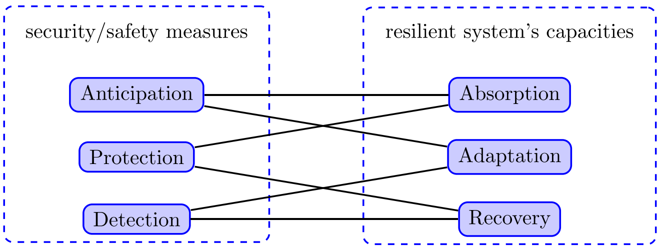

Fig. 1. Relationships between a system's security/safety measures and a resilient system's capacities.

ability to absorb perturbations and to adapt itself to avoid potential damages and also its ability to rapidly recover from perturbations [6–8]. The concept of resilience consists of preparing the system for possible perturbations, as if the latter were inevitable. This requires a regular assessment of the system management plans, security/safety measures, risk analysis and measures to protect the system against these risks, etc. Building and strengthening a resilient system involves implementing systems that incorporate, inter alia, several risk management plans. Fig. 1 describes the relationships between a system's security/safety measures [9] and a resilient system's capacities. Regarding infrastructure security/safety measures, the concept of resilience can be seen as [10] a concept that emphasises on understanding how to overcome perturbations, how people learn and adapt themselves by creating security/safety in an environment which has faults, hazards, trade-offs and multiple objectives.

In this paper, we propose a simulation-based model for quantifying resilience in mass railway transportation systems by quantifying passenger delay and passenger load as the system's performance indicators. The model proposed in this paper simulates mass railway transportation systems' operating conditions and integrates all subsystems that make up mass railway transportation systems: (a) stations, tracks, trains, passengers and their interactions; (b) power subsystem and its interaction with other subsystems; (c) telecommunication and organisation subsystems and their interdependencies with other subsystems.

This work is organised as follows. Section 2 presents a brief state of the art of sociotechnical systems resilience. In Section 3, we describe a model that quantifies the resilience of mass railway transportation systems. Particular attention is paid to components interdependencies in the latter section. This model is applied to the Paris mass railway transportation system in Section 4. We end this paper with a conclusion in Section 5.

2. Related research overview

In this section, we present some definitions and characteristics of a resilient system. We then describe how resilience is quantified in sociotechnical systems, and transportation systems in particular. We end this section with the positioning of the model presented in this work regarding the literature review.

2.1. Some definitions of resilience in sociotechnical systems

The first definition of sociotechnical systems resilience as used in this paper was given in 1973 by Holling when he studied the resilience of ecological systems [11]. Holling defines resilience as the persistence of species in an ecological system and the relationships between the considered species facing man-made disturbances like man's domestic and industrial wastes, changes in fish populations by harvesting, etc. By persistence, the author means the probability of the non-extinction of the system's species. In 1986 and 1992 Holling provided two more definitions of resilience [12,13]. The main idea that emerges in Holling's different definitions concerns the perturbation that can support the system without changing its state (the appearance and/or extinction of species). Since Holling published these definitions, the concept of resilience has evolved considerably. This concept has been adapted to many other fields such as economic [14–16], community [17–19], and sociotechnical system [6,7,20,21].

The most quoted definition of sociotechnical systems' resilience in the literature is that of Bruneau et al. [7] where the authors studied the resilience of hospitals in a region in the aftermath of an earthquake. They define resilience as the ability of a system to reduce (1) its failure probabilities; (2) the consequences from failures, in terms of casualties, damage, and negative economic and social consequences; (3) its recovery time. We note that Bruneau et al. introduce the possibility of acting on the system before the perturbation occurs. This aspect is not taken into consideration in Holling's definition of resilience. Additionally, Bruneau et al. emphasise the ability of the system's organisational components to bring the system back to a state comparable to its normal one. This aspect was also missing in Holling's definition of resilience. Nevertheless both definitions include the system's capacity to fight against the perturbation. Bruneau et al. propose a conceptual view of system resilience that consists of assessing the evolution of the system's performance over time, $Q(t)$, in the aftermath of the perturbation. They therefore formally defined the loss of resilience as:

$$R = \int_{t_0}^{t_1} (Q_0(t) - Q(t))\, dt$$

where t_0 is the time when the perturbation begins and t_1, the end of the recovery time. $Q_0(t)$ represents the performance of the system over time without perturbation.

Bruneau et al. define four characteristics of a resilient system:

- *Robustness*:
  The ability of a system to avoid perturbation or mitigate the consequences of perturbation in order to minimise the loss of the system's performance significantly.
  In mass railway transportation systems, the capacity of some stations to be resistant to some types of explosion or fire by building them with appropriate materials can be considered as robustness characteristic of the system.
- *Redundancy*:
  The ability of a system to continue to operate even if some system functions are failing, due to the redundancy of some of the system's functions, materials or skills.
  One example of redundancy within a railway line is the fact that rectification substations that supply trains with traction power are built in such a way that every part of the line is supplied by at least two rectification substations.
- *Resourcefulness*:
  The ability of a system to detect and analyse perturbations in order to provide adequate measures (monetary, material, technological, human, etc.) in order to overcome these perturbations. During a serious perturbation, the mobilisation of external resources in order to overcome the perturbation can be considered as resourcefulness characteristic of the system.
  The capacity of the organisation in mass railway transportation systems to operate trains on part of a line only when a serious perturbation occurs on this line can also be considered as resourcefulness characteristic of the system.
- *Rapidity*:
  The ability of a system to quickly recover a level of performance at least as good as its original one or an acceptable performance after a perturbation.

In practice, these characteristics are difficult to quantify, especially for mass railway transportation systems. The standard practice for

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