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On analyzing the vulnerabilities of a railway network with Petri nets

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Abstract

Petri nets are used in this paper to estimate the indirect consequences of accidents in a railway network, which belongs to the class of the so-called transportation Critical Infrastructures (CIs), that is, those assets consisting of systems, resources and/or processes whose total or partial destruction, or even temporarily unavailability, has the effect of significantly weakening the functioning of the system. In the proposed methodology, a timed Petri ne<t represents the railway network and the trains travelling over the rail lines; such a net also includes some places and some stochastically-timed transitions that are used to model the occurrence of unexpected events (accidents, disruptions, and so on) that make some resources of the network (tracks, blocks, crossovers, overhead line, electric power supply, etc.) temporarily unavailable. The overall Petri net is a live and bounded Generalized Stochastic Petri Net (GSPN) that can be analyzed by exploiting the steady-state probabilities of a continuous-time Markov chain (CTMC) that can be derived from the reachability graph of the GSPN. The final target of such an analysis is to determine and rank the levels of criticality of transportation facilities and assess the vulnerability of the whole railway network.

Keywords: Railway networks; Critical infrastructures; Petri nets; Vulnerability assessment; Performance analysis

1. Introduction

In the last two decades, the interest of institutions, managers, enterprises, and researchers has been focused on improving the safety and security levels of Critical Infrastructures (CIs). In particular, as regards transportation systems, the interest about this topic has grown due not only to the potentially very high number of people killed or injured when an incident or accident occurs (direct losses), but also to the high costs and the large amount of time

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needed in many cases to restore the infrastructure (indirect losses). Moreover, the main characteristic that makes CI safety and security a particularly important problem to tackle with is the mutual interdependence of their components whose operation depends on the proper functioning of all the others; this is especially true in railway networks where the occurrence of unexpected accidental events (hereafter referred to as safety or failure events) makes some resources of the network (tracks, blocks, crossovers, overhead line, electric power supply, etc.) temporarily unavailable, with consequences that are in some cases amplified by the chain-effect phenomenon resulting from the interdependency of resources. A methodology to assess the consequences of failures in a railway network is presented in this paper; it is based on Petri Nets (PNs), which have been proven to be a valuable and powerful modelling tool to represent and analyze the behavior of discrete event systems, as they are able to capture the precedence relations and interactions among the concurrent and asynchronous events typical of such systems.

While for specific literature relevant to security and safety of critical infrastructures the reader may refer to Lewis (2006) and Macaulay (2008), the problem of assessing the criticality of infrastructures has been faced in Arulselvan et al. (2009), where an approach based on the graph theory is proposed to detect the most critical nodes in large networks. Although the graph theory appears to be a suitable tool for such analyses, Petri Nets may represent a better modelling formalism, being capable to model in a unique framework different kinds of dynamics and to easily model concurrency and synchronism of different events, often in a modular way. In this framework, an interesting application of PNs to infrastructure interdependence analysis is described in Gursesli and Desrochers (2003) where different kinds of critical infrastructures are modelled in a unique framework and some considerations about interdependence of CIs are provided by applying the analysis of PN structural properties (Murata, 1989). In addition, the "intrinsic modularity" of PNs is useful whenever a large network of different kinds of infrastructures has to be considered, such as, for instance, an electric power distribution network and a railway transportation network. For what concerns the modelling capabilities of PNs in the field of transportation engineering, they have been put into evidence by the relevant vast literature. For the cases of highway networks or urban transportation networks, readers can refer, for instance, to Tolba et al. (2005) and Di Febbraro et al. (2016). Instead, for the case of railway systems here considered, it can be mentioned the works of Ren and Zhou (1995), Fanti et al. (2006), Hagalisetto et al. (2007), Giua and Seatzu (2008), Ricci (2009), and Liu et al. (2016). Recently, in Giglio and Sacco (2016) a very detailed Petri Net representation of a railway traffic system has been proposed, with the aim of providing a comprehensive model to be used for analysis, optimization, and control purposes. In this paper, that model is taken into account to analyze the CIs characterizing the railway network and assess the level of criticality of failure events.

The level of criticality of a safety or failure event which affects one or more transportation facility is here considered as the product of a value representing the impact of the occurrence of the event on the system's operation with the probability of being in a state which is affected by the event. This is consistent with the classic definition of risk. In general, the impact is assessed through the computation of a weighted sum of the estimations of some losses (both direct and indirect) caused by the occurrence of the event. In the proposed Petri net-based approach, the impact of a certain failure event will be determined directly by means of the reachability graph of the generalized stochastic Petri net (GSPN) representing the railway network, whereas the probability of occurrence of the event will be calculated through the continuous-time Markov chain (CTMC) that can be derived from the GSPN taking into account the tangible states of the reachability graph, the firing rates of exponentially-timed transitions, and the stochastic switches associated with immediate transitions.

2. The railway network and the adopted Petri net model

The proposed Petri net-based model of a railway network consists of two interconnected PNs that represent, respectively, the physical part of the network (stations, blocks, crossovers, tracks, and so on, as well as the rolling stock moving on the network) and the logical part of it (train schedule over the available lines). A sketch of a railway network with 7 stations and 8 railways is reported in Fig. 1(a), whereas in Fig. 1(b) the overall PN model is illustrated. The two nets have been described in detail in Giglio and Sacco (2016), to which the reader can refer for more details on the modelling approach. The extension presented in this paper is aimed at representing the occurrence of accidents, disruptions, and other unexpected events that make some resources of the network unavailable; this is done by including in the Timed Petri Net (TPN) modelling the physical part of the system some places and some stochastically-timed transitions whose firings model such failure events; the resulting net is the