Performance Evaluation 97 (2016) 36–56

Contents lists available at ScienceDirect

Performance Evaluation

journal homepage: www.elsevier.com/locate/peva

Survivability analysis of a sewage treatment facility using hybrid Petri nets

Hamed Ghasemieh [a,*], Anne Remke [a,b], Boudewijn R. Haverkort [a]

[a] *Design and Analysis of Communication Systems, University of Twente, Netherlands*
[b] *University of Münster, Germany*

ARTICLE INFO

Article history:
Available online 5 December 2015

Keywords:
Model checking
Dependability
Hybrid Petri nets
Case study

ABSTRACT

Waste water treatment facilities clean sewage water from households and industry in several cleaning steps. Such facilities are dimensioned to accommodate a maximum intake. However, in the case of very bad weather conditions or failures of system components, the system might not be able to accommodate all waste water. This paper models a real waste water treatment facility, situated in the city of Enschede, the Netherlands, with Hybrid Petri nets with general transitions, to analyse under which circumstances the existing infrastructure will overflow. Comparing to previous models an structural extension is proposed, and one limitation is tackled. First, we extended the hybrid Petri net formalism with *guard arcs* and *dynamic continuous transitions*, to be able to model dependencies on continuous places and the rates of continuous transitions. Secondly, we tackle the restriction of having only a single general transition, by proposing a new discretization method. We introduce to different discretization methods, and compare their efficiency in a complex case study. Using recently developed algorithms for model checking STL properties on hybrid Petri nets, the paper computes survivability measures that can be expressed using the path-based until operator. After computing measures for a wide range of parameters, we provide recommendations as to where the system can be improved to reduce the probability of overflow.

1. Introduction

Any water that has been affected in quality either by households or by industries is considered as waste water. It is usually conveyed in the sewerage system of the community to the nearest waste water treatment companies. The treatment process consists of several physical, chemical and biological cleaning steps. The goal of the process is to separate the clean water from the so-called sludge, that can later be safely disposed or used as fertilizer. The cleaned water is usually released to surface water in the area.

In the Netherlands, communities normally have contracts with waste water treatment facilities about the maximum amount of waste water that needs to be taken in by the treatment facility. Hence, these facilities are dimensioned to accommodate the treatment of a maximum amount of sewage, often *without* taking into account the possibility of unforeseen events. However, in the case of very heavy rainfall, which is hard to predict, and actually may occur more often due to climate change, it may happen that the amount of waste water in the community sewerage exceeds the available

* Corresponding author.
E-mail addresses: h.ghasemieh@utwente.nl (H. Ghasemieh), anne.remke@wwu.de (A. Remke), b.r.h.m.haverkort@utwente.nl (B.R. Haverkort).

http://dx.doi.org/10.1016/j.peva.2015.11.004
0166-5316/

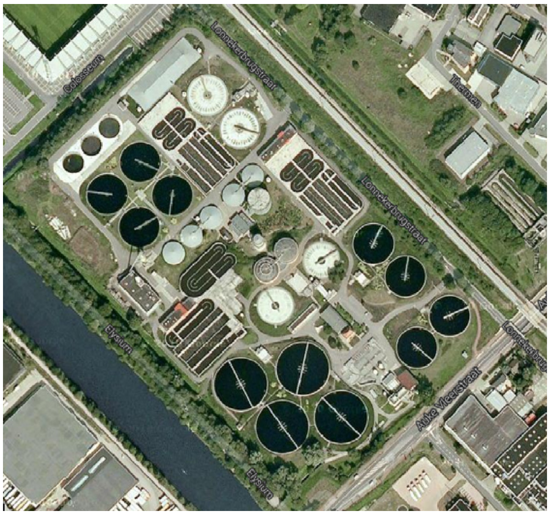

Fig. 1. A bird's eye view picture of the sewage treatment facility in Enschede, the Netherlands. The picture is retrieved using Google Maps.

storage capacity. In such cases, the sewerage system of the community overflows and waste water is spilt on the streets. Recently, this happened in the city of Enschede, the Netherlands [1–3] and caused hindrance to citizens and traffic.

This paper investigates under which circumstances flooding occurs and what can possibly be done to reduce the probability of such flooding. For this purpose we have employed data like the capacity of tanks and the average residence time of water in the different cleaning stages from the treatment facility in the city of Enschede. A bird's-eye view of this facility is shown in Fig. 1. This information is used to model the operation of the treatment facility as a Hybrid Petri-net with general one-shot transitions (HPnG) per different failure scenario.

The modelling formalism of HPnGs has recently been introduced for the analysis of fluid critical infrastructures [4], and efficient algorithms have been introduced for their analysis [5]. This paper is an extension of the work in [6], by allowing more than one general transition. Currently, the exact analysis algorithms of HPnGs are restricted to models with a single general one-shot transition. However, this paper shows how models with multiple general transitions can be analysed by discretizing all general transitions but one. Since the analysis of HPnG models with a single general one-shot transition is extremely quick, this is a feasible approach and the resulting computation times are still reasonable. Clearly, the results obtained with discretization are no longer exact; however, given the speed of the method a very fine grained discretization can be chosen which limits the introduced error. Also, given the lack of analytical methods in this area, the proposed method is very useful from the application point of view, since it allows to evaluate a combination of different failures, which has not been possible before.

Survivability [7–9] is defined as the probability that a system recovers to a predefined service level in a timely manner. It is mostly evaluated for so-called "Given the Occurrence Of Disaster" (GOOD) models. In such models, as the name suggests, the occurrence of a disaster is assumed to happen at a certain time of the day, instead of trying to predict the probability of a disaster using risk management. The focus then lies on the effect, the handling and the recovery of the disaster, once it has happened.

Survivability properties can be expressed for HPnGs using the syntax and semantics of Stochastic Time Logic (STL), that has been introduced in [10], together with algorithms to efficiently check STL properties on HPnGs. Especially the analysis of the path-based until formula is suitable, e.g., to evaluate how well the system performs in the presence of bad weather conditions or failures at the intake to the treatment facility.

In this paper, the HPnG formalism has been extended by two new features, i.e., **guard arcs** and **dynamic transitions**, since they have been shown to be essential when modelling waste water treatment facilities. Guard arcs combine test and inhibitor arcs, as previously present in the formalism, but additionally allow to control discrete events of the system based on the values of continuous variables. Dynamic transitions are continuous transitions, where the rate depends on the rate of other continuous transitions. As will be explained in this paper, both extensions can be incorporated in the analysis and model checking algorithms without increasing their complexity.

Computing measures of interest for the HPnG model of the treatment facility for a wide range of parameters, then allows us investigate how and where the community and the treatment facility could invest best, e.g., by installing larger buffers or more pumping equipment, to reduce the residence time of waste water in the treatment phases in order to decrease the probability of spilling waste water in the streets.

To the best of our knowledge the quantitative evaluation of effects of failures or very bad weather conditions is not usually performed for waste water cleaning facilities in particular or in civil engineering in general. The common way of dimensioning such systems is to use static models and calculations [11]. Risk assessment is generally performed for civil