

Survivability study of a Water Cleaning Facility using Fluid Stochastic Petri Nets

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Abstract—This paper investigates the survivability of a water cleaning facility using Fluid Stochastic Petri Nets (FSPN). Water cleaning facilities are responsible for providing drinking water to a specific district. The provided service is very important and makes such facilities belong to a nation’s critical infrastructures. Therefore, such a facility should be able to recover in a timely manner after the occurrence of disasters. The use of FSPNs in survivability research is new and promising due to its general applicability. In this paper we model and analyze the survivability of the last phases of the water cleaning process in a Dutch water company. Analysis results identify the weaknesses of the process and redundancy is suggested to improve the survivability.

Index Terms—Fluid Stochastic Petri Nets, Survivability, Water Cleaning Facility

I. INTRODUCTION

A nation’s critical infrastructures, such as electricity, gas and water distribution, are required to survive specific failures. Hence, facilities providing such services must have a high survivability. Survivability in this case involves the ability to recover in a timely manner after the occurrence of disasters [1]. The ability to determine weak spots of such a service can help in applying the right kind of redundancies and thus, to reduce the possibility of a complete service failure to a minimum.

A water cleaning facility is responsible for providing drinking water to households and companies in a specific area. Failing to provide drinking water not only has disastrous financial consequences, but also poses a risk to social welfare. Hence, such a facility belongs to a nation’s critical infrastructures. The so-called water cleaning process treats raw water, like seawater or water from a nearby river in several steps, including, for example, ozonisation, (sand) filtration and reducing the hardness (softening). Eventually the drinking water is distributed and delivered to companies and households. A major water supply organization has provided us with some technical details of one of their water cleaning facilities. In this paper we determine the survivability of their water cleaning process. Our contribution is (i) the creation of an Fluid Stochastic Petri Net (FSPN) model of the water cleaning process and (ii) a survivability analysis using the toolset FSPNedit [2].

To determine survivability, we compute the probability that the amount of cleaned water that can readily be distributed reaches a critical lower bound after the occurrence of a failure. For instance, we consider the failure of a tank in the softening

phase and the failure of a pump that brings water to the next phase. Furthermore, we analyze how employing redundancies can improve the process’s survivability. FSPNs have been used in the literature to analyze the dependability of certain systems. For example, [3] presents the analysis of a car safety controller in a road tunnel. A fuel controller is modelled in [4], where an FSPN model is used to show the fuel demand of a gas turbine at various points in time. On the other hand, our work focuses on the analysis of the survivability of a process given the occurrence of a disaster, using an FSPN model.

This paper is organized as follows. Section 2 describes the last phases of the water cleaning process and introduces the FSPN model of these phases. Section 3 presents and discusses the analysis results of various scenarios, and considers how employing redundancies can improve the systems survivability. Finally, Section 4 summarizes the results and hints at future work.

II. MODELLING APPROACH

In this section we introduce the main concepts used in the proposed analysis. We first introduce the water cleaning process, and then summarize the notion of FSPNs.

A. The water cleaning process

Water cleaning facilities treat raw water in a process of approximately 15 steps, before the drinking water is distributed to the consumer. In this paper we focus only on the last few phases of the cleaning process, namely softening, slow sand filtration and storage, leaving the analysis of the full model to future work. Figure 1 shows these phases, which are discussed in more detail in the following. Note that the following description corresponds to a real water cleaning facility.

The first phase under consideration is the softening phase. During this step water is received from the preceding phases. The purpose of the softening phase is to reduce the hardness of the water using a crystallization process. Water is treated in two different sub-locations, each composed of two tanks. Each tank can treat water at a flow rate of $2400m^3$ per hour. As a result, at best $9600m^3$ of water can be treated per hour in this phase if all tanks are operational. Failure of any single tank will reduce this rate by $2400m^3$.

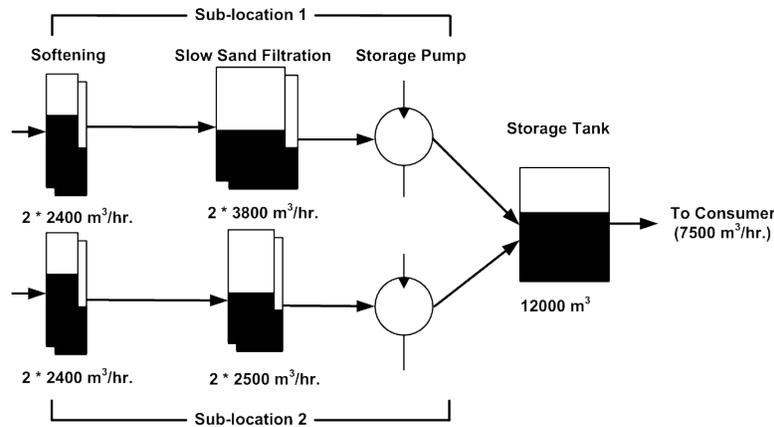


Fig. 1. Last three phases of the water cleaning process

The second phase involves slow sand filtration, where water slowly flows through a filter bed of sand, such that the last suspended particles are trapped. Each sub-location has two beds for performing this treatment, as shown in Figure 1. However the two sub-locations have different capacities. The maximum combined flow rate of all the beds in this phase is larger than the previous one, namely two times $3800m^3$ plus two times $2500m^3$ per hour (i.e. $12600m^3$ per hour). However, this phase has more downtime (e.g., due to maintenance of the filters).

Each sand filtration sub-location collects the treated water in a single storage tank. This is done by a single pump that connects each sand filtration sub-location to the corresponding storage tank. We assume, that the flow rate of each storage pump is such that it will never slowdown the filtration phase, when fully operational. However, it can also be shut down for maintenance.

The drinking water is temporarily stored in a storage tank of $12000m^3$ before it is delivered to the consumer. At best the flow rate of drinking water into this storage tank equals $9600m^3$ (the maximum flow rate of the softening phase). Furthermore, the consumers have an average service demand of $7500m^3$ drinking water per hour. To simplify the model, we consider a constant demand of $7500m^3$ per hour. We assume that the flow rate of each phase in the water cleaning process is only related to the number of operational tanks/beds in that respective phase. The flow rates do not throttle down if the storage tank is full. In that case the additional drinking water is routed to a different sub-location, which is not part of the model. Furthermore, we assume, that when the storage tank reaches a critical level below $500m^3$, the delivery of drinking water to the consumer experiences problems. As a result, the water cleaning process fails to provide its service.

B. Model Primitives

We briefly summarize the definition of a FSPN. An extensive description can be found in [5], [6]. In contrast to Stochastic Petri Nets, in Fluid Stochastic Petri Nets places can be either fluid or discrete. A fluid place contains a continuous

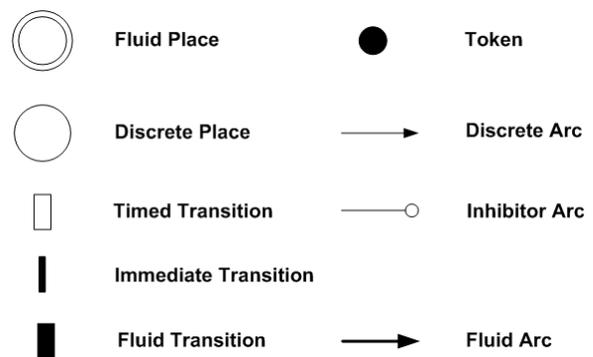


Fig. 2. FSPN model primitives

amount of fluid, whereas a discrete place contains a discrete amount of tokens. Fluid levels in fluid places are changed according to the flow rate of a fluid transition. The flow rate may depend on the complete marking of the Net at a specific point in time. The number of tokens in discrete places is changed according to either immediate, or timed transitions. Firing rates of timed transitions are defined by an instantaneous firing rate that may depend on the marking. Figure 2 shows the model primitives used in this paper for the FSPN model.

C. FSPN Model

The FSPN model resulting from the process description is shown in Figure 3. As in Figure 1, the softening phase is separated into two FSPN sub-models: one for each sub-location. The phase is modelled by four discrete places and four timed transitions. The discrete places represent the number of operating and failed tanks in each sub-location (SOF1_OK, SOF2_OK and SOF1_FAIL, SOF2_FAIL), respectively. The timed transition from SOF1_OK to SOF1_FAIL, or SOF2_OK to SOF2_FAIL has a firing rate representing the failure rate of the tanks. The firing rate of the timed transition to SOF1_OK, or SOF2_OK represents the repair rate of a single tank.

The slow sand filtration phase is, for the same reason as the softening phase, separated into two FSPN sub-models.

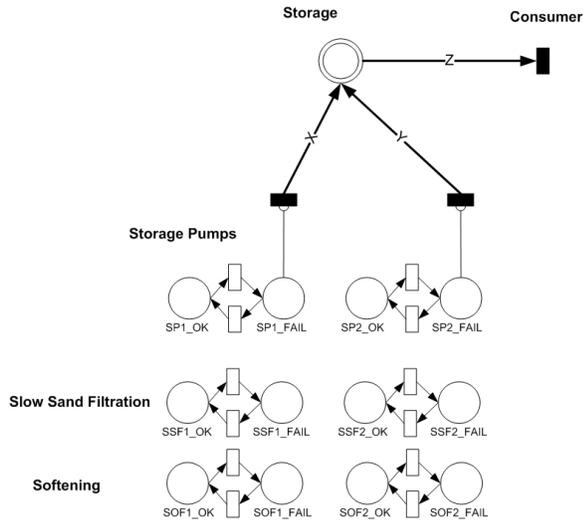


Fig. 3. Model of the last three phases of the water cleaning process

SSF1_OK and SSF2_OK contain the tokens representing the operating filtration beds in each sub-location. SSF1_FAIL and SSF2_FAIL contain the tokens for the failing beds in the two sub-locations. The firing rates of the timed transitions in these two sub-models have the same meaning as the ones in the softening phase. The two single storage pumps can either be operational or not. Each of the two pumps is modelled separately in a different FSPN sub-model. A token in SP1_OK, or SP2_OK represents an operational pump between one sub-location and the storage tank. Similarly, a token in SP1_FAIL, or SP2_FAIL represents a failing pump. The respective fluid transition to the storage tank is disabled using an inhibitor arc in case a pump fails.

The storage tank is the only fluid place in the model, which is filled by two different fluid arcs (X and Y). Each of the two arcs represents the input to the storage tank from a single sub-location. The fluid place is drained using fluid arc Z , which represents the delivery of the drinking water to the consumer. To simplify the model, we define the combined flow rate of $X + Y$ as the minimum flow rate of the softening and slow sand filtration phases (i.e. we neglect the transient effects that the larger capacity of the slow sand filtration facility might have on the flow into the reservoir). The flow rate of $X + Y$ changes according to the discrete part of the FSPN model and has a maximum of $9600m^3$ per hour. The flow rate of Z is considered to be constant at $7500m^3$ per hour.

III. ANALYSIS RESULTS

This section presents the survivability analysis results of the model in the case of some specific failures. It also shows how survivability can be improved by introducing redundancies. The results in this section are based on a real-world dimensioning of the cleaning process and on made-up failure and repair characteristics. The survivability of the model is determined using the fluid level in the storage tank. The probability of a service failure is expressed as the probability of the storage

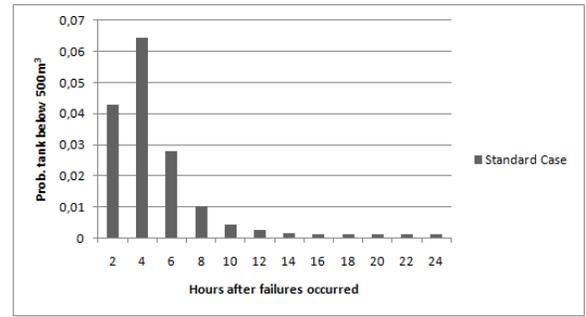


Fig. 4. Probability of service failure (standard case)

tank reaching the critical level (i.e., below $500m^3$). A higher probability of service failure means a lower survivability and vice versa.

A. Standard case

Under ideal conditions the storage tank is full and all components are operational. A storage pump fails on average once in 24 hours and then has an average downtime of 30 minutes. A slow sand filtration bed experiences on average one failure of 60 minutes, every 24 hours. Finally, a softening tank is on average offline twice a day. It takes on average 15 minutes to make it operational again. The firing rates of the timed transitions in the FSPN model are set according to the above (made-up) failure and repair characteristics.

Assuming that at the start of the analysis the two filtration beds with a flow rate of $2500m^3$ per hour in sub-location 2 fail. Also the two softening tanks at sub-location 1 and a single storage pump at this same sub-location fail at the same time. Figure 4 shows the probability of service failure of the cleaning process at a given point in time, after the occurrence of the failures. The results indicate that the maximum probability of the tank reaching a level below $500m^3$ is 0.0703 and is reached at around 3.5 hours after the failures. We also see that the process recovers from the failures due to repairs of the failing components. This is shown by the decreasing probability of service failure with increasing time. At 24 hours, the probability is levelling around 0.00107. The probability of a service failure in this standard case is relatively high compared to the results of the next sub-sections.

B. Increasing redundancy

A way to improve the survivability of the cleaning process is to apply redundancies. This sub-section describes the analysis results in the following two cases. The first considers the installation of a third softening tank at sub-location 1. In the second case, we add a third filtration bed also at sub-location 2. Figure 5 shows the analysis results of the two separate additions.

Adding a third softening tank reduces the probability of service failure. The maximum probability of a service failure, i.e. 0.0214, is now reached a few minutes past the two hour mark. The model also approaches its steady state faster than in the standard case. After about 10 hours, the probability levels



Fig. 5. Probability of service failure (with redundancies)

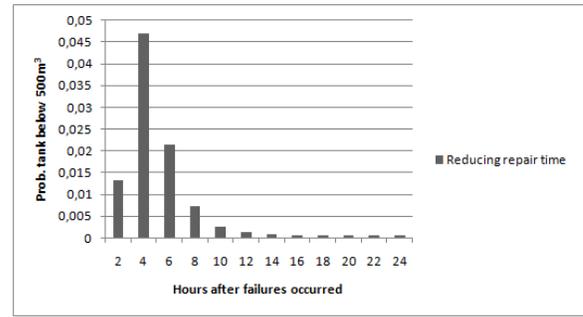


Fig. 6. Probability of service failure (with reduced repair times)

at 0.000326, also showing a better survivability in the long run. This is primarily due to an increase in the maximum combined flow rate of drinking water into the storage tank from $9600m^3$ to $12000m^3$ per hour.

Instead of adding an additional softening tank to the standard case, we can add a third filtration bed to the second sub-location. In this case we obtain a lower probability of service failure. The maximum probability of service failure, i.e. 0.00594, is reached at about 3.5 hours and the system takes longer to reach its equilibrium. At 24 hours after the occurrence of the disaster, the probability is around 0.000418. While both additions increase the system's survivability as compared to the standard case, one can notice, that their improvements highly differ over time. An additional filtration bed reduces the probability of a service failure in the first two hours by a factor 14, compared to the standard case, while an additional softening tank reduces the probability of a service failure in the first two hours only by a factor 2. However, an additional softening tank makes the cleaning process recover faster and results in a slightly better long-run survivability.

C. Reducing repair time

Instead of employing redundancy, it is also possible to improve the survivability by reducing the average repair times. This subsection shows the consequences of decreasing the average repair time of the storage pumps from 30 minutes to 15 minutes. Figure 6 shows the probability of service failure of the cleaning process when applying the reduced repair times. The maximum probability of 0.0476 lies at around 3.5 hours after the failures. The probability reduces over time towards 0.000585 at 24 hours. The survivability of the model is now better than for the standard case, since the failure probabilities are lower. However, note that the resulting probabilities are still higher than when redundancy is increased.

This section shows that applying redundancy and reducing repair times can improve the survivability of the cleaning process. It should be noted that other alterations to the model may also improve the survivability. For instance, one might also reduce the probability of failure of the components, or increase the flow rate of the individual components.

IV. CONCLUSIONS AND FUTURE WORK

This paper shows that Fluid Stochastic Petri Nets can be used to analyse the survivability characteristics of different scenarios over time. This can help to choose an improvement of the current system that fits the requirements of the system engineer. We specifically modelled the last few phases of a water cleaning process. The process's survivability in the standard case was compared with three different improvements. The results show that both adding redundancies and decreasing repair times yield a higher survivability. However, the probability distribution over time differs per setting. This shows that it is worthwhile to model and analyse the different improvements. Choosing the right improvement over the standard system can help a water cleaning company to reduce their probability of service failure and can hence save the company money.

The analytical results were obtained using an FSPN model created in FSPNEdit. Using its semi-discretization function we obtained probability densities for specific points in time after the occurrence of a number of failures.

Future work will compute survivability results for real-world failure characteristics of the water cleaning process and include the consumer behaviour in more detail. Also, the application of FSPN in the field of survivability research may be expanded to include other fluid critical infrastructures and SCADA control networks.

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