Computer simulation for risk management: Hydrogen refueling stations and water supply of a large region

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Computer simulation for risk management: Hydrogen refueling stations and water supply of a large region

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Abstract: Risk management of complex environments needs the supportive tools provided by computer models and simulation. During time, various tools have been developed and been applied with different degree of success. The still lasting increase in computer power and the associated development potentials stimulate and promote their application within risk management. Today, computer supported models as fault trees, event trees and Bayesian networks are commonly regarded and applied as standard tools for reliability and risk practitioners. There are though some important features that hardly can be captured by the conventional reliability analysis models and systems analysis methods. An improvement and alternative to the conventional approach is seen in using Discrete Event Simulation (DES) models that can better account for the dynamic dimensions of the systems. The paper will describe the authors' experience in applying DES models to the analysis of large infrastructures for refueling stations and water supply. Two case studies are described which are concerned with the inherently safer supply and storage of hydrogen at refueling stations and an established drinking water supply system of a large metropolitan area, respectively. For both, the simulation aims at identifying points of potential improvement from the reliability point of view. This allows setting up a list of activities and safety measures to reduce risk and possible losses and mitigate the consequences of accidents. Based on the cases presented the advantages of DES modeling over the conventional models will be exhibited and discussed.

Keywords: Discrete event simulation, risk management, hydrogen refueling station, water supply.

1. INTRODUCTION

Computer simulation models of complex environments as a supportive tool for risk management have been around for many years. However, the rapid increase in computer power and the associated development of easy-to-use modelling tools promote the use of computer modelling and simulation as a standard tool for reliability and risk practitioner. Discrete Event Simulation (DES) models appear a competitive alternative to the conventional reliability analysis models and systems analysis methods. Software packages incorporating DES provide a number of probabilistic distributions, combined discrete and continuous simulation, and Monte-Carlo type simulations. In a broader sense DES is an analysis tool within systems theory as systems dynamics [1], which is a methodology widely used for decision support to describe e.g. complex social, managerial, economic dynamic systems. Within risk management, DES models can rather easy account for dynamic stochastic dimensions of the systems and other important features, e.g. being applied to dynamic situations with:

- Dynamic demand: seasonal - daily changes
- Loss of partial performance and its degradation in time
- Variations in commodity supply, e.g. gas supply
- Condition dependent down times
- Residual time of commodity supply after a system failure has occurred, e.g. gas delivery from line pack storage followed by a gas leakage
- Gradual recovery after a failure, etc.

Furthermore, our experience shows that DES models are a good communication tool between system analysts and domain experts. They simply mimic the behaviour of the systems, which is well understood by the domain experts and which positively contributes to the confidence to modelling results and model validation.

Conventional systems analysis tools that can be used for the model development are fault and event trees, Bayesian networks, cause-consequence, and barrier diagrams. Such models have been used for decades and are very well described, for example, in [2, 3, 4]. While these diagrammatic causal networks have proven to

be very effective tools for reliability and risks analyses, they cannot capture a number of the above mentioned and some other relevant features accurately. Therefore, the analyst often has to turn the problem in a way that it becomes solvable by existing reliability models and hereby evading answering straightforwardly questions posed by the client. This is sometimes called Type III Error [5].

For instance, let us consider a pipeline rupture, and the consecutive failure of gas supply to a customer. Assessing the likelihood of the rupture event is readily done applying any of the conventional tools while these tools can hardly warrant an accurate assessment of the consecutive event. Formally, the link between the probabilities of the two events is the following:

$$P(\text{Supply failure}) = P(\text{Supply failure}/\text{Pipeline rupture}) \times P(\text{Pipeline rupture})$$

Where, $P(\text{Supply failure}/\text{Pipeline rupture})$ is the probability of the conditional event "Supply failure given Pipeline rupture".

To be able to assess the probability $P(\text{Supply failure}/\text{Pipeline rupture})$, one has to know the amount of gas in the line-pack storage at the instant of the pipeline rupture, pressure in the pipeline, hourly consumption at present and the following hours, etc. The hourly consumption, for example, depends in turn on the seasonal demand influenced largely by the ambient temperature, working cycles of the industrial clients and some other. On top of that, assessing the probability of supply interruption during a certain duration, which is often the measure of interest, makes the task hardly affordable for the conventional methods, as more features are to be taken into account like the duration of down times, gradual recovery after a failure, loss of partial performance, and some other. The conventional tools have a difficulty of accounting for the dynamic and continuous dimensions.

Indeed, the mentioned conventional methods appear more difficult to apply when taking into account the dynamic dimensions of an analyzed system such as the unfoldment of an accident scenario in time, time pressure on operators under an accident, seasonal changes in the volumes of fuel supply, residual time of gas delivery from the line pack storage in a pipeline, down times, gradual recovery after a failure, loss of partial performance, and some other relevant temporal features. On the contrary, DES models can rather easily account for these dynamic dimensions and other important features.

Traditionally, DES models are used within operation management to identify week points of existing service, process and production systems. The systems can be a manufacturing plant with machines, people, transport devices, conveyor belts and storage spaces; or a bank with different kind of customers, servers, loan desks, safety deposit boxes, etc; it can also be an emergency facility in a hospital, warehouses, and transportation links; or many others. Identifying probabilistic measures of events and processes and finding the ways of removing week points becomes the objective of DES modeling. There is abundance of literature describing DES models for different applications.

The paper will describe briefly the author's experience in applying DES models to the analysis of safety-critical systems in two different domains. One case is about hydrogen refuelling stations for cars and buses while the second case is about the water supply system of a large metropolitan area. For both cases the simulation aims at identifying weak points of the systems from the reliability point of view, the availability of the systems and uninterruptable hydrogen and water supply, as well as frequencies of hazardous events and some other. This allows setting up a list of activities and safety measures to reduce risk and possible losses and mitigate the consequences of accidents. The DES environment used for both cases was the Arena software. Based on the cases presented the advantages of DES modelling over the conventional models will be exhibited and discussed.

2. THE SIMULATION APPROACH

In discrete-event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system [6]. For example, if a road tanker carrying fuel is simulated, an event could be "*road tanker has arrived to the station*", with the resulting state of "*unloading the road tanker into a stationary tanker at the station*" and eventually (unless one chooses to simulate the failure of the tanker, hoses, or some other equipment) "*unloading completed*"

and "*the tanker is leaving the station*". The road tanker can be identified as an *entity*, which is one of the central concepts in DES: It represents an object which is processed along a timeline in the system. An entity may also need *attributes* to be defined. An attribute is assigned to an entity describing various specific variables or parameters such as the amount of the transported fuel and the amount of fuel pumped out of the tanker. Furthermore, a list of failure events for randomly "arriving" tankers and interrupting the unloading process could be defined as an entity's attributes. These would allow initializing different scenarios following the failure, etc.

A discrete event computer simulation consists in imitating the behavior of a real system or/and undergoing processes during a defined period of time. If it concerns, for example, the activities taking place at a refueling station, the model imitates the arrival of fuel road tankers for unloading and cars/busses for filling up the tanks, queuing cars, cars leaving the station without being filled up because of the long queue, failures of different components possibly leading to a fuel release and accidents. Furthermore - and which is a great advantage of DES models compared to the static systems analysis approaches - daily and seasonal deviations in fuel demand as well as some other dynamically developing or degrading events can be modeled. Worth mentioning is the ability to model human performance of the people acting at the station.

The occurring times, duration of services, waiting time in queues, instances of failures and other events and conditions are randomly sampled imitating the reality and reflecting the complexity of the system. The model runs over a long period of time and different statistics of interest are collected as the output of the modeling which in turn serve as an input for decision making (defining weak spots in the systems, prioritizing improvement and maintenance activities, etc.). Typical examples of collected statistics for reliability and risk analyses are: Expected failure frequency of the components/subsystems of interest, expected repair time, expected number of incidents and accidents, performance characteristics in terms of expected produced quantities, workloads, resource usage and many others.

This modeling concept is as already mentioned above commonly used in operations management and therefore DES software packages provide functionality to simulate service and production facilities including failures of components such as downtimes expressed in MTTF and MTTR and their important cost parameters. The software typically provides the possibility to model other failure states that are important in risk assessment as e.g. mimicking an event tree and fault trees. An example for an uninterruptable power supply system modeled as a fault and event tree, respectively, is shown in Figure 1. For both trees, the failure probability for "*Loss of power supply*" is $1.2*10^{-5}$ assuming arbitrary input frequencies. In Figure 2 the same model is simulated with a simple DES model with a simulation period of 1000 h providing a probability of $0.8*10^{-5}$, while the failure probabilities for the power generator (0.2%) and the switching device (0.097%) are closely predicted using the Monte Carlo type approach within the DES environment. Longer simulation times (larger samples of rare events) increases the precision of such models, e.g. setting the simulation time to 10000h results in a "*Loss of power supply*" probability of $1.1*10^{-5}$in close agreement to the analytical value.

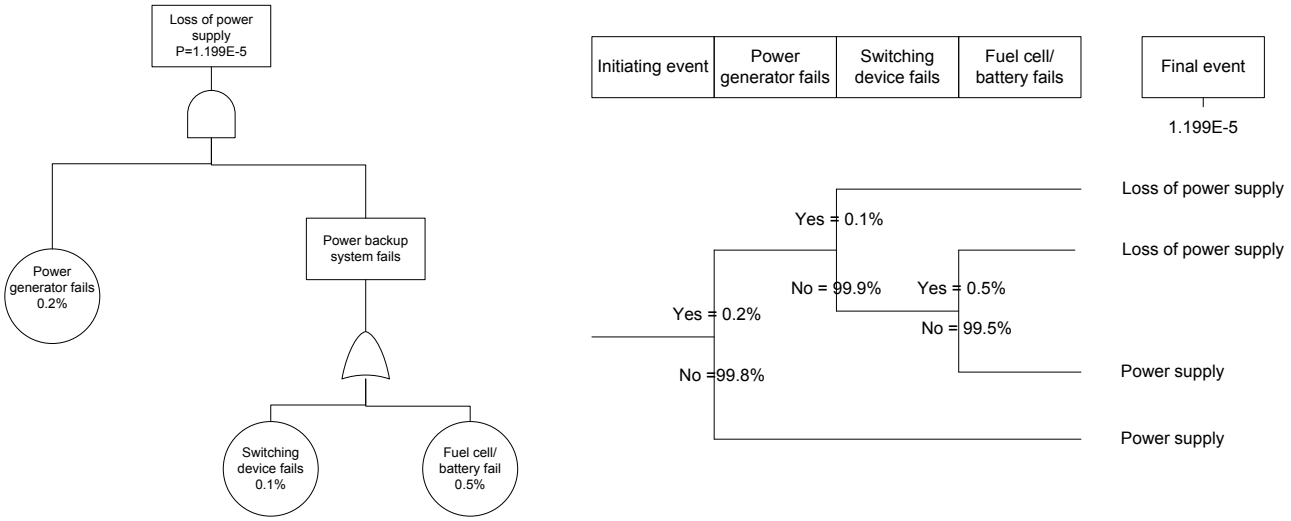

Figure 1. Fault tree presentation (left) of a loss of power supply event taking into account a power backup system and the same using an Event tree presentation (right). The probabilities are shown for the two trees.

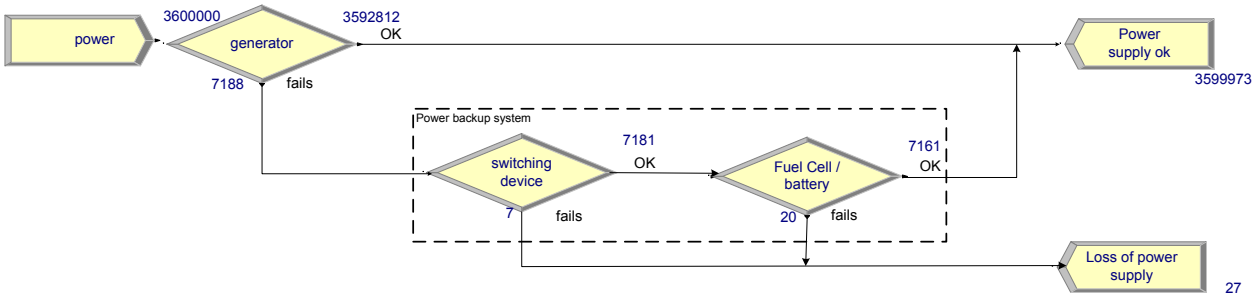

Figure 2. Simple DES model implementation of the power backup system. The "power-entity" is generated with a constant rate of 1 entity/s. Thus the numbers can be regarded as the number of occurred events or run time in seconds. The simulation covers a period of 1000 hours.

3. CASE 1: THE HYDROGEN SUPPLY SYSTEM

The emerging hydrogen technology implies the development of a new refuelling infrastructure for vehicles. Several options to implement the refuelling stations are possible, depending on the specific production path to produce hydrogen: Hydrogen may be produced in a central facility and be transported by pipelines and/or road tankers to the respective refuelling stations as indicated in Figure 3, or it may be produced on site the refuelling stations e.g. using electrolysers [7, 8]. Uninterrupted Hydrogen delivery has to be achieved in all cases to secure refuelling capacity, while an inherently safer approach would be keeping a minimum of on-site hydrogen storage to reduce the risk potential and possibly the operating costs.

Figure 3 Hydrogen infrastructure of refuelling stations with pipeline supply of hydrogen

In the following, the focus is on the modelling and simulation of a single refuelling station that has facilities to refuel cars and busses and that is supplied with hydrogen from pipeline connections or road tanker supply. In the following, not the whole model will be described, but rather some aspects on the reliability type of modelling and how to use the structure of conventional approaches within DES environment.

3.1. Description of the generic refuelling station and its boundaries

The generic station is developed in the NoE HySafe (see [9] about the NoE). A report is established describing the layout of a generic refuelling station that was the basis of a risk assessment benchmark exercise [10, 11]. The following elements are modelled [12]:

- Hydrogen supply by pipeline or road tanker;
- Storage facilities (a main tank, a compressor, and buffer storage);
- Dispensers to refuel car and busses, and
- A cash desk.

3.2. The scope of the modelling and input data

The main focus of the work was to implement various failure modes found in risk assessments published as e.g. [13, 14] into the refuelling station model. A barrier diagram may be developed based on different kinds of hazard identification methods as Hazop, FMEA or Event trees.

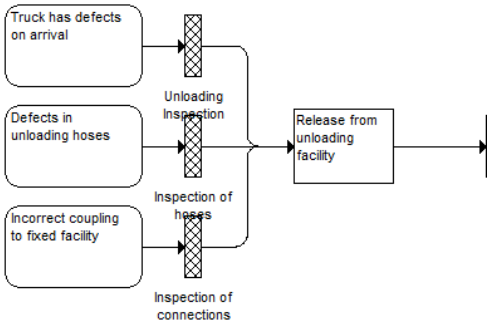

Figure 4. A barrier diagram describing possible failures and protective barriers for Hydrogen unloading.

In the DES environment (Figure 5) such failures may be modelled by a module that uses an entity to create an event such as "*truck has defects on arrival*", by that a global event failure variable is initialized and an alarm signal is raised that may be used to stop the flow process for the unloading procedure (Figure 6). In order to have statistics collected, the failure event is recorded and the time between failures (TBF) is estimated. In order to recover from the failure event, the cause of it has to be repaired that requires a certain time simulated in "*recovering time from failure MTTR*". This process module simply delays the entity from proceeding and records therefore the lasting failure time. In the end, the variables and signals are reset and the entity is disposed.

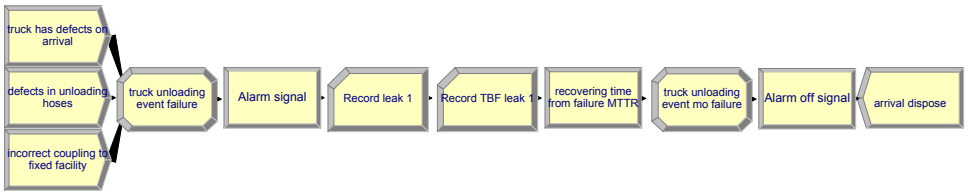

Figure 5. Failures shown in the barrier diagram (Figure 4) are modelled in the DES Environment. This routine is linked to the model of the unloading process shown in Figure 6.

In Figure 6 the unloading process is schematically shown and its DES model is exemplified. It is possible to simulate combined discrete and continuous events.

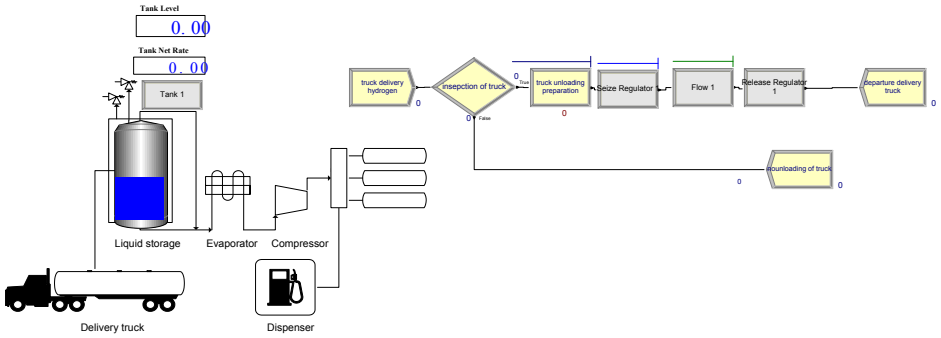

Figure 6. The unloading process and its simulation within the DES environment Arena

3.3. Simulation model and output

The above model is able to predict the real world refuelling of cars and busses including the down times due to failures or fuel shortage caused by insufficient supply and storage capacity. The model has been verified using test data provided from large scale tests in Europe, as e.g. described in the CEP report of stations' activities from 2002 to 2007 [15, 16]. Parameters such as refuelling frequencies for the cars and busses, arrival times at station, etc. have been sampled by triangular distributions. The collection of the data included

a judgement of the data quality using the NUSAP approach [17].The results have though been subjected to a sensitivity analysis comparing the results based on a triangular distribution with other distributions as Poisson, constant time between arrivals and a scheduling pattern. The results for the stations availability and the total number of rejected cars are in close agreement for all the statistical functions used as shown in Table 1.

The needed maximum capacity for the buffer storage is estimated to 990 kg hydrogen per day assuming 112 vehicles per 24 hours - differentiated into 100 cars and 12 busses being refuelled with 4.5 kg and 45 kg hydrogen, respectively. The average needed capacity calculated from various simulation runs (six for the initial model) is found to be 934 ± 9 kg. Thus the estimation of maximum capacity is a conservative approach not being exceeded by the more detailed simulation. It is obvious that in larger scale refuelling stations with a larger variety of vehicles to be refuelled and taking seasonal changes into account the model will enable more precise predictions of the needed storage capacities and by that being a tool to minimize the amount of hazardous fuel stored on-site.

Table 1. Sensitivity of input parameters [12]

Distribution	**Availability %**	**Rejected cars due to failure %**
Triangular	93.8	10.74
Poisson	95.0	10.68
Constant TBA	93.6	10.79
Scheduling	93.7	10.48

4. CASE 2: THE WATER SUPPLY SYSTEM OF A LARGE METROPOLITAN AREA

This study was carried out as part of the asset management carried out by the water department of Københavns Energi A/S (KE). KE supplies the metropolitan area of Copenhagen with drinking water. As resource optimization is of utmost importance for the stakeholders, the necessity of the supply system's high performance is as important as to cope with the associated risks w.r.t. costs and/or health and safety. Currently, and also in the past, several analytical and non analytical approaches have been used in order to determine good practice for asset management, with different degrees of success. In the pursuit of an efficient asset management, KE was willing to apply some novel adequate tools, firstly, to be able to classify their assets against their criticality for the whole system and, secondly, to lay down a basis for a comprehensive tool for managing the operational risk of assets.

4.1. The water supply system in the metropolitan area of Copenhagen

The key characteristics of the KE water supply system in the area around Copenhagen are the following [18]:

- Water is supplied to Copenhagen residents and to the residents of 16 other local authority areas.
- A total of one million people are supplied with clean drinking water
- KE manages: 7 waterworks, 54 well fields, 700 boreholes, 350 km of pressurized piping, a 1,100 km distribution network, and
- Recovers 60 mio m^3 of groundwater every year

The water supply in Denmark consists basically of groundwater which is pumped from water reservoirs with built-in wells. All the wells in a determined zone constitute a well field. The water is then pumped to a water treatment works (WTW), where the water is treated before being supplied to the consumers. That is, the supplying system consists of 3 different phases: (1) raw water extraction, (2) water treatment, and (3) transportation and distribution. Each of them in turn consists of a number of different systems, components and equipment.

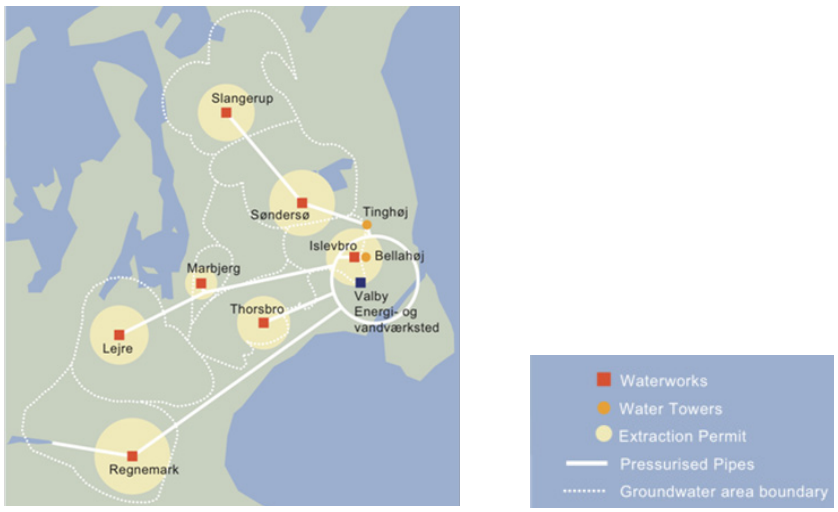

Figure 7. The nodal points of the water supply system in the area around Copenhagen (Courtesy of København Energi A/S)

The key component of the raw water extraction is the pump which can be either a vacuum pump or pressure pump. The water treatment phase is a system of three subsystems: Oxidation, first filtration, and second filtration. After all these processes, the clean water is stored in a clean water deposit ready to be pumped to the consumers. During the final phase the water is pumped through the transportation pipes to the ring pipe which supplies water to Copenhagen and the other municipalities (see Figure 7). Furthermore, there is a back-up system consisting of two deposits filled with water and air. These reservoirs are used as a buffer in order to supply water during daily and weekly demand peaks. They are built of ten independent sections, each of which can be isolated in case of pollution problems. The system is equipped with a numerous number of valves of different types as well as other measuring equipment.

To fulfill the objective of the study, there was no need to model any single component of the system, but only those having major influence on risk and the reliability of the water supply. Considering the current study as a starting point in building up a comprehensive model of the whole system, we limited ourselves to modeling one part of it.

4.2. The scope of the modeling and input data

The system which was modeled includes: The well fields which belong to Slangerup and Søndersø's WTW, the WTWs themselves and the Tinghøj reservoir (Figure 7). In total 10 water fields were included in the model.

The weekly water production of the modeled WTWs since 2007 until today was provided by KE in the form shown in Figure 8. Based on these data the probability distributions of the amount of produced water for each unit were constructed.

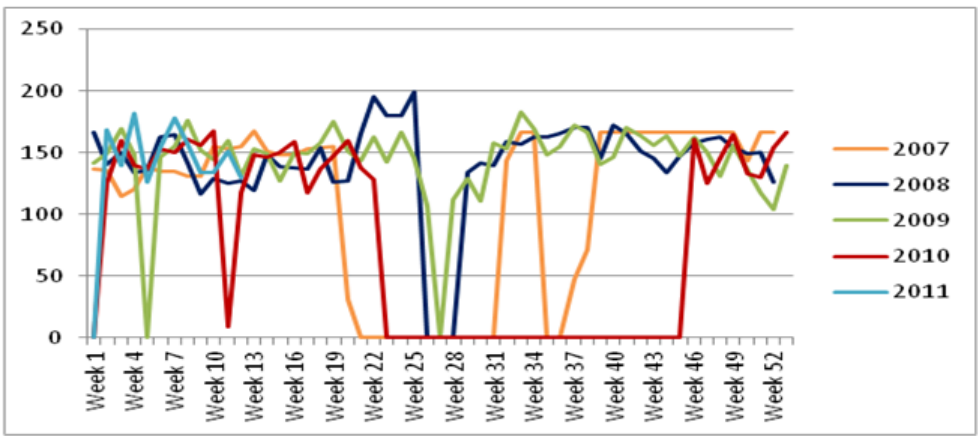

Figure 8. Water production of the Slangerup WTW

For each WTW, well field and the back-up reservoirs a list of critical assets was chosen consisting basically of vacuum, pressure and/or submersible pumps, and inlet and outlet valves. In total there were 37 pieces. Apart from these assets, the transportation pipelines connecting all the nodes of the analyzed part of the system were included in the model.

Different maintenance and check schedules were taken into account for all the assets included in the model. We name few examples: The WTW itself is checked once every month and takes approximately 2 hours. The vacuum wells are checked twice a year. And a small and big service alternate in 6 months. In total it takes approximately 160 hours per year to serve the valves. The well pumps are checked once every month, which takes approximately 36 hours per year. The pipelines which connect Søndersø WTW with Tinghøj are checked twice every year and it takes approximately 90 hours per year.

As the assets fail rarely, no specific failure data was possible to acquire. Instead, generic failure data were provided by the developer of Asset Performance Management software Optimiser+, MaxGrip. The failure probabilities and assessments of down times of all components of the critical assets were available for modeling [19]. Generic reliability data for the transportation pipelines were also acquired. They were probability distributions of time to failure and down time for large and small damages due to high pressure and leakage because of corrosion.

4.3. Simulation model and output

The developed simulation model was simply a replica of the technological process in which some components or whole subsystems can fail possibly resulting in a water supply failure given the capacity of the back-up vessels is exceeded or they fail themselves. The model consists of the following units: Water generation → Water extraction from the well fields → Water treatment at WTWs → Water extraction from WTW → Water arrival to Tinghøj → Water supply to Copenhagen. Each component of the unit is assigned a probability distribution of time to failure and recovery time. All these units, components and their attributes are properly assembled in one integrated simulation model that also takes account of daily and seasonal demands and water production capacities. Then the model is run for a very long simulation time in order to be able to collect a sample of occurrences of rare adverse events. As the rarest failure event was a large damage of the transportation pipeline (1 event per 100 years on the average), the simulation time varied between 10^5 and 10^6 years and it took up to one hour of computer time to complete a simulation session.

A large number of data was produced as an output of the simulation runs. Basically, they were average frequencies of unwanted events, times to failures (average, minimum, and maximum) for different subsystems and down times. The analysis of results' sensitivity to the change of probability distributions of times to failure became also part of the study, which clear demonstrated the degree of influence of different distributions on the output.

It is clear that generic failure data do not take account of any specific features of components' usage. For example, the generic data cannot capture the degree of operational loads on components. Often one can expect that a higher exploitation time results in a shorter wear-out period. In this way, one can expect a higher failure frequency of the components with high loads. Resource usage was also part of the data outputted by the model in the form as shown in Figure 9. From this output we concluded, for example, that the inlet valves from Slangerup, Søndersø and Tinghøj water work (A, B, and C, correspondingly) and the outlet valve from Tinghøj (D) are subjected to higher loads or we can expect a shorter wear-out period or possibly higher failure frequency. This information is useful for possible revision of the maintenance schedule.

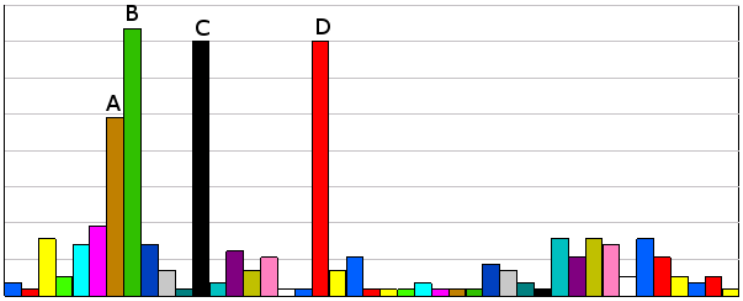

Figure 9. Resource usage

4. DISCUSSION and CONCLUSION

The paper described the application of DES modeling in connection with risk analysis for which dynamic characteristics of the modeled processes cannot be neglected. Hereunder the advantages compared to conventional models used in risk management are shown. It is seen that e.g. event trees and barrier diagrams are rather easily modeled and simulated by DES environments. This enables to make better predictions for dynamical situations with e.g. seasonal variations in input parameters such as the number of vehicles or amount of water consumed. Such models may provide more detailed answers to questions that depend on varying parameters and they retain geographical dependencies and time patterns. It is shown, e.g. in the hydrogen case, that all the following aspects may be implemented in the model, which makes such approaches valuable tools to plan sustainable implementation of new emerging technologies like the future hydrogen infrastructures:

- Secure, uninterrupted delivery to customers
- Seasonal, weekly and daily changes in demand
- Safety aspects (input to calculate individual and societal risk)
- Operational costs
- Minimum staff requirements
- Best location of control room, repair shop, refuelling stations

The model may also predict rare events that may occur during the lifetime of an (pipeline) installation, but the simulation run time may be millions of years as shown in the example, which of course is a drawback compared with situations where analytical calculations can be made.

The quality of safety barriers, as shown here, may to a high degree depend on procedures and maintenance standards as well as on the educational level of the personal. Within the DES environment, it is possible to include human operations such as maintenance or any other task, which has been shown in [20, 21]. By that, technical focused risk assessments can directly take human factors and performance into account.

On a general note, computer simulation refers to methods for studying a wide variety of models of real-world systems by numerical evaluation using software designed to imitate the system's operations or characteristics, often over time. The simulation model can be allowed to become quite complex and if needed to represent the system faithfully. The conventional methods require stronger simplifying assumptions about the system to enable an analysis, which might bring the validity of the model into question [5].

The DES models described in this paper have some other appealing features. By employing them, the focus is shifted from abstract disciplines like Boolean algebra, probability theory, binary decision diagrams, cut sets, etc., to mimicking real processes. As the models imitate the technological processes well understood by the field experts, these experts in turn become active collaborators in the model development, which raises confidence about the outcome and contributes positively to the model validation.

The water supply case study shows that using DES for assessing companies concerning the risk of their assets is a feasible and promising option. The constantly raising and improving capabilities of both computers and simulation software predict a favorable future scenario for this activity. In the current times,

where companies hardly ever have time or money to perform experiments or modifications with their assets, DES is a tool which is time and money saving and which can support the decision taking in a near future.

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