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DISCRETE EVENT SIMULATION IN SUPPORT TO HYDROGEN SUPPLY RELIABILITY

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ABSTRACT

Discrete Event Simulation (DES) environments are rapidly developing, and they appear to be promising tools for developing reliability and risk analysis models of safety-critical systems. DES models are an alternative to the conventional methods such as fault and event trees, Bayesian networks and cause-consequence diagrams that could be used to assess the reliability of fuel supply. DES models can rather easily account for the dynamic dimensions and other important features that can hardly be captured by the conventional models. The paper describes a novel approach to estimate gas supply security and the reliability/safety of gas installations, and argues that this approach can be transferred to estimate future hydrogen supply reliability. The core of the approach is a DES model of gas or other fuel propulsion through a pipeline to the customers and failures of the components of the pipeline. We will argue in the paper that the experience gained in the modelling of gas supply reliability is very relevant to the security and safety of a future hydrogen supply and worth being employed in this area.

1.0 INTRODUCTION

The transition to a hydrogen economy needs the build-up of a new infrastructure to transport hydrogen from the production locations to the specific applications. Taking the example of cars powered by hydrogen, hydrogen has to be produced and delivered to a station where the cars can be refuelled. There are several scenarios to do so as the production can be done locally in small scale reactors or in large scale facilities at remote sites. In the latter case large quantities of hydrogen have to be transported over a longer distance. One excellent and safe option is to use pipelines for this purpose, which can either be new pipelines built specifically to transport pure hydrogen, or established pipelines to transport mixed hydrogen/natural gas (up to a certain hydrogen concentration). Already in 1938 a 240 km hydrogen pipeline was constructed in the Rhine-Ruhr district in Germany, which is still in operation. Presently, based on data from 2004[1], about 3000 km of low pressure hydrogen pipelines are in operation in Europe (1500 km) and USA (1450 km). In Europe the Naturalhy[2] project (2002-2006) was launched to investigate the safe use of natural gas / hydrogen mixtures in existing natural gas pipelines. It must be expected that the pipeline infrastructure will considerably increase within the next decades to satisfy the increasing hydrogen demands, when a presumably considerable number of hydrogen driven vehicles will be on the market. To secure the uninterrupted refueling of vehicles, a stable supply of hydrogen will help to minimize the amount of hydrogen being stored at the refueling stations, which may be placed in densely populated areas.

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[1] Wikipedia artikel "Hydrogen pipeline transport" (2009-03-27); http://en.wikipedia.org/wiki/Hydrogen_pipeline_trasnport

[2] http://www.naturalhy.net/start.htm

In order to secure the uninterrupted delivery of hydrogen to e.g. a refuelling station, the reliability of supply and safety has to be assessed using a predictive model. The model will assess the supply reliability and risk to people, property, and the environment.

2.0 CONVENTIONAL MODELS AND THEIR LIMITATIONS

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 [1-3]. While these diagrammatic causal networks have proven to be very effective tools for reliability and risks analyses, they cannot capture a number of features accurately. These conventional methods appear more difficult to be applied to dynamic dimensions such as seasonal changes, changes in the volumes of gas supply, residual time of gas delivery from the line pack storage, down times, gradual recovery after a failure, loss of partial performance, and some other relevant features.

What the analyst often does is turning 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 [4]. For instance, let us consider the two events related to the same gas pipeline: (1) pipeline rupture, and (2) failure of gas supply to a customer. Assessing the likelihood of the first event can be done with any of the mentioned conventional tools while these tools can hardly warrant an accurate assessment of the second 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.

3.0 DISCRETE EVENT SIMULATIONS

In order to take account of the continuous and dynamic characteristics and the multidimensionality of the system, we employ a Discrete-Event Simulation (DES)[3] environment/software to develop an adequate predictive model to assess the probabilities of complex events. These software packages makes the development of such models very convenient and rather easy as they are offering a graphic interface to build models utilising queuing theory to model discrete events together with continuous models. Such DES models can rather easily account for the dynamic dimensions and other important features that can hardly be captured by the conventional models. DES models executed on a computer have become the method of our choice which opens up new perspective for reliability and risk assessments.

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[3] Widely used DES environments include Arena, ProModel and GPSS.

Traditionally, DES models are used to identify week points of existing systems that serve, process, and/or produce large amounts of certain units. 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. The systems of this kind are characterised by possible delays in deliveries, excessive waiting times and possibly losing lives if hospitals are concerned, shortage of storage place, lack of personnel, etc. Identifying probabilistic measures of such events (week points) and finding the ways of removing them becomes the objective of DES modelling. There is abundance of literature describing DES models for different applications.

As far as the reliability modelling in a DES environment is concerned, human reliability analysis is the area where DES models are a well-known alternative to analytical approaches. In [5] an overview of DES models developed for human performance simulation is given. The use of DES models in reliability predictions of industrial or simply technical systems is a rather recent application area. As an example, the reader is referred to [6] and [7]. To the authors' knowledge, the case study on gas supply reliability presented in this paper is a new application of the DES approach to reliability analysis and it is believed that this approach can be of use to predict the reliability of hydrogen supply.

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 [4].

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, the experts in turn become active collaborators in the model development, which raises confidence about the outcome and contributes positively to the model validation.

Our experience gained in the modelling of gas supply reliability is relevant to the security of hydrogen supply and worth being employed in this area.

4.0 RELIABILITY OF GAS SUPPLY: PROBLEM STATEMENT

The mission of the operator of a gas pipeline distribution system is to deliver uninterruptedly the contracted amount of gas to a customer. As a pipeline network stretches usually over large areas, including off-shore parts, there is a chance that human activities such as construction work, moving vehicles, seafaring, and sabotage may become a cause of the pipeline damage. There are also other causes such as corrosion, natural hazards and spurious failures.

As an example, the following list of failure modes is usually considered when analysing the reliability of an on-shore part of a gas pipeline: a crack, hole, and full bore rupture caused by construction work; a crack, hole, and full bore rupture caused by a collided vehicle; a crack due to corrosion; a crack and hole due to construction defects; an unintentional closure of a remotely operated valve; and a stuck inspection/cleaning pig. As far as the off-shore part of a pipeline is concerned, the following failure modes are considered: a crack, hole, full bore rupture and buckling caused by a crashed airplane; a crack, hole, full bore rupture and buckling caused by an anchoring vessel; a crack, hole, full bore rupture and buckling caused by a sunk vessel; a crack, hole, full bore rupture and buckling caused by trolling; a crack, hole, full bore rupture and buckling caused by a stranded vessel, and a crack due to corrosion.

Having a pipeline damage and a gas leakage up to the full bore rupture does not necessarily mean an immediate failure to deliver the gas to some clients. Parts of the pipeline that are cut off from the feeding source may have a residual volume of gas in the pipeline (line-pack storage) or/and a reserve storage that can continue to supply the gas to the customers for some period of time.

The volume of a line-pack storage depends on the length of the shut-off stretch and pressure. The time within which the customers will be supplied with the gas from the storage depends on the consumption rate which in turn is greatly influenced by the ambient temperature. Taking all this into account, the question to answer is:

What is the probability distribution of time without gas for each customer per year?

The question may also be rephrased as: *What is the frequency of gas supply failure for each customer?*

To answer the question, the time line is divided into several bins, for example, [0,6 hours), [6,12 hours), ...[1 week,1 month) up to [1, > 1 month), and the probability mass (or frequency) for each bin becomes the subject of interest. The outcome of the modelling is a table filled out as exemplified in Table 1 below.

Table 1. Table showing the failure modes and the expected time of interruption of gas supply for customers

Frequency of event, 1/year

Customer	Failure mode	Time without gas supply					
		0 – 6 Hours	6 – 12 Hours	12 – 24 Hours	24 Hours – 1 Week	1 Week – 1 Month	1 Month – ...
1	1						
	M						
Total							

5.0 BUILDING AND RUNNING THE MODEL

5.1. General modelling concepts

A central concept within DES is the so called “entities”. They are used to represent most dynamic parts of the system being simulated, such as a physical element that is moving from one location to another or an element that is changing its state. In the model, these entities can be some passive objects manipulated by some higher level logic, in which case they are merely serving as an information container (i.e. a collection of attributes). Entities may also take an active role in the model, as an agent with their own logic running in parallel to the rest of the simulation, in which case they are typically implemented as independent processes or *threads*.

Entities are by nature well suited to model discrete objects such as cars to be refuelled, including e.g. people’s tasks as maintaining or surveying the technical system. Conversely, continuous or pseudo-continuous elements such as time, liquids, gases, energy, radiations, money, etc. require special attention. One approach is to calculate the exact values between two events. For instance, the exact quantity of water that went through a pipeline when knowing the duration and the flow rate (cf. “Continuous model” in Figure 1). Another approach is to discretise the problem, by approximating the continuous elements with discrete blocks containing a fixed quantity of the given element. In this case, there is a need to define an element resolution (e.g. blocks of 1m^3 of water), and a time resolution (e.g. the position of the blocks of water is updated every d*t* time unit, like every 1 minute) (cf. "Discrete model" in Figure 1). The choice of the element and time resolutions has a direct impact on the processing power and the memory needed to run the simulation.

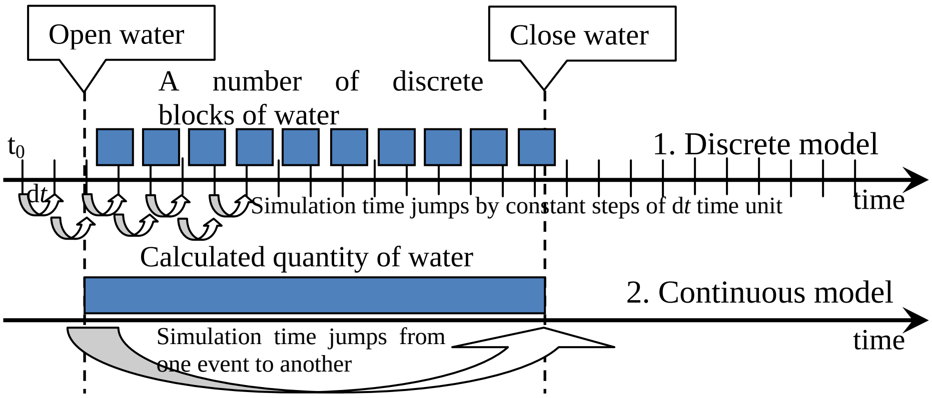

Figure 1. The simulation of time and continuous events (e.g. transmitting some water) in a typical discrete way, versus in a typical continuous events-based way

On the one hand, the discretisation of the continuous elements has the advantage of typically be easier to model and to integrate in the rest of the simulation. On the other hand, keeping the continuous nature of some elements provides a higher accuracy and typically a faster simulation. A more extensive description can be found in the first part of [8].

5.2. The gas supply case study

Piping and Instrumentation Diagrams (P&IDs) is the information based on which the model development starts and which the operators are perfectly familiar with. P&IDs show how industrial process equipment is interconnected by a system of pipelines. P&ID schematics also show the instruments and valves that monitor and control the flow of materials through the pipelines. Under the model development they serve as an interface between the analyst and operator. The P&IDs are simplified by the analyst to the extent needed for the modelling and verified by the operator.

The first step in development of the model of the gas pipeline is to depict the pipeline and all components which have an influence on the reliability of the supply. As an example, the pictorial model of a fragment of a gas pipeline as part of the DES model is presented in Fig. 2.

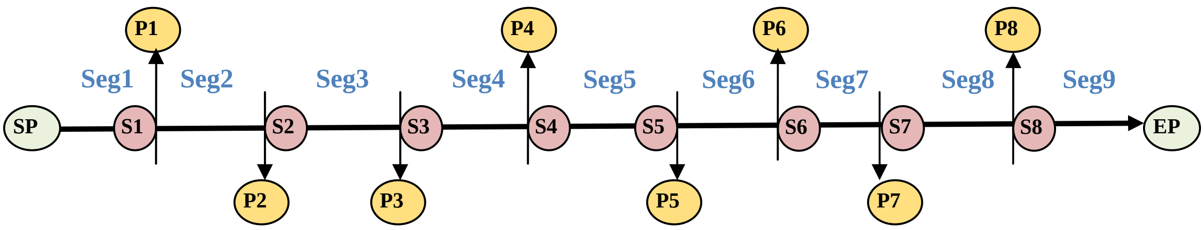

Figure 2. Schematic layout of the gas distribution pipeline.
SP – Starting Point, **SegX** – a stretch X of the stem pipeline between two shut-off valves, **SX** – Station X (shut-off valve), **PX** – Boarder Point X, **EP** – End Point (for details see the explanation below)

The next step is to build an algorithm of the model that will mimic the continuous gas propulsion and failure occurrences. The model logic can be presented in a diagrammatic form or simply descriptively, as it is done in the following paragraphs.

At the start of a simulation run and every d*t* time unit ahead, an entity (simulating a given quantity of gas) starts moving from Starting Point (SP) to Ending Point (EP). This discretisation imitates the gas propulsion through the pipeline. That is, an entity can be thought of as a portion of gas pumped into the pipeline. When an entity passes a point of branching to a customer (Border Point) it sends another entity to the border point imitating gas supply to the customer. On its way along the pipeline, the entity may stop because of a failure of either a certain segment of the pipeline or a station. In such a case, the entities downstream the failure are not sent to the Border Points, which mimics a supply failure from the main pipeline. If this takes place, another mechanism in the model is being launched that mimics the supply of the gas remaining in the line-pack storage. The duration of the gas supply to the customers downstream the failed segment or station is governed by the following considerations.

The profile of gas consumption for some period in the past is known to the operator and this profile can be used to predict the consumption in the following seasons. The prediction can be done rather roughly by providing ranges of gas consumption in cubic meters during the low, medium and high season. Or a finer predictive model could be accepted.

The times between failures of the segments and stations are governed by exponential distributions whose parameters are mean times to failures (or mean failure rates that are the reciprocal values). So, while the simulation time passes, the pipeline components undergo failures followed by repair times. The repair times also have to be established. If they are established in the form of mean times to repair (MTTR), then the probability distribution of time to repair is exponential too. Other distributions can be accepted if this can be substantiated by real data.

To be more specific, let us consider an example of the input that is needed to carry out the simulation and obtain the output data as stated in Section 4, Table 1. Imagine that the off-shore part of the pipeline is Seg1 depicted in Fig. 2 and has a length of 20 km while all the other segments of the pipeline are on-shore parts of the pipeline having some specific lengths. The input data for the on-shore are exemplified in Table 3 (for two segments) while the input data for the off-shore part are presented in Table 2.

While the simulation runs, the statistics of failure occurrences is collected just as if it would happen in real life. As soon as the simulation ends, the probabilities/frequencies are calculated by knowing the number of interruptions of the deliveries and the simulation time.

Table 2. Off-shore part from Starting Point (SP) to Customer P1, 20 km

Failure cause	**Failure mode**	**MTTR, hrs**	**Frequency for segment**
Crashed airplane	**9**. Crack/ Hole/ Full bore rupture/ Buckling	1100	1.30E-06
Anchoring vessel	**10**. Crack/ Hole/ Full bore rupture/ Buckling	1060	2.00E-05
Sunk vessel	**11**. Crack/ Hole/ Full bore rupture/ Buckling	1500	1.40E-05
Stranded vessel	**12**. Crack/ Hole/ Full bore rupture/ Buckling	1130	5.20E-06
Unintentional closure of remotely operated valve	**7**. Valve closed	1	8.28E-03
Stuck inspection pig	**8**. Stuck pig	950	1.00E-06

Table 3. Input data for the on-shore part of the pipeline exemplified by the data for the two segments: Seg2 and Seg6 (see Fig. 2)

Failure cause	Failure mode	MTTR, hrs	Failure frequency, 1/year*km	Customer	Length of segment, km	Frequency for segment
Construction work	**1**. Crack or hole	30	1,15E-04	**P2**	**13**	1,50E-03
	2. Full bore rupture	60	2,40E-05			3,12E-04
Collided vehicle	**3**. Crack or hole	30	3,30E-06			4,29E-05
	4. Full bore rupture	60	2,00E-06			2,60E-05
Corrosion	**5**. Crack	30	5,30E-05			6,89E-04
Construction defects	**6**. Crack or hole	27	5,10E-06			6,63E-05
Unintentional closure of remotely operated valve	**7**. Valve closed	1	8,28E-03			8,28E-03
Stuck inspection pig	**8**. Stuck pig	25	1,0E-05			2,5E-06
Construction work	**1**. Crack or hole	30	1,15E-04	**P6**	**12**	1,38E-03
	2. Full bore rupture	60	2,40E-05			2,88E-04
Collided vehicle	**3**. Crack or hole	30	3,30E-06			3,96E-05
	4. Full bore rupture	60	2,00E-06			2,40E-05
Corrosion	**5**. Crack	30	5,30E-05			6,36E-04
Construction defects	**6**. Crack or hole	27	5,10E-06			6,12E-05
Unintentional closure of remotely operated valve	**7**. Valve closed	1	8,28E-03			8,28E-03
Stuck inspection pig	**8**. Stuck pig	25	1,0E-05			2,5E-06

For the input data as exemplified in Table 2 and 3 a fragment of the simulated output is presented in Table 4.

Table 4. A fragment of the output results for the reliability of gas supply

Frequency of event, 1/year

Border Point	Failure group	Time without gas supply					
		0 - 6 Hours	6 - 12 Hours	12 - 24 Hours	24 - 1 week	1w - 1 mon	1 mon -
P1	9						1,30E-06
	10						2,90E-05
	11						9,80E-06
	12						5,20E-06
Total							**4,53E-05**
P2	1	8,90E-04		3,51E-04			
	2			6,00E-05	3,00E-04		
	3						
	4						
	5	4,00E-05		2,80E-05			
	6	3,50E-04		7,90E-05			
	7	2,10E-05		9,80E-06			
	8						
	9						1,30E-06
	10						2,00E-05
	11						1,40E-05
	12						5,20E-06
Total		**1,30E-03**		**5,28E-04**	**3,00E-04**		**4,53E-05**
6	1	4,60E-03	6,60E-04	1,90E-03			
	2	8,70E-05		7,10E-04	1,60E-03		
	3						
	4						
	5	3,00E-04	2,00E-05	9,80E-05			
	6	2,30E-03	2,60E-04	9,00E-04			
	7	2,00E-04	4,00E-05	6,90E-05			
	8						
	9						1,30E-06
	10						2,00E-05
	11						1,40E-05
	12						5,20E-06
Total		**7,49E-03**	**9,80E-04**	**3,68E-03**	**1,60E-03**		**4,53E-05**

The precision of the calculations depends on the two characteristics: time resolution and simulation time. If, for instance, the time resolution is set to 1 hour which is the time between two consequent entities entering the model, then only those interruptions exceeding 1 hour are registered by the model.

The other characteristic influencing the precision of the results is the simulation time. To attain a precision of the order of 10^{-5} 1/year for the reliability of gas supply, the model has to imitate the lifetime of the pipeline of the order of 10^{8} years. That is, 10 000 000 years of the pipeline lifetime have to be simulated and all failures during this period be registered and used for the frequency assessments.

6.0 CONCLUSIONS

As hydrogen is a rather new fuel, the options and trade-offs for hydrogen delivery from production sites to the stations are still open and researchers are working to better understand them. Along with several factors such as a lower-cost hydrogen compression technology, material for lower-cost hydrogen pipelines, energy-efficient and lower-cost hydrogen liquefaction process, and some other, the reliability of hydrogen supply is one of the decisive factors to take into consideration when making decision on the way the hydrogen is delivered.

From the systems analysis point of view, the factors influencing the reliability of hydrogen supply are not dissimilar from the reliability of gas supply. To mention some of them: the amount of gas/hydrogen in the storage connected to the pipeline as well as 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. As it was argued in the paper, all these and other characteristics of the system and environment are dynamic and continuous, that is the ones the conventional tools have a difficulty of accounting for.

An imaginary case of a hydrogen supply system is presented in Figure 3. If we simplify the layout of the system and depict only the information needed for the simulation, it will boil down to the case shown in Figure 2, which is the layout used for the gas pipeline study.

In order to accurately account for those factors we employ Discrete Event Simulation software to model the system and environment. The model can be run over a time span of millions of years and by that also predict extremely rare events that may occur during the life time of a pipeline installation. By that, such models can be used to improve the planning of secure delivery of hydrogen to e.g. refuelling stations.

Furthermore, such models may be extended to mimic the work of some other systems inherent to hydrogen supply. The example given in the paper to dynamically model a pipeline system may be freely extended also to include e.g. production facilities, refuelling stations and the varying fuel demand by customers. Delivery of hydrogen by cryogenic tankers and their reliability can also be integrated and a comprehensive model of the supply network can be simulated. It is also possible to include human operations to maintain such a system or any other task. Such models may provide more detailed answers to questions that depend on varying parameters such as the minimum quantities of hydrogen necessary to store on-site of a refuelling station that combines secure delivery to the customers, on-site safety aspects and operational costs for a given site. The solution of these questions depend partly on the customer demand, that is dependent on the time of the day, day of the week, seasonal variations, etc. Furthermore, the number of stations and their best locations may be planned on a better informed basis.

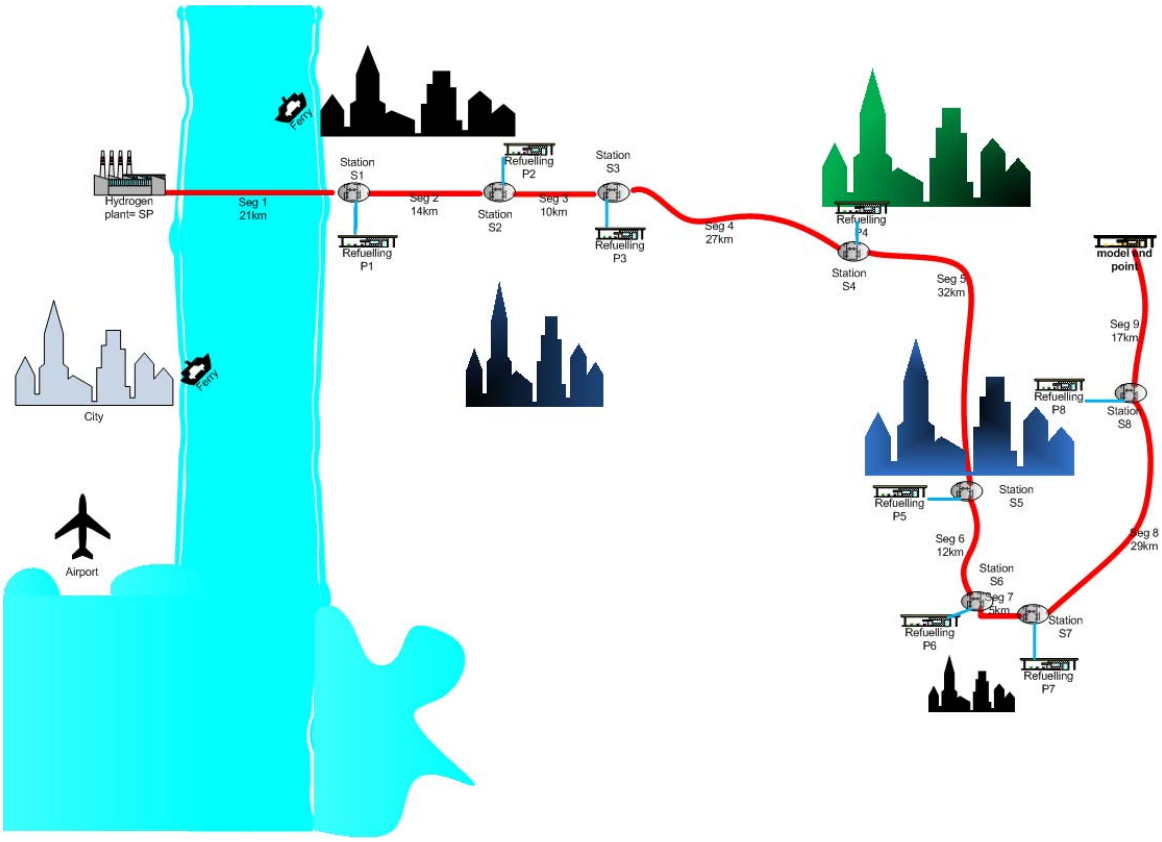

Figure 3. Example for a future refuelling station distribution connected by a pipeline and a central hydrogen producing plant.

The simulation model, if properly developed, can be easily modified to simulate a new structure of the network of delivery.

The experience gained in the modeling of the gas delivery system and similarities to the hydrogen delivery infrastructure make us consider that Discrete Event Simulation models is a promising alternative to assess the safety and reliability of hydrogen supply to customers.

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