Evacuation model managed through fuzzy logic during an accident in a LNG terminal

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Abstract
Evacuation of people located inside the enclosed area of LNG terminal is a complex problem, especially considering that accidents involving LNG are potentially very hazardous. In order to create an evacuation model managed through fuzzy logic, extensive influence must be generated from safety analyses. A very important moment in the optimal functioning of an evacuation model is the creation of a database which incorporates all input indicators. The output result is the creation of a safety evacuation route which is active at the moment of the accident.

Introduction
Due to the ever increasing call for energy in the world, there is more and more need to use natural gas as an energy source and hence the need to open new LNG terminals as shipment by sea is inevitable. Basic information regarding LNG terminals is the capacity and number of LNG storage tanks, as well as the size and the capacity of the tankers which carry out the transport to the terminal. The potential hazard associated with LNG mainly comes from the possibility of an accident with consequences generated by LNG leakage. In such situations, a very possible occurrence is fire and thermal radiation. If the events lead to leakage of a greater quantity of LNG – into a pool – a cloud is created due to the evaporation which contains natural gas, water, steam and air. Due to its weight, the cloud, being heavier than the air, remains at the surface of the earth. The evaporated natural gas may be significantly influenced by the atmospheric conditions and the geographic-topographic features of the terrain. The cloud shifts according to the direction of the wind, while the speed of the wind additionally effects the mixing of the natural gas with the air. This mixture is flammable when the concentration of the natural gas in the air ranges between 5% and 15%. The dispersion of the cloud represents a danger to people, which is increased in the case of flammability. The rapid evacuation of people in such a situation is essential. The risk for employees at the LNG terminal is greatest. Therefore, there is a need for designing evacuation models which apply to those both inside and outside the enclosed part of the LNG terminal.

General description of the evacuation model
This paper describes an evacuation model intended for the people located inside the LNG terminal. The model uses data generated by conducting quantitative risk analysis (QRA) [1, 2] of events involved in LNG leakage accidents. The management or the control of the evacuation model is performed using fuzzy logic [3], where the final output result is the shortest safe evacuation route for each individual located in the LNG terminal.

Quantitative risk analysis
The objective of conducting the QRA is to identify the potential impact of the LNG leakage accident on the workers in the terminal. The analyses result in a time-based and spatial presentation of the

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dispersion of the evaporated LNG, its concentration in the air, as well as thermal radiation. For more precise management of the evacuation, the area of the terminal is divided into cells (smaller blocks), as shown in figure 1.

Fig. 1. Scheme of the modeled LNG Terminal

The areas which are a potential source of an LNG leakage accident are identified well in advance, including the maximum quantity of LNG that may leak. For each cell or area, the consequence from the accident is separately defined (possible size of a crack as a consequence of the accident, maximum quantity of the leaked LNG, the size of the leaked LNG, the area in which the LNG is leaking and so on) and in compliance with these data and other input parameters, the QRA is carried out. Potential accidents with LNG leakage involve cryogenic pipeline systems which are used to transport LNG, storage tanks, mooring LNG tankers during off-loading in storage tanks and so on. Intentional threats may range from insider threats to intentional external attacks. During such events, there is a small chance of complete leakage of LNG from each tank separately, but with the objective to obtain conservative calculations of the dimensions of an accident, we shall presuppose that the tanks have been completely emptied. In this case, we will review the example of an accident that occurs when mooring an LNG tanker during the course of off-loading. The accidents caused by terrorist attacks are scenarios considered to have the biggest negative impact. It has been estimated that in such cases, there is a possibility of a maximal crack in the tanker of 1500 mm [4], creating conditions for a pool of diameter up to 400 m [4, 5, 6, 7]. Our scenario thus includes a crack of 1500 mm and an LNG pool with a diameter of 400 m (Model 1).

The behaviour of the evaporated natural gas from the LNG pool may be calculated by using a Fire Dynamics Simulator (FDS) on the basis of CFD modelling of the dispersion of the natural gas into the surrounding environment [8, 9, 10, 11, 12]. The speed and the direction of the wind plays an immense role when it comes to the length, speed, direction and the time frame of the dispersion of the evaporated natural gas, as well as the flammable concentration of the mixture of natural gas and air. Additionally, in case of fire, one can calculate the quantity of thermal radiation to the surrounding environment, consequently allowing the presentation of this in a spatial and time sense [13, 14]. The scenarios will be conducted using the created 3D model of an LNG Terminal for which the evacuation model will be made. The scenario for Model 1 simulates the evaporation of natural gas from the LNG pool on a water surface with a size of 160,000 m² (400×400 m). The dimensions of the presented model are 3000 m per x axis, 3000 m per y axis and 300 m per z axis. The atmospheric wind has a speed of 2 m/s and disperses the gas cloud in the direction of the wind. The temperature of the sea water is set to 20°C. The simulation of the dispersion is calculated with the use of the FDS program (Fire Dynamics Simulator) [15]. Additional obstacles are considered (vessel, buildings, storage tanks) which might have an influence on the spreading gas.

Figures 2 and 3 show examples of the length of the dispersion with concentration of methane in the air between 5% and 15% depending on the time of the leaked LNG from the moored tanker.

Fig. 2. Dispersion of the LNG vapour after 60 seconds

Fig. 3. Dispersion of LNG vapour after 636 seconds

Through the calculated data from the analyses, we identify the cell, time and magnitude of the danger for the people at the terminal. All of these data should be incorporated into the database. The objective of the database is to understand the influences of the accident, and for creating the rules and procedures under which the evacuation model will be managed with the use of fuzzy logic. For a better
Evacuation model managed/controlled via fuzzy logic during an accident in a LNG terminal

Evacuations happen frequently. People are evacuated from their homes, businesses, ships, and more, in response to actual or predicted threats of hazards such as hurricanes, floods, tsunamis, volcanic eruption, and release of hazardous or nuclear materials, fires and explosions [16]. The term evacuation describes the withdrawal of persons from a specific area because of a real or anticipated threat or hazard. In the last decade the warning process and response, organizational response, behaviour in evacuations, evacuation planning and management has been more in focus than had been the case in the past. The stress has been on the quality of information, the timing of message delivery and compliance with warnings. The new warning technologies include cell phones, the internet, GPS devices, etc. Each individual in the LNG terminal, after being alerted to an accident through with alarm systems, is in a dilemma regarding the best evacuation route to choose. The slightest probability of risk given any chosen route implies potential fatality. The larger the scale of an accident, the greater the probability of an individual making an error in choosing a route. Having said this, there is a need for the development of an evacuation model which is to be managed using fuzzy logic and is meant to relocate individuals via safe routes, as well as via safe areas which are not endangered by the accident. The on-time evacuation of people is of essential significance for the decrease of risk; i.e. minimizing the human consequences of an accident event. Using fuzzy logic, the data from a database provides a clear picture of which cells of the terminal at which time after the recognition of the accident will be at a particular risk. It also provides images of the optimal evacuation routes at given times after the accident. The objective of the use of fuzzy logic is to process the data from the created database toward the selection of the shortest safe route for each individual located in the LNG terminal at a specifically determined time after the leakage of the LNG. Of great importance is the early detection of the accident. The devices for detecting gas or heat indicate the location where the LNG leakage accident happened [17]. This is the starting point for the creation of one dynamic evacuation model. The second important moment is detecting the direction of the wind. As we have mentioned, all locations have been pre-evaluated in terms of potential leakage, as well as the maximum quantities of leaked LNG. The location of the detected accident, the speed and direction of the wind, the atmospheric temperature and the temperature and the type of the surface where the accident takes place are the input parameters which indicate the selection of the scenario by which the dynamic evacuation routes for the individuals are created. For each cell of the terminal in compliance with the scenario, via the QRA, the program will provide insight into the time such a cell will be affected. Also, the safe-havens or shelters which are foreseen in case of an accident are also emphasized. In the end we determine which parts of the travel route at what time are safe for use during a dynamic evacuation. For a successful execution of the evacuation, a GPS device with an installed map, streets and routes and shelters of the LNG terminal which people can use is required. The device provides the accurate location of the individual at the time of the occurrence of the accident. With this, the individual represents the starting point A used to create his/her safety evacuation route. The evacuation route directs the individual to the end point B, which is at a location that will not be affected by the accident. The evacuation management device, at every 30 seconds, depending on the location of the individual identified via the GPS device, refreshes the analysis for creating a safe evacuation route, which in case of change in the initially shown route, and will alert the evacuee to any change, projecting the newly created evacuation route.

Evacuation model managed/controlled via fuzzy logic

The basic elements of any given fuzzy logic system [3, 18] are: rules, fuzzifier, inference engine, and defuzzifier. During the design of the fuzzy logic systems, one defines the input and output variables, identifies the membership functions and creates the database of fuzzy variables. There is a distinction between linguistic and numeric data – i.e. information. The linguistic data usually express a certain experience through words, while the numeric data in reference to a specific phenomenon are generated on the basis of measurements, experiments and statistical analyses. In our case, the
QRA provide us with both, linguistic and numeric data, on the basis of which the input and output variables are created, including the set of fuzzy rules. The basic task of fuzzy logic for management of the evacuation model is to make the proper selection of a route for evacuation for each individual in the terminal, which eliminates the possibility of an error during the selection of an evacuation route when such is created by an individual.

**Evacuation model managed / controlled via fuzzy logic**

The fuzzy logic controlled evacuation model (Fig. 4) uses wind speed and wind direction detectors, gas and heat detectors, automatic and manual alarm systems, and the positions of the terminal workers from different locations of the terminal area with the goal to collect all necessary information for input variables used by the fuzzy logic controller. The controlling is closely related to the previously accumulated experience from QRA, and is copied during the setting of the fuzzy logic controller.

**Input and Output Membership Functions**

There are four membership functions for the evacuation model for each of the input and output fuzzy variable. The table below (Table 1) shows the Input fuzzy variables – the speed of the wind within the area of the terminal (wind speed), as well as the time elapsed after the detection of the accident (time after disaster), as well as Output fuzzy variable – the remaining time to reach a point of unacceptable risk in cell X of the terminal (safe time). For purposes of facilitated use of the system fuzzy variables, the relevant abbreviated forms for the variables shall be used hereinafter.

The graphic display of the membership functions of the language variables is shown in figure 5.

**Table 1. Fuzzy variables for wind speed, time after disaster, and safe time**

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Time after disaster</th>
<th>Safe time</th>
</tr>
</thead>
<tbody>
<tr>
<td>very slow</td>
<td>vs</td>
<td>vs</td>
</tr>
<tr>
<td>slow</td>
<td>s</td>
<td>short</td>
</tr>
<tr>
<td>fast</td>
<td>f</td>
<td>medium</td>
</tr>
<tr>
<td>very fast</td>
<td>vf</td>
<td>long</td>
</tr>
</tbody>
</table>

The y-axis shows the grade of membership for each fuzzy variable. The x-axis shows the input fuzzy variables (wind speed, time after disaster) and the output fuzzy variable (safe time). The set up and identification of these membership functions have been determined according to the QRA and a fulfilled database.

**Fig. 4. General Structure of the fuzzy control system for an evacuation model**

**Fig. 5. Graphical presentation of the membership functions to the FUZZY LOGIC controller**
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Fuzzy Rule Base and Defuzzification

The rules of the FUZZY LOGIC controller are based on “IF-THEN” conditionality. The fuzzy rules for the fuzzy logic guided evacuation model are defined in figure 6.

In this case wind speed and time after disaster are the factors that affect the consequence expressed as safe time. We have two variables with Fuzzy Input with four membership functions. According to this the total number of rules applied to the output fuzzy variable safe time is sixteen. The number of rules can also be lesser in some cases, where it is believed that some rules are not necessary or will not change anything in certain situations. For each cell a separate matrix for fuzzy rules is being created in reference to each scenario which is part of the evacuation model. This is done with the objective that for each individual located in X cell, the fuzzy control system shall use the adequate matrix for the X cell which is intended for the scenario of the accident. As an example, table 2 shows the matrix for fuzzy rules for evacuation Mode I in an event when the individual is located in cell number 4.

Table 2. Matrix for FUZZY Rule Base for evacuation model

<table>
<thead>
<tr>
<th>Safe time</th>
<th>time after disaster</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vs</td>
</tr>
<tr>
<td></td>
<td>s</td>
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<td>f</td>
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<tr>
<td>f</td>
<td>vs</td>
</tr>
<tr>
<td>vs</td>
<td>vs</td>
</tr>
</tbody>
</table>

FUZZY LOGIC controller is using the max-min composition (Mamandi). In the process of defuzzification, the centre of gravity of the received fuzzy set shows the output numerical value. As an example from the following chart (Fig. 7) we can see the max-min composition of the 16 rules in the case where the input variables are: wind speed 2 m/s, time after disaster 160 seconds. These values have a grade of membership of 1. The output numerical

Fig. 6. FUZZY Rule Base for evacuation model

Fig. 7. Graphical presentation of the outcome of FUZZY LOGIC controller
value for safe time after the defuzzification for this case is 55 seconds.

Evacuation Route

In order for the evacuation model to successfully manage the obtained input and output data, it is necessary to produce a software solution which as a final product provides information to the GPS device of the individual in graphic and sound form via presentation of the evacuation route leading to an area which will not be affected by the influences of the accident. The designed program receives information from the fuzzy logic controller for each cell separately, when the cell will be affected by the accident, and in compliance with this, the program designs potential routes for each individual leading him or her to the final safe destination. The shortest route is the first option that appears on the GPS device of the individual for which the route was created. Under the selected Model 1 from the scenario, the individual is located in cell 4. QRA for the starting input data shows that cells 3 and 4 will be influenced by the accident approximately 200 seconds after the accident alert, cells 5 and 6 in approximately 320 seconds, cells 7 and 8 in approximately 380 seconds and cells 9 and 10 in approximately 480 seconds. The evacuation route, starting from cell 4, has an option to lead the individual to one of the three main exits of the terminal located in cells 7, 9 and 10 but also provides additional guidance. The created possible routes primarily indicate the shortest and safest route. Within the whole process of decision-making, an important factor is also the speed of movement of the individual which depends on whether the individual uses a vehicle or is on foot. In situations when time does not allow the individual to be evacuated outside the terminal, the program guides the individual to the nearest terminal safe-haven or shelter.

Conclusions

LNG leakage accidents are potentially very hazardous. Rapid reaction and evacuation of people is of primary significance. The new ideas for the creation of evacuation models may contribute to the creation of a good evacuation model with a high rate of success in the execution of any evacuation. Through the presented evacuation model, we have portrayed the management of an evacuation model using fuzzy logic for a specific scenario. The potential error during the selection of an evacuation route has been brought down to a minimum in comparison with the selection of an evacuation route by an individual who does not have all the information regarding the external influences on the accident. The advantage of the evacuation model managed via fuzzy logic on the basis of the created database through the carried out QRA is that it eliminates the possibility of an error during the selection of an evacuation route when such is created by an individual with less knowledge of influential temporal factors. Additionally, the program creates a separate safety evacuation route in real time for each individual located inside the terminal on the basis of his/her location after the accident alert. The estimated decrease in risk of course influences the location of new LNG terminals, which must be in compliance with certain safety rules. In any case, this is only a starting point in the development of an evacuation model managed through fuzzy logic. We should also review the possibility for expansion of the use of the model for the needs of the general population, located outside the LNG terminal.

References

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