Current work related to hydrogen safety in infrastructures

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Decision support is needed

- How to integrate new HRS with existing refueling stations?
- What is the best strategy to place the HRS in network of refueling stations?
  • Considering for HRS & supply chains:
    - Risk minimization
    - Sustainability
    - Cost benefit aspects and Life Cycle costing
    - …

➤ How to secure a coherent decision support for all requirement?
Quality in Decision support: How to reduce the model and data uncertainty?

- Ensuring for all kinds of decisions:
  - the same system model applies
  - the same assumptions are used for each of the assessments


Mr. Joaquin MARTIN BERMEJO Unit “Energy production and distribution systems” DG Research – RTD/J-2
Development of a “Metamodel”: Functional modelling approach

• A Meta model of the system is established that includes all the aspects of the methods of decision support (RA, LCA, LCC,..)
• The model shall ensure that the same design is analyzed for each RA, LCA, LCC,..
• The model ensure consistency in the assumption to be made
• The model supports data quality → being a reference database for all the data

Produce <Outputs> from <Inputs> by <Methods> respecting <Constraints>
Example of hydrogen system
## Example of hydrogen system: tabular output

<table>
<thead>
<tr>
<th>Code</th>
<th>Inputs</th>
<th>Intent</th>
<th>by</th>
<th>Method</th>
<th>with</th>
<th>Constraints</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>Hydrogen gas, energy, Etc.</td>
<td>Hydrogen storage at large amounts</td>
<td></td>
<td>Cryogenic storage</td>
<td></td>
<td>Max. pressure, Temperature control, Evaporation control</td>
<td>Hydrogen gas / liquid, Engine, pollutants, Etc.</td>
</tr>
<tr>
<td>F4141</td>
<td>Data, Power; remote control Etc.</td>
<td>(HRS) remote control signals</td>
<td></td>
<td>Internet/software HRS safety functions</td>
<td></td>
<td>On-line uninterrupted power supply, intercultural understanding</td>
<td>Control of HRS</td>
</tr>
<tr>
<td>Function</td>
<td>Concept Hazard Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ref</strong></td>
<td><strong>Description</strong></td>
<td><strong>Keyword</strong></td>
<td><strong>Main variance</strong></td>
<td><strong>Consequence</strong>s</td>
<td><strong>Mitigation</strong></td>
<td><strong>Notes</strong></td>
<td></td>
</tr>
<tr>
<td>F12</td>
<td>Water electrolysis</td>
<td>Chemicals: Corrosion</td>
<td>Release → Fire</td>
<td>Heat radiation on equipment</td>
<td>ATEX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F21</td>
<td>Truck transport (pressurized )</td>
<td>Thermodynamic hazards: over temperature</td>
<td>Weakening of truck tank walls under filling</td>
<td>Tank rupture</td>
<td>Slow filling, pre-cooling</td>
<td>Depends on storage type</td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>Hydrogen storage</td>
<td>External: Accidental impact due to obstacle collision</td>
<td>Structural damage: →leakage →insulation</td>
<td>Release of hydrogen / overpressure in cryogenic system</td>
<td>Fences authorization to enter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4141</td>
<td>On-line with data connection</td>
<td>Mode of operation: Abnormal</td>
<td>Off-line → Loss of control of HRS</td>
<td>Possible escalation of minor events</td>
<td>High SIL level local operation</td>
<td>HRS shuts automatically down on loss of data connection</td>
<td></td>
</tr>
</tbody>
</table>
GIS – preservation of geographical relations

- An important issue, when analyzing hydrogen supply and distribution networks, is the knowledge about the specific geographical positions of the hazardous areas:
  - to evaluate for social risk criteria.
  - to decisions on additional preventive and mitigating measures to ensure the acceptance criteria of a given installation.
- Along the networks it is important to know about
  - the population density,
  - the environmental vulnerability and
  - the location of hospitals, emergency service etc.
- For this GIS is a very efficient and valuable tool for QRA
  - Information on system state (amounts, pressures, temperature, etc.) could as well be attached to the graphical objects supporting consequence assessments,
  - while necessary weather, population densities and other data could be provided by respective thematic maps.
Life cycle assessment

Goal definition and scoping → Life cycle inventory → Impact assessment

Interpretation: Guidance for User's

Emission Wastes Heat
Raw materials
Energy

Stage 1: Hydrogen production
Stage 2: Hydrogen storage
Stage 3: Hydrogen transport
Stage 4: Hydrogen distribution

Hydrogen to cars
Dynamic Assessments
Limitations of conventional RA tools

**fault & event trees, Bayesian networks, cause-consequence and barrier diagrams** have proven to be very effective tools for reliability and risks analyses!

But, they **cannot capture a number of features accurately:**

- e.g. difficult to be applied to dynamic situations with:
  - dynamic demand: seasonal - daily changes
  - loss of partial performance
  - gas supply variations (amount gas delivered)
- down times
  - residual time of gas delivery e.g. from line pack storage
- gradual recovery after a failure
Discrete Event Simulations

• DES to model continuous and dynamic characteristics and multidimensionality of systems

• traditionally DES are employed to model e.g. manufacturing plants with machines, people, transport devices, conveyor belts and storage spaces in order to optimize manufacturing processes.
  – different ready-to-use commercial software packages available

• DES open new perspectives for reliability and risk assessment
  – DES for reliability modelling combines discrete and continuous technological and procedural aspects
    • ➔ e.g. it also includes human reliability
Application field

- Such models may provide **more detailed answers to questions that depend on varying parameters**.
- The model **retains geographical dependencies and time patterns**.
- The model may **predict extremely rare events** that may occur during the life time of an (pipeline) installation -> run time may be millions of years.
- Possibility to include human operations as maintenance or any other task.
- Models can be extended to mimic the work flow on refuelling stations incl. the **varying fuel demand by customers**.
OPHRA project

- Feasibility study of offshore oil platform conducted in 2013 sponsored by Dong Energy

- Objectives:
  - Simultaneous & integrated calculation of event trees for consequence assessment, alarm and detection, and Human evacuation
  - To show a system with comprehensive documentation of model, assumptions and results in a transparent way
Simplifying the logic

• Present RA apply conventional fault-tree FT and event-tree ET techniques
  – FT and ET easily grow very complex when capturing all possible accident scenarios

• The accident scenarios, e.g. loss-of-containment events, involve several agents and actions, with mutual dependencies
  – Are treated as “independent” and each may have its own timeline, e.g.:
    • Release – dispersion – ignition – fire and explosion
    • Detection - Alarm – escape from module – mustering – evacuation
    • Detection – shutdown and blowdown
Consequences of a Release

Accident Scenarios – Event Tree

Event Tree Probabilities

- Immediate ignition 0.15
- Delayed ignition 0.30
- Explosion (instead of fire) 0.40

Pressure Vessel Hole Frequencies. Adapted from OGP.

<table>
<thead>
<tr>
<th>Hole Diameter (mm)</th>
<th>Leak Frequency (per vessel year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 3</td>
<td>$2.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>3 – 10</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>10 – 50</td>
<td>$7.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>50 – 150</td>
<td>$4.3 \times 10^{-6}$</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$4.6 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Event Tree Diagram of Gaseous Hydrogen Release through a Hole of a Pressurized Tank. Adapted from Moosemiller. 
Why is an alternative QRA method useful?

Application of dynamic & dependent models

- The event sequences trigger each other and are simulated concurrently.
- Events taking place in one sequence change the conditions in the other sequences (dynamic interaction)
Model logic

1. Sampling hole size & direction
2. Sampling immediate ignition, time to secure workplace, delayed continuous and intermittent ignition and start time for delayed intermittent ignition
3. If either the continuous or intermittent source exists, their positions in the process area are sampled
4. Sample no. and position of people in the process area

**Start**

- **Initialisation**
  1. Sampling hole size & direction
  2. Sampling immediate ignition, time to secure workplace, delayed continuous and intermittent ignition
  3. If either the continuous or intermittent source exists, their positions in the process area are sampled
  4. Sample no. and position of people in the process area

- **Detection & response**
  1. Detects & alarms work or failed
  2. Isolation of release

- **Escape & evacuation**
  1. Modelling securing working places and escape from process area
  2. Modelling reaching the muster ➔ required safe egression time (RSET)

- **Consequences**
  1. Modelling dispersion or jet flame if immediate ignition takes place
  2. If jet flame, modelling impact on people and number of people killed
  3. If delayed ignition, all who not escaped process area are killed ➔ available safe egression time (ASET)

**Visualization**

**Visualization** of release

**Visualization** of escape

STOP SIMULATION Evacuation finished

1. Modelling securing workplaces and escape from process area
2. Modelling reaching the muster ➔ required safe egress time (RSET)

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14 September 2017
1 - Physical phenomena
Interdependencies established

- Release $f(t-t_{release})$
- Ignition $f(t-t_{release})$
  - Cloud size $f(t-t_{release}, \text{Wind}, t-t_{ESD})$
- Alarm & ESD $f(t-t_{Alarm})$
  - Heat radiat. $f(t_{ESD}-t_{ignition})$
  - Explosion $f(\text{Cloud size}, \text{ignition})$
- Escape $f(t-t_{Alarm})$
  - Fatalities $f(\text{Escape, Heat radiation, explosion, ...})$

Fatalities $f(\text{Escape, Heat radiation, explosion, ...})$

Explosion $f(\text{Cloud size, ignition})$

Heat radiat. $f(t_{ESD}-t_{ignition})$

Alarm & ESD $f(t-t_{Alarm})$

Escape $f(t-t_{Alarm})$

Cloud size $f(t-t_{release}, \text{Wind}, t-t_{ESD})$

Ignition $f(t-t_{release})$

Release $f(t-t_{release})$
The off-shore platform
### Example statistical results:

10000 simulation runs

<table>
<thead>
<tr>
<th>Input:</th>
<th>average</th>
<th>st.dev.</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>wind speed (m/s)</td>
<td>11</td>
<td>5</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>wind direction (degrees)</td>
<td>91</td>
<td>52</td>
<td>0</td>
<td>180</td>
</tr>
<tr>
<td>hole size statistic (mm)</td>
<td>12</td>
<td>28</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>No. workers at random positions</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

| Output:                       |         |         |     |     |
| wind speed in module (m/s)    | 0.6     | 0.3     | 0.1 | 1.4 |
| mass flow (kg/s)              | 6.2     | 27.8    | 0.007 | 271.5 |
| SEPmax jet flame (kW/s)       | 40      | 11      | 28  | 93  |
| RSET (s)                      | 240     | 176     | 301 |
| ASET (s)                      | 427     | 0       | >600 |
| No. fatalities per accident   | 1.3     | 1.8     | 0   | 5   |
Results examples

Time dependence of the flammable volume for different size releases

Ratio of ASET and RSET. Values above 1 indicate safe egress conditions.
Supply Chain Design

- Design

Number of compressor: **1**
Average waiting time: **0 min**
Storage capacity: **500 kg**

Number of gate: **1**
Average waiting time: **0 min**

Hydrogen Supply Chain

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Hydrogen Supply Chain

- Sensitive part of the supply chain

**Total Failures over 25 Years: 3'294**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Simulation Values</th>
<th>NREL Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloading Gate</td>
<td>60%</td>
<td>30%</td>
</tr>
<tr>
<td>Loading Gate</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>Storage 1</td>
<td>14%</td>
<td>20%</td>
</tr>
<tr>
<td>Storage 2</td>
<td>16%</td>
<td>20%</td>
</tr>
<tr>
<td>Compressor 1</td>
<td>21%</td>
<td>30%</td>
</tr>
<tr>
<td>Compressor 2</td>
<td>22%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Simulation Result: Distribution per Equipment of the Failures that Occurred during 25 Years in the Supply Chain

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**Table 4.1:** Comparison of the MTBF and MTTR obtained by the simulation with the theoretical values provided by the NREL [1]

<table>
<thead>
<tr>
<th>Equipment</th>
<th>MTBF [days]</th>
<th>MTTR [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Theoretical</td>
</tr>
<tr>
<td><strong>Production Plant</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>13.0</td>
<td>13</td>
</tr>
<tr>
<td>Storage Tank</td>
<td>19.0</td>
<td>19</td>
</tr>
<tr>
<td>Loading Gate</td>
<td>24.0</td>
<td>25</td>
</tr>
<tr>
<td><strong>Refueling Station</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unloading Gate</td>
<td>26.5</td>
<td>25</td>
</tr>
<tr>
<td>Compressor</td>
<td>12.4</td>
<td>13</td>
</tr>
<tr>
<td>Storage Tank</td>
<td>17.6</td>
<td>19</td>
</tr>
<tr>
<td>Dispenser</td>
<td>46.7</td>
<td>48</td>
</tr>
</tbody>
</table>
Discussion

• **The risk assessment of a complete supply chain is analyzed using**
  – the functional modelling approach
  – the conceptual hazard analysis methodology.

• The functional modelling allows the modelling of new designed technologies
  – may be more and more detailed as new information and alternative technologies are implemented.
  – The high level risk analysis enables the efficient risk assessment
    • help to concentrate the assessment to the hazardous parts of concern.

• At a certain level there is a transition where a low level assessment is appropriate,
  • application of FMEA and HazOp
DES model validation

- Domain experts can participate actively in validation, as the models are simple to understand and a change in input can be immediately seen in output.
- Animation of scenarios facilitates significantly validation.
- The models and data for each block can be verified or validated separately.
- DES models provide better transparency on applied models, assumptions made and output.
- Models of the 4 sequences are validated using controlled input both for single runs and for batch simulations.
Concluding remarks

- Discrete Event Simulation modelling has proven viability for the risk analysis of different safety critical systems.
- It works and can produces a great deal of informative output and, in particular, probabilistic risk measures.
- The approach is highly applicable in other areas e.g. fire safety management.
- Results can be treated statistically:
  - Calculation of worst case
  - Minor accidents and major accidents are preserved
THANK you

- Further questions ??

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