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Offshore Platform Hydrocarbon Risk Assessment – OPHRA: Feasibility

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Feasibility study of an alternative method for Quantitative Risk Assessment using Discrete Event Simulation

Production and Service Management – Risk Research

DTU Management Engineering

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Report

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Content

Summary

This report describes the feasibility demonstration of a new method to perform risk assessments for offshore platforms. This method simulates the following phenomena as concurrent sequences of events using the Arena® Discrete Event Simulation (DES) software (version 14.50.00):
- Release, ignition and fire;
- Detection, shut down and alarm;
- Escape and evacuation;
- Exposure and impact on people and equipment

This method leads to a transparent framework for modelling, which helps to demonstrate the correctness and appropriateness of models and assumptions.

The report lists the (type of) models and data needed for the risk assessment framework, and provides specific suggestions for some of those models.

Some preliminary calculations with the DES model have been performed to illustrate type of results that can be obtained and to provide some insight in the accuracy and computational efforts.

Finally, further work is identified in order to develop an operational risk assessment tool.

Acknowledgements

List of abbreviations

ASET	Available safe evacuation time
BD	Blow down
DES	Discrete event simulation
EBD	Emergency blow down
ESD	Emergency shut down
FAR	Fatal Accident Rate
F-N	Cumulative Frequency versus Number of fatalities
IR	Individual risk
LFL	Lower flammability level
PLL	Potential Loss of Life
QRA	Quantified Risk Assessment
RSET	Required safe evacuation time
UFL	Upper flammability level

Offshore Platform Hydrocarbon Risk Assessment – OPHRA: Feasibility

1. Introduction

In order to manage safety and to fulfill regulatory requirements, operators of hydrocarbon producing offshore facilities have to prepare quantitative risk assessments (QRA). Those risk assessments cover, among other hazards, the risk of (major) leaks of hydrocarbons from wells, risers and process equipment. Basically, a risk assessment has the objective to identify everything that may go wrong and, in order to make these findings operational, to predict the event's probability and the event's consequences and final impacts. Therefore, one has to establish the event sequences and their probability of occurrence that lead to an undesired impact to people, property and environment. When hydrocarbons are accidentally released, each event sequence consequences, such as the impact of fire and explosion, depend not solely on the release rate and total amount, but also on prevention and mitigation measures, such as the response of safety systems and personnel. By nature, this is a dynamic process with concurrent events which may be mutually dependent.

The QRA's goal is to demonstrate that installations do not expose personnel to intolerable levels of risk, to identify the most important contributions to risk, and to ensure that risk is reduced effectively and efficiently. The outcomes of a QRA are risk indicators that can be compared with risk criteria (for details see chapter 1.2). The existing and widely accepted risk assessment techniques use static methods to deal with these processes, as e.g. (static) fault and event trees that describe the possible outcomes. Time dependent parameters, that influence the outcomes of the event trees, are used as averages over a period of time, as e.g. an average leak rate per year, average ignition probability or average number of workers in place over a year. There are many other input parameters, as weather conditions, actual amount of hydrocarbon and pressure in the processing equipment that needs simplification in order to take the assessment to a practical level. Still, such event trees may easily become very complex and are by that difficult to use in practice. The simplifications do not allow capturing the dynamic nature of the processes in a convenient manner, normally leading to conservative (i.e. overestimating risk) assumptions to be on the safe side.

The objectives of the present OPHRA feasibility study are twofold:
1. To demonstrate the transfer and application of state-of-the-art operational management techniques (Discrete event simulation, DES) to industrial risk assessment. The goal is to provide an alternative to the static event trees, and develop a dynamic assessment technique, which simulates the concurrent processes following a release of hydrocarbons on an offshore hydrocarbon-production platform (see also chapter 1.1 below).
2. To demonstrate a framework for such assessment technique that allows the risk assessment to be verifiable and easier to use in practice, i.e. a framework that provides the necessary transparency and documentation of all assumptions and arguments used in the course of the assessment (see also chapter 1.3 below).

1.1 Monte Carlo type simulation for Risk Assessment

Computer simulation models[1] of complex environments to support risk management have been around for many years. Today, the broad availability of powerful computers and the associated development of easy-to-use modelling tools promote the use of even complex modelling and simulation as a standard tool for the reliability and risk practitioner.

Discrete Event Simulation (DES) models appear a competitive alternative to the conventional reliability and risk analysis models such as fault and event trees, cause-consequence and barrier diagrams as well as Bayesian networks (Kozine, Markert, Alapetite 2009; Markert and Kozine 2012). While these conventional models have proven to be very effective tools for reliability and risks analyses, they cannot capture a number of relevant features accurately. The main difference between the DES approach and the conventional one is that the former provides a convenient way for developing dynamic models while the latter is a way to construct static models. An attempt to endow the static models with a dynamic dimension (e.g. dynamic fault trees) makes the models too complex and rather impracticable. On the contrary, by employing DES models, 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 analysis framework is based on simulation of the dynamic interactions between concurrent phenomena following loss of containment, specifically:
- The physical processes (outflow, dispersion, ignition, heat radiation, explosion)
- Detection, alarming and emergency shutdown
- Escape and evacuation
- Impact on persons, escalation and impairment of safety functions

The simulation model runs repeatedly loss of containment scenarios to evaluate the associated stochastic events in time with random delays, durations, instances of occurrences and others. The output data sets are collected over all the simulated scenarios and are further processed to predict risk indicators as the Individual Fatality Risk (IR), the Potential Loss of Life (PLL), the Fatal Accident Rate (FAR, at platform and workplace level), and the group risk (distribution of number of simultaneous fatalities).

This way of tackling the problem allows capturing a great deal of specific characteristics of different platforms, dynamic change of people responses and other characteristics. Scenarios with severe consequences can be 'played back' to learn from them and can be animated, which except for the learning effect provides a new way of validation. This also makes the simulation models a good communication tool between system analysts and domain experts.

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[1] Computer simulation refers to methods for studying models of real-world systems by numerical evaluation using software designed to imitate the system's operations or characteristics. The simulation model can be allowed to become quite complex and if needed to represent the system faithfully.

The approach as a whole and the computer model are the tools improving risk assessment by providing an overall framework to describe and simulate the interactions between concurrent chains of events under the hazardous scenarios and produce probabilistic risk measures.

1.2   Outcomes of a risk assessment

The purpose of a quantitative risk assessment (QRA) is to provide a realistic estimate of the likelihood of adverse events (accidents) and the extent of the adverse consequences of these events, i.e. the set of all possible triples {adverse event, likelihood of the event, consequence of the event}. This triple equals the combination of adverse event and its risk. The complete set of adverse events can be considered to represent the total risk in some heterogeneous form of the operation. For complex operations with different types of adverse events, the events may be put into classes of similar events that can be treated in a homogeneous way, e.g. for an offshore platform, examples of such classes can be: ship collisions; releases of hydrocarbons; and loss of structural integrity due to severe weather.

The combined output of assessments for these different classes can be by a mapping of the consequences and likelihoods to a single parameter that describes risk, the risk indicator. This requires some simplification (parameterization) of the consequences, e.g. by simplifying the consequence to the number of fatalities or the financial damage. This allows a way of presenting the multi-facetted aspect of "consequence" together with the likelihood on a two-dimensional graph, displaying the (cumulative) probability distribution of the parameterized consequence, such as the F-N curve.

Alternative ways of reporting the output of a QRA are by means of estimating that some person may be affected by an adverse event (e.g. using the concept of Individual Risk - IR) or the risk at some specific position (location-based risk or local Fatal Accident Rate).

A QRA applies a set of linked models describing possible events and their outcomes. The outcome of the QRA is therefore completely determined by these models and how they are linked. A model is a set of assumptions (hypotheses) concerning relations or dependencies between objects (notions) that represent observations of reality.

1.3   Verification of QRA

By nature of the assessment - an estimate of likelihood of future, very often rare, events - it is impossible to validate a QRA empirically (unless we deal with frequent events that allow statistical analysis).

The quality of the QRA depends therefore on the quality of the single elements of the models and how they are put together. We assume that it may be possible to qualify (verify) single parts of the model, and if that is possible, we assume that we may arrive at an informed opinion whether the results of the QRA are trustworthy.

In order to verify the quality of a QRA we need thus:

- Review the individual models (are the model assumptions realistic, do they represent the best knowledge and understanding of nature, also in the context of the application?)
- Verify independent input data to the set of models (are the input data in agreement with observations?)
- Verify that the final results are deduced correctly from the input data using the model assumptions (can the results be reproduced using an alternative expression (implementation) of the model?)

The models used in a QRA can be distinguished into the following types or combinations thereof:

1. Models of logical reasoning, describing events and conditions with statements of the form "if–then-else": fault tree models are typical examples of models of logical reasoning, providing the necessary and sufficient conditions for the top event to happen, but also many models describing physical phenomena include some (implicit) logical reasoning (if a hole in a tank under the liquid level, then a liquid outflow will occur). Logic reasoning involves assumptions about causality, and is a fundamental element of risk assessment, because it determines what consequences are credible outcomes of adverse events.

2. Probabilistic models. These models describe the output as a probability or probability distribution given some input. A typical example is the Bayesian Belief Network. Note that these models are based on some logic model reasoning, but where 1-to-1 causality is extended to consider alternative outcomes of an initial event, outcomes that are possible but not necessary. If the basic events in a fault tree are assigned probabilities, the top event can be assigned a probability, and the fault tree becomes also a probabilistic model. A special form of a probabilistic model is the Probit model, describing the consequence of exposure of a population (typically humans or animals) to some impact. Here the probability distribution of damage is based on empirical observations. Note that the (joint) probability distributions assigned to the input parameters of the model either can be considered to be an inherent part of the model (as in the case of Probit models) or as specific input for a specific case (for e.g. a Bayesian Belief Network).

3. Deterministic models. These models, typically describing the physics of nature, predict the consequence of certain events using the laws of physics and chemistry, normally with considerable simplifications. Examples are the prediction of the rate of release from a hole, given the physical parameters of the hole (size, shape), substance and thermodynamic state (temperature, pressure), and the prediction of the size and radiation from jet flames. For each release a single (deterministic) value is predicted using appropriate physical models and a given set of input parameters for each scenario. Deterministic models may become probabilistic when probability distributions are assigned to the impact parameters. Such probability distributions may depend on inherent variability of the initial and boundary conditions (aleatory variability) as well as uncertainty in the model (epistemic uncertainty). Aleatory variability can be assessed by repeating the calculations with different sets of related input parameters (Monte Carlo type of calculation). This will produce e.g. the probability distribution of flame length caused by variations in the input and boundary conditions.

1.4 Reporting requirements for QRA allowing for independent review

When performing a QRA, the activity consists of:

1. Developing specific models for the study at hand, i.e. models (typically models of logic reasoning e.g. models defining the full set of accident scenarios), that are unique for this study;
2. Selecting general models, typically models that describe physical phenomena (outflow, cloud growth, explosion);
3. Selecting the specific input data for the study at hand, which also includes that it is ensured that the models that have to be run subsequently provide adequate output for the models to be run next.
4. Performing ("running") the models with the selected input data, while ensuring that models (input/output) are linked correctly.

One issue that should be considered is the following: The QRA is a construction based on the combination of different models. Each model produces a probability and we have ascertained the validity of each model's outcome. But by combining these outcomes, we extrapolate statistical observations that are significant on the level of the single model, to very rare situations (extremely low probabilities) that together will not be observable, let alone verifiable. Combinations of those models assume that the events, described by each of the models, are independent of each other. This is a questionable assumption, which should be scrutinized by the analyst.

In order to allow an independent review of this process to be possible, the analyst has to report these steps in such a way, that the reviewer in principle would be able to reproduce the results of the analysis. However, this is, in view of the enormous amount of data in modern risk assessments, not a trivial exercise.

The report on the QRA needs to include the following:

1. A description of the study-specific models, especially the logic reasoning that define the accident scenarios and the credible "consequence-space". These include typical event trees and scenario diagrams (barrier diagrams).

2. A list of the selected general models, with references to detailed descriptions and validations of those general models. The analyst does not need to describe the general models if that information can be found elsewhere, but the analyst should address why the selected models are suitable, and how uncertainties in these models affect the results of the QRA.

3. The input data put into the models. In principle all decisions made by the analyst when running the models should be documented. In case of complex models, such as 3-dimensional Computational Fluid Dynamics (CFD) models, it may be impractical to provide all input data – in that case one might alternatively provide model results for "simple" cases (e.g. undisturbed boundary layer flow), or cases where validation has been performed, in order to justify the chosen input data.

4. The linking of the models, i.e. how output from one model propagates as input to another model in the study.

1.5 Documentation of the OPHRA framework

The appendices include detailed model descriptions for some of the models that have been developed or adapted to the OPHRA approach. This holds especially for gas dispersion (a model based on the JIP workbook model referenced in (Anonymous 2006), but modified to enable time dependent cloud sizes) and ignition (using direct simulation of continuous and intermittent ignition sources rather than a probabilistic approach, but using the statistical information from (Anonymous 2006))

2. The OPHRA method

The OPHRA feasibility study aims at developing methods that allow a step towards verifiable risk assessments and improving the practical use of QRA results. The hypothesis is that a clear and transparent structure of the inputs and outputs for the simulations and animation of the calculation steps support this. The present study is the first step in this development and develops the needed framework to enable testing the hypothesis.

2.1 Transparent scenarios

One of the objectives of the OPHRA project is to provide a framework which supports verifiable risk assessments. This is pursued by structuring OPHRA using a framework at an overall level that describes subsequent and simultaneous processes during a loss-of-containment (LoC) event. This framework would be the basis for the logic reasoning that defines the accident scenarios. The possibilities of Discrete Event Simulation are exploited by defining the framework as a few separate "event diagrams". Each event diagram describes the sequence of events that are directly linked by causality as a function of time, while the events in separate event diagrams may occur in parallel, so the diagrams form a set of dynamic event trees, allowing for interaction. Such a set of parallel event diagrams, while each diagram is rather simple on its own, allows for a much larger variety of scenarios, than what can be obtained by building one static event tree that should capture all possible combinations (in time) of events.

Each event diagram consists of a number of events that are linked by causal or probabilistic relations. More complex events (such as "jet dispersion") require a separate (deterministic) model to describe the outcome of those events. The structure of the event diagrams with embedded events means that models can be developed individually for those events without too much concern about interactions between the events in the diagram[2]. The framework of diagrams describes the relations between these models, and what requirements these models should fulfil in terms of input and output. These models can be selected and "plugged in" individually, according to the required level of detail or simplification.

Of course, the diagrams in themselves represent a logic model and as such already contain assumptions about the developments and interactions between the phenomena and actions, and the challenge is to keep these diagrams as general as possible.

Verification of risk assessment using the OPHRA method would therefore require:

- An assessment whether the generic event diagrams used in OPHRA present a defendable description of all possible adverse events related to hydrocarbon releases on offshore (production) platforms;
- A validation that the logic, represented by the generic event diagrams, is implemented correctly;
- Validation of the models that are "plugged in" in the event blocks and in the probabilistic relations in the event diagrams, this validation can be provided outside and separate of OPHRA ;
- Verification that correct data has been used as input to the different models.

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[2] Although there is one limitation: the "dynamic" nature of the modelling, where events can happen at any point in time, requires that the physical models also are dynamic, i.e. produce output as a function of time, to be able to generate the correct initial conditions for the next event.

2.2 Demonstrating traceability

The discrete event simulation "simulates" release scenarios. This allows a demonstration of the correctness of the implementation and the trustworthiness of the logic diagrams. Single scenarios can be analyzed step by step, demonstrating the sequence of events in time. This will provide some evidence that the framework provides realistic and traceable outcomes. That is, we can find back to certain scenarios and study the values of all parameters, accidental events and their combination that have resulted in the observed consequences.

Validation of the implementation of the framework can be performed by investigating the response of the software with special input sets and models, for which the output can be predicted analytically.

2.3 Description of the event diagrams

For OPHRA we have selected the partition of the phenomena in four concurrent sequences of events or phenomena, viz.:

1. the causal sequence of release, gas dispersion, ignition, combustion and heat transfer;
2. The sequence of detection and initiation of countermeasures in terms of alarm, emergency shutdown, and blow-down;
3. The sequence of escape and evacuation, i.e. processes related to the presence and movement of personnel; and
4. The assessment of final effects, i.e. the exposure of people and equipment to physical effects (pressure, heat)

Each concurrent sequence is generated by a separate model though heavily dependent on and interacting with each other. All four models "talk" to each other and trigger different responses. Events taking place in one sequence can change the conditions in the other sequences (dynamic interaction). This is depicted in the figure below. The DES model lay-out is described in more detail in Appendix A.
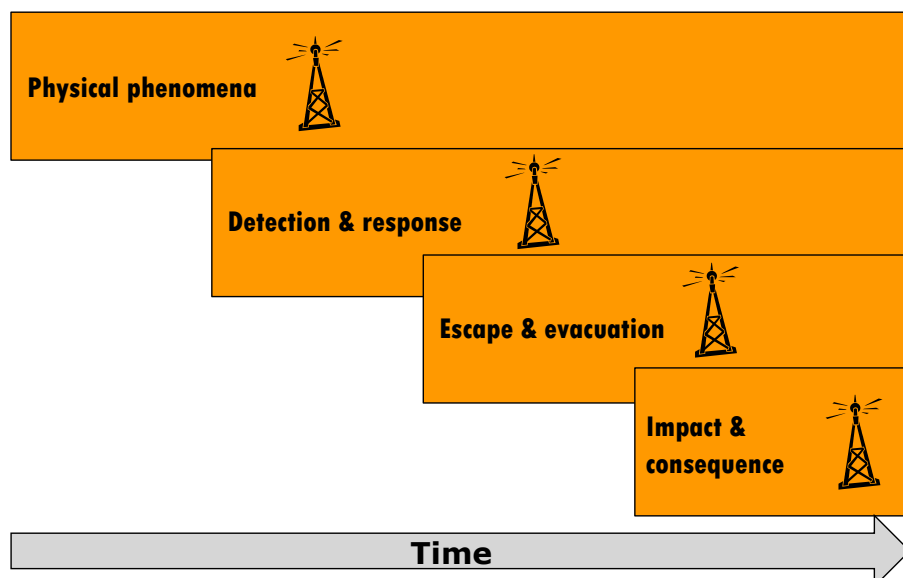

Figure 1. Dynamic and interdependent models of the OPHRA method

These processes are described by means of 4 "event diagrams" The basic assumption of our modelling is that these event diagrams provide a realistic description of hydrocarbon releases on offshore platforms in general. Possible weaknesses of this description is that these sequences are incomplete, or do not allow to account for certain combinations of events.

Apart from the description of the sequences, the analysis needs to account for initial and boundary conditions. These conditions typically relate to:

- Physical lay-out of the platform (location of walls, decks, equipment, process sections, etc. in relation to the release);
- Process conditions in the process sections that determine the thermodynamic state of substances when released;
- Ambient conditions that affect the consequences (typically wind speed and direction);
- Distribution and presence of personnel.

The description of these initial and boundary condition is a simplification of reality, and as such an assumption. It is possible to include very detailed input descriptions, but in general the subsequent models will not be able to account for all interactions (e.g. detailed description of equipment layout is simplified to distributed porosity to allow ventilation estimates). There is therefore a need for a balanced appraisal of the description of initial and boundary conditions in combination with the complexity of the models that are applied later in the risk analysis.

For each of the basic four 4 sequences listed above, an event diagram has been derived. These event diagrams consist of probabilistic elements and deterministic elements. Probabilistic elements are controlled by probabilistic conditions, such as hole size, probability of ignition, wind direction, distribution of personnel, etc. Deterministic elements describe the relation between physical conditions, such as release rate depending on internal pressure, cloud size, heat radiation, etc. Of course there is an interaction between the deterministic and probabilistic events, e.g. the probability of ignition depends on the area covered by the cloud given release rate and wind speed.

The blocks in the diagrams mainly relate to deterministic models, while the links between the blocks (e.g. the "event tree branches") relate to logic and probabilistic models.

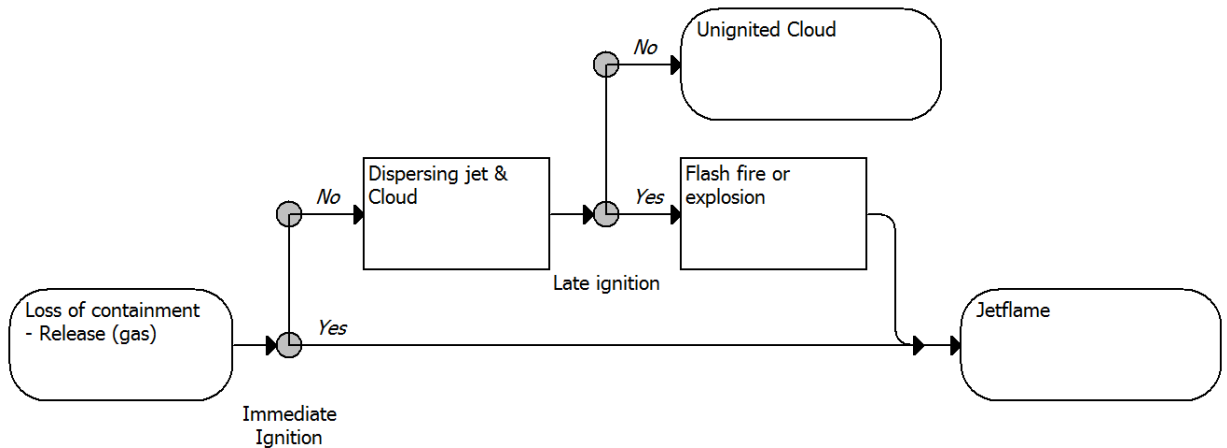## 2.3.1 Diagram and models for the physical processes

Figure 2 Event diagram for physical processes

Figure 2 shows the logic model for the processes directly (physically) related to the loss of containment event. In the feasibility study we only address releases of gas (excluding liquid release, two phase releases, pools, and pool fires). The gas from the release can ignite immediately, leading to a jet fire, or not, in which case the unignited gas disperses and a flammable cloud or jet builds up. Late ignition may ignite this cloud, leading to a flash fire or explosion; after the flash fire or explosion, the remaining gas leaking from the hole will form a jet flame. Alternatively the gas is never ignited.

This diagram needs the following models and input data for completion (references to the corresponding model specification sections in Appendix A are included when such specification has been developed, the underlined models are included in the feasibility study:

- *Release frequencies*: A probabilistic model describing the likelihood of a loss of containment of specific size, location and direction. (Appendix A section 3.3.1).
- *Immediate ignition*: A probabilistic model predicting the probability of immediate ignition as a function of type and size of failure (Appendix A section 3.5.1).
- *Outflow model*: A (deterministic) model that predicts outflow as a function of hole size (and other characteristics), substance, and thermodynamic state of the substance inside the containment. (Appendix A section 3.3.2).
- *Jet-fire model*: A (deterministic) model that describes the extent and position of the jet flame, and other parameters such as radiative and convective heat radiation to (nearby) objects, as a function of outflow, local wind (or ventilation) speed and direction, and nearby geometry. (Appendix A section 3.6).
- *Dispersion model*: A (deterministic) model that describes the development, position and extent of the unignited jet or cloud (e.g. the extent of the flammable contour) as a function of outflow, local wind (or ventilation) speed and direction, and geometry. (Appendix A section 3.4 describes a simple cloud model).
- *Delayed ignition*: A model predicting when or whether the cloud ignites. This contains a probabilistic model of the presence and character (continuous or intermittent) of ignition sources, linked to the output of the dispersion model telling when the cloud will reach such ignition source. (Appendix A section 3.5.2).
- *Flash Fire/Explosion model*: A (deterministic) model to describe the extent of the flash fire (area or volume affected by high temperature) or explosion (overpressures on nearby ob-

jects and structures) as a function of the position and extent of the unignited cloud immediately prior to ignition, local wind (or ventilation) speed and direction, and nearby geometry. (The feasibility study includes the simple assumption that any delayed ignition leads to 100 % fatality of the personnel that is still in the module for any release).

- *Ventilation model*: The models above require input by mean of information on boundary conditions (typically wind speed and direction) and geometry, and some (deterministic) model linking ventilation and wind speed and direction inside the structure to the geometry. (Appendix A section 3.2).

2.3.2 Framework and models for detection and response
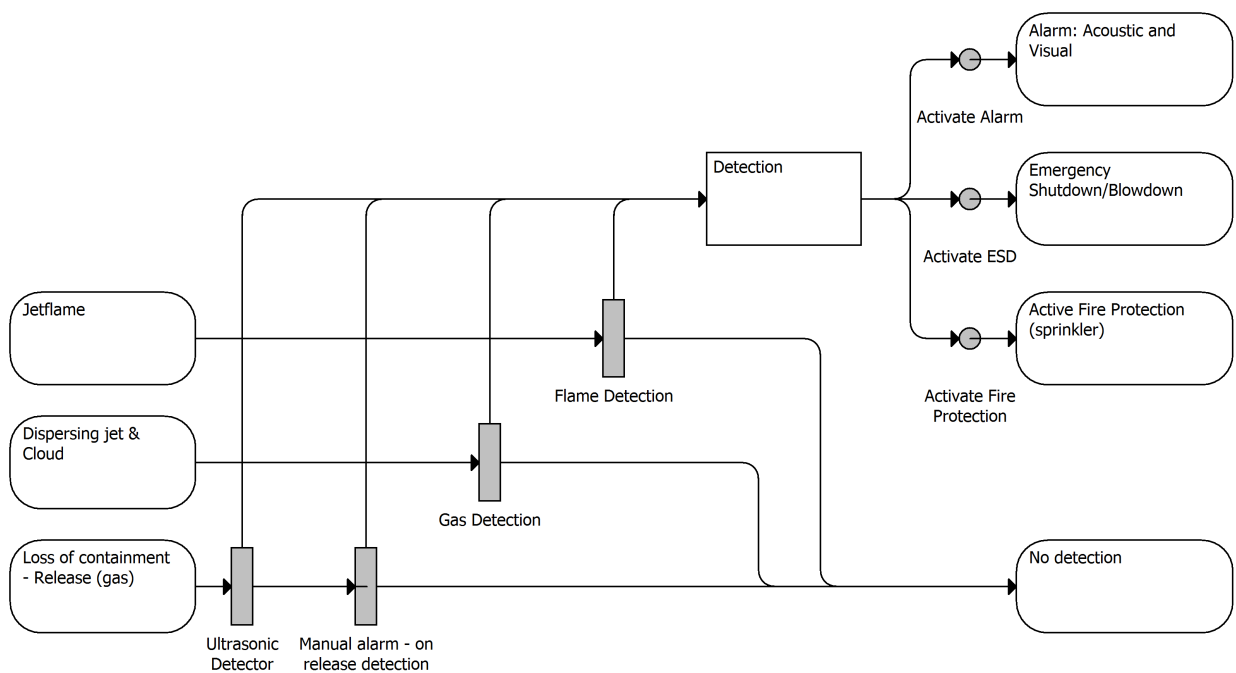
Figure 3 Event diagram for detection and response

Figure 3 shows the framework how detection will react to the basic adverse physical events from the "physical" framework (shown in Figure 2). This framework consists of two parts: first the detection of the event; and second the response by means of alarming personnel, shutdown and blow-down of the hydrocarbon containing sections, and eventually firefighting.

The installation may have installed different detection systems. In this framework the most essential detection systems are included: direct detection of the release (here introduced as an Ultrasonic Detector), detection of flammable gas by gas detectors, detection of fire by some flame or heat detectors, and detection by personnel, typically effectuated by use of a push button. For each of those systems, the QRA need to include some model, predicting the possibility or probability whether and when the respective detector will detect the phenomenon. So the following models are needed:

- *Ultrasonic detector model:* A probabilistic model of the probability of detecting outflow, as a function of the reliability of the detector system, the distance of the detector from the release position, outflow rate, and possibly the type of release (hole or rupture). If several detectors

are installed, the model should be applied on all detectors, considering the position of each of detector. Common mode failures should be considered.

- *Gas detector model:* A probabilistic model of the probability of detecting gas over a certain concentration, when one or more gas detectors is hit by a gas cloud. This model takes input from the dispersion model, which should generate the location and extent of the gas cloud at 10% LFL (or any other detection limit) as a function of time. Further input is the location of the gas detector, and the reliability of the single detector. as well as the joint reliability. (Appendix A section 4.1, in the feasibility model there is only one detector).

- *Flame- and heat detector model*: A probabilistic model similar to the gas detector model. This model takes input from the jet flame and pool fire model, which should generate extent and location of the fire (for convective heat transfer) and radiation to the environment as a function of time.

- *Human detection model*: A probabilistic model describing the response of personnel present in the area to release, dispersion and fire. The model takes as input the presence of personnel, and should consider the "detectability" of the event (size of release, distance to event), time and possibility to reach the push button, and likelihood of surviving this time, given the nature of the events.

- *Detection response model*: A model describing the specific alarm strategy at the platform in response to a set of detections. The model contains a probabilistic part describing the (overall) reliability of the system to provide triggers to alarm, ESD and blow down systems.

- *Alarm model*: A (probabilistic) model describing in what areas personnel are alarmed by acoustic and visual warnings. The feasibility study assumes that any detection leads to alarming the personnel

- *ESD/BD model*: A (probabilistic) model describing what isolation and blow down valves will operate successfully and how fast they will isolate and empty process sections. This model takes as input the description of process sections. The model is linked to the outflow model that should respond to the changed inventory and conditions.

- *Active Fire protection model*: A (probabilistic) model describing where Active fire protection is activated. The model will be linked to fire and dispersion consequence models, changing the likelihood of ignition and heat impact to objects and persons.

2.3.3 Framework and models for escape and evacuation
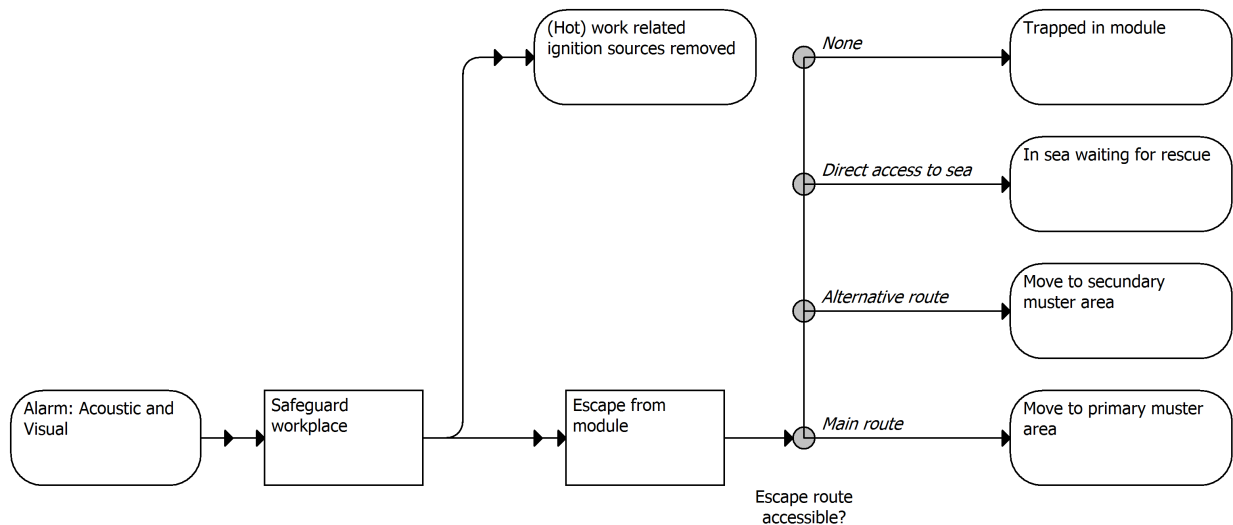
Figure 4 Event diagram for escape and evacuation.

Figure 4 shows the events that are initiated by alarming personnel. They deal with the alternatives of moving away from and avoiding exposure to the hazardous phenomena. The framework involves the following models:

- *Safeguarding workplace:* When alarmed, the personnel (1 to 5 persons at a time) have to leave their workplaces. This may require some time, which is related to working position (e.g. on a scaffold), tools being used, or objects being handled (e.g. performing lifts). The model predicts the time needed to secure the workplace (triangular distribution); the personnel is assumed to stay located on their positions they had when the LoC started. Both predict as part of the RSET (Appendix A section 5.2).

- *Escape from module*: After securing the workplace, personnel will move towards the escape exits of the module towards the escape routes to the muster area. Position as a function of time is modelled probabilistically assuming movement patterns and walking speeds (Appendix A section 5.3).

- *Moving to point of evacuation* (muster, secondary muster, escape to sea, trapped): Depending on what routes are impaired by the release or fire, personnel will decide on moving towards one of the evacuation options. Position on the escape routes is modelled probabilistically assuming walking speeds (Appendix A section 5.4).

- *Change of ignition sources*: Some ignition sources depend on the presence and activities of personnel. The DES framework allows changing the position and presence of ignition sources depending on the movement of the personnel.

2.3.4 Framework and models for impact on people and assets
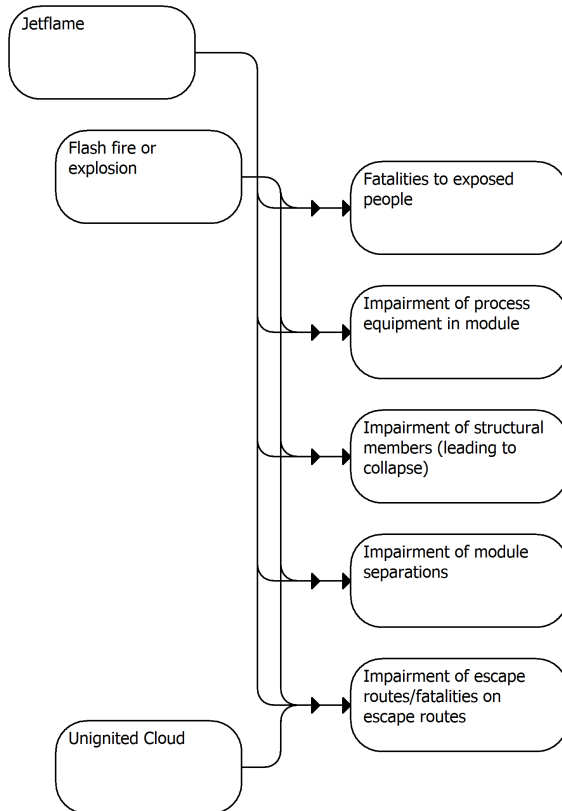
Figure 5 Event diagram for final consequences on personnel and equipment

Figure 5 shows the structure for evaluating consequences. Jet flames and flash fires/explosions can cause direct fatalities to personnel, impair process equipment (with possible escalation when isolation and blow down are not successful), impair the structural members, causing loss of integrity of the platform, impair module separations, leading to escalation to neighboring modules, and impair escape routes. Unignited clouds may impair escape routes.

The impact models are either probabilistic (Probit model for heat radiation impact on persons) or deterministic (heat load on structures). The following models are needed:

- *Fatality of personnel due to heat impact*: This model combines the heat radiation from the fire models, presenting incident radiation at a position, and the position (changing with time) of personnel, to calculate the heat radiation dose received by a person, and estimating fatality. The DES model will use a sampling technique to decide on fatality for a given scenario. (Appendix A, section 6.1) (The feasibility study has implemented a very simple model: if the module is hit by a flash fire or jet fire, all personnel still present in the module are assumed fatalities)
- *Fatality of personnel due to overpressure*: The feasibility study has not considered fatality due to overpressure.
- *Impairment of process equipment*: failure of process equipment is calculated based on total heat load, physical response, presence of passive or active (working) fire protection. Output is failure (and failure mechanism: Rupture, hole, BLEVE) at certain time.

- *Impairment of structural members*: Similar as impairment of process equipment. The response of the whole structure should be related to the criticality of the member within the structure (in a simplified way, full structural analysis will not be included), the simplest approach would be that impairment of any critical member leads to collapse of the platform.
- *Impairment of module separation*: Similar as impairment of structural members. Failure of walls, etc., will lead to adjacent modules being exposed to fire and heat radiation.
- *Impairment of escape routes*: This model will describe the decision by personnel whether or not an escape route is available for escape or not. The model will simulate the information available to the personnel while escaping, which is visual observation and instructions by the PA/Alarm system. Visual information is the presence of smoke and flames, and alarm lights. The issue is that invisible gas clouds may endanger certain escape routes without the impairment being observable for the personnel.

3. DES implementation

The implementation of the algorithm follows the logic shown in Figure 1 and its general structure is presented in Figure 6. The algorithm is implemented in the Arena DES software that is based on the programming language SIMAN and can be controlled through Visual Basic for Applications (VBA).

Most of the input data are stored in an Excel sheet and read by the model during the initialization phase. Some other input data are hardcoded in the VBA script. In principle, all input data including modelling constants and other parameters can be inputted from Excel.

The modelling output in the current version of the model is limited to the number of people died and escaped, which is outputted to the same Excel sheet where the input data are stored.
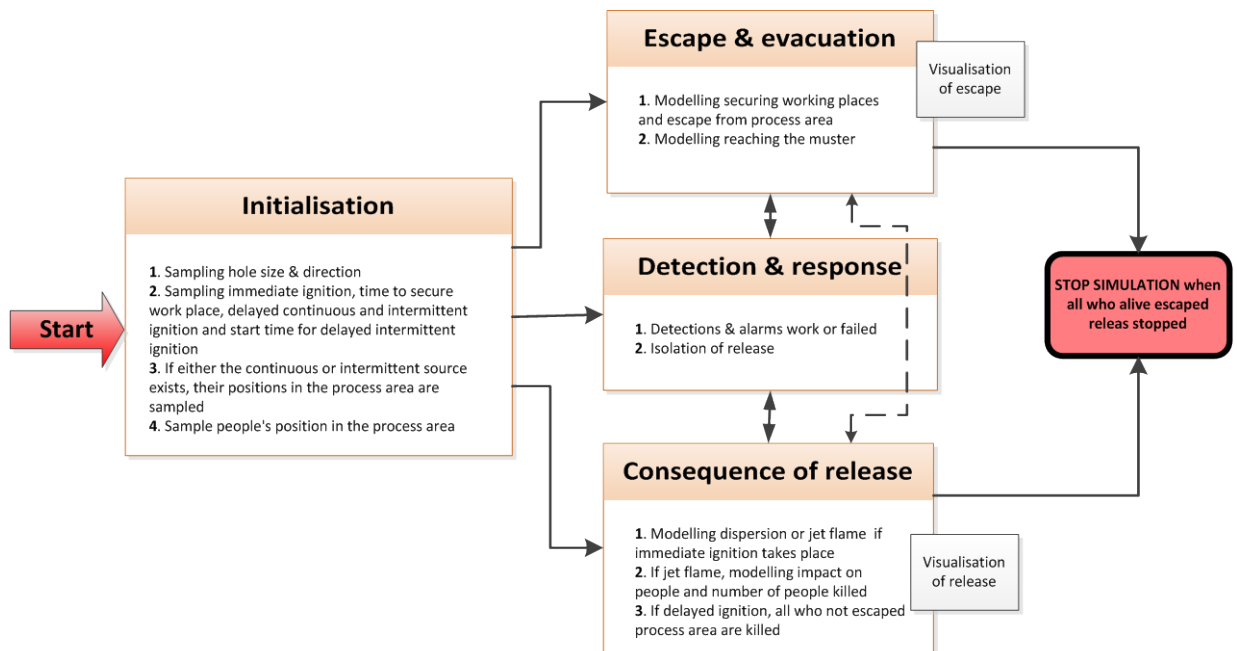
Figure 6. The general structure of the algorithm

The model exists in two different versions. One models a single accident scenario with the visualization of the dispersion and jet flame (if an immediate ignition source is present) and people escape from the process area. The other is the batch mode version that is run repeatedly in one simulation session with varying sampling values.

The output is the accumulated number of fatalities and escaped people following each simulated accident. Based on these data the average number of people dying per accident is assessed as the ration

$$E(N^{died}) = \left(\sum_{i=1}^{N^{runs}} N_i^{died}\right)/N^{runs}$$

. Here N^{runs} is the number of simulated accidents (model runs) and N_i^{died} is the number of people dying in each accident. $E(N^{died})$ can be interpreted as the average number of people dying per accident if the number of simulated releases N^{runs} is large.

$E(N^{died})$ multiplied by the frequency of a gas release taking place on the off-shore platform gives us the risk measure Individual Risk per Annum, which is the output of the batch mode version of the model.

It is also possible to assess the Group Risk measure (FN-curve). It is done by running the model N^{runs} times and storing the set of numbers n_N^{died}, N = 1, …, n^Σ, where n^Σ is the maximal number of people present at the platform and n_N^{died} is the number of simulation runs (out of N^{runs}) the outcome of which was N fatalities. These data allow the assessment of the values of the FN-curve as the formula shows:

$$FN = \left(1 - \sum_{N=1}^{n^\Sigma} \frac{n_N^{died}}{N^{runs}} \right) f^{release}$$

In the above formula $f^{release}$ is the frequency of a gas release.

To run the model one needs to have Arena installed with a version not lower than 13.90

4. Implementation of the feasibility model

4.1 Geometry
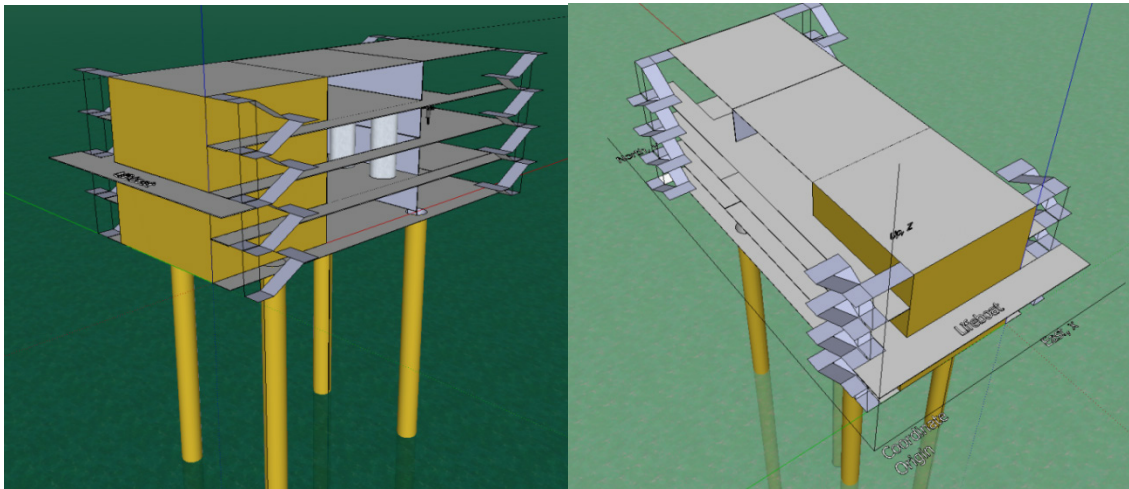
Figure 7 3D views of the demonstration platform
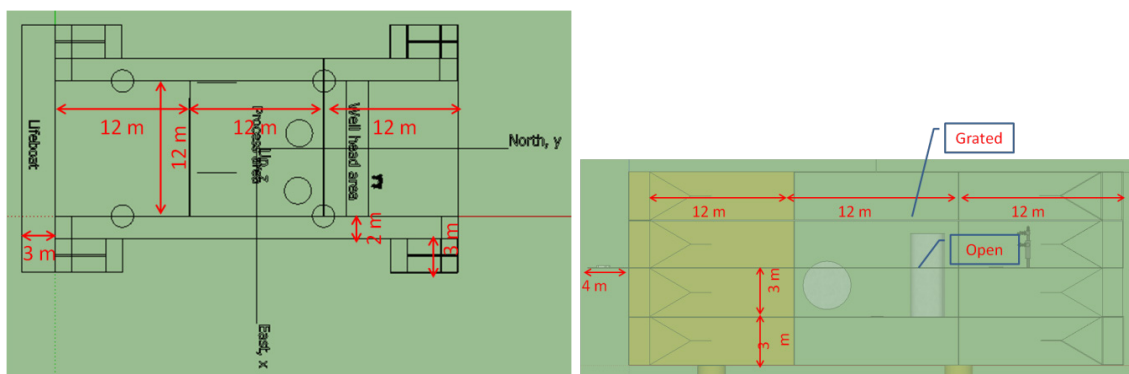
Figure 8 Dimensions of the demonstration platform

The feasibility study makes use of a simple presentation of a platform with 5 deck levels, an accommodation section (at the South end, from level 1 up to 4), a process section (in the center, level 2 and 3, the deck at level 3 is open except for a gang way along the outside of the platform) and a well head section on the north part. Escape routes run North-South along the full length of the platform on both the West- and East side of the platform on all deck levels except the (unobstructed) roof deck. Staircases between the deck levels are on all four corners of the platform.

The lifeboat is on the 3rd deck level north of the accommodation section; for the feasibility study it is assumed that personnel is safe (i.e. they will survive) when they have reached the location of the lifeboats.

4.2 Simplifications for the feasibility study

The feasibility study focused on gas release only. Showing the overall principles will also demonstrate the feasibility introducing other models dealing with liquid phase releases. There-

fore, it is planned to introduce models dealing with liquid and two-phase releases in a next phase.

The consequence calculations are mainly widely used simplified engineering models taken from the Yellow book, unless different approaches have been described in the appendices and referenced in the sections 2.3.1 to 2.3.4.

The evacuation model is based on an ASET-RSET evaluation. RSET is calculated from time to secure working place, the actual position in module to exit and time to reach muster area from the exit. The ASET is calculated from the time difference of the detection time of the gaseous release and the time of the delayed ignition. Once the ignition occurs the number of fatalities is equal to the no. of persons in the module. In case of jet fires the detection time is a little longer than the immediate ignition time and the ASET time is about zero. Nevertheless, people may evacuate away from the jet flame and it is assumed that flames less than 5 m give no fatalities. This is of course a first implementation for the feasibility study, but an explosion, heat radiation and direct impingement model will be established in the next phase.

4.3   Results

This section present some results from calculations performed with the feasibility implementation of the DES-based risk assessment framework. The example considers a process section consisting of a cooler, a separator and a condensate pump, as shown in Figure 9. The corresponding distribution of hole size distribution is based on OGP failure data and shown in Figure 10. The cumulative frequency for a release from this process section is about 0.02 per year. In order to generate some more serious events, a uniform distribution of hole sizes has been used, leading to the same cumulative release frequency, but with an average hole size of about 12 mm instead of between 2 and 3 mm.
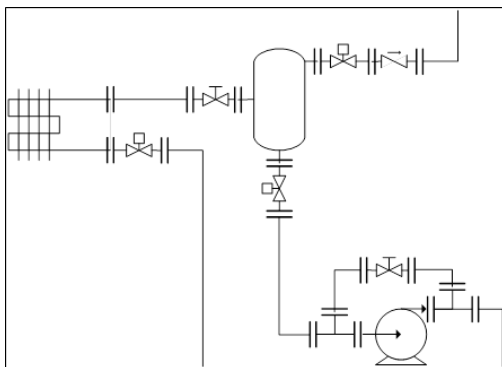
Figure 9 Cooler-separator-pump process section for example calculations

Table 1 shows the statistical results for simulations of 10 000 release scenarios. Given the above mentioned cumulative release frequency, the simulations cover about 500 000 years., Table 1 shows that there are 0.413 fatalities on average per release event, which means that the PLL (for these more serious simulations) in the process module is about or 0.8 per 100 years.
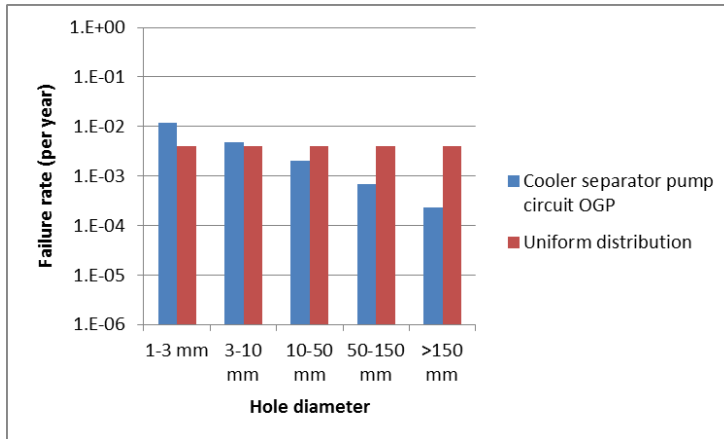
Figure 10 Failure rate distribution from OGP failure data for the process section shown in Figure 9. For the feasibility d a uniform failure rate distribution has been used, leading to the same cumulative release frequency, input for the results presented in Table 1 and Table 2.

Table 1 Example of statistical output for 10 000 release events.

	Average	Half width[3]	Minimum	Maximum
No of release events	10000			
Simulation run time (minutes)	12.87			
No of immediate ignitions (<0.01 s)	508			
Ignition_Start_Time	2.03E-04	1.77E-05	0	0.01
Delayed_Ignition_Time s	172.41	2.5481	0	600[4]
ASET s	429.79	6.321	-0.09	600[4]
Fatalities	0.41303	0.06291	0	5
wind_direction in rad	1.5782	0.01909	0	3.1414
wind_speed m/s	10.563	0.09821	5	19.997
Hole_Direction in rad	1.5708	(Insuf)	0	1.5708
Jet flame length m	13.652	3.0561	0	226.02
Flammabel volume @ LFL_max m3	246.19	8.9892	0	1180.8
Release_Detect_Time in s	0.50275	0.01757	0	34.7
Jet flame SEPmax kW/m2	0.79817	0.07398	0	91.517
C_No_People_Escaped_Zone_1	3.1008	0.05703	0	5
Module air speed m/s	0.56419	0.00681	0	1.3853
Max release time in s	10379	288.95	0	49158
V_Hole_Size m	0.0118	5.54E-04	0	0.19981
V_DetectorReliability	0.94884	0.00442	0	1
V_massflow kg/s	5.9736	0.54116	0	271.27
workers in total	39045			

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[3] Half width corresponding to the 95% confidence level around the average.

[4] The maximum duration of the simulation is 600 s

Figure 11 shows the variation of jet flame length across the simulations. The variation can be explained by the mass flow rate, with minor variation due to wind speed.
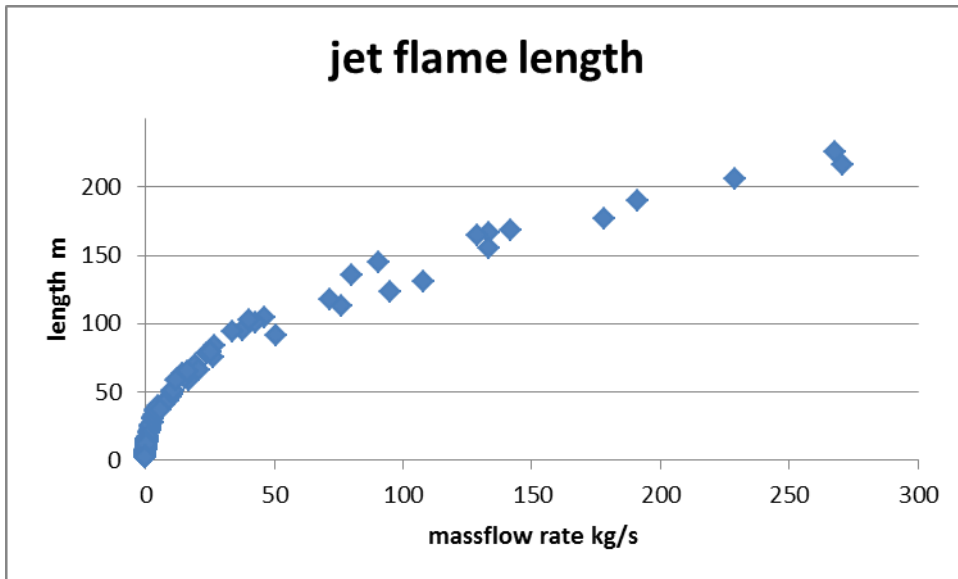
Figure 11 Variation of jet flame length across the simulations

Out of the 10 000 simulations, a small number of cases has been extracted to show details per simulation, see Table 2. An interesting feature shown in this table is that the probability of ignition is seems to be depend on mass flow rate: this is not a feature explicitly modelled, but an emerging consequence of the modelling of the spatial distribution of ignition points and the size and development of the flammable clouds.
Both Table 1 and Table 2 demonstrate what type of output can be generated, without being exhaustive. It will e.g. be possible to provide distributions on group risk (number of fatalities per event) and to make a statistical analysis of the relation between release rate and probability of ignition.

Performing 10 000 simulations took 13 minutes on an ordinary laptop PC. Table 1 contains one parameter which is a single value and not subject to a distribution, viz. the detector reliability (set at 95%). This value is reproduced with a half width of 0.5%. The probability distributions of other parameters may be expected to reproduced with a lower accuracy (because distributions with higher order parameters require more data) and further work should be done to assess how many simulations are necessary to reproduce e.g. group risk distributions with sufficient accuracy. Although full studies involving several modules, process units and more variation in input data would require more simulations to be performed, the computational effort does not seem to be prohibitive.

Table 2 Example of calculation outcomes per run, in the orange cases, the personnel has not been able to escape from the module in time.

No.	Wind uw m/s	wind direc-tion (rad)	Ventilation in module u_module m/s	hole size in m	ignition time in s [5]	massflow kg/s	SEPmax in kW/m2	Jet flame length lb m	ASET s (average for no of workers)	RSET s (average for no of workers)
2	16.4	0.413	1.090	0.1272	0.90	109.9098			0.8000	278.2576
4	5.0	2.390	0.297	0.0508	3.40	17.5152			3.3000	234.2187
5	18.8	2.254	1.037	0.0012	No ignition	0.0095			600.0000	227.9997
6	9.2	0.826	0.526	0.0013	No ignition	0.0118			596.0000	201.0257
7	19.2	1.860	0.710	0.0014	No ignition	0.0139			596.5000	271.2558
8	5.7	2.277	0.318	0.1601	No ignition	174.1864			599.9000	220.0878
9	5.0	2.951	0.344	0.0020	No ignition	0.0279			598.5000	242.5925
10	17.2	2.007	0.775	0.0406	0.80	11.2217			0.7000	232.6303
11	18.5	2.311	1.053	0.0027	0.01 (immediate)	0.0495	43.4363	4.1501	0	227.7665
12	5.0	2.362	0.293	0.0019	No ignition	0.0247			598.3000	218.7077
13	10.0	2.016	0.457	0.0020	No ignition	0.0264			598.4000	228.5326
14	8.6	0.297	0.583	0.0023	No ignition	0.0374			598.9000	237.8085
15	6.5	0.799	0.377	0.0028	0.01 (immediate)	0.0549	33.3542	4.9041	0	225.1228
16	8.9	1.897	0.348	0.0034	No ignition	0.0776			599.4000	262.6267
17	11.9	1.941	0.497	0.0028	No ignition	0.0532			599.2000	230.3137
18	13.0	2.105	0.642	0.0012	0.01 (immediate)	0.0093	32.8078	2.0488	0	204.9413
19	10.2	1.433	0.261	0.1742	0.10	206.2515			0	285.5274
20	5.3	2.708	0.350	0.0023	No ignition	0.0356			598.8000	242.9458

---

[5] Immediate ignition is modelled as ignition at 0.01 s, an ignition at a time > 600 s (the duration of the event simulation) is classified as "No ignition"

4.4 Further work

In order to make the framework operational, the following work needs to be performed:

- Verification of the calculations with respect to the probability distributions of output parameters and assessment of requirements (number of simulations) to obtain sufficient accuracy. This might include the development of techniques to optimize the computational efforts by sing alternative sampling techniques;
- Developing adequate postprocessing and presentation techniques, in order to produce appropriate risk data (IR, PLL, F-N distributions) and for inspection of individual simulations;
- Implementation of a minimum full set of realistic models as a baseline system that is able to perform realistic risk assessments for offshore platforms;
- Demonstrating validity of the modelling framework, comparing results with results from traditional risk assessments and peer review and feedback by domain experts.
- Transferring the model to a non-proprietary software platform.
- Dissemination and feedback from practical experiences.

5. Conclusion

This report describes a preliminary model to perform risk assessment for offshore gas production platforms using discrete event simulation.

The framework of the model is based on a number of relatively simple scenario or event diagrams, which are used to document the modelling process. Each block and each connection between two blocks of these diagrams is assigned a model or a set of assumptions, and in that way, the diagrams also become a framework for documentation of all model elements and other assumptions that the risk analyst has to make in order to produce the output.

This feasibility study has focused on two aspects. The first aspect has been an attempt to produce a comprehensive list of all model assumptions, as a kind of catalogue, and included as Appendix A. At this feasibility stage, a number of models and assumptions are very simple, but it provides an impression of the type of information that should be available to make the risk assessment verifiable (or at least plausible). In this study we have not yet addressed verification or validation of the model implementations.

The second aspect has been the demonstration of the concept of using Discrete Event Simulation to address the concurrent phenomena during a loss of containment event on a gas production platform, based on the aforementioned simple scenario diagrams. It has been demonstrated that it is possible to perform risk assessments using Discrete Event Simulation. Simulations can be performed with acceptable computational effort, and can produce valuable output, e.g. the model can not only be used to generate ordinary risk data, but it also allows a better understanding on e.g. the ignition process by performing parameter studies and implementing different models for ignition sources and gas dispersion.

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Appendix A Model Specifications

List of general symbols

|	
A	Surface area (m^2)
b_o	Radius of the source, $b_o = \frac{1}{2}d$.
C_d	Discharge coefficient of a hole (-)
c_{lfl}	Lower flammability level (concentration by volume -)
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
d	hole size diameter (m)
H_c	Heat of combustion (kJ/kg)
H	Height (m)
L	length, distance (m)
L_m	characteristic length of a module $L_m = (\text{Volume})^{1/3}$.
M	Mass (kg)
m	mass flow rate (kg/s)
p	Pressure (Pa)
Q	Heat flow rate (kW)
q	Heat flux (kW/m^2)
r	radius (m)
t	time (s)
u	velocity (m/s)
u_a	Wind speed (m/s)
u_m	volume-averaged ventilation velocity in a module (m/s)
V	Volume (m^3)
W	Width (m)
$\gamma = \dfrac{C_p}{C_v}$	
τ	Atmospheric transmissivity of heat (-)

Indices:

|	
a	ambient condition
m	related to a module

1 DES model layout in Arena®

Input module

Creation of accident events in form of holes of various size and check of detctor
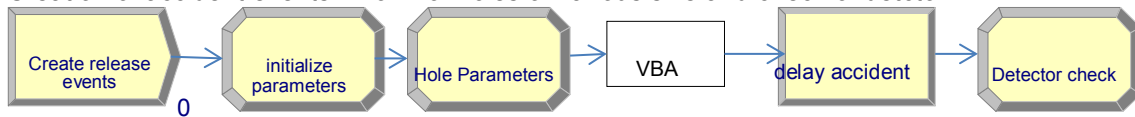
Event development

Deciding between immediate and delayed ignition: The upper branch models the jet fire applying the Chamberlain jet fire model. The assumption is immediate detection by a flame detector and therefore also immediate alarm to the crew modelled in the next figure. The lower branch models delayed ignition using random ignition source points (geographic) on the processing module on the one hand and random ignition sources (time) as the sources may be only available certain periods of time. To trigger the delayed ignition the dispersion model is used calculating the time to ignition. The time between alarm-time and the ignition time is in the feasibility study defined as the available safe evacuation time (ASET).
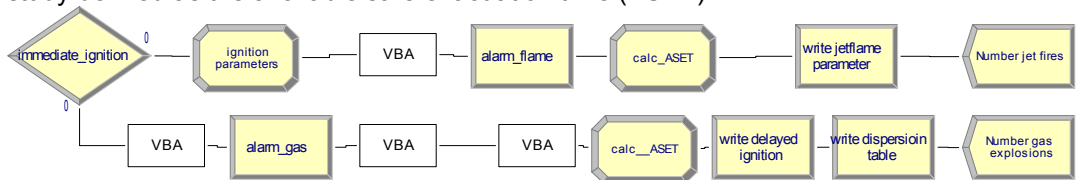
Crew generation and evacuation

Randomly members of the crew staff are generated (3 -5 persons for the feasibility calculations) and distributed randomly at different positions on the platform. The Required safe evacuation time (RSET) is calculated from a random time to secure working place (e.g. avoid certain ignition sources), the position on the module and further escape from the module to the primary muster area.
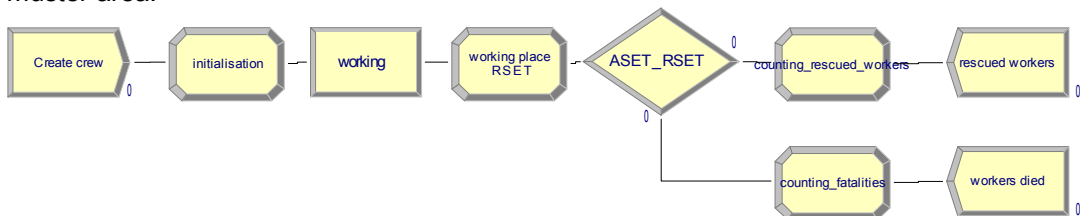
The number of facilities will be calculated more accurately in the next version of the model. It will be assumed that the jet fire and flash fires and explosions will have different effects on the workers. By that the workers still may escape even after ignition has occurred, e.g. having a safe distance to the jetfire (heat radiation) and not lethal impacts of a small gas cloud explosion (heat radiation and pressure impacts). This is shown in the next figure showing a many point estimation of the heat radiation form jetflames calculated by the Chamberlain model. In the next version the heat radiation levels are being transferred into dose effects with distance to the jet flame and the lethal effects for the workers are estimated by that. A similar approach is thought of for the gas cloud effects.
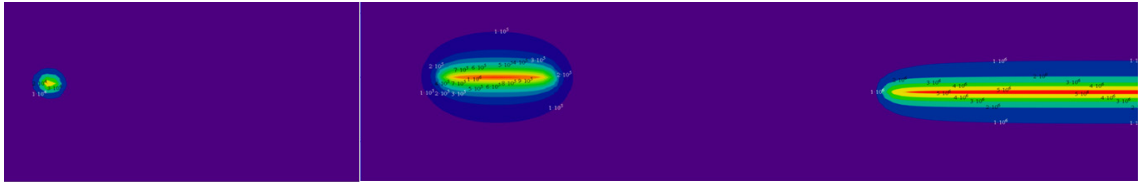
Mass rate 0.15 kg/s d= 4.7mm; 15 kg/s d=47 mm; 300 kg/s d= 200 mm; P= 50 bar

2 Basic specifications

2.1 Input and output

2.1.1 Initial conditions

Platform layout: deterministic:

The topological lay-out:

A platform consists of <u>modules</u>; modules are separated from each other by some physical separation: deck or walls, or the "edge" to the open space around the platform;

Within the modules, we allow to discriminate between "<u>areas</u>", to allow better topological resolution, if needed. A module exists of at least one area. Within a module there is no physical separation between areas, so gas, flames, etc. can disperse from one area to another within a module.

Consequences or hazardous events in (areas in) one module can affect (areas in) other modules depending on physical separation or separation by distance.

Bridges, and the space below the platform (e.g. including the areas where the risers or wells are) are considered as separate modules.

Escape routes can be considered as special areas, e.g. at the outer end of a module. This would facilitate the assessment whether escape routes are impaired.

2.1.1.1 To be described (input):

Relation between Areas in modules (neighbours, boundaries, distances)
Obstructions, distribution

       Walls (closed, open, partly open, integrity)

       Escape routes between areas

       Relation between modules (neighbours, boundaries, type of boundaries (walls, panels))

       Escape routes outside or between modules

       Evacuation means (location of evacuation means, e.g. life boat station, bridges to other platforms)

The Process lay out

The process equipment can be divided into sections.

       We discriminate:

- Isolatable section: process section between Emergency Shutdown valves (ESDV). The inventory of an isolatable section is the minimum amount to be released in case of a leak (provisions may be taken to allow for the effect of blow down for small leaks). We assume that the inventory within an isolatable section has the same pressure and temperature (this means that pumps, compressors and choke valves are also considered to be divisions between isolatable sections, i.e. the inventory of an isolatable section can include the "other side" of such equipment, e.g. the high pressure part of a choke valve), but there may be difference between liquid or gas releases on e.g. different sides of a separator[6]

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[6] In the feasibility study we consider gas releases only

For each section, the sections that are linked to that section should be given: in between these sections there is an ESDV

- Area section: those parts (equipments) of an isolatable section which are located in the same <u>area</u>. This means that a release of an <u>area section</u> always will take place in the same <u>area.</u>
  There may be several area sections in one area, if several isolatable sections cross that area.
- Inventories with the same (chemical) properties are called "streams"
- An area section consists of a set of components: release frequency from the area section depends on component count and individual component failure rates

Meteorological conditions: stochastic:
Wind speed and – direction (statistical distribution)
Sea state (wave height) (relation with wind speed and statistical distribution)
Manning distribution (deterministic and/or stochastic)
Number of personnel per module or area (depends on time of day). This is preferably to be described stochastically: procent of time 1 person is presen, 2 persons are present, etc.

2.1.2 Outputs

Statistical description of fatality, discriminating the following informations:
- Origin of the fatalities (in what module/area was the person when the event started?
- Location of fatalities (in what module/area was the person dying)

From this, to be derived the statistical risk criteria (related to hydrocarbon risks):
-
- Potential Loss of Life
- Individual risk for some personnel categories (operators, …)
- Location-based risk (the risk of fatality when being at in some area/module)
- Fatal Accident Rate, for the whole platform and per area/module.
- Group risk distribution (F-N curve)

3 Model specifications – physical events

This chapter provides the specifications for the models needed to develop the total OPHRA system. Most models are related to blocks in the 4 elementary event trees or barrier diagrams, or describe links between these blocks. The diagrams are included for reference where appropriate.

3.1 Environmental conditions

3.1.1 Wind (wind direction, wind speed, atmospheric stability)

3.1.1.1 Atmospheric stability

Atmospheric stability more than a few kilometres off-coast depends on the temperature difference between water and air, which is, for the North Sea, dependent on the season. During winter, the air is colder than the water, and the lower layer of the atmosphere is unstable. During summer, the air is warmer than the water, and the atmosphere is stable. See Fig. 4.12 in (Committee for the Prevention of Disasters 1996, 2005).
Simplest modelling: Assume neutral stability – within the short distances on a platform, atmospheric stability is not expected to dominate dispersion.

3.1.1.2 Roughness length

The roughness length of the sea depends on the wind speed and sea state. A simple approach is according to (Vickers and Mahrt 2010), relating roughness length to surface friction velocity.
Simplest modelling: Most offshore platforms are about 20-30 m above sea level. Wind speed statistics are normally derived for a height of 10 m above the surface. Using the above reference (Vickers and Mahrt 2010), it can be shown that wind speed at 30 m is 10% higher than at 10 m for a wind speed of about 15 m/s, and this difference is less for lower wind speeds (7% for 4 m/s). So wind speed variation can be neglected, or wind speed at platform height can be set 7% higher than the data from climatological statistics.

3.1.1.3 Wind speed and direction statistics

In principle, wind speed and direction statistics need to be derived from long term (10 years) statistics measured at a meteorological station nearby (or representative for) the location of the offshore platform. This data can normally be obtained from the meteorological services, and some analyses are publicly available on the basis of offshore wind-energy research.
There is meteorological data available from Tyra East from 2008, and platform K13 from 2002 (windfinder.com).
Some data may be incomplete. Some information need to be available about the variation of wind speed (dispersion is strongly dependent on wind speed, both low wind and high wind conditions need to be included in a QRA). Often data is presented as wind direction statistics, and average wind speed per direction. Information on wind speed variation can be included using a Weibull distribution of wind speed. At least 8 wind direction sectors should be distinguished, normal statistics may distinguish between 8 and 16 wind direction sectors.
Based on publicly available data for the North Sea close to the Dutch coast[7] we conclude that a reasonable representation of wind speed for dispersion calculations can be obtained using the following classes. The representative wind speed is based on the average of 1/u (the inverse of

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[7]"NL3 site": http://www.ecn.nl/fileadmin/ecn/units/wind/docs/dowec/10047_002.pdf

wind speed) within the class, as concentration in a passive plume is inversely proportional to wind speed:

Wind speed class	Representative wind speed (m/s)	Approximate probability, time prevalence (%)
< 4 m/s	2	20
Between 4 and 8 m/s	6	40
> 8 m/s	10	40

Simplest modelling: Uniform wind direction probability over 8 sectors, using the wind speed distributions from the table above.

Feasibility modelling: Data according to[7] as shown below and Figure 12.

Sector (centre)	Wind direction frequency (%)	Weibull scale factor A [m/s]	Weibull shape factor k	Average wind speed [m/s]	wind speed frequency[8]		
					< 4 m/s	Between 4 and 8 m/s	> 8 m/s
0	6.4	7.6	2.2	6.8	1.38%	2.93%	2.09%
30	6.4	7.4	2.3	6.6	1.38%	3.09%	1.93%
60	6.6	7.9	2.2	7.1	1.32%	2.92%	2.36%
90	6.2	7.8	2.2	7	1.27%	2.77%	2.15%
120	5.9	7.2	2.3	6.5	1.35%	2.90%	1.65%
150	5.5	7.4	2.3	6.6	1.19%	2.65%	1.66%
180	6.7	8.3	2.2	7.5	1.22%	2.82%	2.66%
210	13.2	9.7	2.3	8.8	1.61%	4.64%	6.95%
240	15.4	10.1	2.6	9	1.33%	5.15%	8.93%
270	11.9	9.5	2.1	8.5	1.79%	4.19%	5.93%
300	8.2	8.8	2.1	7.9	1.43%	3.16%	3.62%
330	7.6	8.6	2.2	7.5	1.29%	3.07%	3.24%
Total	100	8.6	2.1	7.8			

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[8] Based on Weibull distribution with the factors per row.

3.1.2 Sea state (wave height)

Sea state and wave height has little relevance to hydrocarbon risks if escape to and rescue from sea are disregarded.

Sea state and wave height are relevant for pool fires on sea. During the feasibility study, only gas releases are considered, so pool fires are not considered at this moment. As a consequence, sea state is not included in the modelling at this stage.

3.2 Wind speed and ventilation within a module

The module is considered as a rectangular duct, with (more or less) solid top (roof) bottom (floor) and sidewalls. Front and rear of the duct are open, and here the wind enters or leaves the module.

- Mass release rate m' (kg/s) (This may be time dependent)
- Density of the release at ambient conditions ρ_0 (kg/m^3)
- Ventilation velocity in the module u_m (m/s)
- Wind speed in the free air: u_a (m/s)
- Dimensions of the module: Width (W_m), height (H_m), length (X_m), volume (V_m), ground floor area and a characteristic length L_m= (Volume)$^{1/3}$.
- Fraction of the rear and front face of the module being open f_0 (1 for fully open faces; default is 0.8)
- Confinement factor f_5 (see table)
- Congestion factor f_6 (see table)
- Volume blockage ratio in the module v_b (default 0.14, the full-scale experiments ranged from 0.06 to 0.14)

Correlations for ventilation in a module are presented in (Anonymous 2006). According to this model, the ventilation velocity u_m is proportional to wind speed u_a as:

$$u_m = u_a \cdot f_0 \cdot f_4 \cdot f_5 \cdot f_6$$

In this description the parameters have the following meaning:
- Fraction of the rear and front face of the module being open f_0 (1 for fully open faces; default is 0.8)
- Confinement factor f_5 (see table)
- Congestion factor f_6, derived from the volume blockage ratio v_b, see below (the volume blockage ratio has default values of 0.14, the full-scale experiments ranged from 0.06 to 0.14, see table below.)

The factor f_4 in the original model from (Anonymous 2006) has the value of 0.3. Here we try to make it dependent on wind direction. If wind direction is aligned with the direction of the module (considered as a duct), wind can enter freely; when wind is perpendicular to the module, there is no or very little wind driven motion in the module, only due to turbulence or wind direction variations (here taken as 10 %). We model this by describing f_4 as follows:

$$f_4 = \max\left(0.1, 0.4 \cdot \sqrt{|\cos(\alpha)|}\right)$$

Where α is the angle between the ambient wind direction and the direction of the module. Using square root of the cosine accounts for the guiding effect of the walls for small values of α (almost aligned wind). The factor 0.4 is included as to ensure that the average of f_4 over all directions approximates the constant in the original model.
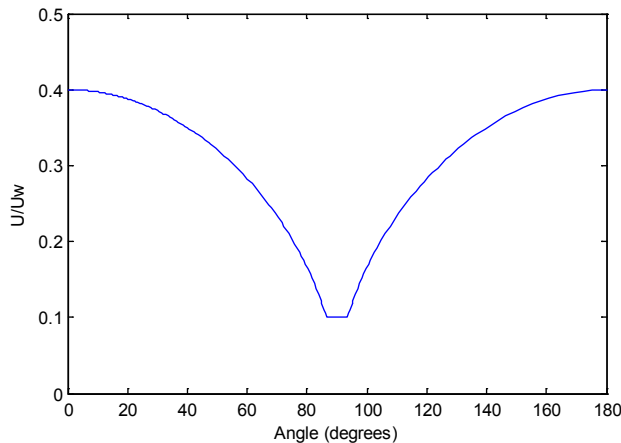
Note that the direction of the wind in the module changes when α passes $\pm\pi/2$.

In principle, f_6 can be calculated by the volume blockage v_b and the ratio between the length of the module l_m and the characteristic length-scale for the module, calculated as the square root of the module's volume. L_m:

$$f_6 = \sqrt{\frac{1}{1 + 29 \cdot v_b \cdot \dfrac{l_m}{L_m}}}$$

Alternatively a direct factor for f_6 can be used. Guidance for the factors f_5 and f_6 are according to the following table:

	Fully En-Enclosed Unit	Partialy closed ended unit	Open ended Unit	Fully Open Unit
f_5	0.2	0.5	1	1
f_6	0.4	0.4	0.4	0.5
v_b	0.14	0.06	0.06	0.06

3.3 Loss of containment – Release
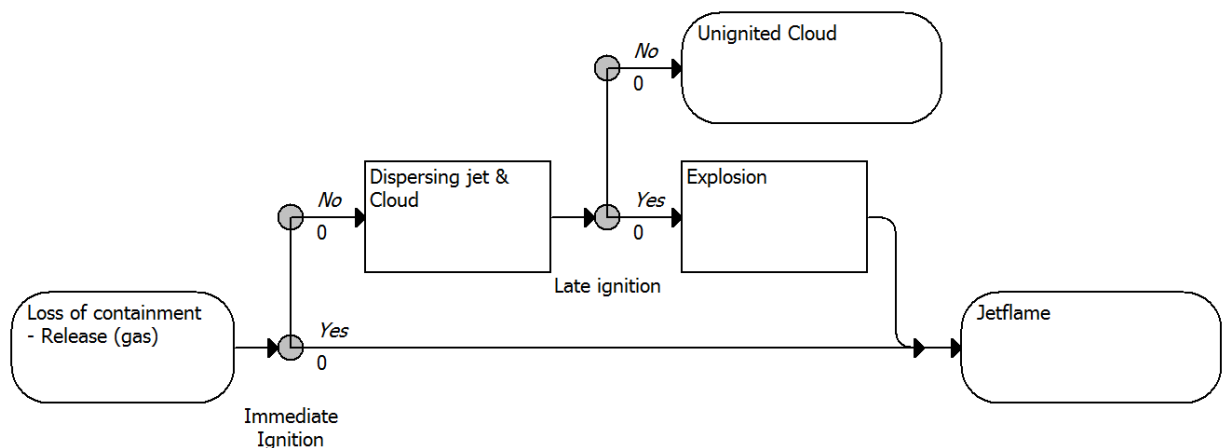
3.3.1 Release frequency, hole size, location and direction

The release **frequency and hole size** depend on the equipment count for the Area-section.
The probability of P(d>D) within a period of time T depends on:
- Equipment type and size of equipment. P increases proportionally with the number of equipments in the Area section.
- Size of equipment is characterized by the largest internal diameter of the pipe or pipe connection (flange)
- Probability is derived from failure rate statistics and may be adjusted for design quality (standard or code), material, maintenance status, exposure to vibration, erosion, corrosion, etc.

Location: Release is at the surface of the equipment in question. Possible simplifications with corresponding assumptions:
1. To assume all releases are in one point (centre) of the Area where the Area-section is located.
2. To assume the release position is distributed (e.g. uniformly) over the Area in question.

Direction: Direction may depend on the orientation of the equipment in question; e.g. holes in pipes, vessels and flanges can be expected to be radial (normal to the main pipe direction), while (pipe) ruptures are axial. Possible simplifications:

Offshore Platform Hydrocarbon Risk Assessment – OPHRA: Feasibility

1. Uniformly distributed in all directions, if φ indicates horizontal direction, and θ the angle of direction from horizontal, then φ is uniformly distributed with probability density $1/(2 \cdot \pi)$ from 0 to $2 \cdot \pi$ and θ has a probability density function of $\frac{1}{2}\cos\theta$ from $-\frac{1}{2}\pi$ to $\frac{1}{2}\pi$;
2. Uniformly distributed in a horizontal plane; horizontal direction φ is uniformly distributed with probability density $1/(2 \cdot \pi)$, $\theta=0$;
3. One direction (downwind) – this assumption is pragmatic in connection with jet or dispersion models that only allow downwind oriented jets.

Simplest modeling – for feasibility we use option 3.

The basic release frequencies for the feasibility studies are taken from (OGP 2010), tables in section 2.0.

The statistical sampling is performed according to the following algorithm. Firstly, the hole size range is sampled. It is one the five: [1, 3], [3, 10], [10, 50], [50, 150], [150, full bore] mm. The frequency attributed to each range is calculated, so that we have five frequencies f_i, i=1, …, 5. Then, one of five integer numbers is sampled according to the weight of the frequency of each range. That is, the weight is $w_i = \left. f_i \middle/ \sum_{i=1}^{5} f_i \right.$. If the sampled number is, for example, 3, this means that the hole size lies in range 3 between 10 and 50 mm.

Secondly, an exact hole size is sampled as a number governed by a uniform distribution within one of the five ranges. That is, if the rage is 3, then a random number is generated in the range [10, 50] mm.

Maximum hole size is equipment size, note that full bore ruptures are more "likely" than almost full bore holes.

(Note that release frequencies for wellheads and Christmas trees are not included in OGP report 434-01)

3.3.2 Release rate

Purpose:

The purpose of this model is to estimate the amount of hydrocarbons escaping from the hole; this amount is input to further consequence assessment.

The section in question has a hole with diameter d [m], starting at time t=0

Model: release rate m(t) [kg/s]

Parameters:

Prop   Properties of the fluid stream that affect the outflow, e.g. molecular mass, c_p, c_v, ...

d   Hole size

C_d Discharge coefficient of the hole

P(t)   Pressure in the section at time t; P_0 is the pressure in the section at t=0.

$M_i(t)$ Array (vector) of masses in the isolatable sections that are in open connection with the punctured section at time t (i.e. the set of linked isolatable sections for which $ESDV_{ik}(t)$ is not "closed"). Each isolatable section has some statuses according to the status of the ESDV: "In open connection with the leaking section" and "Open at both (or more) sides"

$ESDV_{ik}(t)$ Array (vector) of status of the isolation valves between neighbouring isolatable sections i and k (status is at least "open" and "closed"; may be extended with "partially closed"

$BDV_i(t)$ Array (vector) of status of the Blow Down Valve for each isolatable section.

Modelling principle:

At t=0, the outflow is determined by the pressure and material properties in the punctured section. Outflow reduces due to expansion and flow resistance (depending on location of hole and pipe sizing) with time, at first all sections are in open connection, but ESD response and Blow down may reduce mass, thus pressure in the sections that are open with the punctured section.

Simplest modelling (feasibility option)

Flow resistance is ignored, outflow is constant determined by P_0, the pressure in the section prior to the leak. Release continues until sections bounded by closed ESD are empty (Blow down action is ignored on outflow)

Model according to "Yellow Book" (Committee for the Prevention of Disasters 1996, 2005) section 2.5.2.3:

while $\Sigma\ M_i(t) > 0$

$$m(t) = q_0 = C_d \cdot \frac{\pi d^2}{4} \cdot \sqrt{\rho_0 \cdot P_0 \cdot \gamma \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad \text{for critical outflow } \frac{P_0}{P_a} > \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}$$

and

$$m(t) = q_0 = C_d \cdot \frac{\pi d^2}{4} \cdot \sqrt{\rho_0 \cdot P_0 \cdot \frac{2\gamma}{\gamma-1} \cdot \left(\left(\frac{P_a}{P_0}\right)^{\frac{2}{\gamma}} - \left(\frac{P_a}{P_0}\right)^{\frac{\gamma+1}{\gamma}}\right)} \qquad \text{for subcritical outflow.}$$

With $= \frac{C_p}{C_v}$, C_d the discharge coefficient (about 0.62 for sharp holes, 0.95 for full-bore ruptured pipes) and P_a the atmospheric pressure.

$M_i(t)$ is calculated according to the following rule: For all sections open at more than 1 side, and in open connection with the leaking section, $M=M_0$; for the n sections that are open on one side and in open connection with (or equal to) the leaking section, $M_i(t+dt)= M_i(t)-1/n \cdot q(t) \cdot dt$.

3.4 Dispersion

Dispersion modelling will be based on the approach from (Anonymous 2006), page 57, for more details see Appendix B.

Concepts: As for ventilation.

Following parameters are input to the model
- Mass release rate m' (kg/s) (This may be time dependent)
- Density of the release at ambient conditions ρ (kg/m^3)
- Ventilation velocity in the module u (m/s) (see the description of ventilation above)
- Dimensions of the module: Width, height (H_m), length (X_m), volume (V_m), ground floor area and a characteristic length $L_m=$ (Volume)$^{1/3}$.

The expression for the equilibrium or flammable volume is:

$$V_{flammable} = \left(\frac{m'}{\rho \cdot u \cdot k}\right)^{3/2} \cdot \left(c_{lfl}^{-3/2} - c_{ufl}^{-3/2}\right)$$

Here k is an empirical constant that describes the rate of gas transport through the cloud's boundaries. It is shown that k = 0.614

The flammable cloud volume in the module can fill at maximum 60% (according to experiments) of the module.

If the flammable volume is limited by the size of the module, the excess mass would disperse outside the module (in adjacent units or modules) above c_{lfl}. This is not included for the feasibility study.

Cloud growth V(t) can be approximated by formula (A22) in the separate appendix on dispersion modelling for constant m'. V(t) is the time-dependent flammable cloud, which asymptotically will approach $V_{flammable}$.

$$V(t) = V_{flammable} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{flammable} \cdot \rho \cdot c_{lfl}}\right)\right)$$

(A22)

For releases from isolatable sections, we use (for the feasibility) a constant mass flow rate equal to the maximum mass flow rate. When isolation is initiated, we know the total mass to be released (this is the mass released up to time to full isolation plus the mass in the isolated section). The effective release time t_{max} is then calculated as the total mass released divided by the (maximum) mass flow rate – after that, the mass flow rate drops to zero. The development of the cloud can then be approximated by formulas (A22) and (A23).

$$V(t) = \left(V_{max}^{1/3} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3$$

(A23)

valid while $t-t_{max} < (V_{max})^{1/3}$. V_{max} is the cloud volume according to (A22) at t_{max}: $V(t_{max})$. Some special rules need to be applied to ensure consistency (the UFL cloud is always smaller than the LFL cloud) and to obey the observation of a maximum of 60% flammable fill in the module. The complete calculation rules are in Appendix B.
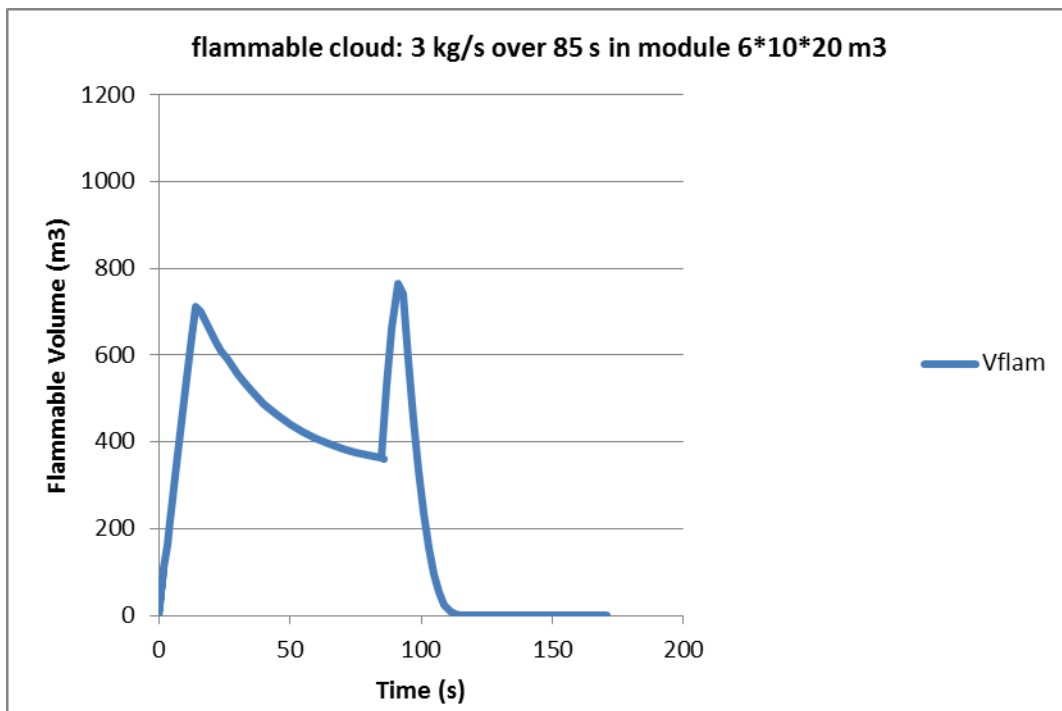
Example of the evolution of flammable cloud in a module. The decrease after the first peak is due to the growth of the UFL volume inside the module while the LFL volume has reached the maximum volume inside the module and is extending outside the module. The second peak is due to the decrease of the UFL volume while the LFL volume is still extending outside the module.

3.4.1 The calculation scheme

This scheme is adjusted in such a way, that the experimental observation that the fraction of a module filled with a flammable cloud is no more than 60%. Note that this limitation may be caused either that a part of the module is below the LFL, either a part is above the UFL.
While m' is non-zero and constant for $0<t<t_{max}$:
The final (equilibrium) cloud size where LFL is exceeded is:

$$V_{>LFL} = \left(\frac{m'}{\rho \cdot c_{lfl} \cdot u \cdot k}\right)^{3/2}$$

And similar for the volume exceeding UFL:

$$V_{>UFL} = \left(\frac{m'}{\rho \cdot c_{ufl} \cdot u \cdot k}\right)^{3/2}$$

For the time-dependent cloud where LFL is exceeded (V_m is the volume of the module):

$$V_{>LFL}(t) = \min\left(0.82 \cdot V_m, V_{>LFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>LFL} \cdot \rho \cdot c_{lfl}}\right)\right)\right)$$

And similar for UFL:

$$V_{>UFL}(t) = \min\left(0.7 \cdot V_m, V_{>UFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>UFL} \cdot \rho \cdot c_{ufl}}\right)\right)\right)$$

(the constant 0.7358 is selected to approximate the analytical solution for time development; the constants 0.82 and 0.7 are chosen as to obey – in most cases - the maximum of 60% flammable fraction in the module).
When m'=0 for $t>t_{max}$:

$$V_{>LFL,max} = \min\left(1.8 \cdot V_m, V_{>LFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t_{max} \cdot m'}{V_{>LFL} \cdot \rho \cdot c_{lfl}}\right)\right)\right)$$

(the constant 1.8 is chosen to allow different sizes of the LFL and UFL cloud when shrinking, and is chosen as to allow – in most cases – the maximum of 60% flammable fraction of the module)

$$V_{>LFL}(t) = \max\left(0, \min\left(0.82 \cdot V_m, \left(V_{>LFLmax}^{\frac{1}{3}} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3\right)\right)$$

And for UFL:

$$V_{>UFL}(t) = \max\left(0, \left((V_{>UFL}(t_{max}))^{\frac{1}{3}} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3\right)$$

For the flammable cloud for all t is then:

$$V_{flammable}(t) = V_{>LFL}(t) - V_{>UFL}(t)$$

For the dimensions of the LFL and UFL clouds use the following rules. Note that the UFL cloud is always smaller than the LFL cloud. A is the area covered by the cloud: A= *Width · Length*; H_m, and W_m are the height and width (perpendicular to the direction of the ventilation flow) of the module. The following formulae assume that Height<Width<Length:

$$A(t) = \max\left(V(t)^{2/3}, \frac{V(t)}{H_m}\right)$$
$$Width(t) = \min\left(A(t)^{1/2}, W_m\right)$$
$$Length(t) = \frac{A(t)}{Width(t)}$$

The location of the cloud is starting at the release point and stretching to the downwind side of the module; if the cloud has reached the downwind side of the module, the upwind side will move upwind.

3.4.2 Time to reach a detector

In order to define when a cloud is detected, we can use the same formulas, when we exchange c_{lfl} by the detection threshold c_{detect}, which is typically 20% of LFL. In this case do NOT apply maximizing the module volume. Note that the empirical constant k is in principal valid for natural gas's LFL concentration, it may not be valid for concentrations that are a factor of 10 smaller. If we know that a detector is mounted 2 m above the floor and 5 m downwind of the release point, we can explicitly derive the time when the cloud will hit the detector:

First define the equilibrium cloud volume for the threshold concentration $V_{equil,detect}$:

$$V_{equil,detect} = \left(\frac{m'}{\rho \cdot c_{detect} \cdot u \cdot k}\right)^{3/2}$$

Then determine the time for the cloud to grow when plume height ($height = \sqrt[3]{V_{detect}(t)}$)>2, and plume length >5 m:

If H_m<5 m, this would lead to (downwind distance being the limiting factor):

$$t_{detect} = -\frac{V_{equil,detect} \cdot \rho \cdot c_{detect}}{0.7358 \cdot m'} \cdot \ln(1 - \frac{5^2 \cdot H_m}{V_{equil,detect}})$$

3.5 Ignition

3.5.1 Immediate ignition

The probability of immediate ignition is taken from the EI report (Anonymous 2006), Section 1.6.4.2, as being 0.1%.

3.5.2 Delayed ignition

Ignition is caused by 2 different types of ignition sources: permanent or continuous ignition sources and intermittent ignition sources.

Continuous sources are sources that, on time frames longer than the whole event sequence, are permanently present. That means that ignition takes place when a gas cloud with a concentration higher than the Lower Flammability Level (LFL) reaches the position of the ignition source. Continuous ignition sources can be hot surfaces of open flames, or equipment producing sparks continuously. The continuous ignition source is characterized by a position (coordinates) and the probability that it exist. The continuous ignition can be linked to a physical equipment (e.g. compressor), and thus may have a fixed position, or use is made of a density per unit area, as provided by data in the EI report, giving a probability of a continuous ignition source being present in some discretely bounded volume. So the process as implemented in the feasibility model is as follows:

1. Sample whether there is a continuous ignition source in the module where the release takes place (for the feasibility model no ignition outside the module has been considered). The probability that there is an ignition source in the module is the probability per unit area (derived from EI report, Table 1.28), times the area of the module.
2. If there is an ignition source, generate a random position for that ignition point.
3. Ignition takes place at the time when the gas cloud (LFL) reaches the ignition point.

Intermittent ignition sources may give sparks at random times. So ignition takes place if a gas concentration is present AND the intermittent source "fires". So in addition to the parameters describing continuous sources, the probability distribution of "firing" need to be known, i.e. typically characterized by the mean time between sparks (and assuming an exponential distribution of time between sparks). Also here, use is made of data from the EI report.

Note that we consider continuous ignition sources by comparison with the time evolution of the event sequence. The EI model considers "hot work" as an intermittent ignition source, as it happens only a few hours per year. We argue that hot work is executed continuously over a period in the order of one hour, while the event development will be faster, and therefore we consider it as a continuous ignition source, but only being present a limited number of occasions.

For the intermittent ignition, we used the data from the EI report, Table 1.28, and partitioned the ignition source density in a spatial probability μ [m^{-2}], and an ignition rate λ [s^{-1}], where λ is the inverse of mean time between ignitions of the source in question. The probability that ignition takes place within an area A and within a time t is then

$$P_{ignition} = A \cdot \mu \cdot (1 - e^{-\lambda \cdot t})$$

The values for "discrete" ignition in EI report Table 1.28 have been partitioned into μ and λ by assuming that the mean time between ignitions is 60 minutes (cf. Table 1.30, where for most equipment 17 minutes has been used). This leads to the following results:

	$\mu_{intermittent}$ (1/m^2)	λ (1/s)	mean time between ignition (min)
Electrical equipment	$1.23 \cdot 10^{-4}$	$2.78 \cdot 10^{-4}$	60
Pump	$4.36 \cdot 10^{-4}$	$2.78 \cdot 10^{-4}$	60
Compressor	$9.80 \cdot 10^{-3}$	$2.78 \cdot 10^{-4}$	60
Generator	$2.25 \cdot 10^{-2}$	$2.78 \cdot 10^{-4}$	60
Other	$3.05 \cdot 10^{-5}$	$2.78 \cdot 10^{-4}$	60
Personnel	$1.02 \cdot 10^{-4}$	$2.78 \cdot 10^{-4}$	60

So the process as implemented in the feasibility model is as follows:
1. Sample whether there is an intermittent ignition source in the module where the release takes place (for the feasibility model no ignition outside the module has been considered). The probability that there is an ignition source in the module is μ (from table above) times the area of the module;
2. If there is an ignition source, generate a random position for that ignition point;
3. Sample at what time the source will "fire" an ignition, using λ and an exponential probability density function;
4. Ignition will take place at time of ignition IF the ignition point at that time is in the flammable part of the cloud.

The probability of both continuous and intermittent ignition sources can change during the sequence of events depending on whether personnel have secured the workplace, and/or have left the module (not implemented in the feasibility study)

3.6 Jet flame

The purpose of this model is to describe the jetflame following ignition, as function of time and release rate. The model need to predict: Size and heat transfer to the surroundings in order to estimate likelihood of detection (by a variety of sensors), direct damage to people (fatality and injury) and damage to platform structural equipment and/or process equipment.

Different models are available, see e.g. section 6.3.2 in (Committee for the Prevention of Disasters 1996, 2005):
- Single Point models
- Multiple Point models
- Models with a predefined, simplified contour or solid shape (typical cones)

- Integral models
- Field (CFD) models.

In order to be applicable for OPHRA, the model should either be able to run very fast within the system, or OPHRA performs an interpolation between predefined results (e.g. from CFD models).

Two types of heat transfer have to be considered, viz. 1) Radiative heat transfer from the (free) flame surface to surrounding objects (surfaces) and 2) convective heat transfer from flames hitting (impinging) or engulfing objects or surfaces. Modelling radiative heat transfer involves determination of flame surface temperature and emission coefficient (emissive power), and view factors from the object to the flame surface; the flame surface can be simplified to a single point. Modelling convective heat transfer involves determination of flame temperature and convective heat transfer which depends on the characteristics of the flow of hot or burning gas close to the object.

Simplest modelling:

The simplest model is the point source model and correlations for heat transfer from chapter 5 in (Oil & Gas UK 2007). This model ignores the influence of wind on the position of the flame, but this model can be combined with some of the aspects of the "Chamberlain" model, described in section 6.5.3 of (Committee for the Prevention of Disasters 1996, 2005).

The point model is a suitable model for radiation heat flux at distances more than 2 flame diameters away. Incident radiative heat flux at a distance *r* is:

$$q_r = \frac{\tau \cdot F \cdot m' \cdot H_c}{4\pi \cdot r^2}$$

Where τ is the atmospheric transmissivity of heat radiation, F is the fraction of heat from the flame transferred by radiation, m' the burning mass flow rate (which is equal to the release rate from the leak), and H_c the heat of combustion of the gas.

Feasibility study: use has been made of the Chamberlain model as described in section 6.5.3 of (Committee for the Prevention of Disasters 1996, 2005).

4 Detection models

4.1 Gas detection

Detectors are located in some array. When the cloud (see section 3.4.2) reaches a detector, the detector will initiate the response (Alarm) with a probability corresponding to the detector's reliability.

5 Models describing escape and evacuation

5.1 Manning distribution

Personnel are distributed within the different modules. This can be deterministic (fixed number of personnel in each module) or probabilistic using a probability distribution for each module, assuring that total Persons On Board (POB) is not exceeded.
Personnel are distributed over the area of the module using a uniform probability distribution. Note that release frequency may be correlated with personnel being present (e.g. due to maintenance-related incidents). No information is available at present.

5.2 Model for securing the workplace

It is assumed that the time needed to secure and leave the workplace can be described by a random variable for each person, where the variable is sampled from a probability distribution. It can be, for example, a triangular, uniform or any other that is best supported by existing evidence. In the current version, the uniform distribution is implemented that samples random values from a range of [50, 70] seconds.

5.3 Model of escape from the module.

This model implements the likely decision from the personnel to move to the exit of the module in a way that always will increase the distance to the point of release. The speed of movement can be sampled from a distribution that is best supported by existing evidence. In the feasibility version of the model it is constant and equal to 2 meters per second. Limits in movements can be implemented, e.g. only routes perpendicular to the walls are possible, to incorporate the presence of equipment and other obstacles limiting free movement. Movement

5.4 Model to move to muster area

Once outside the module on an escape route, the persons have to decide to move to:
* Muster area
* Secondary muster area
* Escape to sea
* Remain in position (trapped)

These decisions are based on whether routes towards the three positions at the moment of decision are impaired by gas, heat, or smoke.
The speed of movement along the escape routes can be sampled from a distribution. Though, for the feasibility study it is constant and equal to 2 meters per second.

6 Models for describing consequences

6.1 Heat radiation impact on persons

For heat radiation due to flash fire and jet fire, the approach as used in the "Purple book" (Committee for the Prevention of Disasters 1999). This model states:

- If a person is within a flame envelope (either a jet flame or a flash fire), the fatality probability is 1;
- If a person at any time is exposed to a heat radiation exceeding 35 kW/m^2 (when all clothes are expected to ignite), the fatality probability is 1;
- If the heat radiation is less than 35 kW/m^2, fatality is calculated by the following Probit function:

$$Pr = -36.38 + 2.56 \cdot \ln\left(q^{\frac{4}{3}} \cdot t\right)$$

Fatality is 14% of the fatality according to this Probit function, where the reduction accounts for the protection of clothing.

For low radiation levels, the Probit is calculated by integrating the dose $q^{4/3} \cdot t$ while the person is exposed to radiation (i.e. the collected dose while at the work place and while escaping).

This model s not implemented in the feasibility study.

Appendix B Development of a time-dependent dispersion model for offshore modules

Overview

Dispersion modelling will be based on the approach from the IP Ignition probability review, page 57.

The expression for the equilibrium flammable volume is:

$$V_{flammable} = \left(\frac{m'}{\rho \cdot u \cdot k}\right)^{3/2} \cdot \left(c_{lfl}^{-3/2} - c_{ufl}^{-3/2}\right)$$

This expression states that an equilibrium cloud size is obtained when removal of the flammable substance by wind over the boundaries of the cloud (proportional to cloud surface area and wind speed) is equal to the influx m'. Here k is an empirical constant that describes the rate of gas transport through the cloud's boundaries. It is shown that k = 0.614

The flammable cloud volume in the module can fill at maximum 60% (according to experiments) of the module.

If the flammable volume is limited by the size of the module, the excess mass would disperse outside the module (in adjacent units or modules) above c_{lfl}. This is not included for the feasibility study.

Cloud growth V(t) can be approximated by formula (A22) in the sections below for constant m'. V(t) is the time dependent flammable cloud, which asymptotically will approach $V_{equilibrium}$.

$$V(t) = V_{equilibrium} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{equilibrium} \cdot \rho \cdot c_{lfl}}\right)\right)$$

(A22)

For releases from isolatable sections, we use (for the feasibility) a constant mass flow rate equal to the maximum mass flow rate. When isolation is initiated, we know the total mass to be released (this is the mass released up to time to full isolation plus the mass in the isolated section). The effective release time t_{max} is then calculated as the total mass released divided by the (maximum) mass flow rate – after that, the mass flow rate drops to zero. The development of the cloud can then be approximated by formulas (A22) and (A23):

$$V(t) = \left(V_{max}^{1/3} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3$$

(A23)

This formula is valid while $t - t_{max} < (V_{max})^{1/3}$. V_{max} is the cloud volume according to (A22) at t_{max}: $V(t_{max})$.

Some special rules need to be applied to ensure consistency (the UFL cloud is always smaller than the LFL cloud) and to obey the observation of a maximum of 60% flammable fill in the module. The complete calculation rules are in the following sections.

In order to define when a cloud is detected, we can use the same formulas, when we exchange c_{lfl} by the detection threshold c_{detect}, which is typically 20% of LFL. In this case do NOT apply maximizing the module volume. Note that the empirical constant k is in principal valid for natural gas's LFL concentration, it may not be valid for concentrations that are a factor of 10 smaller.

If we know that a detector is mounted 2 m above the floor and 5 m downwind of the release point, we can explicitly derive the time when the cloud will hit the detector:

First define the equilibrium cloud volume for the threshold concentration $V_{equil,detect}$:

$$V_{equil,detect} = \left(\frac{m'}{\rho \cdot c_{detect} \cdot u \cdot k}\right)^{3/2}$$

Then determine the time for the cloud to grow when plume height ($height = \sqrt[3]{V_{detect}(t)}$)>2, and plume length >5 m:

If H_m>5, this would lead to (downwind distance being the limiting factor):

$$t_{detect} = -\frac{V_{equil,detect} \cdot \rho \cdot c_{detect}}{0.7358 \cdot m'} \cdot \ln(1 - \frac{5^2 \cdot H_m}{V_{equil,detect}})$$

1. Dispersion in an offshore module

1.1 The free momentum jet model

The basis is the model provided in the Yellow book, section 4.5.4.1

The original model reads:

Centerline concentration c_c and velocity u_c as for $s > \max(C_c \cdot b_0, C_u \cdot b_0)$:

$$c_c(s) = c_0 \cdot C_c \cdot \frac{b_0}{s}$$

$$u_c(s) = u_0 \cdot C_u \cdot \frac{b_0}{s}$$

(A4)

Here b_0 is the source radius.

Radial distribution of concentration c and velocity u:

$$c(y,s) = c_c(s) \cdot e^{-C_{yc}(\frac{y}{s})^2}$$

$$u(y,s) = u_c(s) \cdot e^{-C_{yu}(\frac{y}{s})^2}$$

(A5)

The model in the Yellow Book is presented as if the coefficient C_c, C_u, C_{yc} and C_{yu} are independent, but they are connected through the balances of mass and momentum:

$$C_{yu} = \frac{1}{2}C_u{}^2$$

$$C_{yc} = C_u \cdot C_c - C_{yu}$$

(A6)

For the recommended values $C_u=12$ and $C_c=10$ it follows that $C_{yu}=72$ and $C_{yc}=48$. The Yellow Book recommends experimental values of 94 and 57, respectively. If we want to reproduce the recommended experimental values from the Yellow Book, we have to introduce some factors, which represent apparent loss of momentum and mass from the jet as compared to the release (which may address the processes close to the orifice):

$$C_{yu} = 1.306 \cdot \frac{1}{2}C_u{}^2$$

$$C_{yc} = 1.258 \cdot C_u \cdot C_c - C_{yu}$$

(A7)

Note that C_c and C_u can be adjusted for the density of the released gas (Yellow Book 4.79 and 4.78)

The same mass will pass through a jet with a top-hat profile with uniform values of c_c and u_c with a radius of $s/\sqrt{C_u \cdot C_c}$; for the normally (Gaussian) distributed profile it is adequate to set the radius of the jet at $s/2 \cdot \sqrt{C_u \cdot C_c}$, this means that almost 80% of mass and momentum will pass through the jet within this radius, and the values of concentration and velocity are about 10 to 12% of the centerline values.

1.1.1 Ambient velocity.

The momentum jet model can be adjusted to a jet in an ambient co-flowing stream by considering the velocity difference with the co-flowing stream's velocity u_a. So the formulae for u become:

$$u_c(s) = (u_0 - u_a) \cdot C_u \cdot \frac{b_0}{s} + u_a$$

(A8)

Offshore Platform Hydrocarbon Risk Assessment – OPHRA: Feasibility

$$u(y,s) = (u_c(s) - u_a) \cdot e^{-C_{yu}\left(\frac{y}{s}\right)^2} + u_a$$

<div align="right">(A9)</div>

If the jet is opposite to the ambient flow (i.e. u_0 is negative), the model cannot really be used, because the jet will "flow over itself". An estimate of the maximum upwind extension of the jet can anyway be obtained by calculating the point where $u_c=0$, i.e.

$$s = C_u \cdot b_0 \cdot \left(1 - \frac{u_0}{u_a}\right) \qquad\qquad \text{for } u_0 > -u_a$$

<div align="right">(A10)</div>

1.1.2 Time dependent jet

For the evolution of the jet we assume that the jet front proceeds with the speed of the center-line of the fully developed jet. So at t=0, jet length L(0)=0, and dL(t)/dt=u_c(L).
This ODE can be solved to give:

$$L = 2\sqrt{u_0 \cdot C_u \cdot b_0 \cdot t}$$

<div align="right">(A11)</div>

1.1.3 Explosive limits and volumes

The distance along the jet to some concentration k (e.g. the lower flammability level) is given by:

$$s_k = \frac{c_0}{k} \cdot C_c \cdot b_0$$

<div align="right">(A12)</div>

The radial distance to the concentration k at the edge of the plume is at some position s along the jet is:

$$y = \frac{s}{\sqrt{C_{yc}}} \cdot \sqrt{\ln\left(\frac{b_0}{s} \cdot C_c \cdot \frac{c_0}{k}\right)}$$

<div align="right">(A13)</div>

The mass concentration between c_0 and some concentration k (e.g. the lower flammability level) up to some distance L (which may correspond to the jet length at time t) is given by:

$$M = \frac{\rho_0 \cdot \pi}{6 \cdot C_{yc}} \cdot \left[L^3 \cdot \left(3 \cdot c_0 \cdot \frac{C_c \cdot b_0}{L} - 2 \cdot k\right) - C_c{}^3 \cdot b_0{}^3 \cdot (3 \cdot c_0 - 2 \cdot k)\right]$$

for L<s_k and where ρ_0 is the density of the release at c_0, so that $\rho_0 \cdot c$ is the mass concentration in kg/m^3.
For the mass between two levels, such as the lower and upper flammability level c_{lfl} and c_{ufl}, respectively, this mass is:

$$M = \frac{\rho_0 \cdot \pi}{3 \cdot C_{yc}} \cdot \left(L^3 - C_c{}^3 \cdot b_0{}^3\right)\left(c_{ufl} - c_{lfl}\right)$$

<div align="right">(A14)</div>

The total mass between c_0 and k, i.e. up to length L= s_k is:

$$M_k = \rho_0 \cdot \pi \frac{b_0{}^3 C_c{}^3}{6 C_{yc}} (k - c_0)^2 \left(\frac{2}{k} + \frac{c_0}{k^2}\right)$$

<div align="right">(A15)</div>

The total explosive mass is then:

$$M_{explosive} = \rho_0 \cdot \pi \frac{b_0{}^3 C_c{}^3}{6 C_{yc}} (c_{ufl} - c_{lfl}) \left(\frac{c_0{}^3 (c_{ufl} + c_{lfl})}{c_{ufl}{}^2 c_{lfl}{}^2} - 2 \right)$$

<div align="right">(A16)</div>

Note this formula is different from the one in the Yellow Book (4.83), which is derived by integrating along the jet axis starting at s=0; whereas the jet formula is only valid from s>$C_c b_0$, where we started the integration. The difference is negligible; so one can use the simpler formula from the Yellow Book:

$$M_{explosive} = \rho_0 \cdot \pi \frac{b_0{}^3 C_c{}^3}{6 C_{yc}} c_0 \left[\left(\frac{c_0{}^2}{c_{lfl}{}^2} \right) - \left(\frac{c_0{}^2}{c_{ufl}{}^2} \right) \right]$$

<div align="right">(A17)</div>

This formula can be converted to include the mass flow rate, through the equality of $m = \pi b_o{}^2 c_o \rho_o u_o$:

$$M_{explosive} = m \frac{b_0 \; C_c{}^3}{6 u_o C_{yc}} \left[\left(\frac{c_0{}^2}{c_{lfl}{}^2} \right) - \left(\frac{c_0{}^2}{c_{ufl}{}^2} \right) \right]$$

<div align="right">(A17b)</div>

The jet model does not deal with sonic releases and expansion to ambient conditions. Therefore it is necessary to use the subsonic properties after the jet is expanded to approximately Ma=1/3, i.e. u_o~100 m/s, and density is at standard conditions. Assuming the release is 100% gas, i.e. c_o=1, the pseudo-source radius b_o can be calculated from:

$$b_o = \sqrt{\frac{m}{100 \, [m/s] \cdot \pi \cdot \rho_{o,expanded}}}$$

This value is inserted in formula (A17b) together with 100 m/s for u_o.

1.2   The JIP workbook model

The original reference cannot be found, but the model is described in the IP ignition probability review.

The model tries to describe the volume for the cloud exceeding LFL. This can be thought of as a balance between the mass entering this volume from the release m', and the mass taken out by the ventilation or wind though the boundary area of this volume, i.e. the ventilation of the volume V' (from the first section above) is modelled as A*u, where A is the area of the volume where the air is moving outward *and* the concentration is at LFL, and u the wind or ventilation speed. The area A is considered proportional with the explosive volume's characteristic length scale: A=k*$V^{2/3}$.

The mass taken from the boundary where c=c_{lfl} is thus: ρ*c_{lfl}*u*k*$V^{2/3}$. So balance between inflow and outflow leads to an estimate of the volume V:

$$V_{>LFL} = \left(\frac{m'}{\rho \cdot c_{lfl} \cdot u \cdot k} \right)^{3/2}$$

And similar for the volume exceeding UFL:

$$V_{>UFL} = \left(\frac{m'}{\rho \cdot c_{ufl} \cdot u \cdot k} \right)^{3/2}$$

<div align="right">(A18)</div>

(Note that we assume that k does not depend on the level of concentration – this is a simplification)

The workbook proposes the correlation for natural gas where c_{lfl} = 5% and c_{ufl} = 15%:

$$V_{flammable} = 150 \left(\frac{m'}{\rho \cdot u} \right)^{3/2}$$

$V_{flammable} = V_{>LFL} - V_{>UFL}$.

This leads to:

$$k = \left[\frac{c_{lfl}^{-3/2} - c_{ufl}^{-3/2}}{150} \right]^{2/3}$$

Which leads to k=0.614 or

$$V_{flammable} = 2.077 \left(\frac{m'}{\rho \cdot u} \right)^{3/2} \cdot \left(c_{lfl}^{-3/2} - c_{ufl}^{-3/2} \right)$$

Note that if the volume was a sphere, and outflow would take place over half of the surface or the sphere, k would be about 2.4. This can be considered to be the maximum value that k can take (leading to the smallest volume for a given release/ventilation combination). Note that in the experiments, the ventilation may have been limited by the walls of the module (that would not contribute to mixing), thus leading to low values of k.

Now the IP model estimates how long it will take to fill up this flammable volume. The text uses a build-up time as discussed above, but without considering consistency with the areas and concentration for the JIP workbook model, giving too low times. The excel sheets use a different formula, not included in the text, viz *"... based on flammable volume in Area at LFL divided by volumetric release rate of material, x 2 to allow for some loss during build up of gas in Area"* (comment in IP's Excel sheet):

$$t = \frac{2 \cdot V_{flammable} \cdot \rho \cdot c_{lfl}}{m'}$$

(A19)

In principle, the evolution of the cloud $V_{>LFL}$ with edge at c_{lfl} follows the ODE:

$$\frac{dV}{dt} = \frac{m'}{\rho \cdot c_{lfl}} - u \cdot k \cdot V^{2/3}$$

(A20)

This ODE has no explicit solution for m'<>0, but t can be expressed explicitly in V (i.e. time to reach a certain cloud volume V):

With A=$\frac{m'}{\rho \cdot c_{lfl}}$ and B= $u \cdot k$:

$$t = 3 \cdot \left[\sqrt{\frac{A}{B^3}} \cdot \operatorname{arctanh} \left(\sqrt[3]{V} \cdot \sqrt{\frac{B}{A}} \right) - \frac{\sqrt[3]{V}}{B} \right]$$

(A21)

(note that the cube root of V equals the characteristic length scale L)

It appears that the time to volume according to the simple formula from the IP model is very close to the theoretical solution, when time to 77.77% of the maximum (asymptotical) volume is calculated. There is a constant relation between the time as calculated by (A19) and (A21). This ratio is used to derive an approximate explicit relation for the cloud volume at time t in relation to the maximum cloud $V_{>LFL}$ as calculated by (A18):

$$V_{>LFL}(t) = V_{>LFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>LFL} \cdot \rho \cdot c_{lfl}}\right)\right)$$

And thus

$$V_{flammable}(t) = V_{>LFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>LFL} \cdot \rho \cdot c_{lfl}}\right)\right) - V_{>UFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>UFL} \cdot \rho \cdot c_{ufl}}\right)\right)$$

(A22)

Note that (A22) is valid for constant m' (as calculation of V$_{flammable}$ assumes constant m' over the total development of the cloud). Correct handling of varying m' requires (numerical) integration of (A20). Rather simple integration schemes will suffice due to the asymptotic behavior to an equilibrium condition.

If m' becomes zero (due to isolation), A20 can be solved to give:

$$V_{>LFL}(t) = \left(V_{max}{}^{1/3} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3$$

(A23)

This is valid while t-t$_{max}$ < (V$_{max}$)$^{1/3}$.

Here V$_{max}$ is the maximum flammable cloud size at t$_{max}$ when the mass flow rate drops to zero (note that (A23) describes a linear decrease in the characteristic length scale L).

1.2.1   The final calculation scheme

This scheme is adjusted in such a way, that the experimental observation that the fraction of a module filled with a flammable cloud is no more than 60%. Note that this limitation may be caused either that a part of the module is below the LFL, either a part is above the UFL.

While m' is non-zero and constant for 0<t<t$_{max}$:

The final (equilibrium) cloud size where LFL is exceeded is:

$$V_{>LFL} = \left(\frac{m'}{\rho \cdot c_{lfl} \cdot u \cdot k}\right)^{3/2}$$

And similar for the volume exceeding UFL:

$$V_{>UFL} = \left(\frac{m'}{\rho \cdot c_{ufl} \cdot u \cdot k}\right)^{3/2}$$

For the time-dependent cloud where LFL is exceeded (V$_m$ is the volume of the module):

$$V_{>LFL}(t) = \min\left(0.82 \cdot V_m, V_{>LFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>LFL} \cdot \rho \cdot c_{lfl}}\right)\right)\right)$$

And similar for UFL:

$$V_{>UFL}(t) = \min\left(0.7 \cdot V_m, V_{>UFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t \cdot m'}{V_{>UFL} \cdot \rho \cdot c_{ufl}}\right)\right)\right)$$

(the constant 0.7358 is selected to approximate the analytical solution for time development; the constants 0.82 and 0.7 are chosen as to obey – in most cases - the maximum of 60% flammable fraction in the module).

When m'=0 for t>t$_{max}$:

$$V_{>LFL,max} = \min\left(1.8 \cdot V_m, V_{>LFL} \cdot \left(1 - \exp\left(\frac{-0.7358 \cdot t_{max} \cdot m'}{V_{>LFL} \cdot \rho \cdot c_{lfl}}\right)\right)\right)$$

(the constant 1.8 is chosen to allow different sizes of the LFL and UFL cloud when shrinking, and is chosen as to allow – in most cases – the maximum of 60% flammable fraction of the module)

$$V_{>LFL}(t) = \ \max\left(0, \min\left(0.82 \cdot V_m, \left(V_{>LFLmax}^{\frac{1}{3}} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3\right)\right)$$

And for UFL:

$$V_{>UFL}(t) = \ \max\left(0, \left((V_{>UFL}(t_{max}))^{\frac{1}{3}} - u \cdot k \cdot \frac{t - t_{max}}{3}\right)^3\right)$$

For the flammable cloud for all t is then:

$$V_{flammable}(t) = V_{>LFL}(t) - V_{>UFL}(t)$$

For the dimensions of the LFL and UFL clouds use the following rules. Note that the UFL cloud is always smaller than the LFL cloud. A is the area covered by the cloud: A= *Width · Length*; H_m, and W_m are the height and width (perpendicular to the direction of the ventilation flow) of the module.

$$A(t) = \max\left(V(t)^{2/3}, \frac{V(t)}{H_m}\right)$$
$$Width(t) = \min\left(A(t)^{1/2}, W_m\right)$$
$$Length(t) = \frac{A(t)}{Width(t)}$$

The location of the cloud is starting at the release point and stretching to the downwind side of the module; if the cloud has reached the downwind side of the module, the upwind side will move upwind.

1.2.2 Necessity of the limiting of the maximum volumes.

It has been investigated whether it is necessary to maintain the limiting parameters (0.82 and 0.7, respectively) to limit maximum flammable fraction of 60% in the module. The Figure below shows the effect of the limitation. It can be questioned whether these limiting parameters are necessary to maintain, given the other uncertainties in the model. Without the limiting parameters the maximum flammable fraction in the module is 80% for a narrow interval of the dimensionless release rate instead of 70%, which still may be considered showing sufficient agreement with the experimental observations.
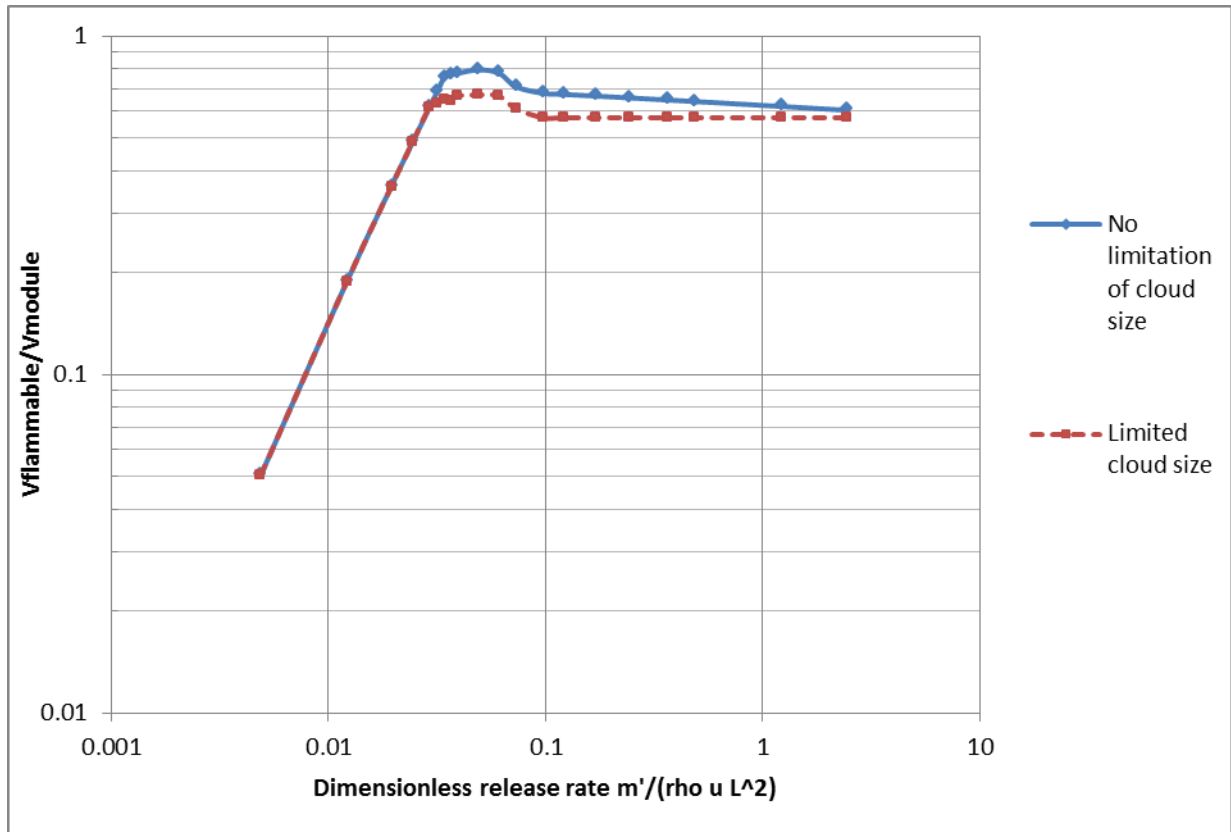
Offshore Platform Hydrocarbon Risk Assessment – OPHRA: Feasibility

This report describes the feasibility demonstration of a new method to perform risk assessments for offshore platforms. This method simulates concurrent sequences of events using the Arena® Discrete Event Simulation (DES) software (version 14.50.00), including release, ignition and fire; detection, shut down and alarm; escape and evacuation; and exposure and impact on people and equipment The method leads to a transparent framework for modelling, which helps to demonstrate the correctness and appropriateness of models and assumptions. The report lists models and data needed for the risk assessment framework, and provides specific suggestions for some of those models. Some preliminary calculations with the DES model have been performed to illustrate type of results that can be obtained and to provide some insight in the accuracy and computational efforts. Finally, further work is identified in order to develop an operational risk assessment tool.