Effect of pressure maintenance by fluid injection on seismic risk (KEM24/ IUC202003010)

Umbrella Report A |

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Project Team

Name	Role
Fugro	Project Management, Geological and Hazard/Risk team, WP0 and WP5, umbrella report
DynaFrax	Technical Project Management, WP1 to WP5, part of WP0
Dr. [redacted]	Review during first phase of the study, reservoir engineering and over-all review
Prof. [redacted]	External review of attachment B

1. Introduction

Fugro has been commissioned by The Dutch Ministry of Economic Affairs and Climate Policy to perform a study for the Knowledge Program on Effects of Mining. This program, called KEM (www.kemprogramma.nl) addresses the recommendations of the Dutch Research Council for Safety (OVV) and aims at enhancing the understanding of hazard and risk of mining activities in The Netherlands. KEM 24 is a study on the effect of pressure maintenance by fluid injection on seismic risk. The KEM24 team was composed by international specialists, covering various disciplines. Our partner for this study is DynaFrax, experts in Dynamics of rock fractures for geo-coupled process modelling and geohazard risk analysis. DynaFrax is a spin-off of Helmholtz Centre Potsdam, German Research Centre for Geosciences (GFZ).

Worldwide, the production of natural gas from subsurface porous reservoirs leads to surface subsidence and induced seismicity. Induced seismicity, in general, is caused by instability of faults due to pressure depletion (directly and indirectly due to compaction) and fluid flow. Fluid injection during or after production is a potential measure to control the reservoir pressure and, hence limit, reservoir compaction (in the gas field) and subsidence (of the surface above the gas field). This intervention may result in a lower risk of induced seismicity compared to scenarios without fluid injection, and it potentially enables stakeholders to increase and/or continue production from gas fields.

Objective of the study

In the Netherlands, dozens of producing gas fields have shown seismic activity. The KEM study is meant to provide a proof of concept to estimate the net benefit of fluid injection, minimizing seismicity and/or subsidence. In 2020, the client has chosen the Groningen field to study this concept, not because it was considered, but because a lot is known from this gas field: geology, seismicity, production and reservoir pressure. This makes it possible to compare the results of model simulations with the observations.

The first objective of the study is to investigate and identify what is the best method to model and quantify the effect of fluid injection on the expected seismicity risk profile. Two main factors will be considered:

(1) using various injection fluids (N2, CO2 and water) or a mixture of natural gas and an injected fluid, and

(2) different injection scheme options, including reusing existing production facilities.

The second objective is to find a reliable method to assess possible additional seismic risks associated with fluid injection itself (as it might locally trigger seismicity) and to determine which factors, circumstances or injection configuration and volumes may increase the probability of seismicity and vice versa. The overall objective is to assess whether the net effect of fluid injection on the seismic risk profile can be positive and to give recommendations to optimize the risk reduction at minimum injection costs.

In previous years, research has been conducted by TNO and NAM on the feasibility of pressure maintenance by large-scale fluid injection (2013-2016). It was concluded that injection can maintain reservoir pressure in depleting reservoirs, such as the Groningen gas field, and that fluid injection is technically feasible. However, the overall net effect of large-scale fluid injection on the seismic risk profile was not quantified and the seismic risk associated with different fluid injection scenarios was only studied in a qualitative way. Therefore, it is unknown whether fluid injection can be used to minimise the risk of induced seismicity in depleting gas fields. A feasibility study for the Groningen gas field (NAM, 2016) indicated that establishing a large-scale fluid injection operation in the short term was hardly feasible, due to the major investments required to produce large volumes of injection fluid (appr. 5 billion Euro), as well as the lengthy time required to construct the injection well infrastructure. It was therefore decided by NAM not to pursue this option any further. However, various experts in the field advocate to continue investigating this option, especially for the Groningen gas field. This would require an extension of the current hazard and risk analysis (HRA) model used for assessing the seismic risk due to gas production in the Groningen field (developed by NAM and reconstructed by TNO), as the current version does not have the functionality to investigate the effect of fluid injection on seismic risk.

The research questions of the study are as follows:

1. What are possible injection scenarios for pressure maintenance during production and for minimising the pressure difference across the field once production has stopped?

2. What are the reservoir stresses and pressures for various fluid injection scenarios (defined in question 1) around wells and over the entire gas field?

3. How to adapt the Groningen seismic module for injection for pressure increase as well as pressure decrease?

4. What is the effect of fluid injection on the overall seismic risk?

5. What is the effect of fluid injection on seismicity near injection wells?

6. What is the most optimal configuration of injection wells?

7. What is the overall effect of fluid injection on seismicity and what are the recommendations for the Groningen HRA model?

2. The study

The steps of this project were divided into six work packages, as shown in Figure 1. They outline the workflow, from the generation of 2D Groningen gas field geological models to seismic hazard map generation for the largest simulated earthquakes.

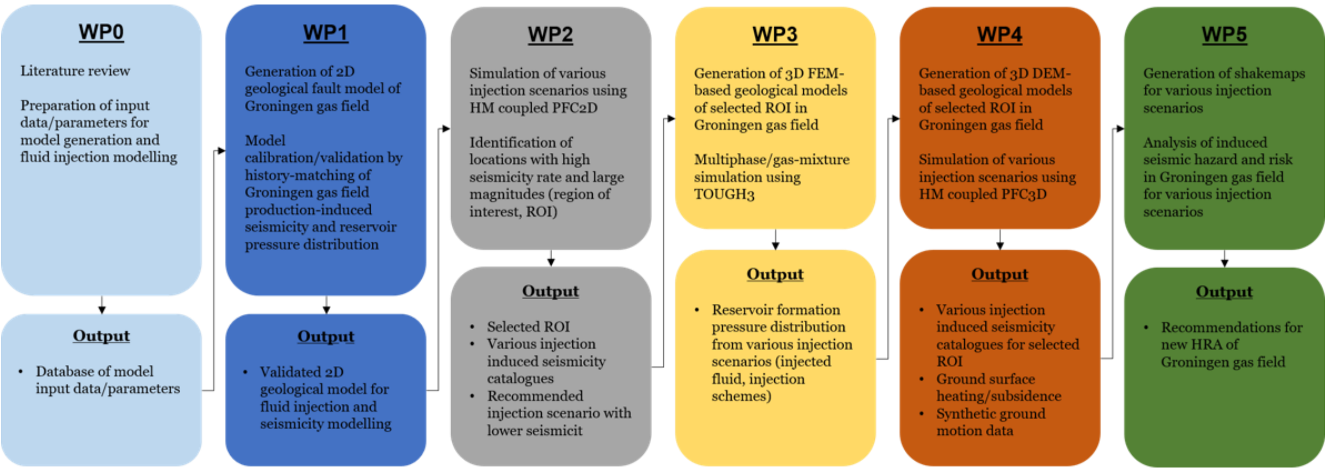

Figure 1*: Work package progression and their inter-relations.*

WP0: Review of past studies and compilation of input data/parameters for Groningen gas field modelling

WP0 is the preparation stage where earlier studies pertaining to the Groningen gas field are comprehensively reviewed in order to prepare data sets that are needed to generate the numerical model of the Groningen reservoir.

WP1: Modelling of depletion-induced seismicity in Groningen gas field using 2D hydro-mechanical coupled discrete element modelling

In the first phase of this project, 2D hydro-mechanical coupled discrete element modelling (Yoon et al., 2014) are used to simulate the seismicity by pressure depletion within the Groningen gas field. The modelling code used in this study is PFC2D (Particle Flow Code 2D), a commercial code of ITASCA, with in-house developed hydro-mechanical coupled and seismicity computing models. We modelled the entire field of Groningen gas reservoir with 40 km by 50 km in size with the complex reservoir faults. The model is in 2D which we considered valid due to its long horizontal extent (40-50 km) compared to the net thickness of the reservoir (200-300 m), like thin-sheet model in other studies (Bourne & Oates, 2017).

Production history is closely simulated in order to monitor changes in the geo-mechanical processes of the fault system, in particular focusing on fault system stress paths associated with gas production, and their correlation with seismic events. Depletion modelling generates seismicity catalogues, the resulting seismicity is compared to observed earthquakes, as reported by KNMI, to further refine the geological model and fault parameters. The resulting spatial distribution in pressure decline is used to design injection scenarios in the next work package of the project, with the goal of compensating major areas of pressure loss and mitigating resulting seismicity.

WP2: Modelling of various fluid injection scenarios in the Groningen gas field and induced seismicity using 2D hydro-mechanical coupled discrete element modelling

After modelling the depletion-induced seismicity history, multiple fluid injection scenarios are designed and simulated using PFC2D, to understand how the fault system would respond to injection. These scenarios are designed with the intention of recovering pressure in areas with the large observed decline, to assess the effect on seismicity near injection and in the rest of the gas field. The injection locations are chosen in the Central East cluster, near the area with the most pressure decrease. Injection scenarios were simulated with and without simultaneous production at other locations. Not only future scenarios were simulated, but also scenarios to test how seismicity changes if injection would have started in the past.

WP3: Modelling of multiphase/gas-mixture injection using TOUGH3

In this work package, modelling of injection of N2 and CO2, in a reservoir with mixture of CH4 and water, was performed using the TOUGH3 software. The aforementioned injection gas and their mixture with CH4 and water in the reservoir are tested, providing temporal evolution of the reservoir pressure change, which would then be used back in the PFC2D modelling.

WP4: Modelling of fluid injection induced fault activation using 3D hydro-mechanical coupled discrete element model

Fault activation by fluid injection is simulated using 3D hydro-mechanical coupled discrete element modelling. 3D modelling was intended to simulate dynamic response of near-field faults to fluid injection. The 3D model was intended to focus on complex fault system at Loppersum region.

WP5: Induced seismic risk assessment

The numerical seismicity catalogues generated from WP2 are collected and analyzed to develop an induced seismic hazard model of the Groningen gas field. The hazard analysis was performed with output from the PFC2D modelling which was provided in 2021 (presented in the appendix of Report B). Since then, the development of the modelling by DynaFrax continued. As agreed with the client, additional hazard analyses, based on the latest output, were considered not relevant or necessary, given the uncertainties of the output of the PFC2D modelling so far.

3. Deliverables

Table 3.1 provides an overview of the technical reports that make up the deliverable.

Table 3.1: Overview of technical reports

Technical Report No.	Title	Report
1020-169309.R01 V01, 30 September 2022	KEM-24 Effect of pressure maintenance by fluid injection on seismic risk, *Umbrella report*	Report A primary author: Fugro
KEM24 Final report, 30 September 2022	KEM-24 WP0 to WP4 Effect of pressure maintenance by fluid injection on seismic risk *Simulation of reservoir depletion and injection induced seismic events using hydro-mechanical coupled Particle Flow Code 2D modelling on Groningen reservoir geological fault model; including external review*	Report B primary author: DynaFrax
172147-REP01-FNV_SHA_KEM24 V03, 30 September 2022	KEM-24 WP5 Effect of pressure maintenance by fluid injection on seismic risk *Hazard analysis*	Report C primary author: Fugro

The data that was used as input for the study and the data-files that were made by the KEM24 team will be made accessible to the client digitally. Because of the amount and size of the data this will be organized separately.

During the study, some changes have been agreed with the client, which is part of the explanation why the reports, planning and answers are not fully in line with the original scope and planning:

- The collection of data and information relied on external parties and took longer than anticipated
- After Fugro completed the WP0 report as input to DynaFrax, some additional information and data was considered, which in general was not reported by Fugro but by DynaFrax
- A lot of effort has been put in WP1 and WP2. Although the first results were promising, it turned out to be difficult to get a satisfying fit between calculated and observed seismicity and pressure distribution. However, considerable progress was made by adjusting the model more to known and/or plausible characteristics but making it more complex.
- The 3D analyses of WP3 and WP4 turned out to be only feasible for a relatively small area, with less complexity of fault structure, because of computational limitations. It was not possible to integrate vertical processes like compaction into the model
- WP5 was performed by Fugro based on intermediate modelling results from DynaFrax (appendix in Report B). Due to the large uncertainty of the output from DynaFrax, it was not relevant to update the WP5 report based on later results from DynaFrax; the overall conclusions from WP5 are considered, together with the results from DynaFrax, in this umbrella report.

4. Summary of modelling results

Based on best estimate of geophysical parameters and pressure history of the production clusters, we tried to simulate the past 60 years of depletion induced seismicity that covers the time range from year 1960 to 2020. The spatial distribution and order of magnitude of seismicity of the first models was consistent with observations, which means that the 2D simulation was able to generate seismic events at locations where fault stresses were critical. However, the (average) pressure history in the field appeared to be not matching: the pressure decrease in the model was under-estimated at distance from production wells and there was fluid flow into the field from the surrounding. The effect of this deviation was that after simulating a production stop, the pressure at closed production clusters increased rapidly, making any injection not effective.

It appeared to be necessary to adjust the number of production wells to reality: this number was increased to more than 300, so average pressure decline would be more in line with observations. Originally, this was considered not relevant, and the production capacity was modelled less detailed. Also, the outer boundary of the reservoir was made impermeable and the permeability of the faults was varied, depending on fault throw.

The average pressure history matched better to observations and spatial distribution and the seismicity was partially consistent with KNMI earthquake-catalogue data, though fewer earthquakes were generated from the PFC2D simulations than were observed between 1992-2020. Ultimately, the depletion model adequately captured the spatial distribution of observed earthquakes above local magnitude ML 2.0, rendering their spatial seismicity distributions consistent with that of KNMI earthquake-catalogue data. However, the seismicity from the model did not show the strong increase after 30 to 40 years of production, as observed. This might be explained by the fact that the vertical component and compaction, which builds up in time, was not captured in the 2D model.

We simulated future seismicity, assuming that the gas production stopped in year 2020 and all the production wells are shut-in. Very little seismicity was generated during these shut-in periods. Based on these results, the injection scenarios were designed with the intention to increase spatial homogeneity in pressure recovery, to reduce the number and magnitude of seismic events triggered by the model as a result of increased differential stress. Both CO_2 and N_2 injection were tested. The N_2 injection appeared to be much more effective. Also, N_2 injection will not make the production gas unusable, since it already contains a significant percentage of N_2. Mixing diluted gas with high calory gas could be a solution to use the gas as Groningen gas quality.

The injection-rate was taken relatively high in all injection scenarios, to get more certainty about any negative effects of the injection itself, given the uncertainties of the model parameters. Injection could be a tool to continue and increase production, without the negative effects of pressure depletion. The injection scenarios without simultaneous production were compared to scenarios with simultaneous production. As a test case, the injection was modelled in the central eastern cluster and the production was continued in the other clusters. This was done for injection scenarios starting in 2020 and also for what-if scenarios with injection starting in the year 2000 or 2010.

The results of the injection scenarios and what-if scenarios, with or without continued production are not conclusive about the net benefit of fluid injection. The injection scenarios introduced in Section 8 of report B indicate that the combination of N2 injection at the Central-East well cluster results in the lowest seismicity rates, without completely stopping production in the other clusters. However, relevant parameters were not varied and injection and production rate and locations were not explored. Calibration of model production and injection rates to realistic volumes should be performed.

In case continued production is considered, with or without injection, the study should be adapted to the reality: availability of wells, introducing realistic scenarios for production and injection. Some starting points could be taken into account, like possibility of dilution of production gas, preventing of injection near critical faults. A feasibility study seems urgent, given the current critical security of supply and extreme energy prices that lead to stress and disruption. The Netherlands and Europe were used to unobstructed availability of cheap natural gas. The production limitation in Groningen amplifies the tension on the energy market. Current high gas prices have 3 effects on the feasibility of injection scenarios:

- The investment that are connected to preparation, building and maintaining injection are paid back quickly in case of high gas prices
- Fluid injection could secure access to cheap gas in the long term and within the accepted norm of collapse (LPR<0,001%/year)
- Lower energy prices have economic and social benefits; the higher the price of import gas, the higher the benefit of local production

It is suggested, apart from scenario 1 that is the current closing scenario, to perform a feasibility study for 2 injection scenarios:

- Injection scenario 2, based on collapse criterium LPR<0,001%/year, starting of fluid injection in 2026. Volumes 4 to 8 bcm (gas year 2022-2023), decreasing to 3 to 6 bcm (2025-2026 and later). Injection volume close to production volume after 2026: 3 to 6 bcm
- Injection scenario 2, based on guaranteeing availability of cheap gas and mitigate stress and disruption due to high prices. Fluid injection starting in 2025. Volumes 20 bcm (gas year 2022-2023), decreasing to 5 to 10 bcm (2023-2024) and 3 to 6 bcm (2024-2025 and later). Injection volume close to production volume after 2026: 3 to 6 bcm. In this scenario, the standard for risk of collapse for a number of buildings within the current reinforcement program, can be temporarily exceeded

At this moment, it is not possible to take decisions about continued production, because of a number of factors:

1. Geopolitical instability and vulnerability of security of supply of energy, which both are critical
2. Stressed and variable energy market

3. Insufficient knowledge of the positive effect of production limitation/ production stop on stress-related health problems and disruption in Groningen
4. Insufficient knowledge of the negative effect of production limitation/ production stop on affordability of energy, stress-related health problems and disruption in the Netherlands (and Europe)
5. Insufficient knowledge of fluid injection as a measure to produce the available gas in Groningen safely and economically
6. Scenarios, based on continued gas production, were not tested with the public SRDA. In the past, the HRA's by NAM reported various scenarios with continued gas production until 2030, and they indicate that the risk is hardly dependent on current and future production. However, these past analyses have to be updated.
7. There is contradicting and insufficient publicly available information about actual risk of collapse of the current building stock

It is advised to get as much clarity as possible regarding the uncertainties that are described above.

5. Answering the research questions

From the Groningen gas field, a lot of information is available of the geology, faults, pressure, gas production and seismicity. However, in detail still a lot of information lacks and can't be integrated into a model. Important parameters like permeability of matrix and faults, and strength of faults, can vary in space, both horizontally as well as vertically, and it is not possible to capture this reliably.
It was not possible to make a relevant, reliable and working 3D model of the region of interest, being the Loppersum area, where in practice all higher Magnitude earthquakes have taken place in a 10x10 km^2 area. The main results of the study consist of 2D analyses that were compared with observations. In general, this gives another limitation: 2D analyses can't capture the vertical component. The thickness of the field varies significantly over the gas field. Also, the compaction of the field is much larger in the middle of the field. The stresses over faults are higher in case of higher compaction and differential pressure and compaction. The vertical component leads to a concentration of seismicity in the area with the largest compaction. Any deviation between the simulation results and observations can be partly explained by this limitation of the model, being 2D instead of 3D. Technically, it appeared to be not feasible to build a working 3D model of the required size.

In general, it must be concluded that the KEM24 study must be seen as a first step to develop a method to simulate injection scenarios and calculate net positive effects, if any. Also, the study was not started as a feasibility study for the Groningen reservoir, but as a proof of concept-study. Several starting points were theoretical, like availability of wells and possible injection rates. The answers to the research questions must be seen in this light, and there is still a lot uncertain that has to be studied to test injection modelling as a tool, and possible injection scenarios for Groningen.

The research questions can be answered as follows:

1. *What are possible injection scenarios for pressure maintenance during production and for minimising the pressure difference across the field once production has stopped?*
    a. During significant additional production, Groningen gas field: it is not yet clear if injection would have net benefit and what rate would be optimal. In the current study, the production and injection volumes have not been calibrated. Results indicate that:
        i. No injection should be carried out in/near Loppersum area because of the stress-criticality of the fault system.
        ii. No injection should be carried out near producing wells, to avoid sharp pressure variations
        iii. Injection scenario would have to be adapted to the starting point regarding dilution of the production gas and feasibility of injection and production rates and locations. As an example, injection was simulated in the central east side of the field; probably the tested injection rate was chosen conservatively high, lower rates of pressure rise at the injection well should be tested further;
    b. After production, Groningen gas field. It seems that in case of complete production stop, fluid injection will not have benefit regarding seismicity. Results indicate that

        i. injection does not lead to an (significant) overall reduction of seismicity in short term.
        ii. Shut-in scenarios without injection show a sharp reduction of seismicity after shut-in.
        iii. Some injection scenarios show no significant increase of seismicity in the 2D simulations and

2. *What are the reservoir stresses and pressures for various fluid injection scenarios (defined in question 1) around wells and over the entire gas field?*
    a. Stresses around wells, see WP3 and WP4 for preliminary results; adaption of scenarios to practical feasibility is obliged. The 2D model has to be calibrated based on volume-pressure ratios
    b. Stresses over the entire gas field: see WP2; take into account that the fit without injection is not satisfying, and the effect of injection is highly dependent on the injection rate, number of wells and locations. Sensitivity study is necessary to test dependence of results for variation of various parameters.
3. *How to adapt the Groningen seismic module for injection for pressure increase as well as pressure decrease?*
    a. This question can't be answered, however, the team is available for discussion with the client and TNO.
4. *What is the effect of fluid injection on the overall seismic risk?*
    a. The effect is strongly dependent on type of injection, injection rate, location. In general, for Groningen, in case of (nearly) stopping of production, fluid injection seems to be not necessary or preferable. However, the effect of very limited injection is not studied yet. In theory, an even increase of gas pressure decreases stresses on the long term.
    b. In case of significant additional production from the Groningen field, additional study, including sensitivity tests, are necessary to determine whether fluid injection is beneficial and/or necessary.
5. *What is the effect of fluid injection on seismicity near injection wells?*
    a. The study was performed with high injection rates, and near injection wells no significant seismicity was predicted. Further study is recommended to minimize possible negative effects.
6. *What is the most optimal configuration of injection wells?*
    a. In theory: see answer 1a. In theory, there are multiple options. During the study, multiple models were developed and multiple injection locations were tested. However, the models used did not give sufficient fit with observed pressure decrease and seismicity. Eventually, the central east cluster was used for fluid injection because it is in the vicinity of the area with the greatest pressure decrease. Also, injection near Loppersum or in the southern production clusters is not preferred. However, it is possible to study alternative injection locations.
    b. In practice; any considered continued production should be preceded by the collection of practical starting points. It seems possible to make use of existing production wells, if available. However, many production locations are in the process of permanent

closure, which limits the possibilities. It is advised, in the current situation, not to dismantle the production wells in the currently available 11 clusters in central east and southern clusters. A feasibility study could indicate that alternative injection locations would be preferable, making the drilling of new injection locations necessary.

7. *What is the overall effect of fluid injection on seismicity and what are the recommendations for the Groningen HRA model?*
    a. The effect of fluid injecting can be positive, however this could not yet be proven with this study. Additional study is necessary, with varying location of injection, rate of injection, duration of injection, parameters. In general, it is recommended to inject and produce carefully, in a moderate rate, to prevent instability of near-field faults by pressure increase effect and to prevent instability of far-field faults due to the poro-elastic triggering effect. If dilution of production gas is acceptable, production could be continued for multiple decades.
    b. Regarding hazard and risk analyses based on seismic risk: it is likely that the methodology that was developed in the past, gives a limited insight to weigh the overall effects of gas production and injection. Production limitation during the past 10 years, combined with the yearly increase of technical knowledge, ultimately, has placed us in a situation where the risk of collapse meets the standard. In the same period, the stress-related health problems of the residents have risen dramatically. There is no indication that the complete closure of the field will have a positive effect on the indirect risk, however, for the authorities these are arguments to stop the production. The current problems of lack of cheap gas are amplified by the closure of the Groningen gas field. Given the changed circumstances and the fact that further limitation of the production not only is beneficial, an integral evaluation of direct and indirect risk could be considered. The reliability of the weighing of interests and choosing the most effective measures could benefit from integration of emotional effects in the HRA: the development of knowledge would be guaranteed and emotional risks could be better evaluated and decreased.
    c. Best fluids to be used: 3 options are considered: water, N_2 and CO_2, with the following results:
        i. water is not advised because it will not be able to increase pressure at distance from injection wells and the cooling effect can cause seismicity (which is studied in KEM15).
        ii. CO_2 dissolves much better in water than N_2, which makes N_2 much more effective to increase pressure with a similar quantity of gas.
        iii. N_2 seems the best option, also because the present gas also contains N_2 and in case of dilution of production gas, mixing the diluted production gas with high calorie gas would make original Groningen gas quality.

Report A

1020-169309.R01 V01

30 September 2022

KEM-24 Effect of pressure maintenance by fluid injection on seismic risk

Umbrella report

Report B

KEM24 Final report

30 September 2022

KEM-24 WP0 to WP4 Effect of pressure maintenance by fluid injection on seismic risk

Simulation of reservoir depletion and injection induced seismic events using hydro-mechanical coupled Particle Flow Code 2D modelling on Groningen reservoir geological fault model; including external review

Report C

172147-REP01-FNV_SHA_KEM24 V03

30 September 2022

KEM-24 WP5 Effect of pressure maintenance by fluid injection on seismic risk

Hazard analysis