Methodology

Optimisation of the Production Distribution over the Groningen field to reduce Seismicity

29 May 2017

1 Contents

1 Management Summary

As part of the Instemmingsbesluit Winningsplan 2016 (Article 3), NAM is asked to investigate whether an alternative distribution of gas production across the Groningen field can reduce the seismic hazard or risk. To be able to comply with this requirement, NAM has prepared and is executing a study program. These studies include an upgrade of the Groningen field reservoir model, to better assess future developments in reservoir pressure changes, reservoir compaction, the resulting seismic event rate, hazard and risk. These calculations of seismicity, hazard and risk are implemented in line with the modelling work done for NAM's Hazard and Risk Assessments (Ref. 3 and 4). Consequently, the model is based on a statistical analysis of historical earthquakes in the Groningen area, representing the event rate through a Poisson Point Process.

A mathematical optimizer can evaluate different production offtake scenarios for event rate, hazard and/or risk. By including either one of those outputs in an objective function, the optimizer can find the minimized solution through various iterations in a control loop. The validity of the results depends on the predictive capability of the model. Therefore, it is important that the model is based on a good history match, both temporal and areal.

For reasons of speed and simplicity, the approach currently explored is to exclude the surface network model from the optimizer. But the production distribution outcome from the optimizer should be executable in the field, within all the operational constraints. Various simplified operational constraints can be applied in the optimization tool, and the ultimate result will be validated in dedicated runs including the surface network, and by careful review in the operations team.

The optimisation will be bounded by both the physical limitations of the Groningen production system and the regulatory constraints imposed in the Instemmingsbesluit. To allow this process to explore the full optimisation space, both scenarios where regulatory constraints and the physical limitations of the production system are relaxed, will be tested. Insights gained from these optimisation scenarios will be used to challenge both operational and externally imposed constraints.

2 Introduction

2.1 Instemmingsbesluit - Winningsplan 2016

The Instemmingsbesluit Winningsplan 2016 (Article 3), requires NAM to perform an optimisation of the areal distribution of the gas production from the field, with the objective to reduce seismic risk. Article 3 mentions three deliverables with three corresponding milestone dates (Figure 2-1):

> *The Nederlandse Aardolie Maatschappij BV investigates whether an alternative distribution of the production over all regions of the field lead to a lower seismic hazard or seismic risk and submits a report to the Minister of Economic Affairs latest 1st November 2017, to the satisfaction of the inspector of Mines. In support the Nederlandse Aardolie Maatschappij BV will latest 1st February 2017 present a plan of approach to the inspector of Mines. Latest 1sr September 2017 the Nederlandse Aardolie Maatschappij BV will submit a draft report for review by the inspector of Mines. An alternative distribution of the production will not be implemented before it is to the satisfaction of the inspector of Mines.*

Artikel 3
2. De Nederlandse Aardolie Maatschappij B.V. onderzoekt of een alternatieve verdeling van de productie over alle regio's tot een lagere seismische dreiging of seismisch risico leidt en brengt daarover uiterlijk 1 november 2017, ten genoegen van de inspecteur-generaal der mijnen, een rapport uit aan de Minister van Economische Zaken. Hiertoe dient de Nederlandse Aardolie Maatschappij B.V. uiterlijk op 1 februari 2017 een plan van aanpak in bij de inspecteur-generaal der mijnen. Uiterlijk op 1 september 2017 dient de Nederlandse Aardolie Maatschappij B.V. ter beoordeling van de inspecteur der mijnen een concept-rapportage in. Een eventuele alternatieve productieverdeling wordt niet ingevoerd voordat deze ten genoegen van de inspecteur-generaal der mijnen is.

Figure 2-1 Article 3.2 from the "Instemmingsbesluit Winningsplan Groningenveld".

In Article 5.1 an additional milestone date was given to supply a Methodology of Production Optimization by 1 June 2017 (presented as per this document):

> *A methodology by which an optimal distribution of production with respect to seismic risk will be estimated*

Artikel 5
1. De Nederlandse Aardolie Maatschappij B.V. dient uiterlijk op 1 juni 2017 bij de Minister van Economische Zaken een nieuw Meet- en regelprotocol in, waarin tot genoegen van de inspecteur-generaal der mijnen wordt beschreven:
a. het risicobeheerssysteem waarmee het seismisch risico en de schade zo veel mogelijk worden beperkt;
b. de beslis- en escalatiestructuur;
c. de inpassing in het bedrijfsmilieuzorgsysteem (ISO 14001);
d. de halfjaarlijkse publicatie van meet- en monitoringsresultaten;
e. de methodiek waarmee een optimale verdeling van de productie uit oogpunt van seismisch risico wordt bepaald.

Figure 2-2 Article 5.1 from the "Instemmingsbesluit Winningsplan Groningenveld".

2.2 SodM feedback on the Plan of Approach

On 1st February, NAM shared with SodM a "Plan of Approach for the Optimisation of the Production Distribution over the Groningen field to reduce Seismicity" outlining the study plan to develop the capability to perform this optimisation and carry out the actual optimisation. In the letter of 6th April, SodM commented (Figure 2-3):

> *In your plan of action, you describe a study plan to arrive at a detailed methodology for risk-oriented optimization of production in the Groningen field. After analysis, SodM concludes that the proposed approach is in line with the latest scientific insights regarding performing a production optimization.*

In uw plan van aanpak beschrijft u een studieplan om te komen tot een uitgewerkte methode voor het risicogericht optimaliseren van de productie in het Groningenveld. Na analyse concludeert SodM dat de voorgestelde aanpak in lijn is met de laatste wetenschappelijke inzichten ten aanzien van het uitvoeren van een productie optimalisatie.

Figure 2-3 Fragment from letter of SodM to NAM of 6 April 2017 (SodM reference 17047942)

Furthermore, SodM made two additional comments (Figure 2-4):

- Reference to comments on the seismological model also voiced earlier for instance in the advice to the Minister following Winningsplan 2016.
- The scope of the optimization of production is bounded by the capability of the production system. NAM is asked to investigate which adjustments to the production system could increase flexibility for the optimization and lead to further reduction in the seismic hazard or risk. This is addressed in (Chapter 3).

U stelt voor om het bestaande op compactie gebaseerde seismologische model te gebruiken als onderdeel van het systeem om de productieoptimalisatie te berekenen. Ik heb begrip voor het feit dat het ontwikkelen van een nieuw of verbeterd seismologisch model op korte termijn niet mogelijk is omdat de wetenschappelijke inzichten op dit gebied momenteel tekort schieten. Desalniettemin voorzie ik wel dat daardoor alle in eerdere adviezen naar voren gebrachte beperkingen van dit seismologisch model ook zullen doorwerken in de resultaten van een risicogestuurde geoptimaliseerde productieverdeling.

Ten tweede stelt u voor de huidige operationele en infrastructurele beperkingen van het bovengrondse systeem van pijpleidingen, overslagen, etc als gegeven mee te nemen in de methode. Ik vraag u te onderzoeken welke aanpassingen in het bovengrondse systeem kunnen leiden tot een verdere verlaging van de seismische dreiging of seismisch risico. en deze op te nemen in de methode en uitwerking daarvan.

Figure 2-4 Fragments from letter of SodM to NAM of 6 April 2017 (SodM reference 17047942)

2.3 Constraints on Production

The areal distribution over the field of production off-take from the field is to be optimised to minimise seismicity (Article 3.2). The optimisation space is limited both by constraints imposed in the Instemmingsbesluit, and by constraints in the production system.

2.3.1 Regulatory Constraints in the Instemmingsbesluit

The “Instemmingsbesluit – Winningsplan 2016” contains several articles (articles 2, 3 and 4) impacting the production of gas from the Groningen Field:

Article 2.1	Sets a Field Cap of 24 Bcm/gas-year,
Article 2.2	Additional volume depending on degree-days up to 6 Bcm/gas-year (with appendix on calculation of degree –days),
Article 2.3	Additional volume depending on technical issues (transport restriction, failure GTS system and hi-cal composition) up to 1.5 Bcm/gas-year,
Article 2.4	Administration of additional volume failure GTS system,
Article 2.5	Administration of additional volume depending on degree-days
Article 3.1	Regional off-take from the field pro-rated to the regional caps,
Article 3.3	Five Clusters around Loppersum reduced to minimally required volumes,
Article 4.1	Reduction of seasonal variations and monthly variations; temporal flat production,
Article 4.2	Introduction of production changes.

The regional caps in Article 3.1 refer back to the areal offtake distribution restrictions as imposed on 30/1/2015. In summary[1]:

LOPPZ[2] clusters:	Stand-by rates for security of supply only (to a maximum of 3 Bcm[3])
Eemskanaal cluster:	2.0 Bcm per year,
South-West clusters:	9.9 Bcm per year,
East clusters:	24.5 Bcm per year.

Note that although the sum of the regional caps exceeds the total field production cap of 24 N Bcm/year, the requirement to maintain a pro-rated regional offtake leaves limited operational flexibility.

[1] All caps are in 100% Wellhead N.m3
[2] The LOPPZ clusters are located in the earthquake prone Loppersum area, and constitute of **L**eermens, **O**verschild, De **P**aauwen, Ten **P**ost and ‘t **Z**andt
[3] NAM tries to minimize this volume, in 2016 1.0 Bcm was used.

2.3.2 Operational Constraints

In addition to the regulatory constraints, there are the technical limitations on the Groningen production system. On a high level, the following components make up the Groningen production system (Figure 2-5):

Clusters — There are currently 20 production clusters, and two satellites (Froombosch is a tie-back to Slochteren, and Sappemeer is a tie-back to Tusschenklappen). The clusters (and satellites) have in average 12 wells from which gas is produced, one compressor to compress the gas and process equipment to bring the gas to gas sale specification. The satellites are not equipped with a compressor and process equipment.

- **Wells** — From some 250 wells gas is produced in the field. Well capacity is limited and depends on the (declining) reservoir pressure.
- **Compressors** — The compression capacity is limited by the power of the compression drivers and the compressor operating envelope.
- **Gas process** — Produced gas is brought to gas quality as stipulated in the Gaslaw (Regeling van de Minister van Economische Zaken van 11 juli 2014, nr. WJZ/13196684, tot vaststelling van regels voor de gaskwaliteit (Regeling gaskwaliteit) making use of Jules Thompson effect.

Ring System — To evacuate the produced gas, clusters are connected to NAM's gas pipeline grid commonly referred to as the 'Groningen ring' but consists of a more complicated configuration and consists of 136 valves and 59 different sections of pipeline (total 162 km). Via the pipeline system gas is distributed from the production clusters over the custody transfer stations.

Custody Transfer Station — By means of 7 custody transfer stations, at which gas quality and quantity is measured, the Groningen ring is connected to the GasUnie pipeline grid. Every transfer station feeds one GTS pipeline and could be considered as the starting point of a pipeline. Offtake per custody transfer station is controlled by GTS by manipulating pressure in the GasUnie pipelines.

Underground Gas Storage — Working-volume produced from the Norg UGS in the production season is reinjected in the injection season. The UGS Norg is connected to the Groningen ring with a dedicated pipeline (NorGron pipeline). By controlling the pressure in this pipeline the efficiency of working-volume injection is controlled. This involves the need for an increased pressure and high gas demand in the south-western part of the Groningen ring system, where the tie-in to the Norg-Groningen pipeline is situated.

The fraction of the production capacity of this total production system that is available at any point in time is governed by the availability of the system. Scheduled periods for maintenance and unscheduled stops caused by failures impact availability.
The Groningen production system cannot be seen in isolation, as it is pivotally linked to the functioning of the gas supply system in the Netherlands (and parts of Belgium, France and Germany). Operational changes (can) have immediate impact on the transport system operation.

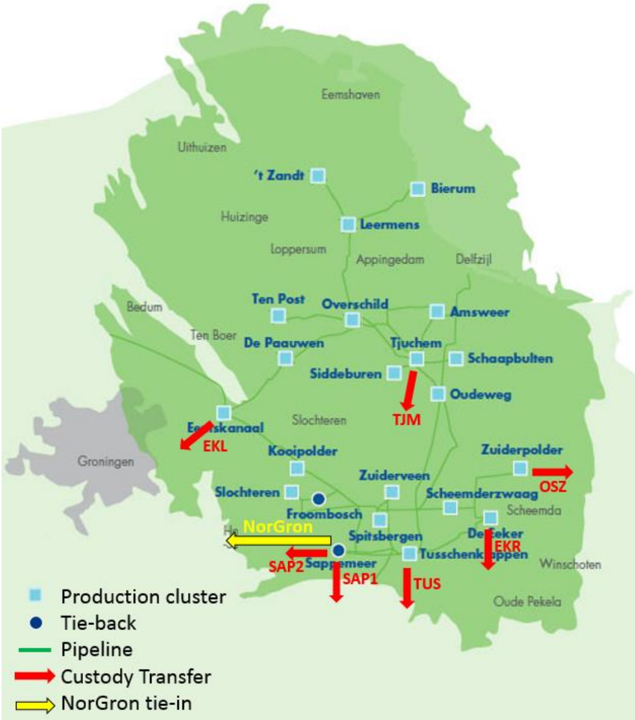

Figure 2-5 Groningen production system

2.3.3 Reflection of the constraints in the optimisation

The optimisation space, within which the optimisation process can establish the minimal seismic production solution, is a function of the boundary conditions (section 5.4.3). For an optimisation with respect to the status quo, the boundary conditions should reflect both the regulatory constraints and the operational constraints. However, to establish a truly optimized result, relaxation of some of these regulatory and operational constraints should be investigated. This will create a larger optimisation space by relaxing constraints in the “Instemmingsbesluit” and adjustments to the production system to extend the capability of finding a risk optimized distribution of the production over the production clusters. The operational constraints and options for adjustments in the surface infrastructure to further reduce the seismic hazard or risk will be discussed in Chapter 3.

2.3.4 Scope for change in surface facilities that may lead to further reduction in seismic hazard/risk

For the optimiser, each production cluster represents a control, an offtake point from which it can choose to produce more or less gas (within certain constraints and boundary conditions). Hence the optimiser can establish the maximum reduction in seismicity if it has maximum ability to increase or reduce production from a cluster. Operationally the volume of gas that can be withdrawn from each production cluster is bound by a maximum and a minimum:

Absolute minimum

- The absolute minimum production from a cluster is zero (full shut-in).

Minimum for security of supply

If NAM is required to keep clusters online for security of supply, the clusters have a minimum flow-rate.

- Cluster
    - Well capacity
      The wells have a minimum flow-rate due to lift die-out. This rate is a function of the reservoir pressure in the vicinity of the well. Typically the minimum well rates are not constraining the cluster minimum rate, as individual wells can be switched off.
    - Cluster minimum flow
      The cluster minimum rate is constraint by gas processing limitations, and depends on the ambient temperature; the colder it gets, the higher the required minimum flow.
    - Compressor
      The compressor has operating envelope (compressor performance curve) in which it can be operated, and has a recycle modus. Therefor the compressor does not affect the minimum flow of a cluster.
- Custody Transfer Station
  Each Custody Transfer Station (OV) has a minimum flow-rate at which it can operate. If there is a requirement to supply areas across multiple OV, potentially an OV can be shut-in and the gas re-distributed over the GTS gas distribution network.

Maximum rate

- Cluster
    - Well capacity
      The well capacity is a function of the manifold pressure, reservoir pressure, completion and tubing size. Before the production caps, those were typically optimised for maximum capacity. Hence the remaining scope for optimisation is rather limited. On a few individual wells there is still scope to change-out the tubing to higher diameter tubing, or re-perforation jobs, but the capacity gains are limited.
    - Compressor
      The compressor typically determines the manifold pressure. The lower the manifold pressure, the higher the well capacity, but the lower the compressor throughput. This relationship is governed by the compressor performance curves (which are also a function of ambient temperature).
- Availability
  Availability is the degree to which the gas production from the system can be relied upon and committed. It can be split in planned and unplanned shutdowns (reliability).
- GTS requirements
  By means of 7 custody transfer stations (OV) the Groningen ring is connected to the Gasunie pipeline grid, which is operated by GTS. Every OV is connected to one GTS pipeline feeding a dedicated part of the gas market. An OV could be considered as the starting point of a GTS pipeline. Offtake per OV is controlled by GTS through manipulation of the pipeline pressure. The flow distribution requirements as set and controlled by GTS across the various OV's will determine the pressure drop across the ring for any production cluster. At worst, this could

induce up to an additional 10 bar back-pressure to a cluster, and a subsequent reduction in capacity.

- Ring system
  The 20 clusters are connected to NAM's gas pipeline grid which is referred to as the 'Groningen ring', but has actually a more complicated configuration and consists of 136 valves and 59 different sections of pipeline (total 162 km). The pipeline system has been designed and constructed in the 1960 and operated since then to deliver maximum capacity at highest reliability. (Automatic or manual) manipulation of valves allows NAM to change the ring configuration allowing NAM to by-pass pipeline sections and/or OV's. However, every manipulation in the Groningen ring does impact GTS operations, and might influence the gas supply in the Netherlands (and parts of Germany, Belgium and France).
  The Southern part of the 'Groningen ring' was constructed with a double pipeline, which allows for operational flexibility with respect to filling the Norg UGS in summer (Figure 3-4). The northern clusters are connected with single pipelines, which leaves less flexibility. Given that the design, permitting and commissioning of a pipeline is typically a process of multiple years, the pipeline network is considered a given within the timespan of this optimization effort. Once the optimization effort provides more directionality towards redistribution of production, the existing setup of pressure control valves can be investigated to evaluate if there are scenarios where an extended functionality can contribute to reducing the seismic hazard or risk.

2.3.5 Interplay Meet- en Regelprotocol and optimisation.

The Meet- en Regelprotocol[4] describes a three-tier system for control over the seismicity of the Groningen field. Relevant parameters are monitored in the field. For each of the five parameters monitored in the field as part of the Meet- en Regelprotocol, there are three tiers of threshold values defined. When a (combination of) threshold value(s) is exceeded due to a seismic event, this may trigger actions in the field, depending on the (combination and) tier of exceedance. In total 5 parameters are monitored:

- Three parameters can be exceeded by a single event; highest measured PGA and PGV and occurrence of DS2
- One can be tracked over times as an indication for the seismicity over the full field; number of earthquakes with magnitude larger than M = 1.5 during the previous 12 months.
- One can be tracked over times as an indication for the seismically most active area; earthquake density (M >= 1.0) over the previous 12 months.

Especially this last parameter is important for an optimisation of production with respect to risk. The optimisation with respect to risk will preferentially move the hazard to areas of low exposure. It will for instance preferentially tolerate large hazard below the Eems estuary and other areas where relatively population density is low or buildings are relatively strong (able to withstand seismic loading). The optimisation could therefore cause a higher seismic rate and/or a higher chance of exceedance of a threshold value of the earthquake density over the previous 12 months in a low exposure area (whilst still reducing overall risk).

[4] The Meet- en Regelprotocol is the Measurement and Control Protocol for the Groningen field.

2.4 Optimisation of Distribution Production in Winningsplan 2016

As part of the Winningsplan 2016 submission, NAM investigated an alternative expert judgement optimization of the offtake across the various production clusters, in order to minimize the seismic risk (Ref. 5, Technical Addendum to the Winningsplan Groningen 2016, Chapter 5). As part of this work an observation was made with respect to the field offtake as dictated by the regulatory constraints as of November 2015. The predicted risk associated with this offtake showed that the area of highest risk roughly coincides with the band Bedum – Loppersum – Appingendam – Delfzijl, and that in the North-East of the field there is an area which is poorly drained, but imposes more limited risk (Ref. 5 and Figure 2-7). A production distribution scenario was formulated to increase offtake from this area (North-East of the field), and decrease the offtake from the Eemskanaal cluster (located towards Groningen city), while keeping the same offtake from the full field.

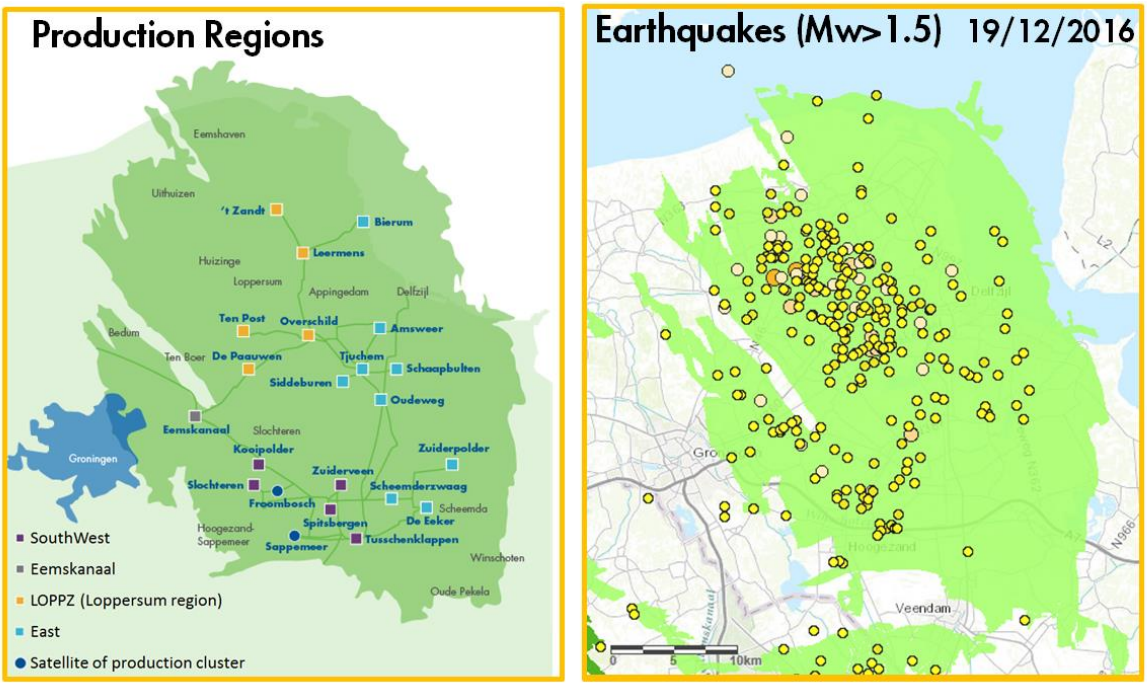

Figure 2-6 Production regions and earthquakes to date (Mw>1.5)

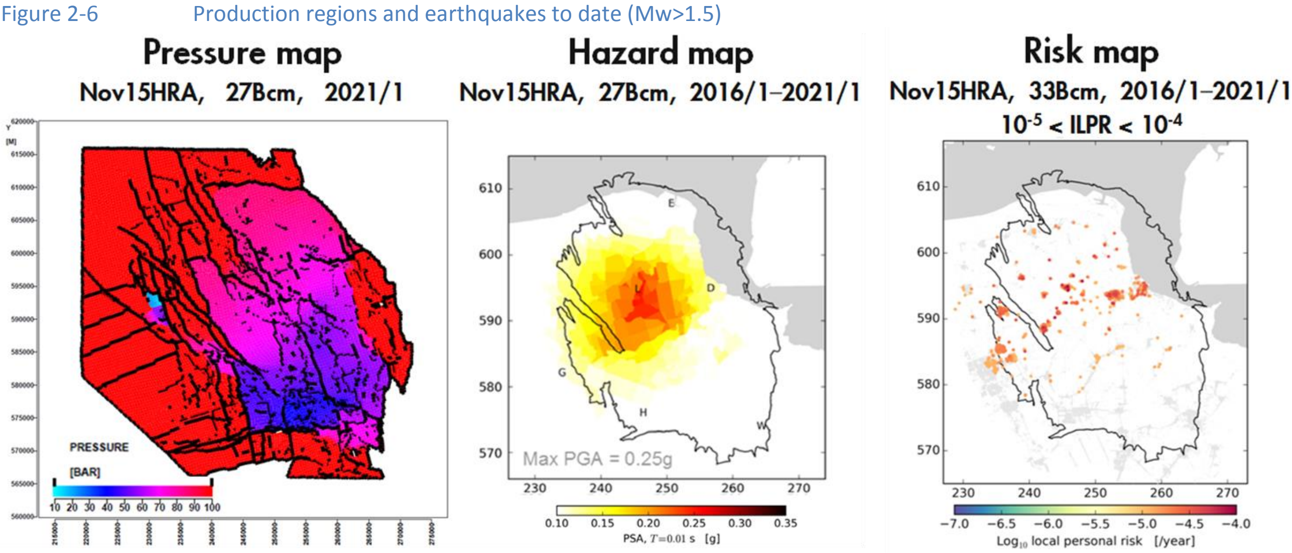

Figure 2-7 Combined visualization showing 1) the expected reservoir pressure distribution across the field in 2021 as per the Nov2015HRA forecast at 27Bcm/y ; 2) the associated Hazard map ; 3) the Risk map at 33Bcm annual offtake

This distribution was not chosen as the base case production scenario in the Winningsplan 2016, because the effect of the optimisation on seismicity was assessed to be relatively small.

2.5 Model driven optimization

To comply with the Ministerial request for optimisation of the areal distribution of gas production (Instemmingsbesluit Art. 3), NAM has embarked on a model driven optimization effort. The existing reservoir simulation model (which is calibrated in a history matching workflow, chapter 3) calculates the reservoir pressure response for a given production offtake scenario. Furthermore, this model calculates reservoir compaction assuming a linear model, which in turn is used to history match on subsidence. Conceptually the objective of the study is to extend this reservoir model to allow calculation of (a proxy for) earthquake activity, hazard and ultimately risk. As such this allows for inclusion of the model in a control loop, which can be steered towards minimizing earthquake activity and/or risk.

Around November 2015 Shell's Quantitative Reservoir Management team in Rijswijk was engaged to commence development of this mathematical optimization of areal production offtake distribution in order to minimize the seismic hazard and the seismic risk. By close corporation with the NAM asset team, this tool will be constrained such that it can identify a field offtake distribution which can actually be operationally realized, while minimizing seismic risk.

The envisaged timeframe for the optimization is 5 years. After that, the understanding of the seismicity and associated risk is expected to have advanced further, in combination with development of risk reduction measures like house inspections and the strengthening of buildings.

3 Operational limitations

The Groningen production system was largely designed and constructed in the 1960's. The design was focussed on the highest capacity and reliability during periods of high demand (winter), and did not anticipate any operational requirements with respect to management of production induced seismicity. In this chapter the components making up the Groningen system are described, along with recent changes in operating philosophy resulting from the requirement to manage induced seismicity, providing background for potential further adjustments to reduce seismic hazard and/or risk.

3.1 Link to the gas market

The Groningen production system is part of an integrated system in Northwest Europe that supplies gas into a market of highly variable demand (Figure 3-1). Gas is transferred from NAM's Groningen system to the system of GasUnie Transport Services (GTS) across seven "Overslagen" (custody transfer stations, or OV's). Offtake distribution per OV is controlled by GTS by manipulation of the pipeline pressure and taking into account the actual market demand. Given that the entire Groningen quality gas market has evolved around the Groningen field, the field forms the starting point for the GTS infrastructure and sits at a cross-roads of the GTS pipeline network. Consequently, any change in operating the Groningen ring potentially impacts GTS operations and its ability to re-distribute gas within its own existing network. Traditionally GTS relied on Groningen ring to supply gas into its various pipeline networks towards the different gas markets. On a high level, there are three main gas markets:

- Towards West Netherlands
- Towards Germany
- Towards South Netherlands/Germany/Belgium/France

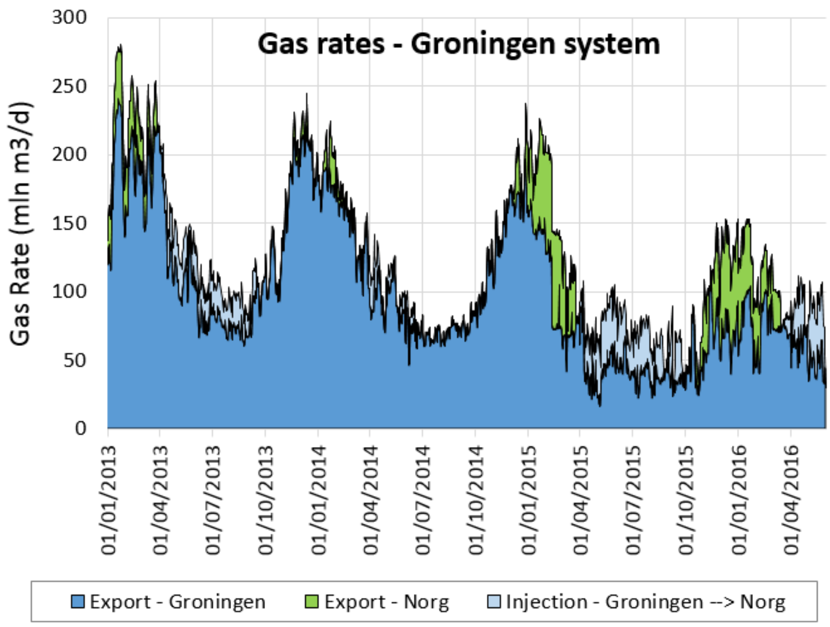

Figure 3-1 Production fluctuations over the period from 2013

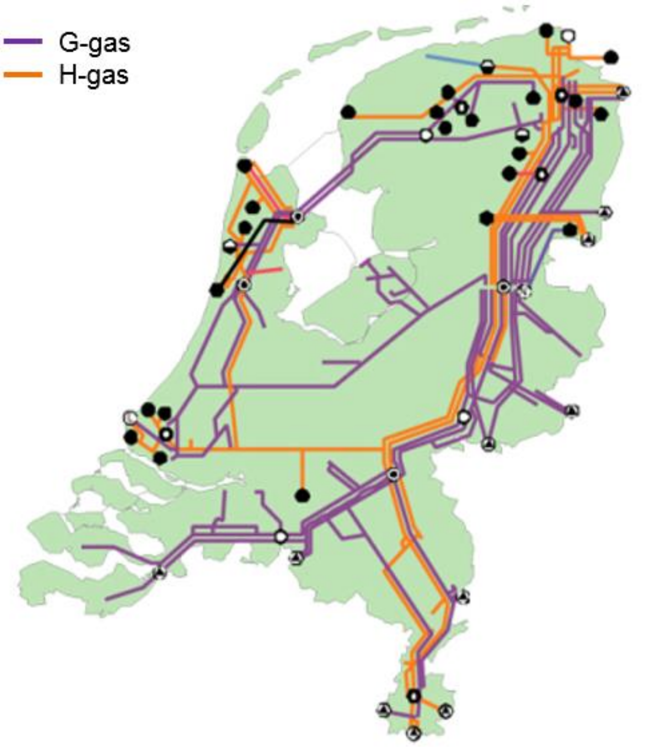

Figure 3-2 Gasunie Transport Solutions pipeline grid in the Netherlands. All L-gas pipelines originate from the Groningen field.

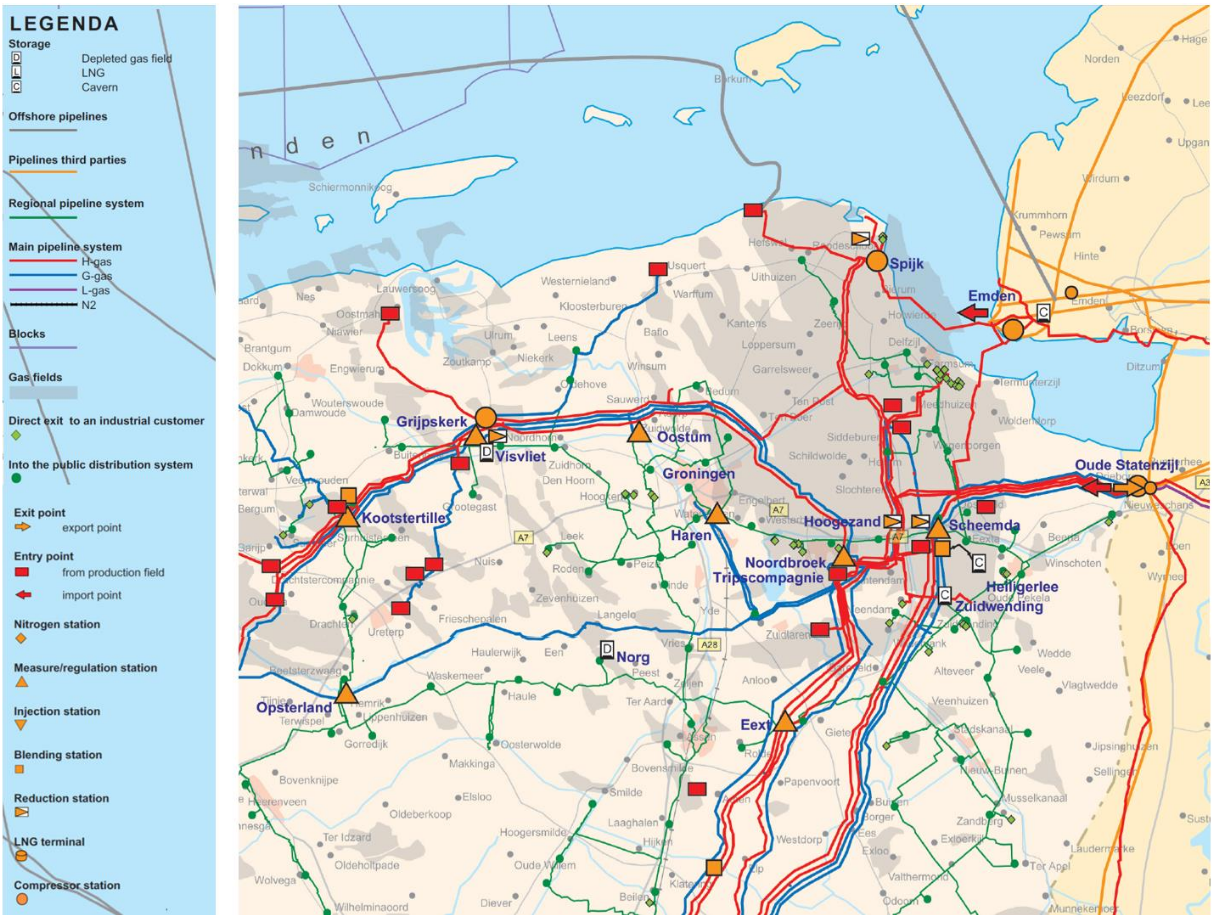

Figure 3-3 A closer look at the Gasunie Transport Solutions pipeline grid around Groningen (source: GTS).

Based on the Grid Connection Agreement between NAM and GTS, gas leaving the Groningen ring at the OV's into the GTS grid needs to meet the following specifications[5]:

- Pressure specification between 55 and 65 bar
- Wobbe Index between 43.46 to 44.41 MJ/Nm^3.
- Contaminant Limitations.

The custody transfer stations at Oude Statenzijl (OSZ) serves the German market and is operated by GTS. As GTS is not able to manipulate the flow from OSZ, it relies on NAM to supply at the higher end of the contractual pressure window to ensure delivery to the North-German gas market downstream of OSZ.

3.2 Ring System and Underground Gas Storage

The Groningen production clusters and the custody transfer stations (OV's) are interconnected by a pipeline network that roughly makes up a ring. This setup allows for a very high operational flexibility, as any cluster can ultimately flow over any OV. Due to the mutual distances some configurations are more practical than others, as there may be up to 10 bar pressure drop involved.

Due to the 'Instemmingsbesluit' requiring to keep Groningen production flat (section 2.3.1), there is an increased utilization of/dependence on the Norg Underground Gas Storage (Figure 3-1). Norg is produced in winter, and re-filled with Groningen gas in summer. Thus Norg acts as a capacity provider, which can be used to keep the demand on the Groningen field much more constant throughout the seasons.

It was foreseen the UGS Norg would be filled via the dedicated NorGron pipeline (OV Sap to Norg) using the central located production clusters. However with the restriction on most of these clusters, taking into account the most flexible utilisation of the Groningen ring, the UGS is mainly filled with Southern clusters, making use of splitting the ring in a high pressure and low pressure section, and a number of flow control valves. Alternative options to feed UGS Norg are feasible but would require shut-in of one or more OV and consequently impacting GTS operation.

In case GTS would be able to accommodate custody transfer over only a limited number of OV's, relatively simple set-ups of the ring split would be possible (with a high operational flexibility). To date, more complicated splits are used (which provide less operational flexibility), Figure 3-4.

[5] These specifications are described in Article 11 and 12 of the Gaswet

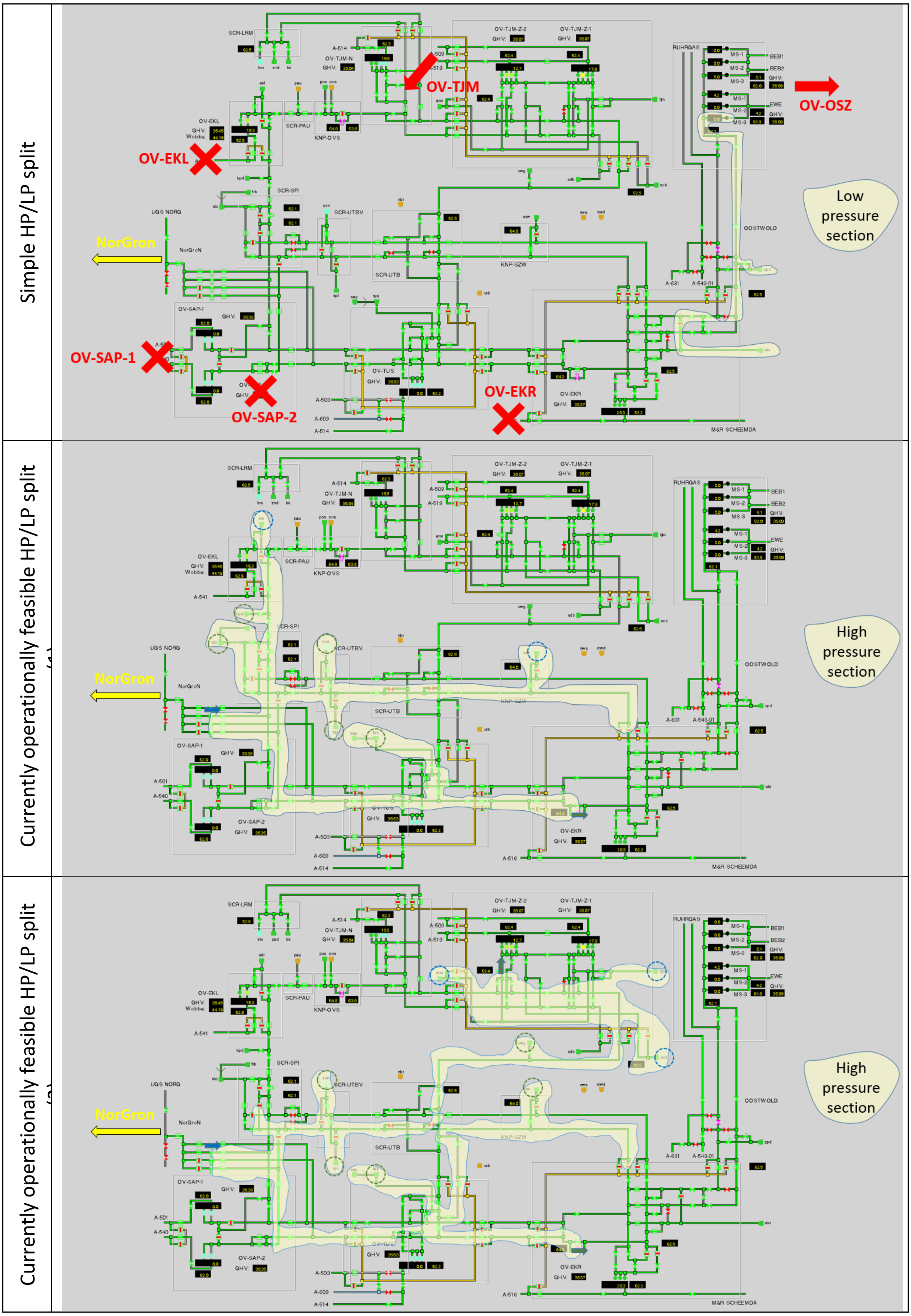

Figure 3-4 HP/LP ring split configurations

3.3 Gas Production Wells

Due to the excellent reservoir quality, typically the Groningen wells are highly productive. However, with depleting reservoir pressure the well capacities are steadily declining.

3.4 Clusters and Compressors

The current Groningen production system comprises 20 production clusters, which are all on compression. All clusters are on first stage compression (B-bundle cartridge[6]), with the exception of:

- Schaapbulten (SCB), 2nd stage
- Eemskanaal (EKL), 1st stage with an A-bundle cartridge

The 22 clusters include two tie-backs (no dedicated compressor):

- Froombosch (FRB) is a tie-back to Slochteren (SLO)
- Sappemeer (SAP) is a tie-back to Tusschenklappen (TUS)

A schematic representation of the main components making up a production cluster are given in Figure 3-5. Figure 3-6 gives an overview of the actual set-up in the field. As can be seen in Figure 3-5, in a steady operation all components run within a certain pressure and temperature domain. A so-called cold start-up implies a start-up period of several hours up to several days before the full cluster process train has reached stable operations within the required operating envelopes. This start-up period will depend on the duration of the preceding production stop, the ambient temperature, and the total number of locations involved in the start-up to produce at a certain production flow.

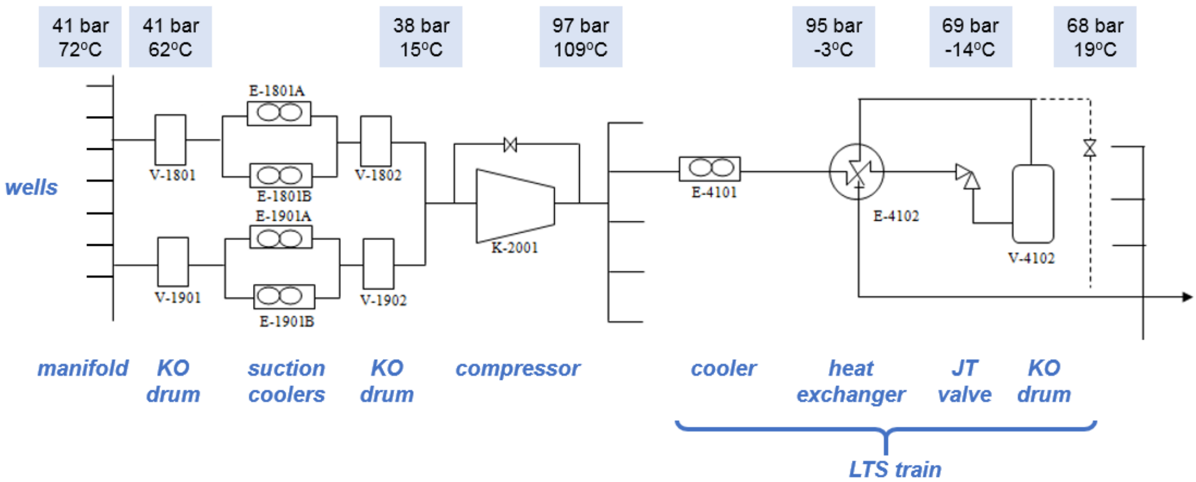

Figure 3-5 Simplified process diagram for a Groningen production cluster

[6] The difference between the A- and B-bundle is the configuration of the rotor (8 blades versus 5 blades). The impact on the compressor operating envelope can be seen in Figure 5-8.

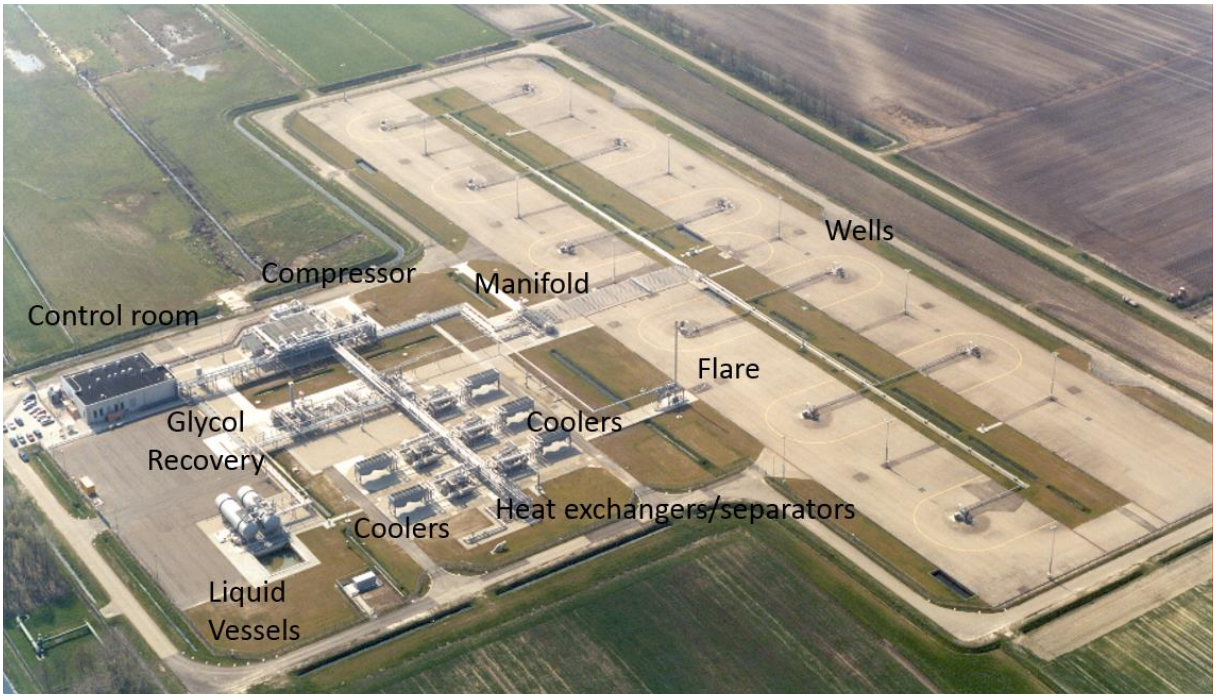

Figure 3-6 Overview of a production cluster location.

3.5 Conclusion operational constraints

The Groningen production system is currently operated outside the envelope anticipated during its design and construction. The interplay of the many components and requirements make the operation of the Groningen system therefore a complex task.

Over the last years' experience has been gained in operating the Groningen gas production system outside the originally intended operating envelope. Although not all combinations of requested offtake at the overslagen have been tested, with this experience a more flexible operating philosophy of the network has been implemented.

In order to investigate which additional adjustments in the surface system may lead to a further reduction in the seismic hazard or seismic risk, NAM and GTS will need to align on requirements for Groningen delivery across OV's. Possibly field tests are required for GTS and NAM to test the operating envelopes.

4 Update of the Groningen Model based on results of recent studies and new data - History Matching

4.1 The Reservoir Model of the Groningen Field

The reservoir model of the Groningen field was built in 2003 and regularly updated. It models the flow of gas through the reservoir along with changes in reservoir pressure through time. It was used for reserves prediction and business planning. In 2009 a total re-build of the model was undertaken. This was completed early 2012.

This model has since then been regularly updated in support of studies into compaction and seismicity. Especially, the faults in the reservoir were mapped in great detail in support of geomechanical studies. Updates made to the model are described in various reports (Ref. 1, 2 and 5).

The production (and resulting depletion) induced seismicity on the Groningen field imposes a world-wide unique situation. There are no “industry-standard” tools available to help understand and control seismicity, and consequently NAM has embarked on a studies program to develop these required tools. As part of this program, the conventional history matching process of the Groningen dynamic reservoir model was extended to allow for history matching of subsidence (since subsidence is a surface reflection of reservoir compaction, which is believed to be the driving energy source for the seismicity) (Ref. 5). The world-first workflow[7] is part of an ongoing effort to ensure the best possible subsurface representation of the reservoir, which forms the foundation of the Hazard and Risk Assessment workflow.

With new data becoming available and the demands on the capability of the model increasing, the model is planned to be further updated and enhanced. The plans for this are described in the “Study and Data Acquisition Plan – Post-Winningsplan 2016” (Ref. 3 and 4). For this optimization study, the latest available version of the dynamic reservoir model is used (GFR2015-V4), which includes some further updates with respect to the (GFR2015-V2.5) model used in the work for the Winningsplan 2016 submission (Ref. 6).

[7] As per the awareness of the authors

4.2 New Data Available since WP2016

The GFR2015-V4 dynamic reservoir model currently used in this study has a number of further updates with respect to the GFR2015-V2.5 model used in the Winningsplan 2016 update (Ref. 1 and 2):

- A newly reprocessed seismic cube has been used to obtain a porosity model via seismic inversion. This has been used as a proxy to constrain the porosity distribution in the static and dynamic models.
- Improved resolution of the reservoir pressure dataset in recent years, by including converted closed-in tubing-head pressure data to bottom-hole conditions (CITHP-CIBHP).
- The compressibility model is updated using model-based subsidence inversion.
- Production data and measurements results acquired have been actualised to January 2017.

4.3 New Studies Completed

The following studies have been completed in support in support of current and potential future model optimizations:

- Promise Inversion of the Groningen field (Ref. 7),
- Petrographic analysis of samples from well Zeerijp-3A (Ref. 8),
- Compilation of petrographic data from the Groningen field Ref. 9).
- Facies interpretation of core from the Groningen field Ref. 10),

The results of the Promise inversion work have been incorporated in model GFR2015-V4 to constrain the distribution of porosity in the Groningen static and dynamic reservoir models. The facies study concludes that a porosity scenario based on differences between facies is not feasible with the data currently available. The petrographic studies were carried out to obtain a better understanding of mineralogical and/or textural controls on reservoir properties. This may be used to constrain future property models.

4.4 Update of the History Match

Given the new data mentioned in section 4.2 the dynamic reservoir model was reconstructed and history matched. The starting point is a static geological model that incorporates the porosity proxy derived from seismic inversion (Ref. 7). Overall the process and data used is the same as described in previous reports like section 2 of the Technical Addendum to the Winningsplan 2016 (Ref. 5). However, some improvements have been made specifically to address the ability of the model to accurately predict seismic events.

4.4.1 CITHP to CIBHP dataset

The primary historic data used for history matching is the reservoir pressure measurements as obtained through Static Pressure and Temperature Gradient (SPTG) surveys. Up to 2014 the regional offtake from the production clusters was managed in such a way as to keep the reservoir pressure balanced across the field, yielding stable trends in pressure decline across the field. Consequently, over the last 20 years the SPTG survey frequency was reduced to about 1 survey per 5 years for each production cluster. Following the production restrictions in the LOPPZ clusters the offtake distribution and regional flow patterns of gas have drastically changed. With the reduced offtake in the north and west, a pressure difference across the field has been established. This pressure difference is currently about 25 bars from north to south. This differential is causing gas flow from the north towards the south of the reservoir. The strength and pattern of this flow is in part dependent on the sealing behaviour of faults.

To capture the dynamic response of the field in terms of reservoir pressure, the reservoir pressure data resolution was increased by including tubing head pressure data, converted to downhole conditions. Since 2011 all production wells in Groningen have been equipped with tubing-head flow and pressure sensors that are continuously recording data. Empirical correlations have been developed for all production clusters converting pressure at surface to reservoir conditions during periods of no flow. The accuracy of this conversion is typically very good (within 1 bar of actual downhole measurements) and since most clusters are typically closed-in at least a few times every year (for more than 1 day) this has created an abundant source of additional reservoir pressure data.

This CITHP-CIBHP dataset from 2011 onwards is now included in the history matching process for all production wells. In Figure 4-1, comparisons for a few selected wells are shown. For the two LOPPZ wells, ZND-9A and PAU-2, a steady pressure decline has been established over the last 2 years, as gas is flowing from the Loppersum area towards the south.

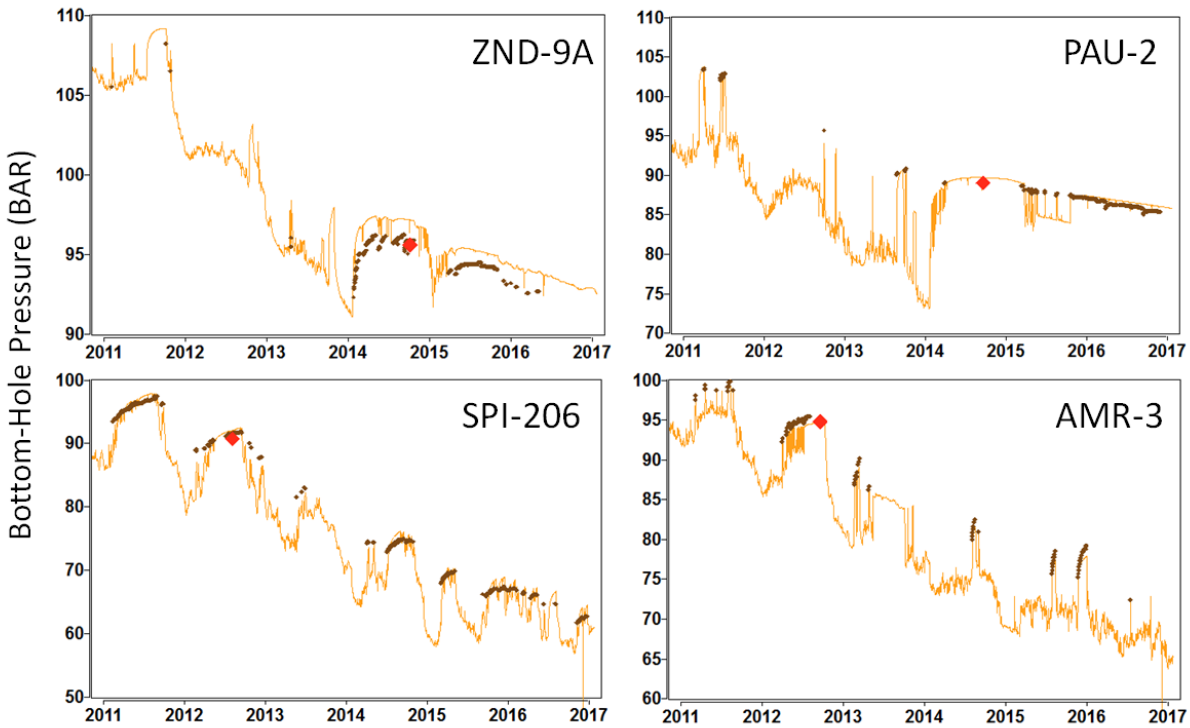

Figure 4-1 Preliminary comparison of modelled bottom-hole pressure (lines) to SPTG data (red points) and CITHP-CIBHP data (brown points) for selected wells.

4.4.2 Compressibility model

Reservoir compaction is thought to be one of the most important contributing factors to earthquakes in the Groningen field. The ability to accurately history match and predict compaction within the dynamic reservoir model is of vital importance since this is the subsurface representation that will be used for the optimization workflow. Compaction is controlled through the assignment of a compressibility factor to each grid cell. In the previous (Winningsplan 2016, Ref. 6) version of the model, the assigned compressibility was derived from core experiments. For this iteration the assigned compressibility is the result of a geomechanical inversion from observed subsidence, using among other things the modelled reservoir pressure as input (Figure 4-2). Essentially, we are now integrating the levelling data used for subsidence prediction into the dynamic reservoir model. The compressibility model is the same as used by the models used for the 2016 Hazard and Risk Assessment.

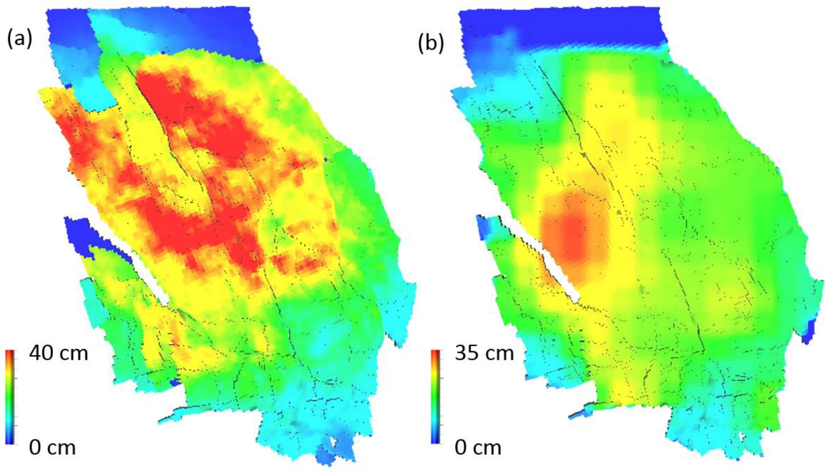

Figure 4-2 Preliminary comparison of estimated compaction at 31st Dec 2016 when using compressibility data from core data (a) versus subsidence inversion (b). The compressibility values used are assuming a linear model in pressure.

4.4.3 History matching seismicity

4.4.3.1 Historic data and match

The seismic activity rate model using strain thickness, as described in Ref. 11 and 12, has been implemented in the dynamic model (see also section 5.3.1). The ability to history match earthquakes both in time and areally is obviously a pre-requisite to having confidence in any production optimisation workflow to reduce seismicity.

The areal history matching requires striking the right balance between statistical significance and areal resolution. The historic earthquakes are discrete events. Representing those in a model of seismicity as a continuous function of compaction in time, and acknowledging the probabilistic nature of the seismicity, imposes a need for some form of areal upscaling. However, sufficient areal resolution needs to be preserved in order to allow for a meaningful areal optimization of production offtake.

The resolution choices will be further investigated, whereby acceptance criteria for the quality of the match will be determined. In Figure 4-3 the field-wide preliminary predicted number of earthquakes is shown (magnitude greater than 1.5[8]). In Figure 4-4 preliminary results of the areal distribution of predicted earthquakes are shown. The results are compared to historical data smoothed with a Gaussian kernel function using a 2km standard deviation. The results are further displayed on a regional basis in Figure. In Figure 4-6 a selection of modelled properties are shown as annual changes since 2013, including earthquake density. Although these figures show intermediate study results, it can be seen that both the temporal and the areal development of seismicity are captured by the model.

[8] The choice of magnitude 1.5 is consistent with references 11 and 12 and represents the maginitude of completeness going back to 1995.

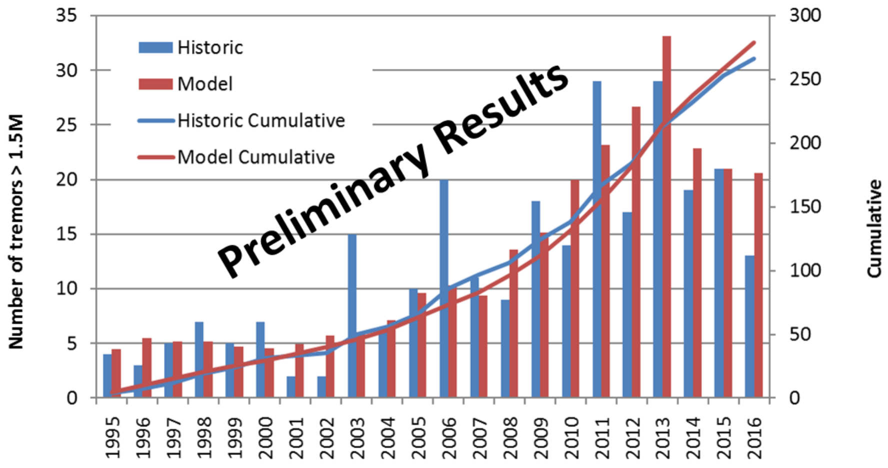

Figure 4-3 Historic and preliminary model predicted earthquakes greater than magnitude 1.5 across the Groningen field

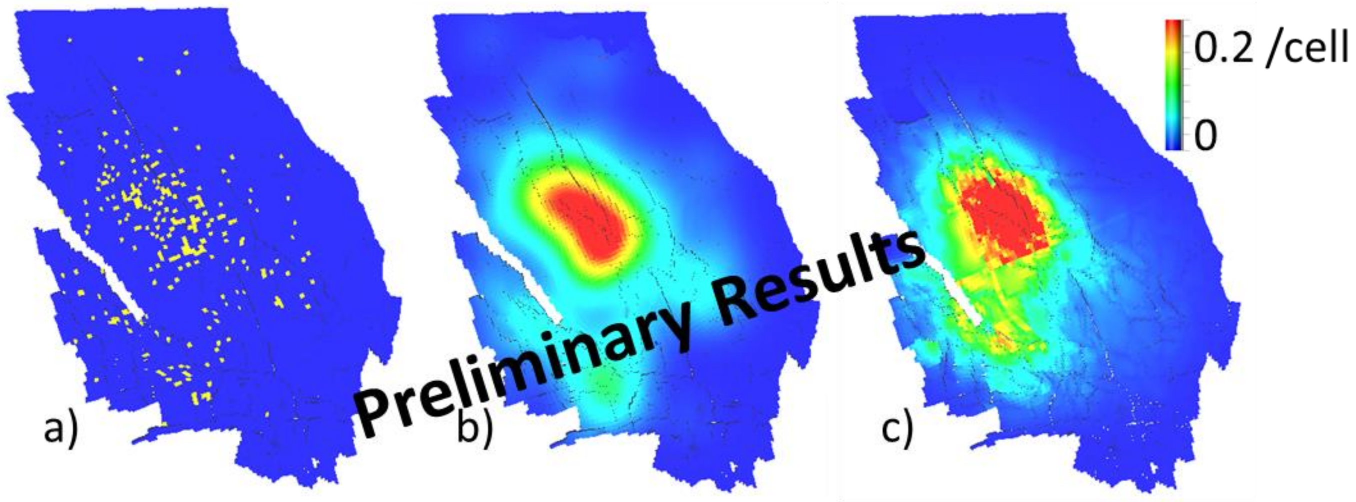

Figure 4-4 (a) Historic locations of earthquakes of magnitude greater than 1.5 at the end of 2016. (b) Historic earthquakes smoothed using a Gaussian filter kernel with standard deviation of 2 km. (c) Preliminary history matching of cumulative earthquakes using a thin-sheet strain thickness model combined with the dynamic reservoir model.

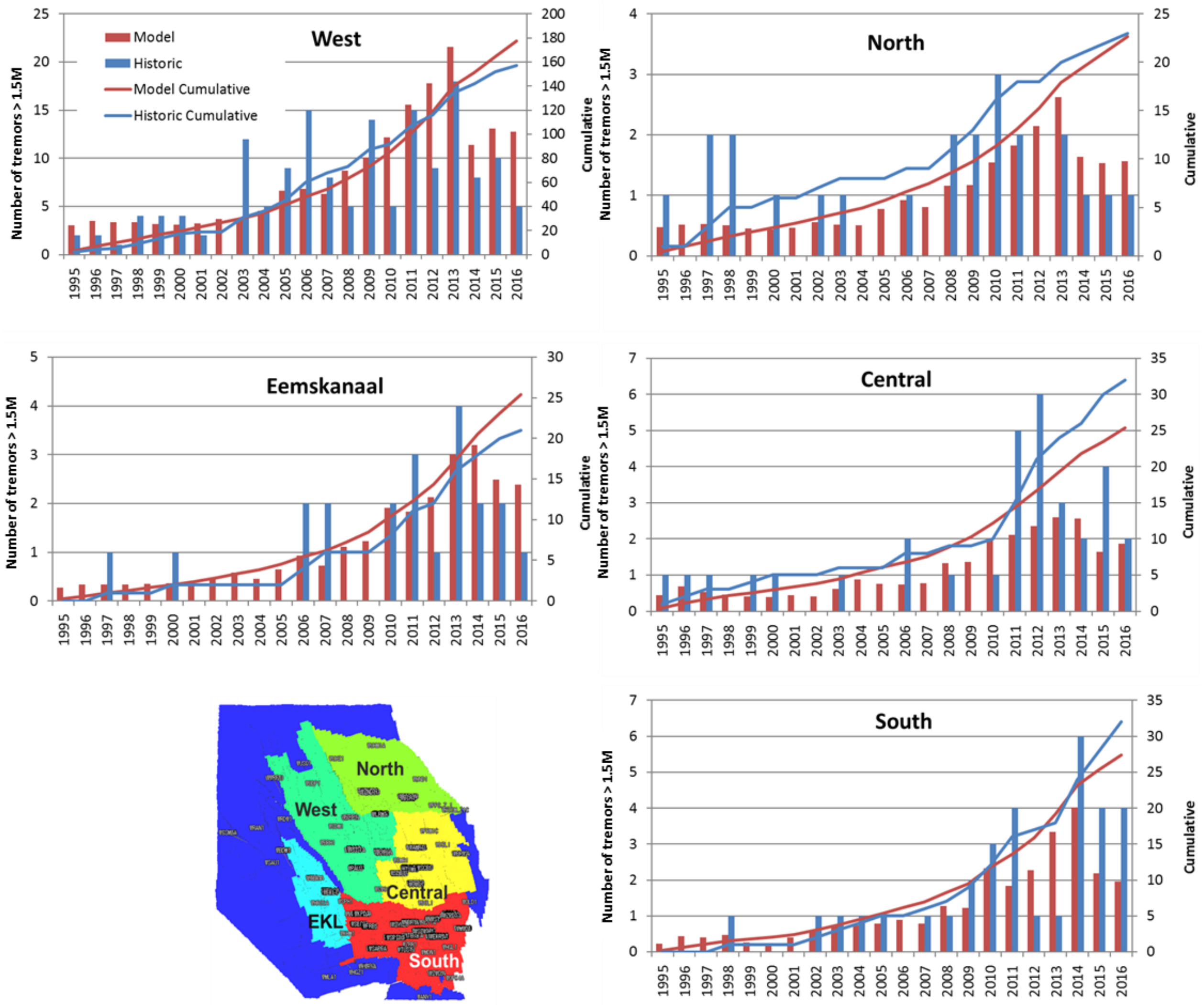

Figure 4-5 Historic and preliminary model predicted earthquakes greater than magnitude 1.5 grouped by regions across the Groningen Field.

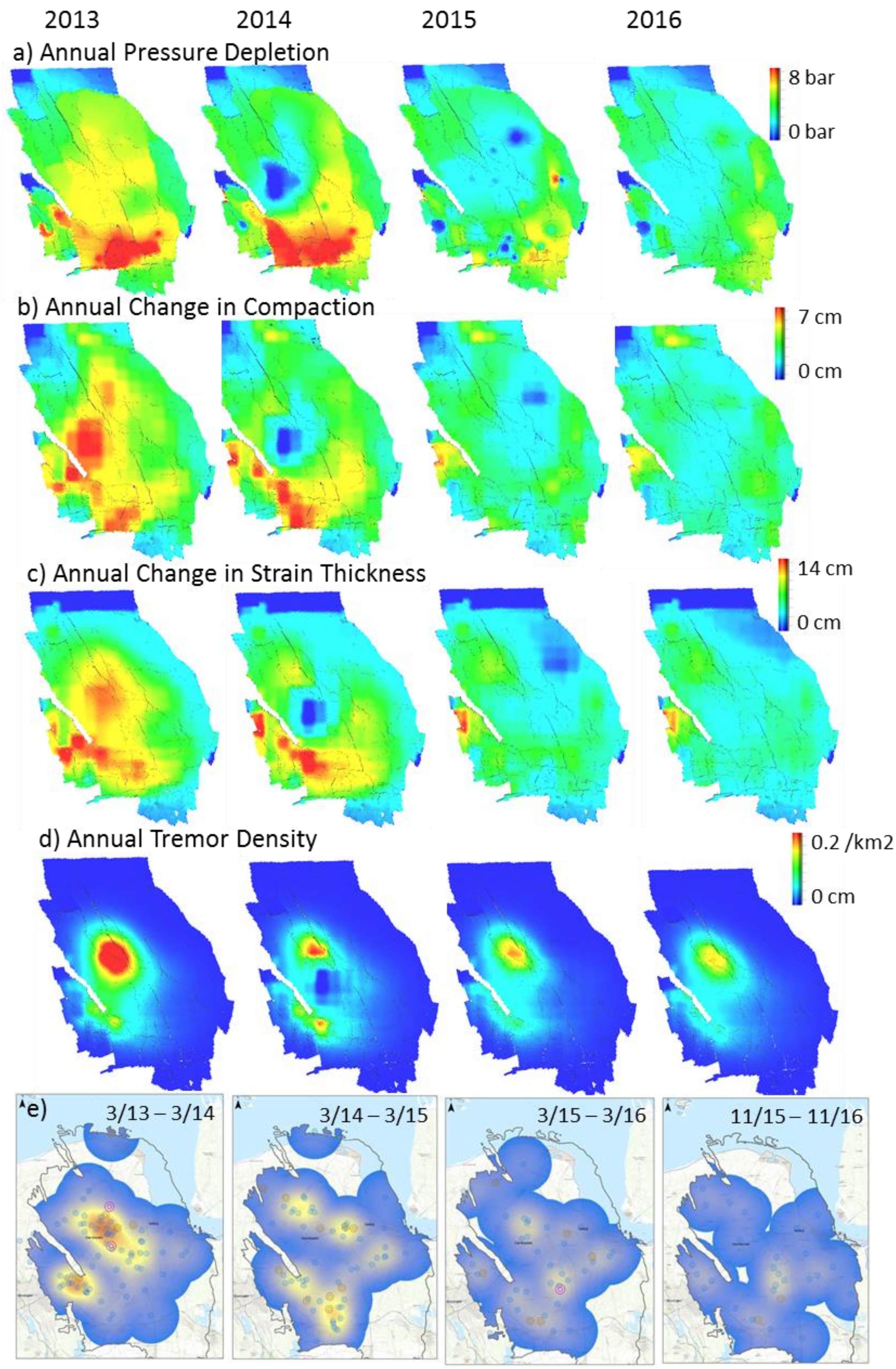

Figure 4-6 Annual changes in properties (2013-16) as estimated by MoReS. Actual Earthquake Density maps in e) are as reported in Reference 15.

4.4.3.2 Predictive Capability

The changes in field production following the LOPPZ restrictions provide an opportunity to test the ability of the model to forecast seismic event rate. The main changes in the production (both field offtake and distribution over the field) from the field are:

- A first production cap was imposed on 17/1/2014, constraining the production from the LOPPZ clusters to 3.0 Bcm/y.
- On 14/4/2015 this constraint was further enhanced by reducing the LOPPZ production to stand-by rates for security of supply only (some 1.6 Bcm/y).
- The seasonal swing was reduced from 2015 onwards.

Figure 4-7 shows the impact of these changes on the daily production.

A predictive test was done by calibrating the reservoir model with historical seismicity up to 1/1/2014. Next the response was assessed for the remaining years of seismicity data, which was found to yield a good match, see Figure 4-8. The performance of the model following 2014 is almost equal to that when using the entire history (Figure 4-3 and Figure 4-5). The compressibility model that is underlying the activity rate model is also calibrated to data from prior to 2014 (no levelling surveys have been conducted since).

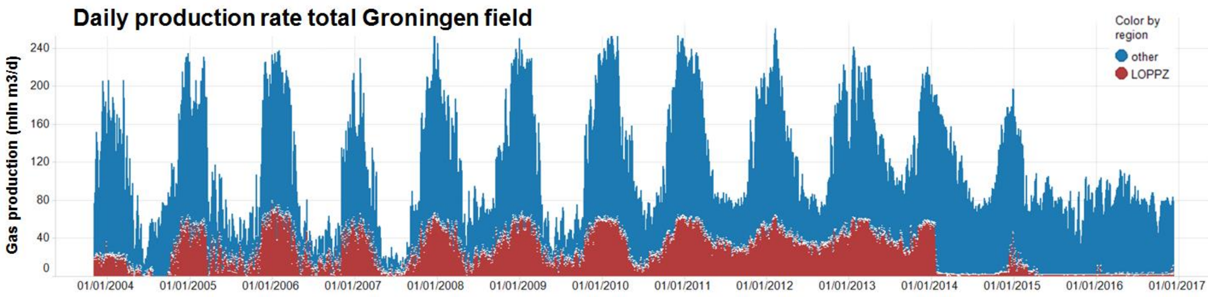

Figure 4-7 Daily production rates for the Groningen field, highlighting the production from the LOPPZ clusters.

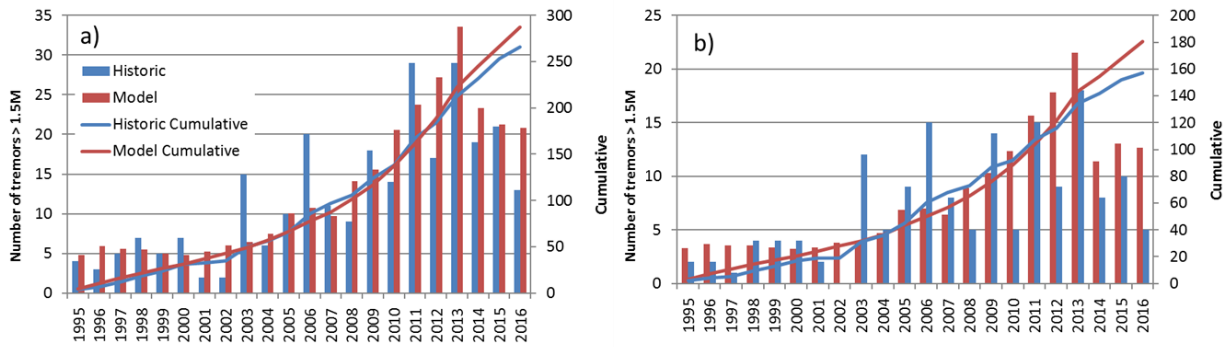

Figure 4-8: History matching seismicity excluding historic data after 1/1/2014. a) Model versus historic data for a) entire Groningen Field and b) the western region only.

5 Production Distribution Optimization

5.1 Seismological Model

Ref. 5 describes NAM's latest Hazard and Risk Assessment, which was prepared as part of the Winningsplan 2016 submission. The associated calculation methods are referred to in this document as the "HRA engine". At this point in time the HRA engine is thought to give the best possible probabilistic description of seismic activity resulting in hazard and risk. It constitutes a model which relates reservoir pressure behaviour (resulting from gas production) through compaction to a probabilistic assessment of seismic event rate (Ref. 11 and 12), culminating in associated hazard and risk. This model is based on geomechanical considerations and a statistical analysis of the historical earthquake record in the Groningen area, representing the event rate through a Poisson Point Process. The modelling approach, as laid out in this document, is based on models developed for the HRA engine.

The production optimisation methodology as described in this document can be applied similarly using alternative seismological models, should these be established as a better/complementary representation. For instance, alternative seismological models may include a 'creep' effect whereby seismic moment can leak-off and dissipate. However, at this moment no model, suitable for integration into the optimization workflow described in this document, has been identified.

5.2 'Systems and Control' Framework

5.2.1 Model driven optimization in a control loop

Around November 2015, Shell's Quantitative Reservoir Management team in Rijswijk was engaged to commence development of a mathematical optimization of areal production offtake distribution in order to minimize the seismic hazard and the seismic risk. Conceptually the idea is that the reservoir simulation model (which is calibrated in a history matching workflow, chapter 3) is used in an earthquake control loop, which can predict earthquake and/or risk (Figure 5-1). This setup allows for a model driven optimization. The modelled cause and effect chain is as follows:

⇨Production from clusters

⇨ Pressure depletion

⇨ Compaction

⇨ Event Rate (Earthquakes)

⇨ Hazard (PGA)

⇨ Risk

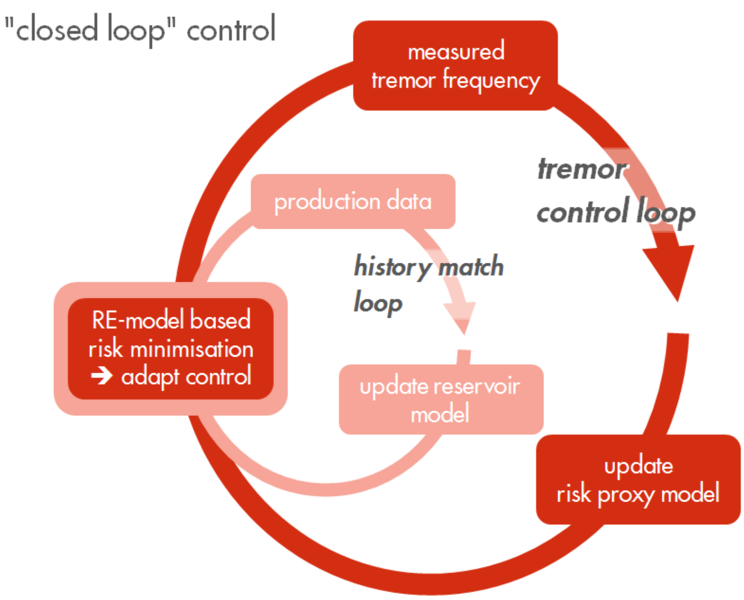

Figure 5-1 Schematic representation of the model based optimization loop

5.2.2 Optimisation Tool

At this stage the Shell proprietary Dynamo tool suite is used for the construction of the optimization tool, using the Mores[9] dynamic reservoir model in combination with Multirun[10]. No surface network model (representing pipelines and gas treatment and compression facilities) is currently included in order to keep the software setup transparent and calculation speed high.

From Ref. 11 and 12 the number of seismic events Λ until some time t_j, across some surface S is given by:

$$\Lambda(t_j) = \int_S \beta_0 c(\boldsymbol{x}, t_j) e^{\beta_1 c(\boldsymbol{x}, t_j)} dS$$

Where $c(\boldsymbol{x},t_j)$ is the strain thickness at a location $\boldsymbol{x}$ until time t_j. This model is based on a Poisson Point Process model. In the MoReS model this equation is discretized on a two-dimensional x,y-grid. The strain thickness of a vertical stack i of gridblocks is then given by:

$$\Lambda_i(t_j) = A_i c_i(t_j) \beta_0 e^{\beta_1 c_i(t_j)}$$

where:

A_i	cross sectional area of a stack of grid cells at location i.
β_0, β_1	global parameters to fit the cumulative historical seismic activity in Groningen
$c_i(t_j)$	strain thickness of gridblock stack i, from $t = t_0$ to $t = t_j$.

Strain thickness is assumed to be the product of topographic gradient, as described in Ref. 12, and compaction, $C_i(t_j)$. For a stack of grid blocks compaction is given by:

[9] Mores is a 3D dynamic reservoir simulator, part of the Dynamo toolsuite.
[10] MultiRun is an application to handle large numbers of simulation runs, part of the Dynamo toolsuite.

$$C_i(t_j) = c_p \cdot \varphi \cdot h_i \cdot |\Delta p(t_j)|$$

where:

c_p pore compressibility

φ porosity

h_i net thickness

$\Delta p(t_j)$ absolute pressure change from initial conditions

Assuming a Poisson ratio of 0.25 and a Biot alpha of 1.0 the relation between the pore volume compressibility and the uniaxial rock compressibility is:

$$C_R = c_p = c_m / \varphi$$

where:

C_R pore compressibility (MoReS input)

c_m uniaxial rock compressibility

Note that in this setup the events (earthquakes) are calculated as an expected real number for a given rock volume (i.e. stack of grid cells), rather than discrete events (like in reality). So it is a mathematical approximation, without a probabilistic generator which releases the compaction energy in deterministic events.

In the hazard and risk engine, a range of global fitting parameters, β_0 and β_1, are found along with relative likelihoods. Within MoReS only single values for the β parameters are estimated by minimizing the cumulative difference between the model and historic earthquakes. Work is continuing to more fully capture the uncertainty in β within MoReS and the optimization framework. This will allow us to better report confidence intervals around earthquake predictions.

5.2.3 Limitations

As a consequence of omitting the surface network model some significant simplifications are introduced:

- non-ring constrained
- non-Wobbe constrained
- non-surface network constrained (except for total field rate)

Once an optimized offtake distribution has been proposed by MoReS, this is subsequently run with the full surface network model attached to validate that the proposed production rates are feasible.

5.3 Optimization Framework

5.3.1 What to Optimise – The Objective Function

Various measures are currently under consideration as objective functions for minimization:

1) Hazard
    a. Total number of estimated earthquakes over the optimization timespan (calculated as the integral or total sum over the two-dimensional grid as introduced in section 5.2.2)
    b. Peak earthquake density (in time and space)
    c. Peak ground acceleration (PGA). This assumes a coupling between the HRA engine and MoReS during the optimization workflow.
2) Risk
    a. People weighted event count (combining estimated number of earthquakes with population).
    b. Number of people exposed to Inside Local Personal Risk levels in excess of 10^{-5} per annum (Commissie Meijdam norm), or more stringent norm if 10^{-5} can be met.
    c. Number of houses exposed to PGA greater than 0.2g. This relates to the house strengthening effort.

Calculation of 1c) and 2b) will require a coupling between the HRA engine and MoReS during the optimization workflow. Work is ongoing to achieve this. Initial results based on MoReS only, has focused on 1a) and 2a).

5.3.2 Minimising the Seismic Activity Rate

The tools to optimise the gas production distribution from the field are built incrementally, with increasing complexity. In this section we will show some of the recent results. Especially the areal resolution that can be achieved will be discussed.

5.3.2.1 First optimization attempt

A first attempt at optimization was made using the Mores model of the November 2015 Hazard and Risk Assessment (Ref. 13), based on a gas production forecast with a 27 Bcm/year production cap. This optimisation was done with the objective to minimise the seismic event rate over the 5 year optimization timespan.

The optimization tool is used to find an optimised alternative gas production forecast based on this model, as of 1/1/2016 for the 5 year window. In the optimisation the production is allowed to be scaled within each region as defined by the Ministerial decision within a field cap of 27 Bcm/year (i.e. the total production from all the regions should still add up to 27 Bcm). Because the cap on the LOPPZ region was maintained, effectively there were 3 control parameters. These were the scaling parameters of the other three regions. Figure 5-2 shows that indeed the forecasted cumulative number of events is decreasing. Some 15% scope for reduction was found for the total number of events over the 5 year period. It is important to note that the underlying equations used for estimating earthquake activity rate in this initial optimization attempt was based on compaction only, and not strain thickness as described in the previous sections. The reduction in earthquake activity quoted in this section do not necessarily reflect what can be achieved when using the updated activity rate model based on strain thickness.

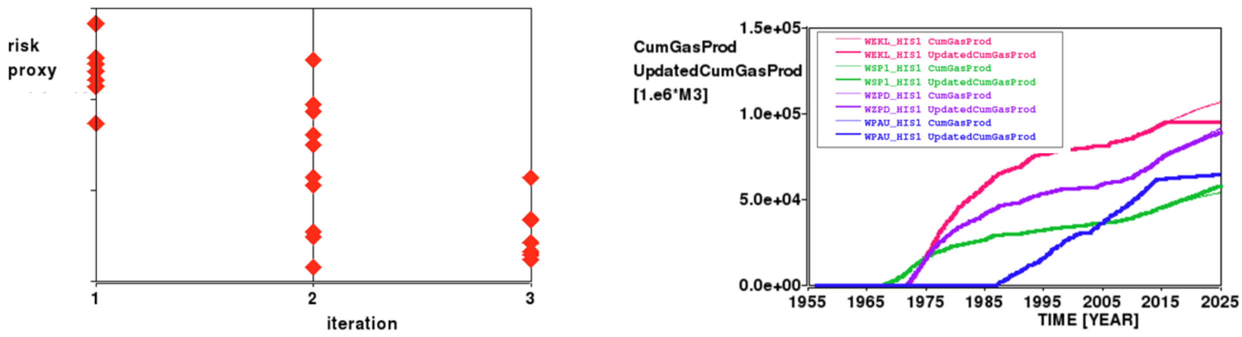

Figure 5-2 First attempt optimization results

5.3.2.2 *Areal refinement*

Initially, the controls were associated with areal production regions, with the clusters associated with a region forming a control. Various stages of increased areal refinement were investigated:

- 3 regions
- 27 regions (based on the initialization regions of the model)
- Maximum freedom case:
  - By applying a checker-board type raster over the field, 192 groups of grid blocks were created. In this configuration all (but one) production clusters are in a separate region, yielding 21 independent controls, which allows for the maximum degree of freedom for the optimizer (Figure 5-3).

It was found that the objective function (minimized total number of seismic events) was reducing with increasing controllability of the system (i.e. allowing independent controls on the individual clusters), see Figure 5-4. In effect there are no associated production regions associated with the optimization controls, with every production cluster being allowed to vary independently. Only where clusters are very close (SCB-TJM and ZVN-SPI) are they lumped as a single control.

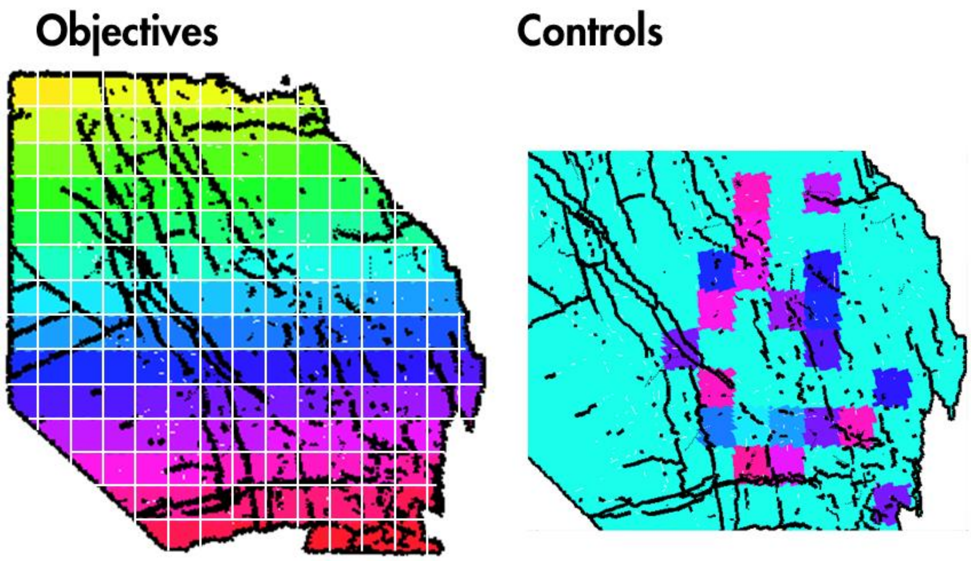

Figure 5-3 Dividing the field in 192 regions, of which 21 are controllable.

Based on the higher degree of freedom for the optimisation space, an improvement in the objective is observed compared to the initial optimisation based on a three region control. However, these results should be interpreted with caution as this optimisation is based on total event rate. This optimisation can lead to an increase of production in areas with higher exposure. Based on an optimisation that takes exposure into account a different distribution of the field production would potentially be achieved with potentially a different objective increment.

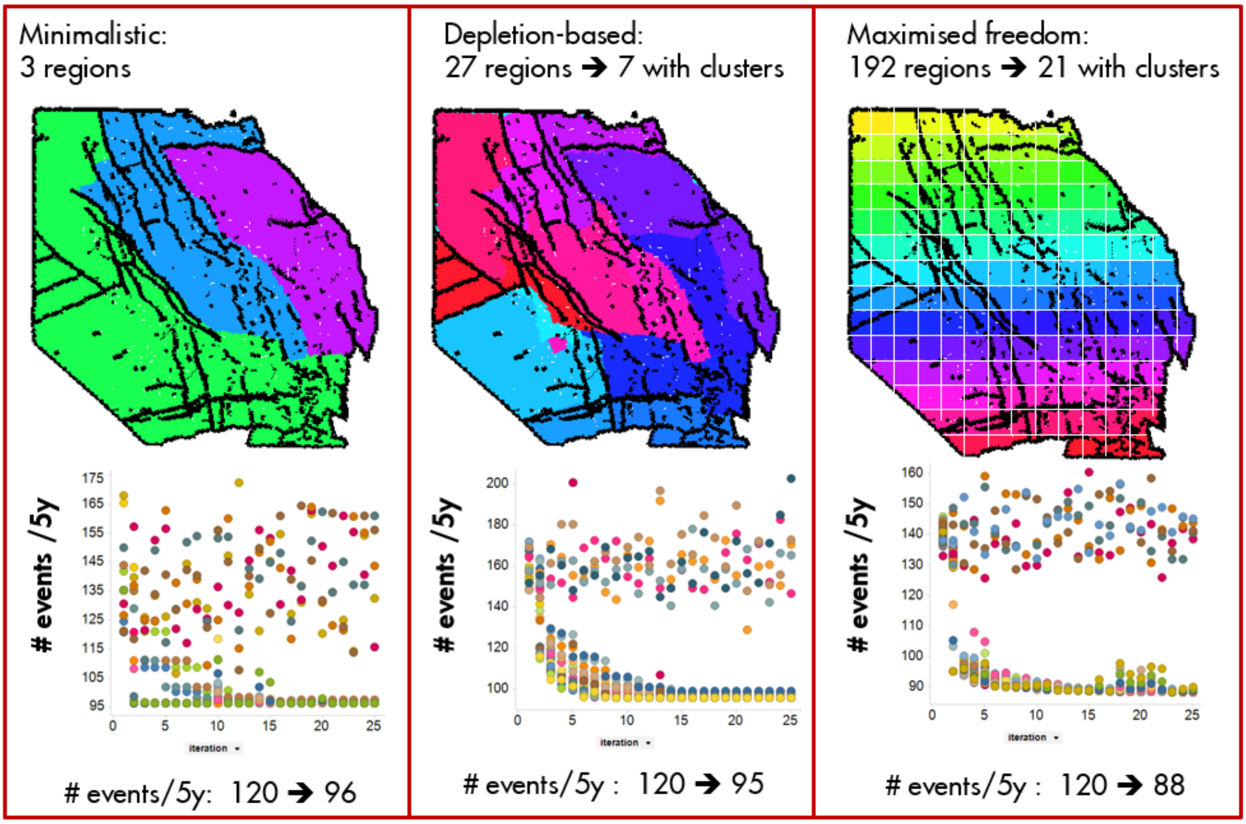

Figure 5-4 Various stages of areal refinement and their respective optimization result over 25 iterations.

5.3.3 Minimising Seismic Risk

The next step that is envisaged for the optimisation, is to switch from event rate to a risk proxy. This will potentially yield highly different results from the previously presented optimization based on event rate. Different conceptual approaches are currently investigated for this step.

The feasibility and practicability of the extension of the current optimisation tool from an event rate objective function to a risk objective function needs to carefully consider the impact of incorporating additional complexity on computer runtimes. The current optimisation based on an event rate objective function is already computer intensive. Further extension will make further demands on run-time.

An intermediate step to go from hazard to risk, which is easy to implement, is to apply population density as a weighting factor to the hazard. It is anticipated that this may give a very rough first order approximation of risk. The lateral effects of earthquake s (e.g. impact away from the epicentre) will need to be reflected in the calculation.

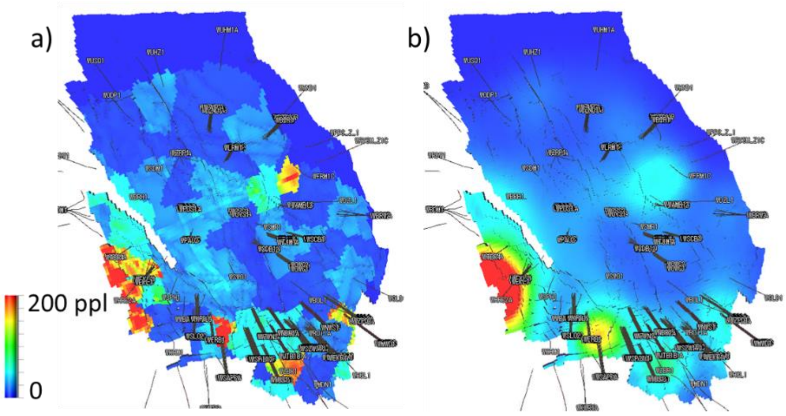

Figure 5-5 a) Population mapped onto the grid of the Groningen Field on a per grid cell basis. b) A smoothing kernel is applied to the population map prior to use as a weight factor. In this example a 2km standard deviation is used.

An alternative route that is explored is to integrate the HRA engine (which is currently available as both a Python and C based executable) directly into Dynamo. Hence the optimizer would pick an areal distribution of offtake, and impose that to the Mores reservoir model. In turn the Mores model calculates reservoir pressure and compaction in time. These compaction values are then used as input to the HRA engine, which will calculate a grid with the areal distribution of the risk levels (Figure 5-6). From this a single value will be used as input to the optimizer objective function, as outlined in section 5.3.1. Alternatively, peak ground acceleration can be used in case of a hazard optimization. The optimiser will then redistribute the areal offtake distribution to minimize the objective.

Other options include application of design of experiment techniques to establish a response function that can approximate the outcome of the full HRA engine. Alternatively, some proxy for risk calculation may be implemented, either directly in Dynamo or as a lightweight add-on. Investigations into the development of such a proxy is in progress by the Shell's Statics and Chemo Metrics group.

Given the current early status of this part of the optimisation effort, different strategies will be pursued in parallel to progress the optimisation tool from hazard to risk.

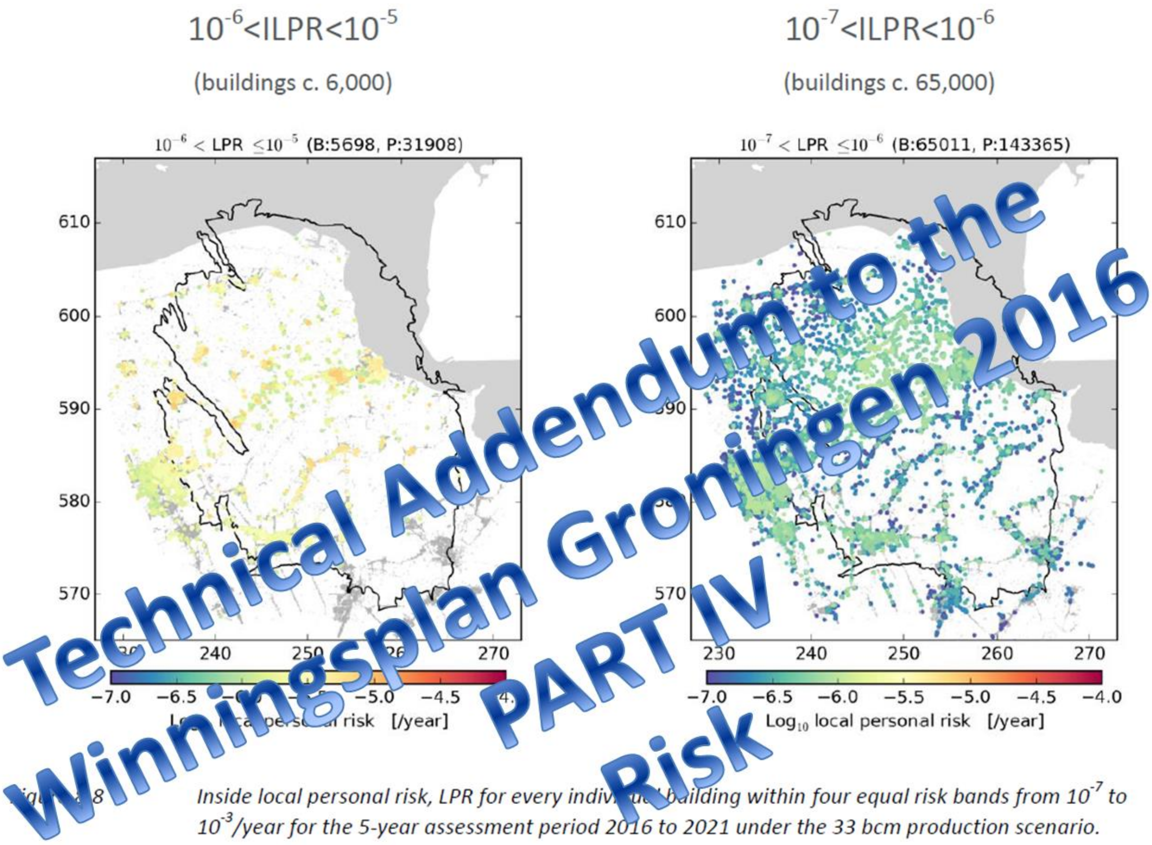

Figure 5-6 Examples of a grid representation of calculated risk

5.4 Operationalising of the Production Distribution

5.4.1 Operational considerations

Given that (currently) the optimizer tool is based solely on a stand-alone reservoir model without attaching a surface network model, it is important to properly constrain the forecasts, such that the optimized results can actually be achieved in the field (see chapter 3). Some of the operational considerations are:

- Ability to deliver across various Overslagen
- Ability to inject in Norg
- robust for trips/shut-downs/failures (grouping of clusters rather than single cluster targets)
- flat production / seasonal fluctuation
- Robust across full potential annual volume range (24 + 6 + 1.5 Bcm)
- Honour compressor rpm[11] constraints

5.4.2 Model implementation

As a first order implementation of the operational limitations, the following constraints are implemented in Mores:

- Planned/Unplanned downtime is reflected by an uptime factor:
    - 90% in winter (October-March)
    - 80% in summer (to reflect planned shut-downs)
- The Mores model is PQ[12] matched, hence a first order approximation of well/cluster capacities can be assigned by means of a minimum THP applicable for that cluster:
    - 40 bar for Eemskanaal cluster (1st stage compression – A-bundle)
    - 12 bar for Schaapbulten cluster (2nd stage compression)
    - 20 bar for all other clusters (1st stage compression – B-bundle)

As a next step, a way to represent the compressors was devised in Mores (the reservoir model) without the need to attach a full surface network model. This was done by use of functionality implemented in the reservoir simulation tool for Underwater Manifold Centres (UMC) (Figure 5-7), which essentially offers the option to assign an additional pressure-drop table downstream of the wellheads. Here, the compressor performance curves (Figure 5-8**Error! Reference source not found.**) were attached. However, because the UMC entails an implicit calculation, the impact on run-times is significant (slow-down by a factor of 2).

[11] Rpm – revolutions per minute
[12] PQ stands for pressure – volume flow

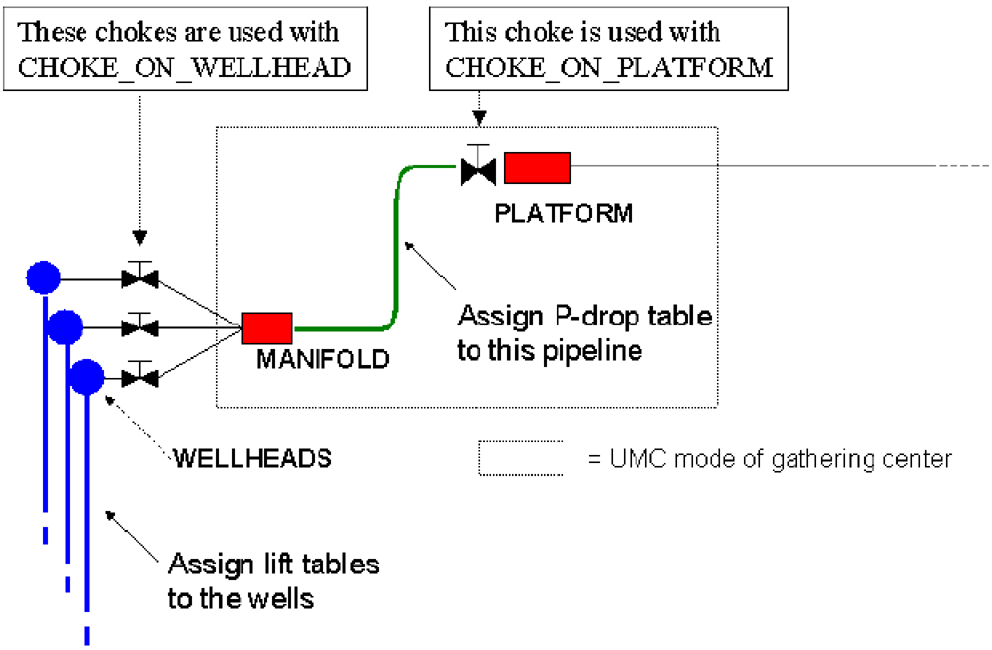

Figure 5-7 Mores implementation of compressor performance curves by means of the Underwater Manifold Centre functionality

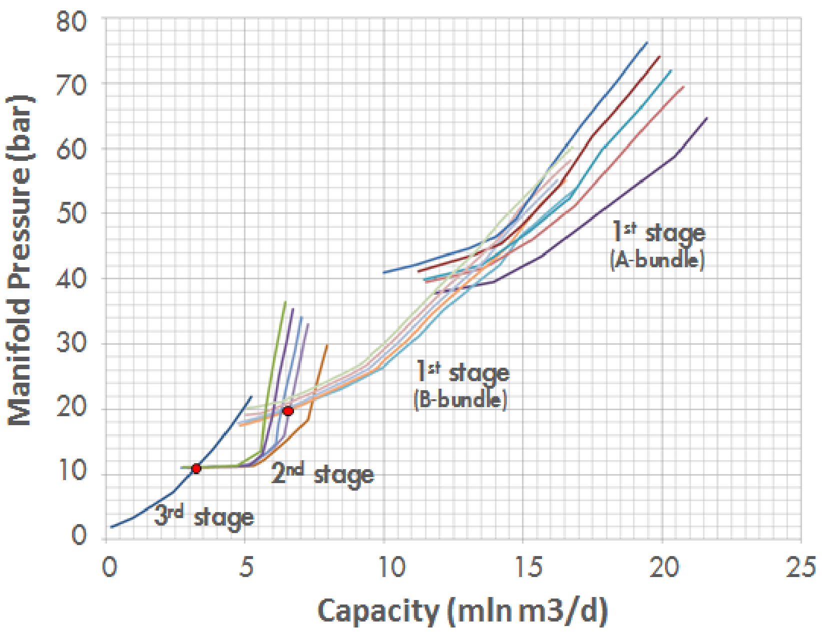

Figure 5-8 Typical compressor performance curves for various compressor stages and ambient temperatures.

5.4.3 Boundary conditions

At this stage, the following boundary conditions are imposed for the optimization tool:

- Optimize for a 5 year period (2018-2022)
- Each cluster[13] is to be produced at a minimum stand-by rate of 0.5 Bcm/year, and 0.2 Bcm/year for each LOPPZ clusters (=1.0/5) (for average winter conditions).
- The optimizer is allowed to vary all controls (i.e. cluster volume constraints) in order to minimize the objective, including those of LOPPZ clusters like 't Zand.
- 21.6 Bcm annual cap, with a flat production profile of 1.8 Bcm/month (with maximal seasonal swing up to 20%, e.g. within 1.44-2.14 Bcm envelope)
- Simple uptime assumption of 90% uptime in winter, and a 80% in summer (reflecting shut-downs for maintenance).

For now, it is assumed that volume delivery across dedicated Overslagen can be solved operationally by GTS.

Given the 5 year window for the optimization and the 21.6 Bcm field cap, there is no requirement for restaging of the compressors within the optimization window. Note that restaging (from 1st to 2nd stage compression) will further complicate the optimization problem.

5.4.4 Operationalization

In order to ensure delivery of the forecast in light of the operational constraints and gas demand, it is proposed to establish an *operational bandwidth* around the proposed scenarios, which should provide flexibility around the volume distribution.

Although the optimizer is allowed to control individual clusters independently, there clearly are areal trends in an optimized scenario where groups of close-by clusters have similar production behaviour. Thus the production clusters can be grouped based on their production rates (or load factor). The lower limit of the operational envelope (*low case operational performance*) can then be established by means of a *degrading method:*

- within a cluster group it is assumed that one cluster will be unavailable for 6 months per year

It is envisaged that the final optimized scenarios are validated through the reservoir model dynamically coupled with the detailed surface network and facility model (Mores - Genrem[14]).

[13] Each double cluster (SZW, EKR, SPI) is confined to a total of 0.5 Bcm/y.
Each tie-back cluster (FRB, SAP) is confined to a minimum rate of 0.5 Bcm/y.

[14] GENREM is a gasfield planning tool developed by NAM, which can handle detailed surface network elements to establish (long-term) forecasts of the predicted capacity of gasfields.

6 Schedule

In line with the milestone dates in the Instemmingsbesluit, NAM has delivered a "Plan of Approach" to SodM on the 1st of February 2017 and will deliver the following reports:

- 1 June — Methodology - Optimisation of the Production Distribution over the Groningen field to reduce Seismicity (the current document),
- 1 September — Draft report of the Optimisation of the Production Distribution,
- 1 November — Final report of the Optimisation of the Production Distribution, to the satisfaction of SodM's Inspecteur-Generaal der Mijnen.

Updates to the Groningen reservoir model are being carried out in line with Ref. 14. All elements highlighted in Table 6.1 are planned to be incorporated in the optimisation study.

Study Activity	**Report available and published at Onderzoeks-rapporten site**	**Results incorporated in update of hazard and risk assessment**
Petrographic study 1 ***	1st January 2017	1st June 2017
Petrographic study 2 ***	1st January 2017	1st June 2017
Sedimentological study	1st January 2017	1st June 2017
Top Carboniferous mapping / Sub_Salt faulting	1st October 2017	1st November 2017 (preliminary) 1st November 2018
Carboniferous velocities	Intermediate Report 1st November 2017	Long-term study effort
Cenozoic faults interpretation	1st October 2017	Section 6, page 55
Gas in aquifer study	1st July 2017 (will include results new PNX logging).	1st November 2017
Incorporate gravity survey results in dynamic model	1st September 2017	1st November 2017
Incorporate compaction measurements in dynamic model	1st September 2017	1st November 2017
Incorporate Tubing Head Pressure data in dynamic model***	1st April 2017	1st June 2017
High permeability area in Central part of field	1st July 2017	1st November 2017
Closed-loop compressibility modelling in dynamic model	1st September 2017	1st November 2017

Table 6.1 Milestone dates for further studies in support of enhancement of the Groningen Reservoir Model as reported in Reference 14. The reports for the studies marker in the table with *** are available on the studies page of the website www.nam.nl/feiten-en-cijfers/onderzoekspagina.

The schedule is planned to meet all imposed deadlines in the Instemmingsbesluit Winningsplan 2016.

7 References

1. Groningen Field Review 2015 Subsurface Dynamic Modelling Report, Burkitov, Ulan, Van Oeveren, Henk, Valvatne, Per, May 2016.
2. Independent Review of Groningen Subsurface Modelling Update for Winningsplan 2016, SGS Horizon, July 2016.
3. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Part 1, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
4. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Part 2, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
5. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART I – Summary and Production, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
6. Winningsplan Groningen 2016, Nederlandse Aardolie Maatschappij BV, 1st April 2016.
7. Subsidence inversion on Groningen using leveling data only, Nederlandse Aardolie Maatschappij BV (Onno van der Wal, Rob van Eijs), December 2016.
8. Petrographic study of well Zeerijp-3A (ZRP-3A) Final Report, Panterra Consultants, November 2016.
9. Petrographic Aspects of the Rotliegend of the Groningen field Inventory and quick-look analysis of petrographic data from the Groningen field, Nederlandse Aardolie Maatschappij BV (Clemens Visser), November 2016
10. On the implementation of sedimentological data in porosity modelling for the Groningen field, NAM (Clemens Visser, Richard Porter and Jose Solano Viota), August 2016
11. An activity rate model of induced seismicity within the Groningen Field, (Part 1), Stephen Bourne and Steve Oates, February 2015.
12. An activity rate model of induced seismicity within the Groningen Field, (Part 2), Stephen Bourne and Steve Oates, June 2015.
13. Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), Hazard and Risk Assessment for induced Seismicity Groningen – Interim Update, 7th November 2015.
14. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Progress and Schedule, December 2016.
15. Staatstoezicht op de Mijnen, Technische bijlage Advies Groningen gasveld n.a.v. Rapportage recente aardbevingen Wirdum en Garsthuizen 2016/2017, 13 April 2017.