Compressor Station Facility Failure Modes: Causes, Taxonomy and Effects

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Contents

Foreword

Compressor stations are key active elements of gas transmission networks. Their role consists in pressurising natural gas to overcome pressure drops due to friction, positive slopes and demand nodes, and make possible the transport of gas along transmission pipelines. Their partial or total failure may endanger the transport of gas, the network not being able to supply the required quantities of gas to demand nodes at the right delivery pressure. The importance of these facilities has been the driver in developing this pioneering study on failure modes, their causes, taxonomy and possible effects. This work was developed by contractors Tractebel and RAMS&E, with the collaboration, support and critical review of JRC staff. The work was developed within the competitive Action CIPS 2012, between DG-HOME and DG-JRC to address Critical Energy infrastructure protection.

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Abstract

This report addresses the failure modes of compressor stations as key facilities of gas transmission networks. This is done by finding possible failure causes, establishing a taxonomy and identifying possible effects. Given the interest of this study to analyse and identify potential critical facilities in gas transmission networks, and their possible impact on energy security, loss of capacity (partial or total) has been identified as the effect of interest of the different failures. Probabilistic results provided are unavailability, expected number of failures per year, downtime and average downtime.

1 Introduction

Compressor stations are key active elements of gas transmission networks. Their role consists in pressurising natural gas to overcome pressure drops due to friction, positive slopes and demand nodes, and make possible the transport of gas along transmission pipelines. Their partial or total failure may endanger the transport of gas, the network not being able to supply the required quantities of gas to demand nodes at the right delivery pressure. Under some circumstances, compressor stations (CS) could be considered critical facilities within the natural gas infrastructure. The objective of this study is to identify all significant failure modes of compressor stations, their causes and possible effect on gas transport. Another objective is to establish a taxonomy of this type of facilities that may simplify reliability estimates.

This study was based on the review of 56 compressor stations located in different countries of the EU (Germany, France, Spain, Poland, the Czech Republic and Austria). This has helped identifying the most frequent layouts, based on which the classification of CS has been developed. Basic probabilistic failure rates of components have been extracted from different data sources and databases. The analysis of the operation of compressor stations and the possible impact of failures led to the consideration of loss of capacity as the main effect of components failures.

Regardless of the framework where the results of this study can be used, typically either critical infrastructure protection or security of gas supply, Risk Assessment is the most adequate methodology, requiring reliability estimates in order to be applied. The reliability variables addressed in this study are unavailability, expected number of failures per year, downtime and average downtime.

This report is divided in five sections. After the introduction, the second section addresses the creation of a taxonomy of compressor stations. Section 3 is the core of the report, where the scope of the methodology is set, the functional analysis and the identification of critical elements are performed, damage classes are defined and CS components are modelled. Results are then finally provided, after performing a Fault Tree analysis. Section 4 is dedicated to a thorough analysis of natural hazards that can affect negatively compressor stations. Section 5 contains the conclusions of the study.

2 Taxonomy

2.1 Objective, Sources of Information and Relevant EU Compressor Stations

The present section is the establishment of a taxonomy of the most relevant compressor stations types in the EU gas transmission network, based on the following basic facility data:

- Installed compression power;
- Number of input and output pipelines;
- Types of prime movers and compressors;
- Redundancy levels.

For this purpose, a variety of sources of information have been used in order to collect the necessary data:

- Technical data and documents from projects where Tractebel Engineering has previously carried out design and consultancy services (mainly for Clients in Belgium, France and Italy);
- Information from Transmission System Operators (TSO) which have close relationships with the different Tractebel European offices, e.g. the gas operators part of GDF SUEZ group, Belgium's Fluxys, Italy's Stogit (SNAM group), the Czech Republic's Net4Gas or Poland's Transit Gaz-system S.A.;
- Interviews with gas compressor station Senior Experts from Italy's TSO;
- Websites of European gas operators.

A total number of 56 compressor stations located all around the European Union have been identified and assessed for this study, in particular 9 compressor stations in Germany (Bunde, Eischleben, Lippe, Mallnow, Olbernau, Reckrod, Rehden, Reuckersdorf and Weisweiler), 5 compressor stations in Belgium (Berneau, Winksele, Weelde, Zeebrugge and Zelzate), 2 compressor stations in France (Etrez and Saint-Avit), 18 compressor stations in Spain (Alcazar de San Juan, Algete, Almendralejo, Baneros, Chinchilla, Cordoba, Crevillente, Denia, Haro, Montesa, Navarra, Paterna, Puertollano, Sevilla, Tivissa, Villar de Arnedo, Zamora and Zaragoza), 11 compressor stations in Italy (Enna , Gallese, Istrana, Malborghetto, Masera, Melizzano, Messina, Montesano, Poggio Renatico, Tarsia and Terranova), 5 compressor stations in Poland (Ciechanow, Kondratki, Szamotuly, Wloclawek and Zambrow), 5 compressor stations in Czech Republic (Breclav, Hostim, Kralice, Kourim and Veseli n/L) and 1 compressor station in Austria (Eggendorf).

Examples of operational facilities are shown in the simplified diagrams of the following pages, in order to give a representative set of samples of gas compression stations showing the variety and the flexibility of the facilities available in Europe. All figures shown are examples of CS normal operation Process Flow Diagram (PFD), which implies stations in a steady state working condition:

- Valves shown as Normally Open (NO) are Open;
- Valves shown as Normally Closed (NC) are Closed;
- Spare machines are in a stand by conditions, which means stopped but ready to start up, with standby lube oil circuits fully working, seal gas flowing into turbine and compressors barriers and all alarms cleared.

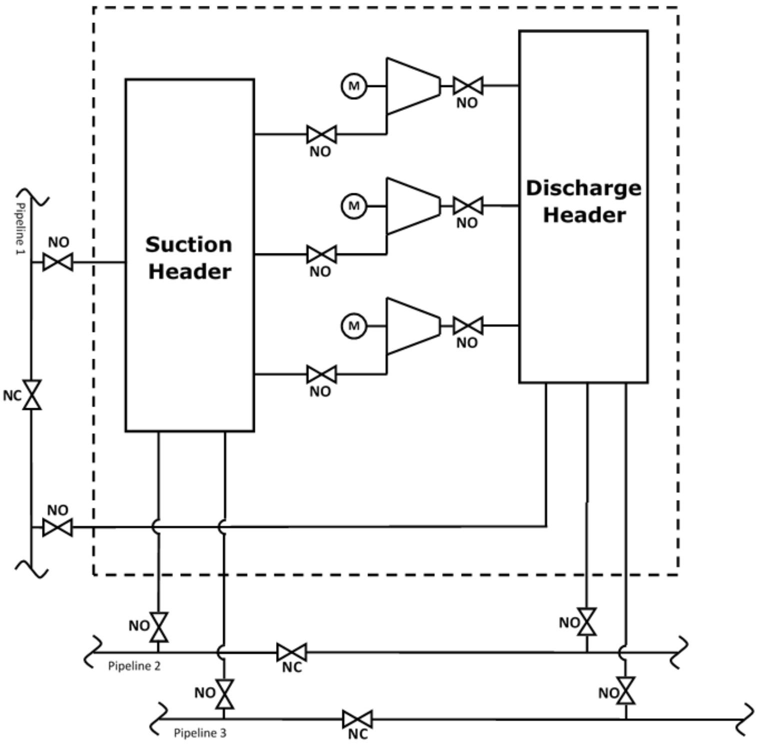
2.2 Methodology

The aforementioned basic facility data were obtained from the sources of information described above and used to define a taxonomy comprising 8 categories or Equivalent Compressor Stations (ECS). This taxonomy was established by making some considerations on the basic facility data, as discussed below.

Regarding the installed compression power it is possible to draw the conclusion that no general rule exists for the choice of the rated power of the prime movers. Prime mover sizing takes into account especially company standardizations in use and market evolution, meaning this parameter is not relevant for producing a meaningful taxonomy. Furthermore, installed power was not considered a key parameter for the model definition since the availability/reliability of the units and their maintenance and repair downtime are not dependent upon the units' number/size and installed power, the relevant aspect being rather the functional architecture of the compressor station, i.e. its redundancy level as discussed later.

As far as the number of input and output pipelines is concerned, it was decided not to consider this parameter in the taxonomy since the battery limit of compressor station is at the suction header and at the discharge header according to the data and information analysed, as per the following representation:

Figure 1 - Battery Limits.

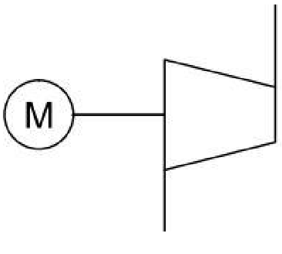


Source: Tractebel, 2016.

Because of the presence of this inlet and outlet manifold (ring), plant reliability and availability are independent from the number of input/output pipelines.

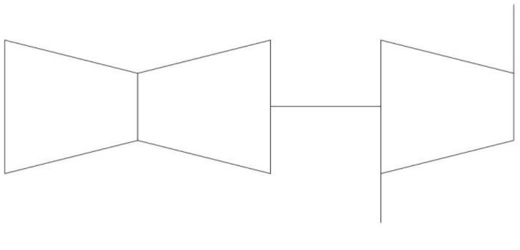
Regarding the type of primes movers and compressors, all natural gas compressors encountered are driven either by electric motors or gas turbines, these possibilities being the key parameters in characterizing compressor stations given the fact they introduce significant differences regarding maintenance issues, downtime repairs and the different numbers of parts that can fail. Since steam turbines are very rare they will not be considered (only one steam turbine was encountered in the survey mentioned above, at Mallnow in Germany). Two examples of compressors moved by an electric motor or a gas turbine are illustrated in Figures 2 and 3.

Figure 2 – Motocompressor.



Source: Tractebel, 2016.

Figure 3 – Turbocompressor.



Source: Tractebel, 2016.

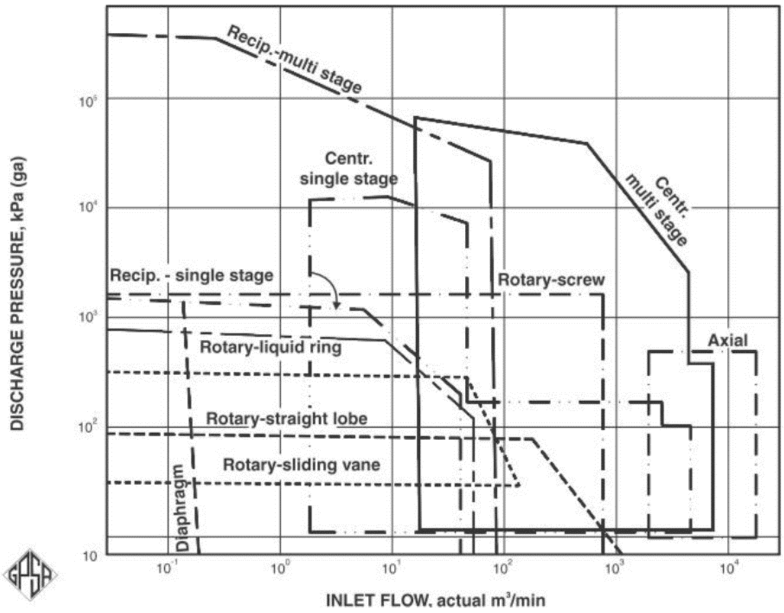
Only centrifugal compressors were considered in the present document. This decision was made based on the compressor coverage chart presented in Figure 4 (Gas Processors Suppliers Association, 2004), where the actual inlet flow is shown on the x-axis and the discharge pressure on the y-axis. All the compressor stations considered here present the following characteristics:

- Flow rate between 100 and 1000m^3/min (at 25°C and 45 barg), corresponding to a range between 294.000 and 2.940.000 Sm^3/h;
- Discharge pressure equal to 7500 kPa(g),

A centrifugal multistage compressor is in fact the only possible choice, as borne out by the observation of the numerous facilities covered in this study, where no reciprocating compressor is present. Whenever the compressor flow is mentioned in this document, reference is made to the nominal or design flow.

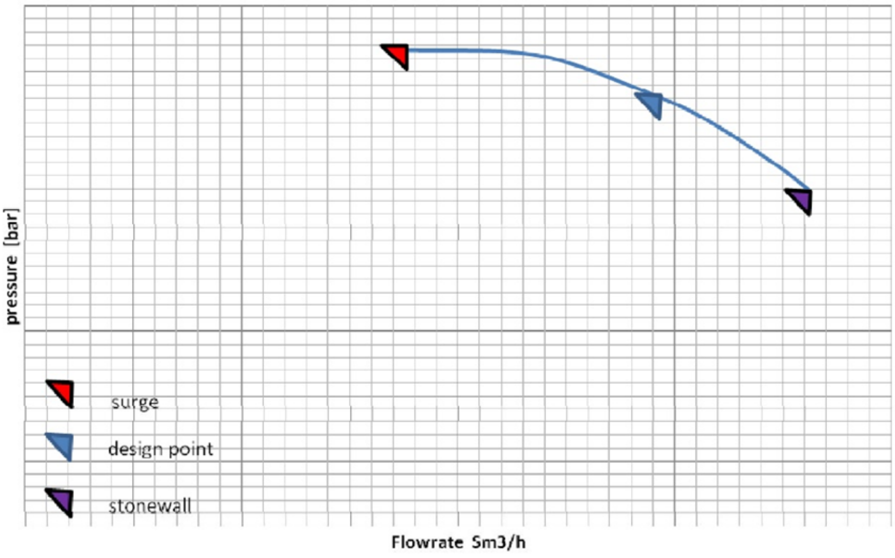
The compressor design flow is related to the normal operating condition of the machine, defined in as the condition at which usual operation is expected and optimum efficiency is desired. This point is usually the point at which the vendor certifies that performance is within the tolerances stated. Such a condition will henceforth be designated as “100% flow”. The design flow, following good engineering practice, is normally centred in the performance curve as detailed in Figure 5 and Table 1.

Figure 4 - Compressor chart.



Source: GPSA, 2004.

Figure 5 - Typical centrifugal compressor performance curve



Source: Tractebel, 2016.

Table 1 - Compressor operational limits

Surge	0.75 x Normal Flow
Design Point	Normal Flow
Stonewall	1.2 x Normal Flow

Source: Tractebel, 2016.

Another important factor is the redundancy level of the compressor station. By analysing the information available and extrapolating when data is not available (some TSOs are reluctant to provide the mentioned information) it can be stated that as general rule the compressor redundancy level is normally set at n+1, where n is the number of running compressors and "+1" denotes a standby unit. This leads to the following considerations:

- If the number of compressors is greater than 3 the CS is considered to have Partial Redundancy
- If the number of compressors is 2 two further scenarios arise:
  - Total redundancy (1 compressor running and 1 in standby)
  - Null redundancy (2 compressors running with no standby available)
- If the number of compressors is 1 the CS has no redundancy.

It should be noted that in case of partial redundancy the n running compressors do not normally handle 100% of their nominal/design flow and can thus provide a measure of further redundancy if required. For example, in a 9+1 configuration (where a single compressor is in stand-by) 8 running compressors can easily recover a potential lack of flow rate due the trip/failure of one unit by working closer to the stonewall point (as per Figure 5).

Based on the considerations above, the following 8 different ECS (showing normal operational conditions) have been built, properly covering the overwhelming majority of the gas compressor stations in Europe:

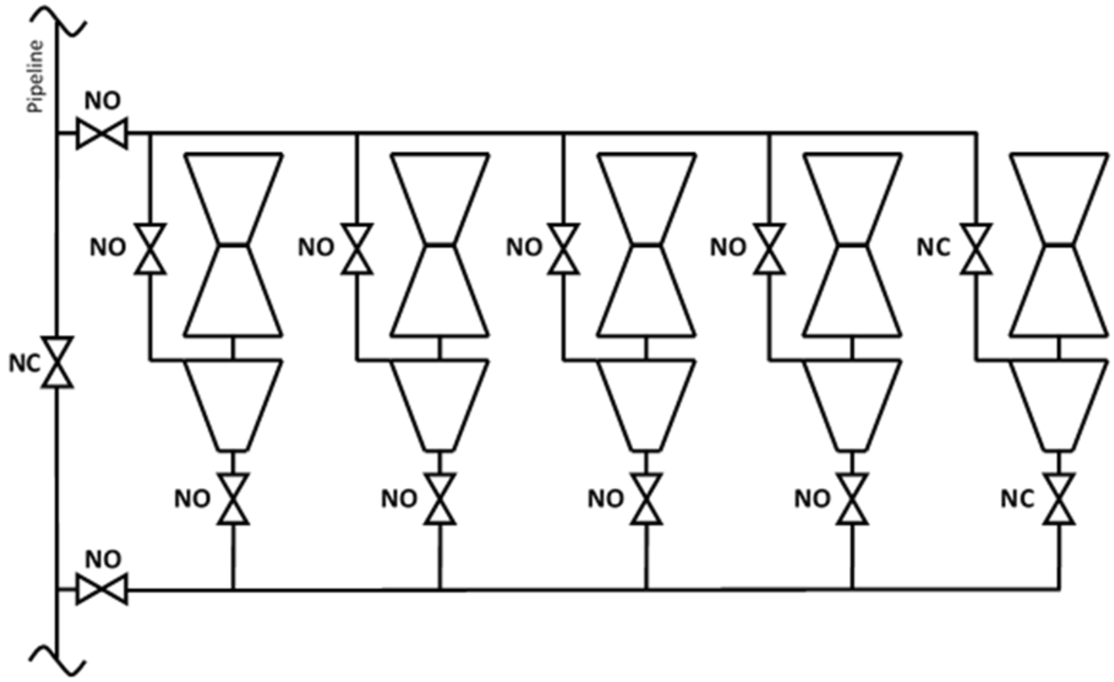
"N" denotes at least 3 machines, "TUCO" stands for turbocompressors, "MOCO" for motocompressors, "RP" means Partial Redundancy (e.g. 2 at 50%), "RN" means Null Redundancy and "RT" stands for Total Redundancy. The schematic diagrams of the 8 ECS are illustrated below and will be the main input data for the functional analysis and risk assessment to be discussed afterwards. "NO" denotes normally open valves, while "NC" denotes normally closed ones.

Table 2 - Equivalent compressor stations

Type	Number of Compressors	Type of Compressors	Redundancy Level
1	N	TUCO	RP
2	N	MOCO	RP
3	2	TUCO	RN
4	2	MOCO	RN
5	2	TUCO	RT
6	2	MOCO	RT
7	1	TUCO	RN
8	1	MOCO	RN

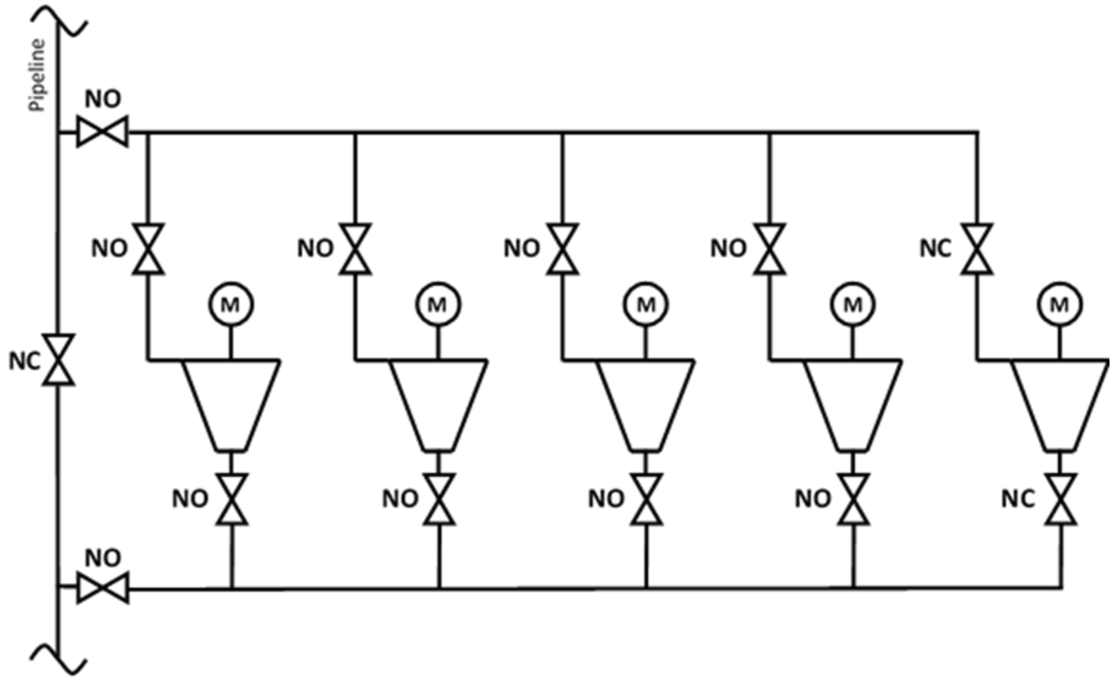
Source: Tractebel, 2016.

Figure 6 - Type 1 ECS: N-TUCO-RP



Source: Tractebel, 2016.

Figure 7 - Type 2 ECS: N-MOCO-RP



Source: Tractebel, 2016.

Figure 8 - Type 3 ECS: 2-TUCO-RN

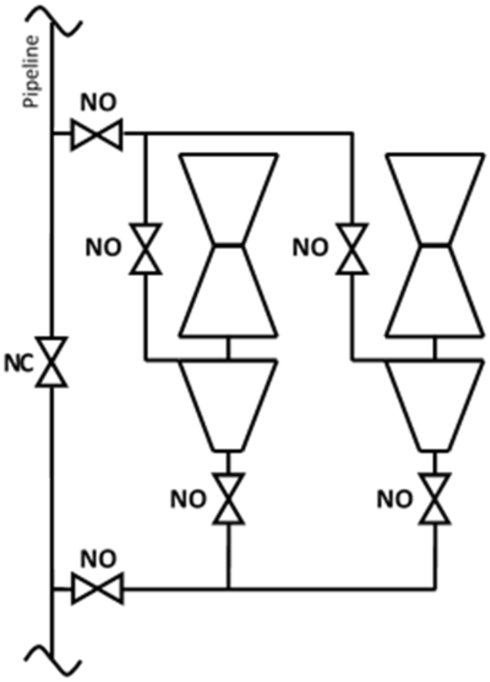


Figure 9 - Type 4 ECS: 2-MOCO-RN

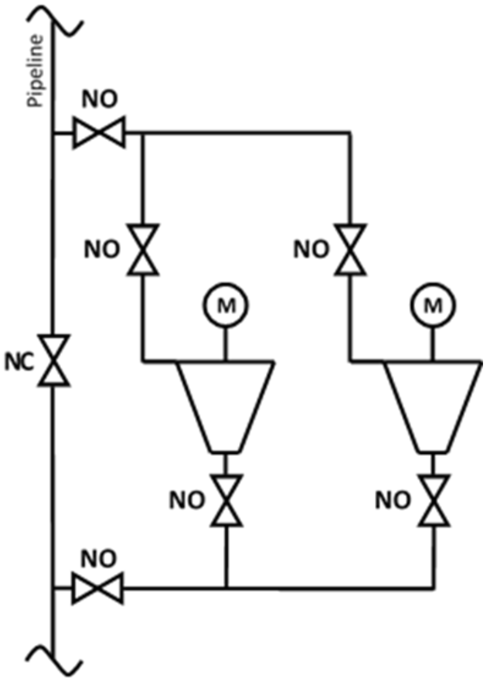


Figure 10 - Type 5 ECS: 2-TUCO-RT

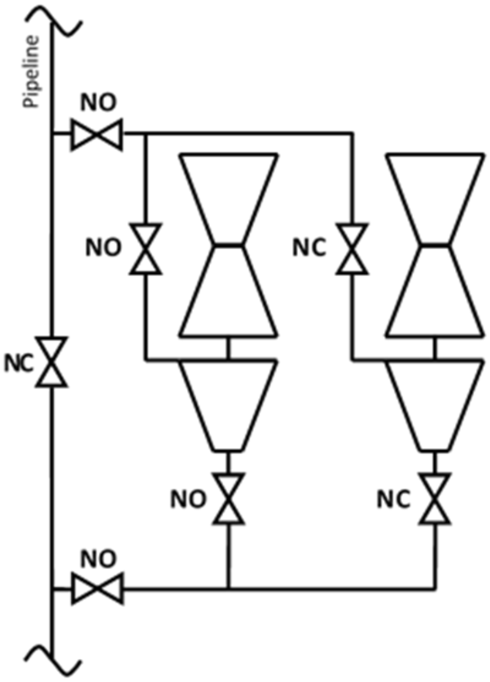
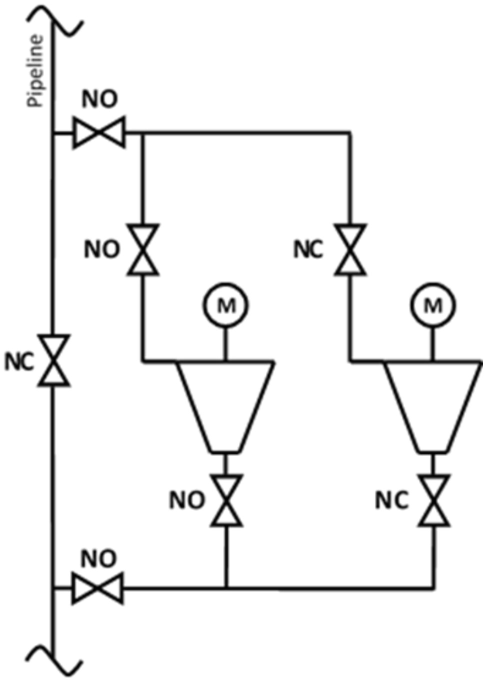


Figure 11 - Type 6 ECS: 2-MOCO-RT



Source: Tractebel, 2016.

Figure 12 - Type 7 ECS: 1-TUCO-RN

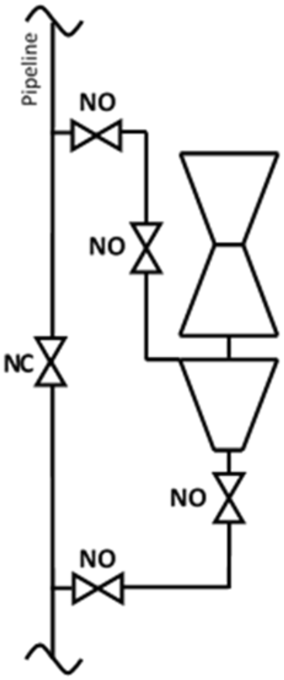
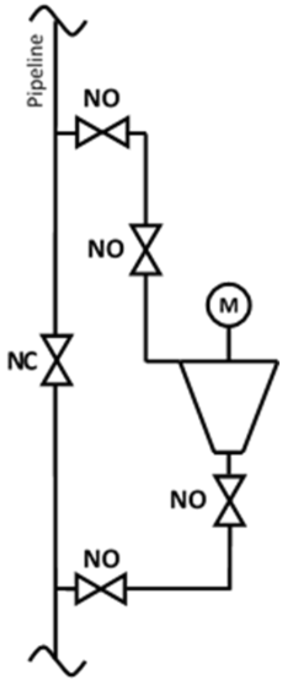


Figure 13 - Type 8 ECS: 1-MOCO-RN



Source: Tractebel, 2016.

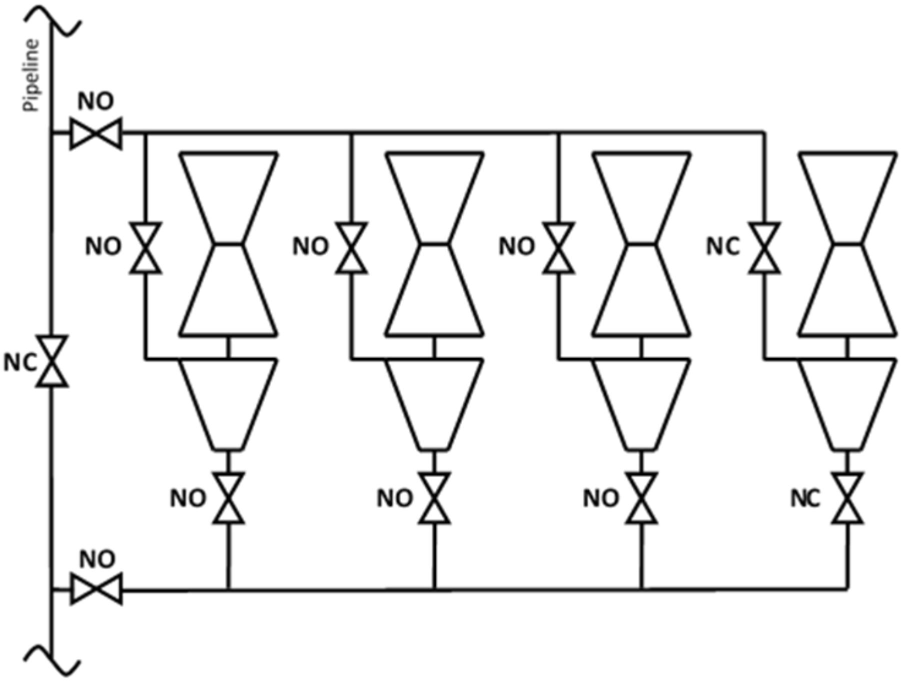
Given the non-trivial number of compressor stations with 3 compressors running and one in standby, two further ECS have been added to main 8 listed above as subsets of the N-TUCO and N-MOCO equivalent models:

Table 3 - Particular models

Type	Number of Compressors	Type of Compressors	Redundancy Level
1a	4	TUCO	RP
2a	4	MOCO	RP

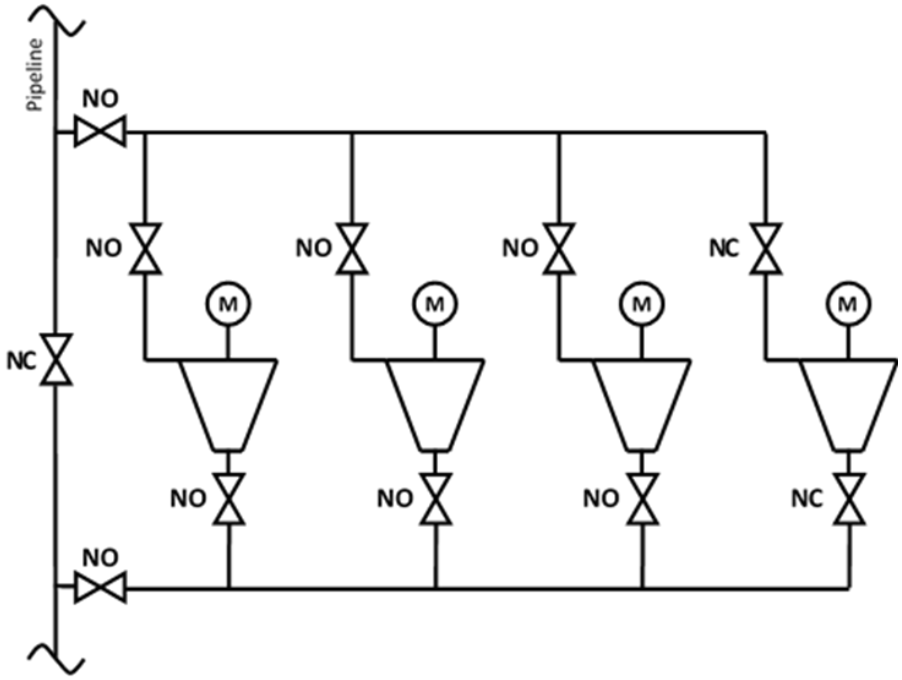
Source: Tractebel, 2016.

Figure 14 - Type 1a ECS: 4-TUCO-RP



Source: Tractebel, 2016.

Figure 15 - Type 2a ECS: 4-MOCO-RP



Source: Tractebel, 2016.

It is worth mentioning that a small number of facilities in the EU are considerably larger in terms of the number of compressors and total installed power, such as Ommen in the Netherlands (16 compressors in total, split between high caloric and low caloric networks) or Baumgarten in Austria. It was however considered that these "complex" facilities do not need to be acknowledged specifically and analysed as additional categories, as explained above. The reliability/availability characteristics of this type of installation do not depend on number and size of compressor units but again on their architectural configuration, i.e. ultimately on the redundancy level and spare part management philosophy of the facilities.

Other facilities should also be mentioned given their importance:

- Underground Gas Storage (UGS) Facilities - Natural gas can be stored in depleted reservoirs in oil and/or gas fields, in aquifers and in salt cavern formations. Gas is stored by means of gas compressors (generally intercooled multistage compressors) and is extracted through the sheer pressure difference. A UGS facility comprises three main sections: the underground gas reservoir, a gas treatment plant and a gas compression/injection station. Compressors used in UGS compressor stations are typically turbine-driven multistage centrifugal type (flow rates above 270.000 Sm^3/h being normal values) with no standby units. In fact, although the required compression ratio is normally higher than in pipeline compressor stations (2 to 3 times), it is achievable by a single multi-stage train, with no need of multiple compressors in series configuration. For this reason, the UGS compressor station can be assimilated to and modelled as a standard compressor station.
- Liquefied Natural Gas (LNG) Terminals - In regasification terminals the LNG is stored and regasified for dispatch in pipelines. Terminals consist mainly of cryogenic atmospheric tanks in which LNG is stored at about −160 °C. LNG is first compressed by pumps submerged in the storage tanks (Low Pressure pumps); afterwards an additional compression stage (High Pressure pumps) is performed to reach the network pressure, the LNG is vaporized and brought at about 3-5°C to be sent to the pipeline. Usually a boil-off gas (BOG) compressor is installed in order to handle the BOG that is generated in the tanks during the loading phases. This compressor has not been considered in the equivalent model for this study, since it works intermittently (a few hours during a loading operation) and its operation does not directly affect the gas send out from the terminal. For this reason the BOG compressor normally has no spare (any maintenance activity can be easily carried out between two loadings).

3 Internal Security Risk Scenarios Identification and Characterization

3.1 Scope and Methodology

This section provides a detailed description of the implemented methodology, its application and obtained results. The objective of the present section is the identification and characterization of internal security risk scenarios. The present analysis is focused on successions of events leading to facility failures, the likelihood/probability of such scenarios, as well as the determination of flow and pressure effects and facility downtimes. The analysis is performed on the taxonomy of the most relevant compressor stations types identified previously, including for compression stations of UGS and LNG facilities.

The procedural steps can be summarized as follows:

- Functional Analysis, to identify a functional model (i.e. hierarchical structure) for the typical functions performed by compressor stations as a reference to define typical station/equipment failures;
- Critical elements identification, to highlight the most relevant equipment failures contributing to gas compression disruption among those identified during functional analysis;
- Damage Classes identification, to set the reference scenarios to be evaluated by a probabilistic assessment to characterize gas compressor station failures;
- Component modelling, to collect data characterizing component failure modes in terms of failure and repair;
- Fault Tree Analysis, to estimate the probability of occurrence of each Damage Class, for each typical configuration identified earlier.

3.1.1 Functional Analysis

A Functional Analysis is a procedure performed to identify the main functions of a system in order to provide a description (model) of the system itself according to its functions. The functional model has been set according to a hierarchical structure to split the most general functions into sub-functions in order to reach elementary functions performed by single equipment or small sets of components. A portion of the functional model is shown in Table 4. It has been applied to drive a HAZID (HAZard IDentification) session involving some experts in gas compression stations, in order to discuss the relevance of each function, operative problems, consequences in case of failures and typical approaches to malfunction recovery, resulting in a systematic mapping of functions and failures, with particular regard to operability and availability, typology, architectures and possible criticalities encountered in operation, as reported and discussed below.

Table 4 - Functional Analysis Example.

FUNCTION	DESCRIPTION	NOTES
1	Gas entry in the station	
1.1	Pipelines coming in the station	
1.2	Entry pipeline pigging lines	
1.2.1	Venting of the traps	
2	Gas filtration/ separation	
2.1	Sending the line gas to filtering/separation	
2.2	Line gas filtration/ separation	
2.3	Sending the line gas to compression	

Source: Tractebel, 2016.

3.1.2 Critical elements identification for Gas Compression Stations

Among the thousands of components present in a typical gas compressor station, those most responsible for the unavailability of gas station operations must be identified. In order to have a quantitative ranking of the criticality of components and equipment installed in a generic Gas Compression Station, a complete and detailed availability study for an existing Gas Compression Station performed by RAMS&E in the past has been selected and analysed.

This ranking is fundamental for the next steps of the analysis in order to focus on critical components in the probabilistic analysis, for each typical configuration presented above, thus avoiding a huge amount of work on components that do not contribute significantly to put the station out of service. By using this approach it was possible to quantitatively evaluate the relative influence of the various sub-components in the station unavailability and to put in evidence the most critical elements in a Gas Compression Station.

An historical analysis, to highlight the causes and location of technical failures, has also been performed on the database provided by PHMSA (Pipeline and Hazardous Material Safety Administration Database – U.S. Department of Transportation) (Pipeline and Hazardous Materials Safety Administration, 2014).

3.1.3 Damage Classes Identification

The ultimate goal of the work presented here is to define a set of failure scenarios for typical EU gas compressor stations and the related probability of occurrence. Damage Classes represent the set of scenarios to be identified and analysed in this study. Each Damage Class is representative of a different degree of degradation of the service expected by gas compression station for the network.

Starting from the taxonomy, and particularly the redundancy level of the different station types, the Damage Classes are identified and presented as the percentage of the nominal outlet flow available at the station in case of failure. No classes have been defined in terms of “output pressure reduction” since pressure and flow rate are directly connected by the load curve of the compressors/pumps; in addition it must be pointed out that the function of the station is to enable the mass transfer rather than the per se pressurization of the network. For these reasons, Damage Classes have been based on different grades of flow rate reduction. A confirmation of this point has been provided during the expert operators’ interview.

All the compressors, for each compression station, have been considered equivalent (for typology, power and characteristics). The same approach has been used to analyse pumps present in Liquid Natural Gas (LNG) storage facilities.

3.1.4 Components Modelling

The various compression stations and the LNG facilities have been exploded in their components to be evaluated in terms of availability. Component characterisation must be performed setting two parameters for each failure mode affecting the component itself:

- Failure Rate (FR), in (1/hours);
- Mean Time to Repair (MTTR), in hours.

For failure rate data, several databases have been considered (Chudoba, 2014) (EXIDA, 2008) (EXIDA, 2007) (Lees, 2005) (OREDA, 2009). Failure rates are almost independent of the power of the specific machinery (compressors/pumps), at least considering the power range usually applied in this kind of applications. Failure Rates have been assumed to be constant over time and mainly characterised by their mean values, and the probabilities of failures have been characterised by the use of a negative exponential distribution over time. No additional considerations about wear-in and wear-out impacts have been made, considering the equipment under study in the optimal reliability range of its lifetime, when failures can be considered characterized only on a random basis. The previous assumptions are normally applied during usual availability studies for complex installations. MTTR is the out of service time due to a failure and it must be set taking into account different contributions for this kind of installation:

- Active Repair, the time necessary to repair or replace the component, plus a final functional test;
- Technical Delay, the time required to prepare the machinery or system for maintenance (e.g. blow down, purging,...) and the time necessary to restore the operating conditions (e.g., the pressurization at the end of repair);

- Logistic Delay, the time necessary to provide spare parts (stocks), maintenance operators and special tools if necessary.

Active repair times have been taken from (OREDA, 2009). Technical delay times have been assumed on the basis of engineering assumptions.

In order to take into account different plant locations, the presence of available stocks, etc. three logistic delay times have been considered:

- 1 h logistic delay time (spare part present in plant warehouse);
- 24 h logistic delay time (spare part shortly available);
- 1 week logistic delay time (spare part not readily available).

Calculations have been run with these different assumptions for logistic times in order to have results representative of plants equipped with spare parts or situated in easily reachable areas and plants in areas difficult to reach. For compression stations where dated or unusual machinery are present (e.g. of Soviet construction) it is generally standard to have spare parts in the warehouse at least for the most critical or hard to find on the market components. In the present analysis it is assumed that this condition is satisfied. Fault location and detection has been considered as negligible since all gas stations are locally manned. The format for the reliability data is illustrated in Table 5.

Table 5 - Format for the reliability data.

Component	Failure Mode	Failure Rate [1/h]	Failure-on-Demand Probability	Active Repair Time [h]	Technical Delay Time [h]	MTTR [h]			Notes	Reference
						Logistic Time				
						1 h	24 h	168 h		

Source: Tractebel, 2016.

3.1.5 Fault Tree Analysis

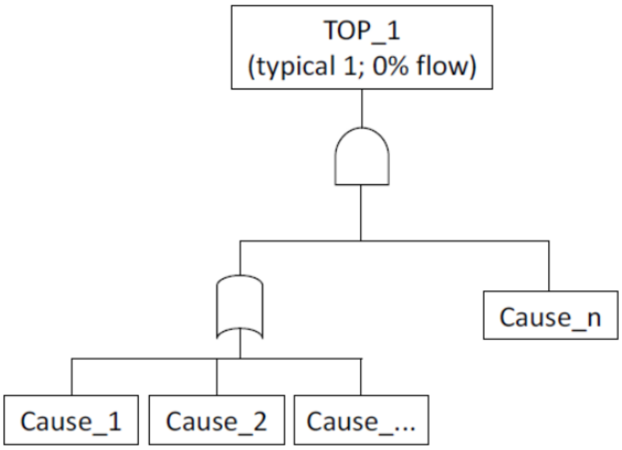
For each type of compression station and for the LNG facilities, the Fault Tree Analysis (FTA) technique has been used to calculate the probability of the station to be in each specific Damage Class. FTA allows the calculation of a Top Event (system failures/damage class) probability as resulting by the combinations of elementary failures (components failure modes) and the related statistical data (FR and MTTR). For the Top Event two different estimations were performed:

- Unavailability: the probability of out-of-service condition, expressed as the ratio between the system downtime due to failures and the overall theoretical time of operations (i.e., the operational time for an ideal failure-free system);
- Unreliability: the probability of system failure before a given period of time, or alternatively the expected number of failures referred to a period of time.

A fault tree example is presented in Figure 16.

The output of this analysis is, for each configuration identified earlier and for all the defined Damage Classes (considering various logistic delay times), the probability that the facility is in the specified Damage Classes, and the frequency of these occurrences. In addition, criticality indexes for components are provided, i.e. the contribution of each component failure to the overall unavailability or unreliability of the entire station; this result allows identifying the weak points of the installations for each Damage Class and for each configuration.

Figure 16 - Fault Tree.



Source: Tractebel, 2016.

3.2 Functional Analysis

3.2.1 Gas Compression Station

In order to highlight the functions of the subsystems of a generic compressor station a Functional Analysis has been performed. This analysis splits the installation into its main functions, which are further decomposed into the elementary functions that constitute the main one. The functional model has been set according to hierarchical structure to split the most general functions into sub-functions to reach elementary functions performed by single equipment or small sets of components. A list of main functions and relative sub-functions has been produced.

The Functional Analysis has been used to facilitate the subsequent HAZID analysis, performed with the support of experts in gas compression stations in order to concentrate the analysis on systems actually representative of installations present in Europe. During the analysis the HAZID team added notes about the most commonly encountered architectures and specific operational problems of the various identified sections. Table 6 presents a summary of the considerations deriving from the HAZID process.

Table 6 - Summary from HAZID session.

FUNCTION	DESCRIPTION	NOTES
1.	Gas entry in the station	No particular issues for the availability of the compression station; at most there could be leakages from the pig trap
1.1	Pipelines reaching the station	
1.2	Entry pipeline pigging lines	
1.2.1	Venting of the traps	
2.	Gas filtration/ separation	Gas sent to compressors undergoes separation
2.1	Sending the line gas to filtering/ separation	

2.2	Line gas filtration/ separation	For cartridge filters redundancy is always provided; these filters are usually substituted in about one hour. Cyclone separators require very little maintenance and generally do not give operative problems
2.3	Sending the line gas to compression	
3.	Compression of gas	
3.1	Compressors	
3.1.1	Power transmission	
3.1.2	Compressor unit	
3.1.3	Control and monitoring	The control and monitoring system of the driver and of the compressor is generally integrated and can be restored in few hours (three hours is assumed). The compressors are tripped by low inlet pressure, high outlet temperature and high outlet pressure (and other causes such as vibrations, rotor position, lubricant oil pressure/ temperature, dry gas seal low pressure etc.)
3.1.4	Lubrication system	Lubrication pumps can be electrically driven or mechanically driven by the gas turbine/ compressor. Lubrication pumps are always provided with electrical spare pumps. If the gas turbine/compressor is equipped with mechanically driven lubrication pumps the spare electrical pump is used also during start-up and shut-down transients during which the mechanically driven pump would not have the right speed to supply the correct oil flow to bearings
3.1.5	Shaft seal system	
3.1.6	Miscellaneous	
3.2	Gas Turbine	Gas turbines undergo main maintenance about every 25’000 hours (down time about 1 month) and minor maintenance about every 10’000 hours (down time about 1 week)
3.2.1	Starting system	The starting of a gas turbine can take about 20 minutes
3.2.2	Gas generator	
3.2.3	Power turbine	
3.2.4	Control and monitoring	The control and monitoring systems of the driver and of the compressor is generally integrated and can be restored in few hours (three hours is assumed)

3.2.5	Lubrication system	Lubrication pumps can be electrically driven or mechanically driven by the gas turbine/ compressor. Lubrication pumps are always provided with electrical spare pumps. If the gas turbine/compressor is equipped with mechanically driven lubrication pumps the spare electrical pump is used also during start-up and shut-down transients during which the mechanically driven pump would not have the right speed to guarantee the correct oil flow to bearings
3.2.6	Miscellaneous	
3.3	Electrical motor	
3.3.1	Control and monitoring	The control and monitoring systems of the driver and of the compressor is generally integrated and can be restored in few hours (three hours is assumed)
3.3.2	Cooling system	
3.3.3	Electric motor	The electric motors maintenance is usually scheduled to be performed every 3 years (26'280 hours) and involves a downtime equal to 14 days (336 hours)
3.3.4	Lubrication system	
3.3.5	Miscellaneous	
3.4	Cooling the compressed gas	Compressed gas could be cooled in air coolers (cooling requirement depends on pipeline temperature design). The principal deviation for these systems is the fan electric motor failure (these motors can be substituted in about one hour)
3.4.1	Heat exchanger	
3.4.2	Air cooler	
3.4.2.1	Fans	
4.	Sending the gas from the station	No particular issues for availability of compression station; at most there could be leakages from the pig trap
4.1	Exit pipelines pigging lines	
4.1.2	Venting of the traps	
4.2	Departure of pipeline from station	
5.	Auxiliary services	

5.1	Main power supply	Electricity is transformed into “low voltage” in the compression station
5.2	Emergency power supply	Both emergency generators (generally diesel engine driven) and batteries are usually present
5.2.1	Emergency generator storage fluids	
5.3	Supply fuel gas to users	Fuel gas to users is obtained by reducing the pressure of line gas
5.3.1	Pressure Reduction	The fuel gas for turbo gas turbines pressure could be reduced and temperature raised before the combustion chamber. The fuel gas heating is performed in a heat exchanger via hot water from a dedicated boiler
5.3.2	Sending the fuel gas to Turbo gas	In case of gas spilled from the line to be used as fuel gas in gas turbines cartridge filters are always present in order to avoid plugging of burner orifices
5.3.3	Sending the fuel gas to the auxiliary boiler	Fuel gas for boiler burners is heated, before pressure reduction, by an electric heater
5.4	Compressed air	Compressed air can be used to actuate smaller valves (e.g. control valves)
5.4.1	Air supply	
5.4.2	Air dehumidification	
5.4.3	Filtering	
5.4.4	Air compression	Air, to actuate valves, is compressed to about 14 barg pressure; 2 compressors are present (one compressor spare)
5.4.5	Storage	A buffer (allowing valves operations with air compressors not available) is present
5.4.5.1	Main storage of compressed air	
5.4.6	Compressed air distribution	
5.5	Heating water to the users of the station	2 boilers (one boiler spare) are used to pre-heat fuel gas for turbo gas turbines (before pressure reduction); one additional boiler is for general use (buildings, sanitary)
5.5.1	Gas supply via dedicated line	
5.5.2	Heat generation	
5.5.3	Heating sanitary water	

6.	Safety Services	Gas compression stations are equipped with fire and gas sensors that shut down the station. The station is divided in isolatable sections that can be separately vented. The isolatable section including the compressor is about 45 m at 75 barg; sometimes a buffer volume to discharge the gas is present, the gas stored here in case of emergency can be reintroduced in the line by a reciprocating compressor
6.1	Protection against internal events	
6.1.1	Containment basins	
6.1.2	Fire detection system	Fire detectors activate station shutdown
6.1.2.1	Firefighting system with water of the station	
6.1.2.1.1	Firefighting water distribution	
6.1.2.1.1.1	Lines of firefighting water distribution	
6.1.2.1.1.2	Hydrants	
6.1.2.2	Firefighting system with slaved CO2 to vent machines.	
6.1.2.2.1	CO2 storage	
6.1.2.2.2	CO2 distribution	
6.1.2.3	Firefighting with water	
6.1.2.3.1	Water storage	
6.1.2.3.2	Distribution of water	
6.1.3	Portable fire extinguishers	
6.1.4	Fire detection: smoke, heat etc. detectors	
6.1.5	Alarm System	
6.1.6	Distributed control with DCS	
6.1.7	Gas detection	Gas detectors activate station shutdown
6.2	Protection from external events	

6.2.1	Flood protection	
6.2.2	Protection against earthquakes	
6.2.3	Protection from external projectiles	
6.2.4	Protection from tornadoes	
6.2.5	Protection from lightning	Gas stations are not generally provided with lightning conductors as they are auto-protected; a grounding system is provided

Source: Tractebel, 2016.

Other general results obtained during HAZID were obtained:

- Generally, interruption of compression functionality for few hours (up to 4 hours) is not critical for the gas network due to the line pack, i.e. the pressurized gas present in piping. The network is pressurized between 55 and 75 barg, the flow velocity is about 8 – 15 m/s during normal operations and 2 – 3 m/s during pigging of the lines.
- Due to efficiency reasons compressors generally work in the upper part of their working range. It has been pointed out that if the compression group (driver, compressor and relative accessories) works properly it can ensure the nominal pressure of the network, the latter as a whole defining the pressure.
- Natural gas flowing in gas pipelines, due to his low hydrogen sulphide content, is not chemically aggressive for steel; corrosion allowance is not used.
- Valves can be actuated by “gas over oil” (pressure of the line gas is reduced to about 45 barg) or, for smaller valves (e.g. control valves), by compressed air (about 14 barg pressure). In case of “electrohydraulic” valves, 3 strokes of valves are guaranteed in case of circuit low pressure.

The architecture of compression stations for UGS is not dissimilar from that used for line compressor stations, enabling the extension to UGS facilities of considerations done for these installations. It is also possible to identify the systems that constitute LNG installations: tanks, LP pumps, HP pumps and vaporizers. Pumps are typically driven by electric motors. It is therefore possible to study the unavailability of these subsystems and its contribution to the unavailability of the whole system.

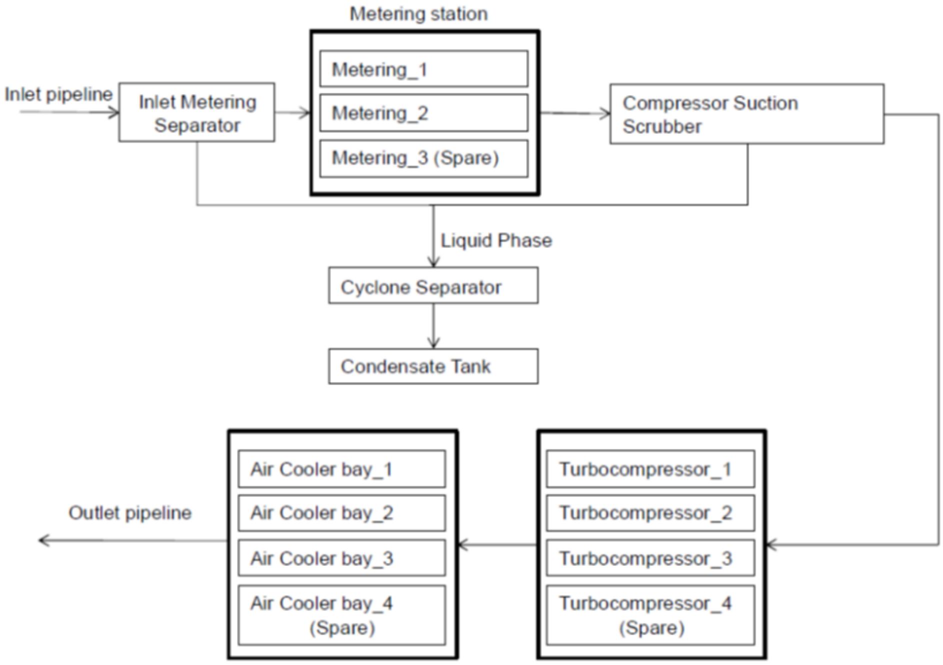
3.3 Critical element identification for Gas Compression Stations

3.3.1 Availability study applied to an existing gas compression station

In order to have a quantitative ranking of the criticality of sub-units present in a generic compressor station, a previously performed complete availability study applied to a compressor station representative of a generic installation has been analysed. It is therefore possible to evaluate the contribution of the main subsystems and components to the unavailability of the station. The selected compression station is composed of four turbo compressors driven by gas turbines (3 operating and one spare).

Before being sent to compressors, gas coming from the compression station inlet pipeline passes through a separation section (Inlet Metering Separator), through a Metering Station composed of three lines (3 x 50%), each equipped with a ultrasonic flow sensor, and through another separator (Compressor Suction Scrubber); the liquid phase collected in the two separators is sent to a Cyclone Separator and stored in a Condensate Tank. Most of the gaseous phase is sent to compressors, a small fraction being sent to the fuel gas system. Fuel gas is designed to feed the turbines of compressors and the emergency power generation. After compression, gas is cooled in Air Coolers (4 bays, 3 operating and 1 spare, each one with 2 fans). The functional scheme of the above described compression station is illustrated in Figure 17.

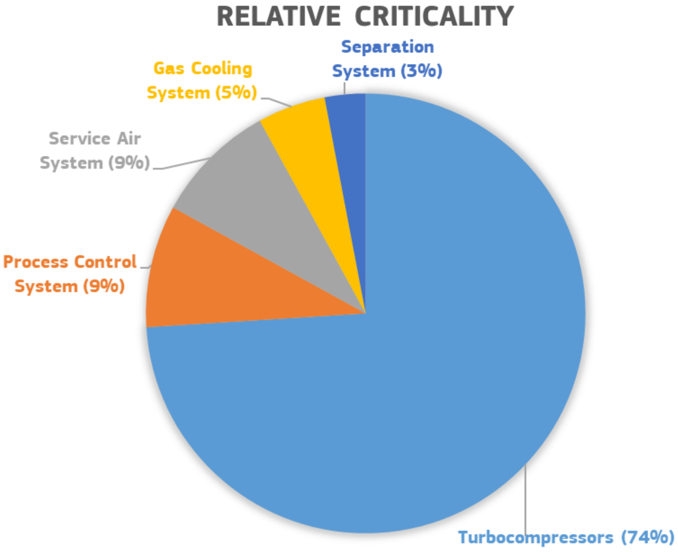
Figure 17 - Functional schematic of generic compressor station.



Source: Tractebel, 2016.

The study performed to calculate the availability of the aforementioned compressor station demonstrated that (neglecting inferior order contributions) the contribution of the subsystems to the station unavailability is mainly due to turbo compressors (74%), Process Control System and Service Air System contribute at 9% each, the Gas Cooling System has a contribution of 5% and the Separation System contributes for 3% (mainly due to malfunction of high level switches on condensate separators and condensate tank). Figure 18 illustrates the relative criticality of the main subsystems of a Gas Compression station.

Figure 18 - Criticality of main subsystems.



Source: Tractebel, 2016.

From the results of this analysis it is evident that compressors give the main contribution to the unavailability of the gas station; it is important to include in the failure of compressors and their drivers, since the process control system has a non-negligible contribution. The effect of "Service air failure" has a significant contribution. The Gas Cooling System has a lower contribution to gas station unavailability; HAZID analysis evidenced that this system is not always present and, if present, gas cooling is performed by air coolers. The influence of the separation system is minor; in the plant considered in the availability study, the level switches present on the condensate tank and on the condensate separator activate plant shut down. The spurious intervention of these sensors gives a non-negligible contribution to system unavailability.

3.3.2 Historical Investigation

Relevant information about gas transportation facilities is present in the database created by PHMSA (Pipeline and Hazardous Materials Safety Administration, 2014), which requires pipeline operators to submit reports for incidents following the directives issued by Title 49 of the Code of Federal Regulations (49 CFR Parts 191, 195), published in the Federal Register by the executive departments and agencies of the federal government of the United States (United States Department of Transportation, 2014). The aforementioned database includes reported incidents that meet the sequent definitions (see Regulation 49 part 191.3):

"Incident means any of the following events:

(1) An event that involves a release of gas from a pipeline, or of liquefied natural gas, liquefied petroleum gas, refrigerant gas, or gas from an LNG facility, and that results in one or more of the following consequences: (i) A death, or personal injury necessitating in-patient hospitalization; (ii) Estimated property damage of $50,000 or more, including loss to the operator and others, or both, but excluding cost of gas lost; (iii) Unintentional estimated gas loss of three million cubic feet or more;

(2) An event that results in an emergency shutdown of an LNG facility. Activation of an emergency shutdown system for reasons other than an actual emergency does not constitute an incident.

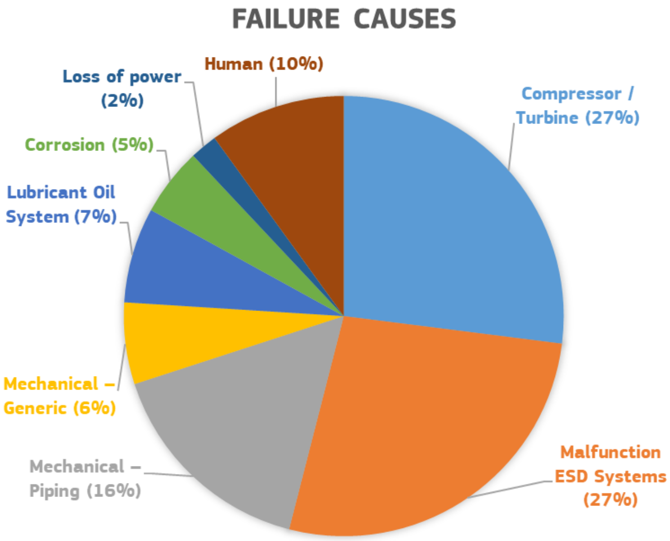
(3) An event that is significant in the judgment of the operator, even though it did not meet the criteria of paragraphs (1) or (2) of this definition."

From the conditions reported above it is evident that the database contains only major accidents. From this database, reports of accidents that occurred in compressor stations in the period 1986 – September 2014 have been selected. Figure 19 illustrates the different causes of failures of a gas compression stations.

Accidents due to technical causes or human errors (184 accidents) have been taken into consideration.

About 50% of accidents is due to Mechanical Failures: in 27% of cases it is expressly reported that the failure occurred at the compressor or at the turbine; in 16% of cases the fault location is specified in piping (fittings, gaskets, flanges, valves etc.); in 6% of cases the fault location is not indicated or it is different from the others above cited. Another important cause of failure is the malfunction of controls or ESD systems, responsible for 27% of the failures (generally ESD spurious intervention). The lubricant oil system caused 7% of failures (generally leakage of oil that caught fire). Corrosion was responsible for 5% of failures. Loss of power, loss of electric power and emergency generators or batteries failure on demand, caused 2% of failures of gas compression stations. Human errors (errors during maintenance, vehicle collision, improper operation, etc.) contributed for 10% of total cases of failure of gas compression stations.

Figure 19 - Causes of failure in compressor stations.



Source: PHMSA, 2014.

Some reports indicate a shut down time due to various accidents, such data being available only for recently issued reports (2010–2014). Table 7 illustrates mean downtimes for various causes, 29 accidents having been considered:

Table 7 - Shutdown time by accident cause.

Cause	Mean Downtime [h]
Mechanical, Compressor/ Turbine	206
Malfunction, ESD/ Control System	28
Mechanical, Piping	46
Human	80
Lubricant oil system	40
Corrosion	220
Loss of power	2

Source: PHMSA, 2014.

A detailed historical analysis is presented later in the present document in order to put in evidence the influence of natural phenomena on accidents involving gas compression facilities.

3.4 Damage Classes

The compressor station taxonomy presented above was analysed to identify the relevant Damage Classes that are possible for these installations and that are liable to affect the operation of the transportation network. Such an identification of is based on the following considerations:

- Eight typical configurations have been identified for compressor stations (also representative of UGS facilities) and are characterized by different redundancy levels; for each configuration, all compressors have been considered identical in power and characteristics. Such typical configurations can also be used as building blocks for the description of more complex stations as a series or parallel arrangement of such different configurations.
- Regarding LNG facilities a dedicated typical configuration has been identified; from its architecture and redundancy it is possible to identify Damage Classes as reduction of LNG flow due to pump (or its driver or accessories) failure, or to cryogenic tank leakage or to vaporizer failure.
- Analogously to compressor stations, in the case of LNG facilities all pumps of each type (Low Pressure and High Pressure) have been considered equivalent in power and characteristics; storage tanks and vaporizers have also been considered equivalent among them.

Damage Classes have been defined in terms of flow rate reduction only, without considering the reduction of the output pressure, since the function of the stations is to enable mass transfer rather than providing per se network pressurisation.

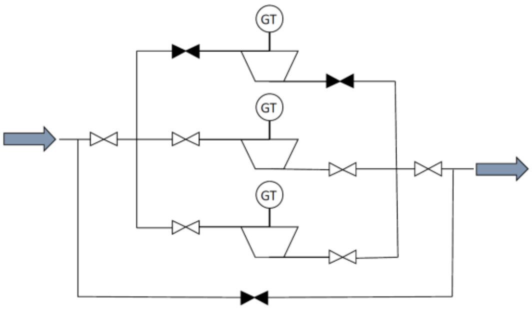
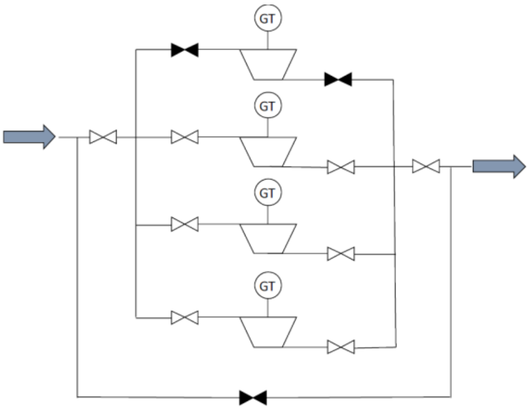
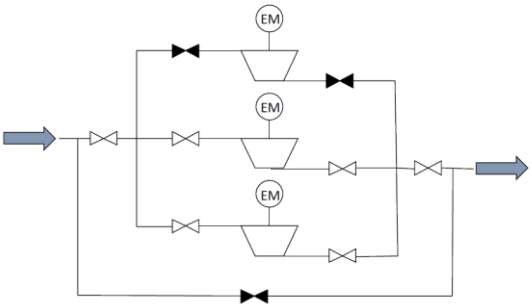
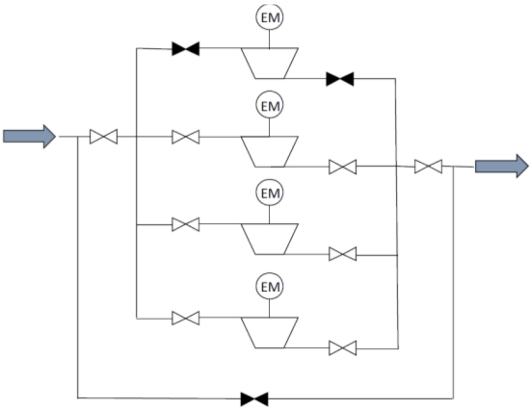
3.4.1 Gas Compression Stations/ UGS Facilities

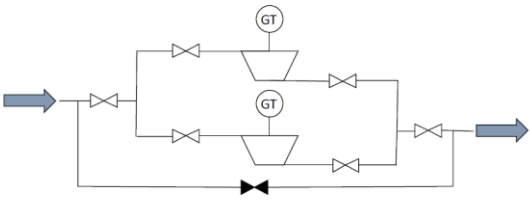
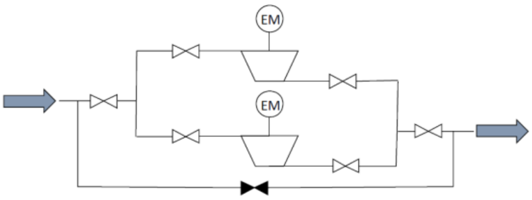
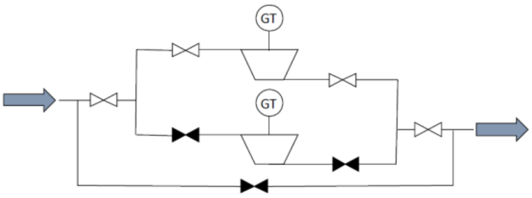
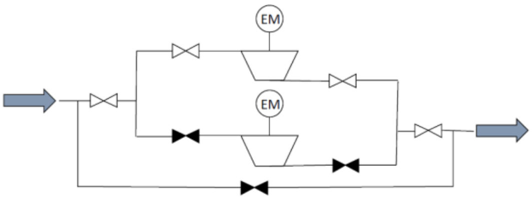
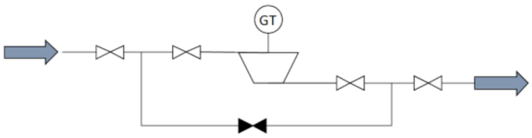
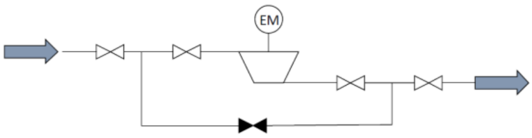
Damage Classes have been set for gas compression stations and UGS facilities:

- The 0% flow damage class represent a scenario in which the compressors stops and the bypass valve fails to open, resulting in a total absence of gas flow through the station. This class takes place when the compressors and the valve that opens the bypass all fail simultaneously.
- The 33, 50 and 66% flow damage classes (nominal pressure) are the scenario in which each percentage of the nominal flow is delivered.
- The “Bypass” damage class is the case of the compression station completely bypassed without performing compression (the pressure having essentially its value upstream of the station), without flow interruption. The occurrence of this class needs the concurrent failure of all the compressors but the correct functioning of the bypass valve. This class is of course not relevant for UGS facilities.

The flow rate reduction refers to the “nominal” flow rate expected by each typical configuration, according to network pressure. In configurations with 3 compressors, 2 compressors running and 1 compressor spare (configurations 1 and 2) the 33% and 66% flow damage classes are not applicable. In configurations with 4 compressors, 3 compressors running and 1 compressor spare (configurations 1a and 2a) the 50% flow damage class is not applicable. In configurations s with 2 compressors both running, no spare (configurations 3 and 4) the 33% and 66% flow damage classes are not applicable. In configurations with 2 compressors, one spare (configurations 5 and 6) the 33%, 50% and 66% flow damage classes are not applicable (one compressor running ensures the nominal flow). In configurations with 1 compressor and no spare (configurations 7 and 8) the 33%, 50% and 66% flow damage classes are not applicable (the only compressor ensures the nominal flow). In Table 8, for each typical architecture, the applicable Damage Classes have been marked. These classes are also applicable to Underground Gas Storage (UGS) Compression Stations.

Table 8 - Damage classes for compressor stations/ UGS facilities.

Configuration	Sketch	Damage Class				
		0% Flow	33% Flow	50% Flow	66% Flow	Bypass
N-TUCO-R (3 compressors gas turbine driven, 1 spare)		X		X		X
4-TUCO-RP (4 compressors gas turbine driven, 1 spare)		X	X		X	X
N-MOCO-RP (3 compressors electric motor driven, 1 spare)		X		X		X
4-MOCO-RP (4 compressors electric motor driven, 1 spare)		X	X		X	X

2-TUCO-RN (2 compressors gas turbine driven, no spare)		X		X		X
2-MOCO-RN (2 compressors electric motor driven, no spare)		X		X		X
2-TUCO-RT (2 compressors gas turbine driven, 1 spare)		X				X
2-MOCO-RT (2 compressors electric motor driven, 1 spare)		X				X
1-TUCO-RN (1 compressor gas turbine driven, no spare)		X				X
8-1-MOCO-RN (1 compressor electric motor driven, no spare		X				X

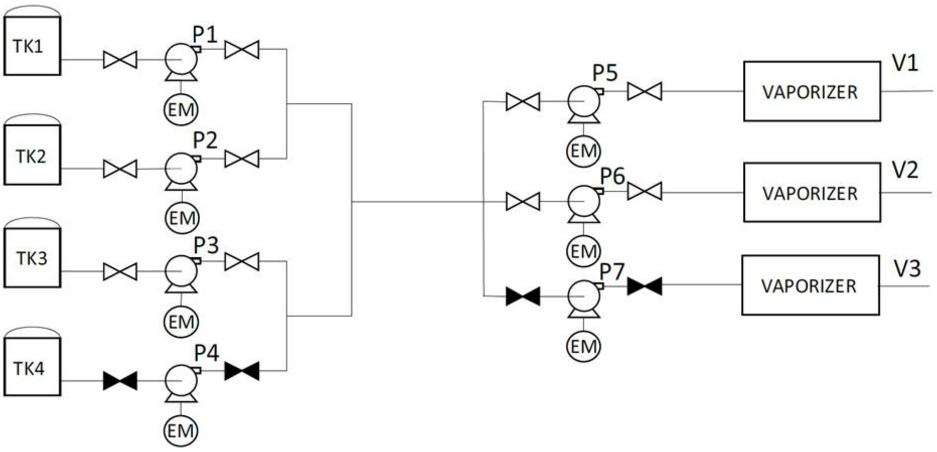
Source: Tractebel, 2016.

3.4.2 LNG Facilities

The selected typical configuration for the LNG Terminals is illustrated in Figure 20.

TK1-4 are the LNG storage tanks, P1-4 are the Low Pressure pumps, submerged in tanks 1-4 (3 pumps are operative, one pump in standby), P5-7 are the High Pressure pumps (two pumps are operative, one pump in standby), V1-3 are the vaporizers in which the regasification process takes place. In the typical analyses in the present study all pumps are driven by electric motors. In this case, considering the level of redundancy, four Damage Classes were identified at 66, 50, 33 and 0% of the nominal flow. The “Bypass” damage class is not relevant for LNG facilities.

Figure 20 - LNG Terminal schematic.



Source: Tractebel, 2016.

3.5 Components Modelling

The various compressor stations and the LNG facilities have been decomposed into their components to be evaluated in terms of reliability and production availability, in order to estimate how component failures contribute to the time spent by the system in each Damage Class along the year (system production unavailability - Q) and the number of transitions from the normal operation to each Damage Class (system unreliability or Expected Number of Failures - ENF).

Component characterisation must be performed setting two parameters for each failure mode affecting the component itself:

- Failure Rate (FR) – [1/h];
- Mean Time To Repair (MTTR) – [h].

Failure Rates have been assumed to be constant over time and mainly characterised by their mean value, and the probabilities of failures have been characterised by the use of a negative exponential distribution over time.

No additional considerations about wear-in and wear-out impact have been done, considering the equipment under study in the reliability optimal range of its lifetime when failures can be considered characterized only on a random basis.

MTTR is the out of service time due to a failure and it must be set taking into account for different contributions, for this kind of installations:

- Active Repair, the time necessary to repair the component or for its substitution and a final functional test;
- Technical Delay, the time required to prepare the machinery or system for maintenance (e.g. blow down, purging, …) and the time necessary to restore the operating conditions (e.g. pressurization at the end of repair);
- Logistic Delay, the time necessary to provide spare parts, maintenance operators and special tools if necessary.

Active repair times have been mainly taken from (OREDA, 2009).

Technical delay time has been assumed as:

- 8 h for components in contact with Methane;
- 2 h for components not in contact with Methane;
- 48 h for LNG submerged pumps;

- 72 h for LNG tanks;
- 2 h in case of spurious valve operation (considered as actuator failures).

In order to take into account different plant locations, the presence of available stocks, the availability of the maintenance team and tools, all the calculations have been made using three different logistic delay times:

- 1 h logistic delay time (spare part present in plant warehouse);
- 24 h logistic delay time (spare part shortly available);
- 1 week logistic delay time (spare part not readily available).

Calculations have been run with these different assumptions for logistic times in order to have results representative of plants equipped with spare parts, situated in easily reachable areas or in remote/hard to reach areas.

Fault location and detection has been considered as negligible since all gas stations are locally manned.

Preventive maintenance has been evaluated by considering typical indications from manufacturers and interviews with experts: electrically driven compressors were considered undergo total overhauls every 26280 h with downtimes of 336 h, while gas turbines were considered to be maintained every 25000 h with downtimes of 720 h, besides minor maintenances every 10000 h with downtimes of 168 h.

The influence of preventive maintenance has been taken into account as an additional contribution to unavailability estimated as the rate between the downtime for maintenance and the time interval between maintenances. Preventive maintenance does not affect the unreliability of components since the failure rates used to characterise component failure modes refer to machinery subjected to a typical preventive maintenance cycle similar to the one hypothesized above. The unavailability due to preventive maintenance downtime has been considered in failure trees as an additional event.

Preliminary analyses show the relevant contribution of compressors to the whole system unavailability. For this reason both they and their drivers have been characterised considering critical failures that also take into account lubrication, control and monitoring systems or shaft seal systems (for compressors).

Regarding LNG storage facilities, data for equipment dedicated to this specific application, in particular pumps, valves, tanks and vaporisers, has been considered. Failure rates for LNG pumps are available but typically as data relative to “Major Failure”, “Minor Failure” and “Safety Related Failure” (Lees, 2005) rather than split by failure mode.

Conservative availability and reliability estimations led to two different failure modes being considered (“fail while running” and “fail to start”), the difference between the two scenarios being the repair time.

The following failure modes have been considered for the various components:

- Air cooler: leakage; fan failure (electric motor spurious stop);
- Compressor: critical failure (active compressor); failure on demand (standby component);
- Electrical motor: critical failure (active component); failure on demand (standby components);
- Filter: blockage;
- Gas turbine: critical failure (active component); failure on demand (standby component);
- LNG Pump: major failure (active component); failure on demand (standby component);
- LNG Tank: cold spot;
- LNG Valve: failure (both active and stand by components); spurious operation (motorised valves);
- Valve: external leakage; fail to operate; spurious operation (motorised valves).

Failure Rates and repair data used in this study are illustrated In Table 9.

Table 9 - Failure rates.

Component	Failure Mode	Failure Rate [1/h]	Active Repair Time [h]	Technical Delay Time [h]	MTTR [h]			Notes	Reference
					Logistic Time				
					1h	24h	168h		
Air cooler	Leakage	7,50E-5	12	8	21	44	188		Lees 3rd Ed.
Air cooler	Fan Failure	4,32E-6	1	2	4	27	171	Electric motor spurious stop	OREDA 2009
Compressor	Critical failure	7.60E-5	49	8	58	81	225		OREDA 2009
Compressor	Fails to start	2,59E-5	27	8	36	59	203	1 year test interval considered	OREDA 2009
Electrically driven compressor	Critical failure	6,72E-5	12	2	15	38	182		OREDA 2009
Electrically driven compressor	Fails to start	9,13E-6	11	2	14	37	181	1 year test interval considered	OREDA 2009
Electrically driven pump	Critical failure	1,25E-5	14	2	17	40	184		OREDA 2009
Electrically driven pump	Fails to start	4,17E-6	4	2	7	30	174	1 year test interval considered	OREDA 2009
Filter	Blockage	1 E-6	1	8	10	33	177		Lees 3rd Ed.
Gas turbine	Critical failure	3,42E-4	26	2	29	52	196		OREDA 2009
Gas turbine	Fails to start	1,06E-4	26	2	29	52	196		OREDA 2009
LNG pump	Major failure	2,86E-5	18	48	67	90	234	Active repair time from OREDA 2009	Lees 3rd Ed.
LNG pump	Fails to start	2,86E-5	8	48	57	80	224	Active repair time from OREDA	Lees 3rd Ed.

								2009	
LNG tank	Cold spot	1,00E-5	168	72	241	264	408	Active repair time estimated at one week	Lees 3rd Ed.
LNG valve	Failure	5,00E-8	6	8	15	38	182	Active repair time from OREDA 2009	Lees 3rd Ed.
LNG valve	Spurious operation	8,00E-8	6	2	9	32	176		OREDA 2009
LNG vaporizer	Major failure	1,25E-4	4	8	13	36	180	Active repair time from OREDA 2009 (heat exchanger)	Lees 3rd Ed.
Valve	External leakage	3,60E-7	32	8	41	62	208		OREDA 2009
Valve	Fails to operate	1,00E-6	5	8	14	37	181	1 year test interval considered	OREDA 2009
Valve	Spurious operation	8,00E-8	6	2	9	32	176		OREDA 2009

Source: Tractebel, 2016.

3.6 Fault Tree Analysis

The various architectures representative of gas compressor stations, UGS and LNG Facilities were analysed using a fault tree analysis technique for the different Damage Classes mentioned above and taking into account different Logistic Delay Times (1 h, spare part present in plant warehouse; 24 h, spare part shortly available; 1 week spare part not readily available).

3.6.1 System modelling by Fault trees

Fault trees have been analysed using the STARS Studio (Version 0.9 December 99) software. Two calculation runs have been performed to evaluate the effects of Corrective and Preventive Maintenance. For configurations where spare machinery is available, the following hypothesis have been made:

- In case of failure of a machine, the lost flow rate is guaranteed by the spare (i.e. the lost flow rate cannot be provided by increasing the power of the running machines);
- Preventive Maintenance is performed when the machinery is in standby, without stopping operations.

The mission time has been considered of one year. It has been assumed that compression stations are equipped with batteries of filters and air coolers; these batteries are common to all compressors present in the station, respectively at the suction and at the discharge of compressors. It has been assumed that 2 air coolers and 2 filters are installed for each active compressor, plus an additional air cooler and an additional filter. Moreover, it has been assumed that each compressor needs two air coolers and two filters to run properly. Three valves for compressor, 2 valves for each filter and other 8 main valves in the compression station have been considered.

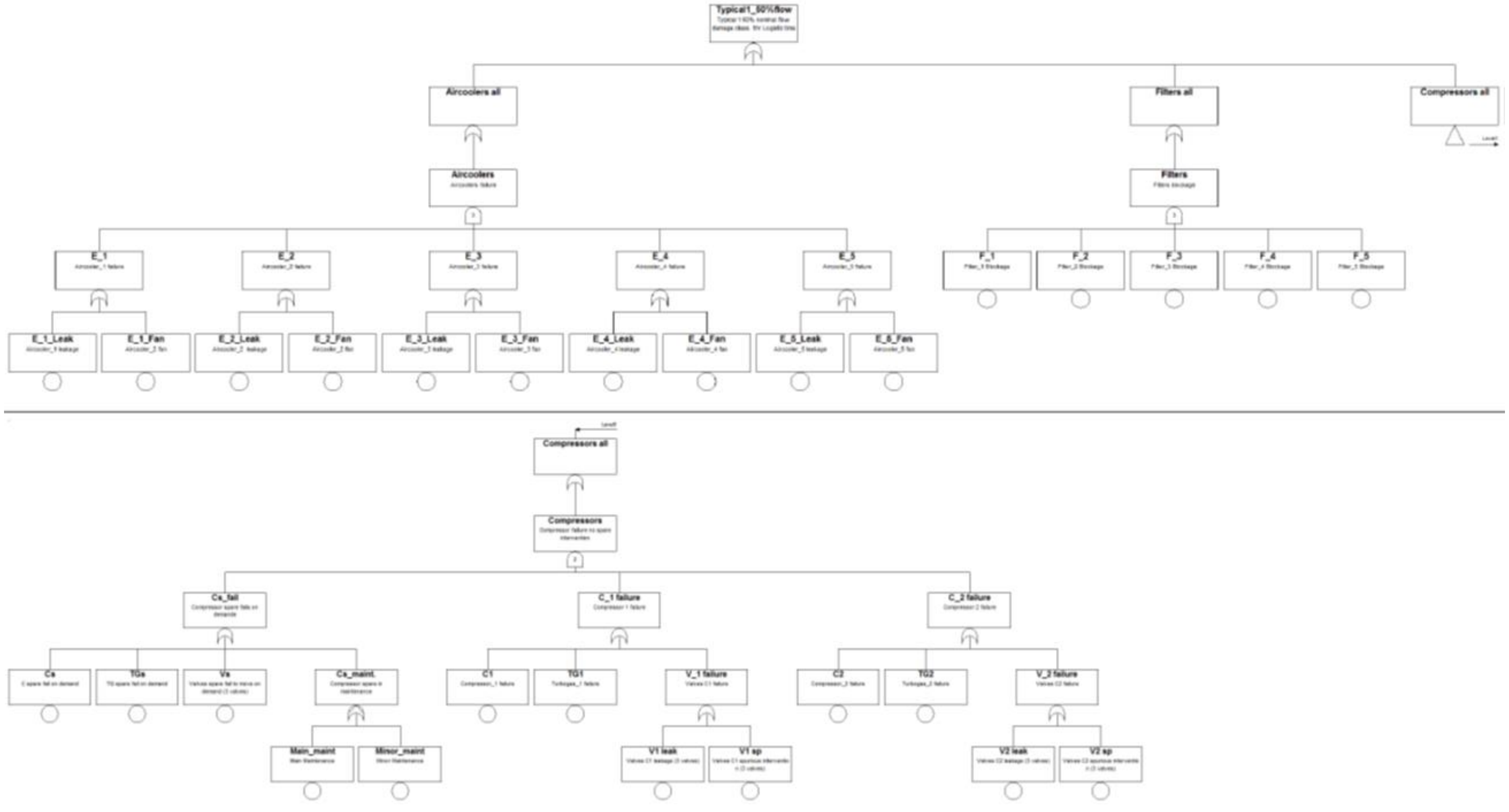
In the case of the “Bypass” and “0% flow” damage classes, the influence of Common Cause Failures (CCF) has been taken into account. CCF gives the possibility to take into account single events that are able to compromise the effectiveness of redundant systems due to external impacts, maintenance errors, and of equipment manufacturing defects. The calculation of CCF is particularly relevant for components set in parallel, i.e., filters, air coolers, compressors and their drivers.

The CCF contribution has been set equal to the 2% of the component failure rate according to the assumption usually made for these types of situations.

Natural causes have not been included in the CCF contribution since they have been considered separately later on.

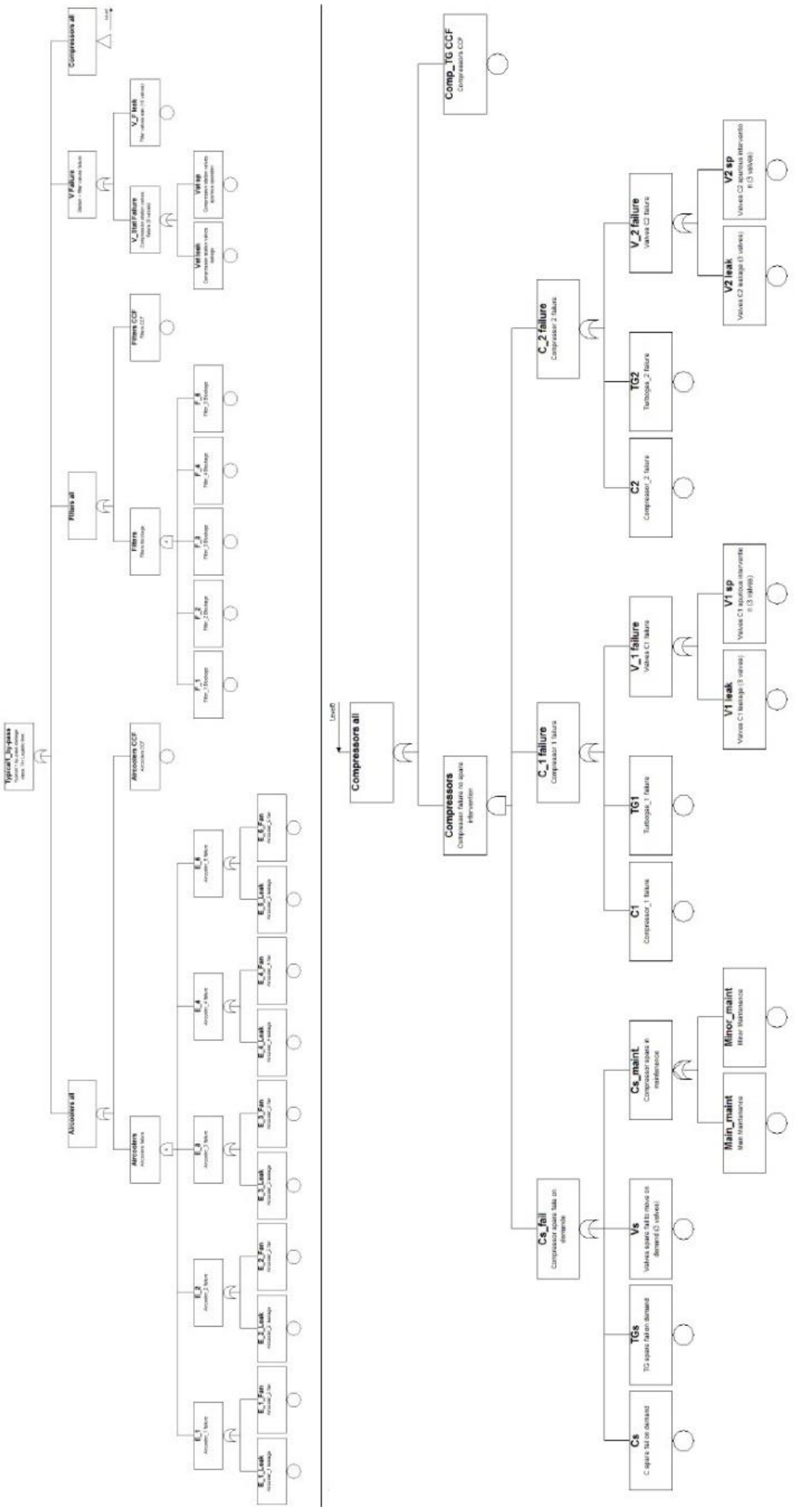
Figures 21-23 provide an example of application of the fault tree analysis to configuration N-TUCO-RP, for the various Damage Classes, taking into account the contribution of both corrective and preventive maintenance.

Figure 21 - N-TUCO-RP; 50% Flow Damage Class; Corrective + Preventive Maintenance – Fault Tree.



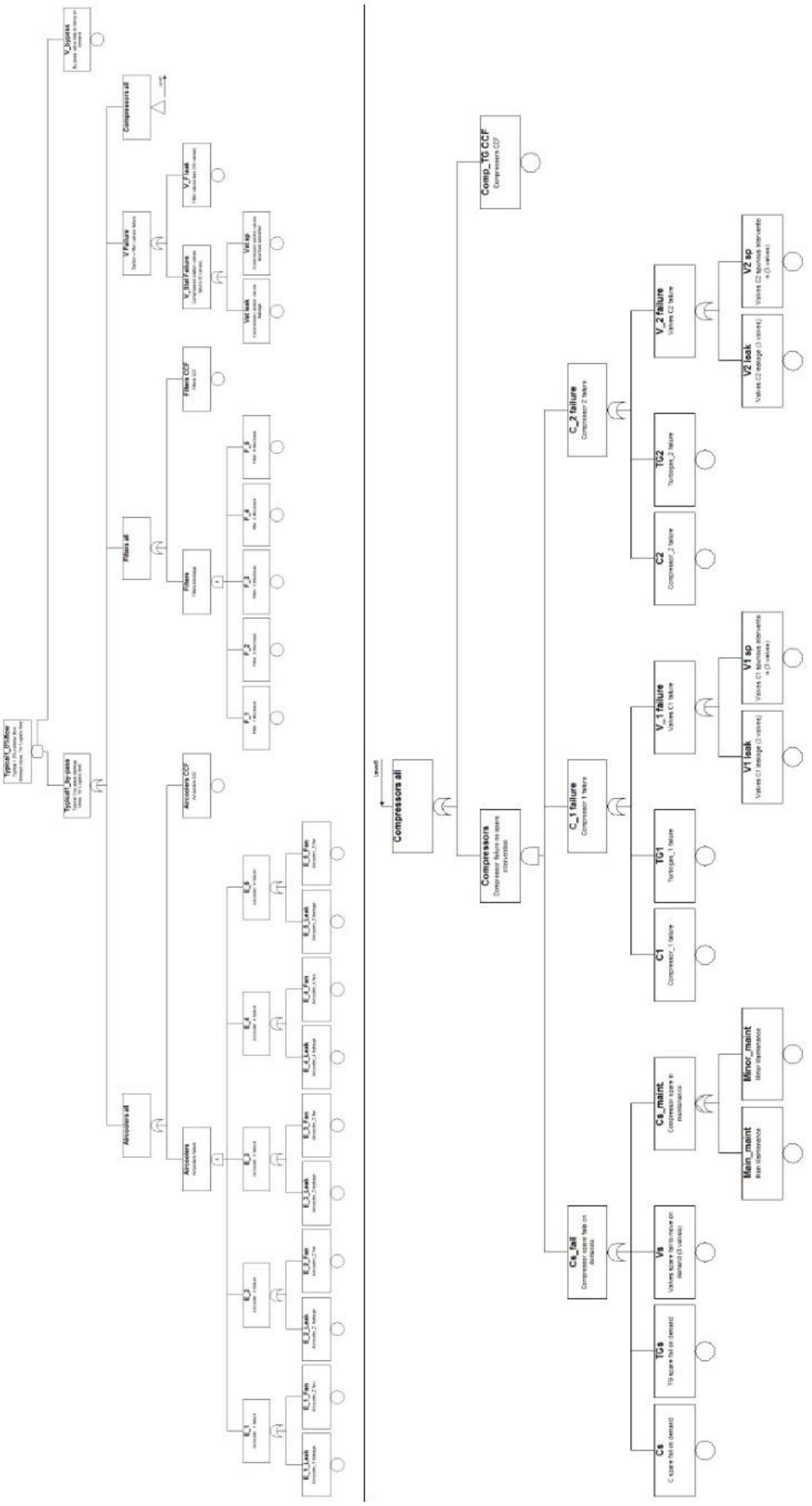
Source: Tractebel, 2016.

Figure 22 - N-TUCO-RP; “Bypass” Damage Class; Corrective + Preventive Maintenance – Fault Tree.



Source: Tractebel, 2016.

Figure 23 - N-TUCO-RP; 0% Flow Damage Class; Corrective + Preventive Maintenance – Fault Tree.



Source: Tractebel, 2016.

Note that the partial results containing corrective maintenance only do not make sense in practice since the failure rates used for component modelling are derived by statistics on real components managed by preventive maintenance policies. The developed fault trees are listed in Table 10.

Table 10 - List of developed fault trees.

Configuration	Damage Class
1: N-TUCO-RP	50% Flow
	Bypass
	0% Flow
1a: 4-TUCO-RP	66% Flow
	33% Flow
	Bypass
	0% Flow
2: N-MOCO-RP	50% Flow
	Bypass
	0% Flow
2a: 4-TUCO-RP	66% Flow
	33% Flow
	Bypass
	0% Flow
3: 2-TUCO-RN	50% Flow
	Bypass
	0% Flow
4: 2-MOCO-RN	50% Flow
	Bypass
	0% Flow
5: 2-TUCO-RT	Bypass
	0% Flow
6: 2-MOCO-RT	Bypass
	0% Flow
7: 1-TUCO-RN	Bypass

	0% Flow
8: 1-MOCO-RN	Bypass
	0% Flow
LNG	66% Flow
	50% Flow
	33% Flow
	0% Flow

Source: Tractebel, 2016.

3.6.2 Reliability Analysis

This section provides a description of the obtained results. The calculations performed do not consider the influence of natural hazards that are expressly evaluated later on.

The results related to configuration N-TUCO-RP (Table 11) are taken into consideration here below to discuss their interpretation. Typical results from Fault Tree Analysis are:

- Unavalilability (Q): the probability for the system to be in the considered damage class, i.e. the fraction of time spent by the system in the considered damage class;
- Expected Number of Failures (ENF): the mean number of failures (leading to the considered damage class) expected in one year;
- Downtime: the cumulative time in a year in which the system is in the considered Damage Class;
- Average Downtime: the mean down time of the system for a failure leading to the considered Damage Class, i.e. the average time that is necessary to recover from the failure and get out from the considered Damage Class.

Unavailability decreases as the damage class severity increases (50% nominal flow, “bypass”, 0% flow) and increases as Logistic Delay Time increases.

Table 11 shows that in case of class “50% Nominal Flow” and considering the presence on site of spare parts and operators (Logistic Delay 1 hr) the unavailability is 2.08E-2 (Corrective + Preventive Maintenance); These values increase in case stocks are not on site, arriving to 9.69% and 11.6% in the worst logistic conditions case. This unavailability is produced by an average number of failures that is in the order of 4 – 6 failures per year.

The increase of Logistic Delay slightly increases the number of station failures, since in case of failure of the working machinery, the availability of the redundant component is reduced.

Table 11 - 1-N-TUCO-RP, Unavailability (Q), Expected Number of Failures (ENF), Downtime [h/year], Average Down Time [h].

Configuration	Damage Class	Parameter	Corrective + Corrective Maintenance		
			Logistic Delay Time		
			1 h	24 h	168 h
1: N-TUCO-RP	50% nominal flow	Q	2,08E-02	3,46E-02	1,16E-01
		ENF [occ/year]	4,98E+00	5,07E+00	5,62E+00

		Downtime [h/year]	1,82E+02	3,03E+02	1,02E+03
		Average Downtime [h]	3,65E+01	5,96E+01	1,81E+02
	Bypass	Q	7,37E-04	1,39E-03	8,06E-03
		ENF [occ/year]	2,19E-01	2,65E-01	5,45E-01
		Downtime [h/year]	6,46E+00	1,22E+01	7,06E+01
		Average Downtime [h]	2,95E+01	4,59E+01	1,30E+02
	0% nominal flow	Q	3,41E-06	6,58E-06	4,09E-05
		ENF [occ/year]	1,05E-03	1,31E-03	2,90E-03
		Downtime [h/year]	2,98E-02	5,76E-02	3,59E-01
		Average Downtime [h]	2,84E+01	4,39E+01	1,24E+02

Source: Tractebel, 2016.

In case of “bypass” Damage Class (all compressors failed and opening of the station bypass valve) and considering the presence on site of spare parts and operators (Logistic Delay 1 hr) the unavailability is 7.37E-4 (Corrective + Preventive Maintenance); this result is mainly due to the contribution of failures and repair since the Preventive Maintenance can be performed on the spare machine, when out of service, without relevant contributions on system operations.

These values increase in case stocks are not on site, arriving to 0.806% under the worst logistic conditions. This unavailability is produced by an average number of failures that is in the order of 2–6 failures every 10 years.

The unavailability and the expected number of failures are lower in case of “bypass” Damage Class than for “50% nominal flow” class, because the “bypass” class is often reached after a higher number of failures occur contemporaneously.

The increase of Logistic Delay results in an increase the number of station failures, since the period of operation without any redundancy is longer. The number of expected failures increases in proportion more in case of “bypass” class than in case of “50% nominal flow” class, due to the fact that the “bypass” class is often induced by the failure of more components.

In case of 0% flow Damage Class (all compressors failed and station by-pass valve failed on demand) and considering the presence on site of spare parts and operators (Logistic Delay 1 hr), the unavailability is 3.41E-6 (Corrective + Preventive Maintenance); The contribution of Preventive Maintenance is very low since the most part of unavailability is due to failures and repair operations. These values increase in case stocks are not on site, arriving to 0.00409% in the worst logistic conditions case. This unavailability is produced by an average number of failures that is in the order of 1–3 failures every 1000 years.

The unavailability and the expected number of failures are lower in case of “0% flow” class than for the other classes because a higher number of failures compared to the other classes has to occur contemporaneously, or because the failures leading to this status are quite rare.

As in the other Damage Classes, an increase of Logistic Delay Time leads to an increase of the expected number of failures in one year, as discussed above. The relative influence of logistic delay in this case is higher than in the others. The reason is that, in case of failure of working machinery, the period of operation without any redundancy is increased and as a consequence of that the probability to fall in the "0% flow" condition increases; the "0% flow" class is more sensitive to this parameter than the other classes due to the higher number of contemporaneous failures needed.

Regarding downtimes, it should be noted that the values do not change greatly since they represent the time necessary to recover from the Damage Class. In fact, a lot of simultaneous failures are necessary to fall in the worst Damage Classes and, according to the needs of Fault Tree Analysis, the repair activities of different items are considered as independent. This situation leads to the unavailability of the station during the "overlapping" of parallel repair activities that are normally shorter than the duration of the repair of the single failures. For this reason the down time does not increase in the worst Damage Classes and in some cases it could be shorter.

3.6.3 Criticality

The importance of the single components, in terms of contribution to the total system unavailability, has been evaluated. The Fussell–Vesely (FV) parameter has been adopted; it is an estimation of the contribution of the unavailability of each failure mode on the overall gas station unavailability.

As an example, the Fussell–Vesely importance indexes have been reported for N-TUCO-RP in Table 12, considering the different Damage Classes and Logistic Delay Times and taking into account Corrective and Preventive Maintenance. Components are ordered by decreasing FV Importance. In the same Table the unavailability of the single components is also reported. In this table, for components logically set in series (e.g. leakage of valves), the unavailability and the FV Importance have been calculated for the single component, in order to make it easier to perform a comparison independently of the number of components present in the compression station.

As expected, the most critical elements are the gas compression station machines (compressors and Gas Turbines) whereas air coolers and filters have minor or negligible importance. Components with the highest FV importance are the components that contribute most largely to the system unavailability and therefore that deserve attention in terms of design, operation & maintenance activities and monitoring.

The 50% nominal flow Damage Class, with 1 hr Logistic Delay Time, shows that in this case the FV importance of Gas Turbines and Compressors is more than two orders of magnitude larger than that of the other components. This result highlights the importance of machines in gas compression stations, related to failure rates and repair time of these complex components but also to the architecture of gas compression stations. The increase of Logistic Delay Time increases the unavailability of the various components but it does not influence significantly the FV importance.

In case of "bypass" and "0% flow" Damage Classes, the CCF (Common Cause Failure) has also been considered. In these Damage Classes the influence of common cause failures affecting the whole compressor, driver and compressor related valves, has shown a preeminent importance. Only in case of the longest considered Logistic Delay Times (168 hr), CCF related to machinery are exceeded in importance by the failure of gas turbines, both active and spare. This result evidences the importance of common causes for critical components and confirms the criticality of turbines and compressors that, like in case of the 50% nominal flow Damage Class, are the most critical items.

A relatively high importance for "bypass" and "0% flow" Damage Classes is also shown by valves leak, and air coolers CCF. In case of "0% flow" Damage Class the most important component is the station by- pass valve (fail to open on demand); this damage class is reached if all the compressor present in the compression station are failed and the by-pass valve fails to open; in other words, if the by-pass valve works properly the 0% flow damage class is never reached. The influence of Logistic Delay Time on FV Importance is not particularly significant for high Importance components whereas it is strong on low Importance components.

Table 12 - Criticality: 1-N-TUCO-RP with Corrective + Preventive Maintenance.

Configuration	Damage Class	Logistic Delay Time [h]	Component	Unavailability	FV Importance
1-N-TUCO-RP	50% Nominal	1 [h]	Gas Turbine (spare)	4,64E-01	6,38E-01

	Flow		Gas Turbine (active)	9,82E-03	3,51E-01
			Compressor (active)	4,39E-03	1,57E-01
			Compressor (spare)	1,13E-01	1,56E-01
			Main maintenance	2,88E-02	3,96E-02
			Minor maintenance	1,68E-02	2,31E-02
			Valve compressor spare	4,37E-03	6,02E-03
			Valve compressor active leak	1,48E-05	5,27E-04
			Valve compressor active spurious	7,20E-07	2,58E-05
			Air cooler Leak	1,56E-03	1,12E-06
			Air cooler Fan	1,73E-05	1,24E-08
			Filter	1,00E-05	2,89E-13
		24[h]	Gas Turbine (spare)	4,64E-01	6,37E-01
			Gas Turbine (active)	1,75E-02	3,81E-01
			Compressor (spare)	1,13E-01	1,56E-01
			Compressor (active)	6,14E-03	1,34E-01
			Main maintenance	2,88E-02	3,95E-02
			Minor maintenance	1,68E-02	2,31E-02
			Valve compressor spare	4,37E-03	6,01E-03
			Valve compressor active leak	2,31E-05	5,02E-04

			Valve compressor active spurious	2,56E-06	5,56E-05
			Air cooler Leak	3,29E-03	6,65E-06
			Air cooler Fan	1,17E-04	2,36E-07
			Filter	3,30E-05	6,24E-12
		168[h]	Gas Turbine (spare)	4,64E-01	6,38E-01
			Gas Turbine (active)	6,28E-02	4,36E-01
			Compressor (spare)	1,13E-01	1,56E-01
			Compressor (active)	1,68E-02	1,17E-01
			Main maintenance	2,88E-02	3,95E-02
			Minor maintenance	1,68E-02	2,31E-02
			Valve compressor spare	4,37E-03	6,01E-03
			Valve compressor active leak	7,47E-05	5,19E-04
			Valve compressor active spurious	1,39E-02	1,54E-04
			Air cooler Leak	1,41E-05	9,77E-05
			Air cooler Fan	7,38E-14	8,15E-06
			Filter	1,77E-04	2,86E-10
	Bypass	1 [h]	Comp_TG CCF	2,86E-04	3,88E-01
			Gas Turbine (active)	9,82E-03	1,38E-01
			Gas Turbine (spare)	4,64E-01	1,28E-01

			Compressor (active)	4,39E-03	6,17E-02
			Air coolers CCF	3,19E-05	4,33E-02
			Compressor (spare)	1,13E-01	3,13E-02
			Valve station leak	1,48E-05	2,00E-02
			Valve filter leak	1,48E-05	2,00E-02
			Main maintenance	2,88E-02	7,93E-03
			Minor maintenance	1,68E-02	4,63E-03
			Valve compressor spare	4,37E-03	1,21E-03
			Valve station spurious	7,21E-07	9,78E-04
			Filters CCF	2,00E-07	2,71E-04
			Valve compressor active leak	1,48E-05	2,08E-04
			Valve compressor active spurious	7,20E-07	1,01E-05
			Air cooler Leak	1,56E-03	3,32E-08
			Air cooler Fan	1,73E-05	3,68E-10
			Filter	1,00E-05	5,43E-17
		24[h]	Comp_TG CCF	4,77E-04	3,43E-01
			Gas Turbine (active)	1,75E-02	2,17E-01
			Gas Turbine (spare)	4,64E-01	1,88E-01
			Compressor (active)	6,14E-03	7,62E-02

			Air coolers CCF	6,85E-05	4,93E-02
			Compressor (spare)	1,13E-01	4,59E-02
			Valve station leak	2,31E-05	1,66E-02
			Valve filter leak	2,31E-05	1,66E-02
			Main maintenance	2,88E-02	1,16E-02
			Minor maintenance	1,68E-02	6,79E-03
			Valve compressor spare	2,55E-06	1,84E-03
			Valve station spurious	4,37E-03	1,77E-03
			Filters CCF	6,60E-07	4,75E-04
			Valve compressor active leak	2,31E-05	2,86E-04
			Valve compressor active spurious	2,56E-06	3,17E-05
			Air cooler Leak	3,29E-03	3,75E-07
			Air cooler Fan	1,17E-04	1,33E-08
			Filter	3,30E-05	3,41E-15
		168[h]	Comp_TG CCF	6,28E-02	4,54E-01
			Gas Turbine (active)	4,64E-01	3,68E-01
			Gas Turbine (spare)	1,68E-03	2,08E-01
			Compressor (active)	1,68E-02	1,21E-01
			Air coolers CCF	1,13E-01	8,99E-02

			Compressor (spare)	2,97E-04	3,69E-02
			Valve station leak	2,88E-02	2,28E-02
			Valve filter leak	1,68E-02	1,33E-02
			Main maintenance	7,48E-05	9,28E-03
			Minor maintenance	7,48E-05	9,28E-03
			Valve compressor spare	4,37E-03	3,47E-03
			Valve station spurious	1,41E-05	1,75E-03
			Filters CCF	7,47E-05	5,40E-04
			Valve compressor active leak	3,54E-06	4,39E-04
			Valve compressor active spurious	1,41E-05	1,02E-04
			Air cooler Leak	1,39E-02	2,17E-05
			Air cooler Fan	7,38E-04	1,15E-06
			Filter	1,77E-04	4,87E-13
	0% Nominal Flow	1 [h]	V_bypass	4,38E-03	1,00E+00
			Comp_TG CCF	2,86E-04	3,68E-01
			Gas Turbine (active)	9,82E-03	1,66E-01
			Gas Turbine (spare)	4,64E-01	1,62E-01
			Compressor (active)	4,39E-03	7,44E-02
			Compressor (spare)	3,19E-05	4,11E-02

			Air coolers CCF	1,13E-01	3,95E-02
			Valve station leak	1,48E-05	1,90E-02
			Valve filter leak	1,48E-05	1,90E-02
			Main maintenance	2,88E-02	7,52E-03
			Minor maintenance	1,68E-02	4,39E-03
			Valve compressor spare	4,37E-03	1,53E-03
			Valve station spurious	7,21E-07	9,27E-04
			Filters CCF	2,00E-07	2,57E-04
			Valve compressor active leak	1,48E-05	2,50E-04
			Valve compressor active spurious	7,20E-07	1,22E-05
			Air cooler Leak	1,56E-03	3,15E-08
			Air cooler Fan	1,73E-05	3,49E-10
			Filter	1,00E-05	5,15E-17
		24[h]	V_bypass	4,38E-03	1,00E+00
			Comp_TG CCF	4,77E-04	3,18E-01
			Gas Turbine (active)	1,75E-02	2,55E-01
			Gas Turbine (spare)	4,64E-01	2,32E-01
			Compressor (active)	6,14E-03	8,96E-02
			Compressor (spare)	1,13E-01	5,66E-02

			Air coolers CCF	6,85E-05	4,56E-02
			Valve station leak	2,31E-05	1,54E-02
			Valve filter leak	2,31E-05	1,54E-02
			Main maintenance	2,88E-02	1,08E-02
			Minor maintenance	1,68E-02	6,29E-03
			Valve compressor spare	4,37E-03	2,19E-03
			Valve station spurious	2,55E-06	1,70E-03
			Filters CCF	6,60E-07	4,39E-04
			Valve compressor active leak	2,31E-05	3,37E-04
			Valve compressor active spurious	2,56E-06	3,73E-05
			Air cooler Leak	3,29E-03	3,48E-07
			Air cooler Fan	1,17E-04	1,23E-08
			Filter	3,30E-05	3,16E-15
		168[h]	V_bypass	4,38E-03	1,00E+00
			Comp_TG CCF	6,28E-02	4,97E-01
			Gas Turbine (active)	4,64E-01	4,23E-01
			Gas Turbine (spare)	1,68E-03	1,80E-01
			Compressor (active)	1,68E-02	1,33E-01
			Compressor (spare)	1,13E-01	1,03E-01

			Air coolers CCF	2,97E-04	3,18E-02
			Valve station leak	2,88E-02	1,97E-02
			Valve filter leak	1,68E-02	1,15E-02
			Main maintenance	7,48E-05	8,00E-03
			Minor maintenance	7,48E-05	8,00E-03
			Valve compressor spare	4,37E-03	3,99E-03
			Valve station spurious	1,41E-05	1,51E-03
			Filters CCF	7,47E-05	5,92E-04
			Valve compressor active leak	3,54E-06	3,79E-04
			Valve compressor active spurious	1,41E-05	1,11E-04
			Air cooler Leak	1,39E-02	1,87E-05
			Air cooler Fan	7,38E-04	9,91E-07
			Filter	1,77E-04	4,20E-13

Source: Tractebel, 2016.

3.7 Results and Conclusions

Table 13 provides a summary of results for all configurations and 24h Logistic Delay. Results are given in terms of Unavailability (Q), Expected Number of Failures (ENF), Downtime (h/year) and Average Downtime (h), considering both Corrective and Preventive Maintenance contributions.

Table 13 - Corrective + Preventive Maintenance: Unavailability (Q), Expected Number of Failures (ENF), Downtime [h/year], Average Downtime [h].

Corrective + Preventive Maintenance – 24 hr Logistic Delay Time						
Typical	Parameter	Damage Class (nominal flow percentage)				
		66%	50%	33%	Bypass	0%
1: N-TUCO-	Q	X	3,46E-02	X	1,39E-03	6,58E-06

RP	ENF [occ/year]	X	5,07E+00	X	2,65E-01	1,31E-03
	Downtime [h/year]	X	3,03E+02	X	1,22E+01	5,76E-02
	Average Downtime [h]	X	5,96E+01	X	4,59E+01	4,39E+01
1a: 4-TUCO-RP	Q	5,52E-02	X	1,32E-03	1,08E-03	4,76E-08
	ENF [occ/year]	8,12E+00	X	3,65E-01	1,67E-01	7,35E-06
	Down Time [h/year]	4,84E+02	X	1,16E+01	9,46E+00	4,17E-04
	Average Down Time [h]	5,96E+01	X	3,17E+01	5,67E+01	5,67E+01
2: N-MOCO-RP	Q	X	3,67E-03	X	6,96E-04	3,07E-07
	ENF [occ/year]	X	4,99E-01	X	1,06E-01	4,69E-05
	Downtime [h/year]	X	3,21E+01	X	6,09E+00	2,69E-03
	Average Downtime [h]	X	6,44E+01	X	5,76E+01	5,73E+02
2a: 4-MOCO-RP	Q	5,94E-03	X	5,09E-05	7,72E-04	3,38E-08
	ENF [occ/year]	8,06E-01	X	1,32E-02	1,14E-01	5,01E-06
	Downtime [h/year]	5,20E+01	X	4,46E-01	6,76E+00	2,96E-04
	Average Downtime [h]	6,46E+01	X	3,38E+01	5,93E+01	5,91E+01
3: 2-TUCO-RN	Q	X	1,31E-01	X	5,77E-03	2,54E-05
	ENF [occ/year]	X	7,44E+00	X	4,94E-01	2,16E-03
	Downtime [h/year]	X	1,14E+03	X	5,06E+01	2,22E-01
	Average Downtime [h]	X	1,54E+02	X	1,02E+02	1,03E+02

4: 2-MOCO-RN	Q	X	4,24E-02	X	5,77E-03	2,54E-05
	ENF [occ/year]	X	2,56E+00	X	4,94E-01	2,16E-03
	Downtime [h/year]	X	3,72E+02	X	5,06E+01	2,22E-01
	Average Downtime [h]	X	1,45E+02	X	1,02E+02	1,03E+02
5: 2-TUCO-RT	Q	X	X	X	1,14E-03	5,02E-06
	ENF [occ/year]	X	X	X	1,40E-01	6,14E-04
	Downtime [h/year]	X	X	X	1,00E+01	4,39E-02
	Average Downtime [h]	X	X	X	7,15E+01	7,15E+01
6: 2-MOCO-RT	Q	X	X	X	2,31E-03	1,22E-05
	ENF [occ/year]	X	X	X	3,33E-01	1,77E-03
	Downtime [h/year]	X	X	X	2,02E+01	1,07E-01
	Average Downtime [h]	X	X	X	6,06E+01	6,05E+01
7-1-TUCO-RN	Q	X	X	X	6,81E-02	3,06E-04
	ENF [occ/year]	X	X	X	3,80E+00	1,66E-02
	Downtime [h/year]	X	X	X	5,96E+02	2,68E+00
	Average Downtime [h]	X	X	X	1,57E+02	1,61E+02
8-1-MOCO-RN	Q	X	X	X	2,19E-02	9,64E-05
	ENF [occ/year]	X	X	X	1,36E+00	5,94E-03
	Downtime [h/year]	X	X	X	1,92E+02	8,45E-01
	Average	X	X	X	1,41E+02	1,42E+02

	Downtime [h]					
LNG Storage	Q	3,48E-03	1,12E-02	1,95E-05	X	3,08E-04
	ENF [occ/year]	2,54E-01	2,13E+00	2,73E-03	X	5,40E-02
	Downtime [h/year]	3,05E+01	9,83E+01	1,71E-01	X	2,70E+00
	Average Downtime [h]	1,20E+02	4,61E+01	6,25E+01	X	5,01E+01

Source: Tractebel, 2016.

In the case of compressor stations and for each configuration (except stations with 4 compressors, 1a-4-TUCO-RP and 2a-4-MOCO-RP), the Unavailability (Q) becomes lower as the Damage Class becomes more severe (the Damage Class severity increases in this order: 50% nominal flow (where applicable), "bypass", 0% flow, the Expected Number of Failures (ENF) following the same trend. In the case of stations with 4 compressors the unavailability due to "by-pass" Damage Class is often higher (especially in case of electrical motor driven compressors) due to the "33% nominal flow" Damage Class. This result can be explained with the high importance of CCF and leakages from filters and station valves that are pertinent for "bypass" and 0% nominal flow Damage Classes but not for the 33% Damage Class; in fact these failures lead to the complete loss of the station capability and not to degraded production scenarios. These considerations apply both to cases in which preventive and corrective maintenance have been taken into account and to cases in which only preventive maintenance has been considered.

Configurations in which the compressors are driven by electric motors are affected by lower unavailability and lower Expected Number of Failures compared to those having the same configuration but gas – turbine driven compressors; the reason is the higher availability of electric motors.

For Damage Classes 0% Nominal Flow and "bypass", 2-TUCO-RN (two gas turbine-driven compressors, no redundancy) shows a higher availability than typical 5-2-TUCO-RT (two gas turbine-driven compressors, total redundancy); the reason is the higher unavailability (fail on demand) of compressors, gas turbines and electrical motors when set in stand – by mode. The same consideration apply to 2-MOCO-RT compared to 2-MOCO-RT. The worst configurations in terms of Unavailability and Expected Number of Failures (comparing compressors with the same driver gas turbine or electrical motor), are those characterised by single gas compressors, i.e. 1-TUCO-RN and 1-MOCO-RN.

Regarding LNG Facilities, low pressure branches (formed by tank and low pressure pump) and high pressure branches (formed by high pressure pump and vaporizer) are present; low pressure branches have a higher functional redundancy (each branch supplies 33% of the nominal flow of the facility: 4 branches are present, one spare) than high pressure branches (each branch supplies 50% of the nominal flow of the facility: 3 branches are present, one spare). 66% and 33% Nominal Flow Damage Classes are due to failure in low pressure branches of the plant whereas 50% Nominal Flow Damage Class is due to failure in the high pressure branches; 0% Nominal Flow Damage Class can be due to failures in both locations. The 66% and 50% nominal flow Damage Classes have a Minimal Cut Set (MCS) of order 2; the 33% nominal flow Damage Class has a Minimal Cut Set of order 3; the 0% Damage Class has a Minimal Cut Set of order 1 due to influence of CCF (Common Cause Failure).

Pumps and their drivers set on high and low pressure branches have been considered identical. The higher unavailability (considering failure, repair rate and test interval) of vaporizers compared to that of tanks justifies the lower unavailability in the 50% nominal flow Damage Class than in the 66% nominal flow Damage Class, given the equal minimum order of MCS present.

The influence of shut-down due to preventive maintenance appears stronger for configurations with no redundancy (2-TUCO-RN, 2-MOCO-RN, 1-TUCO-RN, 1-MOCO-RN) than for configuration with redundancy.

The increase of Logistic Delay Times increases the unavailability of the systems, by about an order of magnitude, whereas the expected number of failures is less affected by the change of this parameter.

4 Natural Hazards

4.1 Scope and methodology

Possible effects of natural hazards on compressor stations, UGS sites and LNG facilities have been investigated. Flooding and seismic hazards are mainly analysed along with other hazards such as external fires (forest, nearby facilities), extreme winds (hurricane, tornado), extreme precipitation (in the form of rain, hail or snow), extreme temperatures, electromagnetic phenomena (lightning, solar flare), air contamination (salt storm, sand storm), sea storms, tsunamis (for LNG offshore terminals) and extreme humidity (mist, white frost and drought).

In order to evaluate effects of natural hazard on the various facilities a 4 step methodology has been applied:

- Historical investigation: a research on accident data banks has been performed in order to identify past accidents occurred on this kind of facilities, caused by natural hazards. This investigation allows a preliminary overview to identify the typical hazards able to compromise operations in gas compressor stations, the severity of the events and the related effects on the facilities;
- Lessons learned: interview with experts, in order to catch operator's experience in case of natural disasters to identify the effects on the station operations, timing for recovery and restart, affected components, etc.;
- Natural Hazard classification in EU: this step consists in the identification of the typical approaches, in EU, to classify and map natural hazards, in order to set a coherence between the grade of natural risk in a specific location and the related enhancement of the gas station Damage Class probability;
- Definition of a set of "worsening factors", for each specific natural hazard, for the corrections of the Damage Class probabilities estimated in Task 2.

4.2 Historical investigation

A research on accident databases, news, reports and academic articles has been performed in order to identify in which way operations in compressor stations, UGS sites and LNG facilities have been compromised by natural causes, and in particular to find a relation between the sustained damage and the severity of the events for each type of hazard.

4.2.1 Gas Compressor Stations

Several data banks have been taken into consideration. The FACTS (Failure and Accidents Technical information System) database created by TNO at the end of the seventies does not contain information pertinent to the incidents object of the present investigation (TNO, 2015). Similarly, the JRC-developed eMARS (Major Accident Reporting System) does not provide data suitable for the purpose of this analysis (EC-JRC, 2016). The EGIG database only records incidents on gas transmission pipelines while incidents involving equipment or components such as valves and compressors are not recorded (EGIG, 2015).

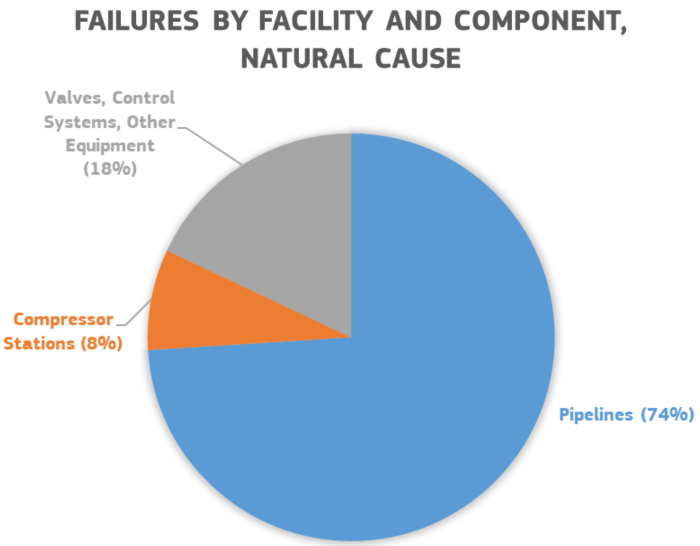
Relevant information is present in the database created by PHMSA - Pipeline and Hazardous Materials Safety Administration (Pipeline and Hazardous Materials Safety Administration, 2014), which requires pipeline operators to submit reports for incidents following the directives issued by title 49 of the Code of Federal Regulations (49 CFR Parts 191, 195), published in the Federal Register by the Department of Transportation of the Federal Government of the United States (United States Department of Transportation, 2014).

The database contains reports related to the entire gas transmission pipeline system, including pipelines, control and relief valves, metering stations, vessels and compressor stations. It contains a total of 2869 reports recorded between the year 1986 and September 2014. Incidents which happened between 1970 and 1986 were also recorded but almost all their reports did not include details about their cause.

Filtering the database by cause of accident, 293 accidents have been identified as caused by natural events, 22 of which related to compression stations.

Figure 24 shows how the number of reported failures by natural cause for compressors compares to that for other components. The incidents reported for compressor stations include those involving compressors, control and emergency shutdown systems and any other auxiliary equipment present in the facilities. It is evident how pipelines are, among the components of the entire transmission system, the most affected by natural hazards.

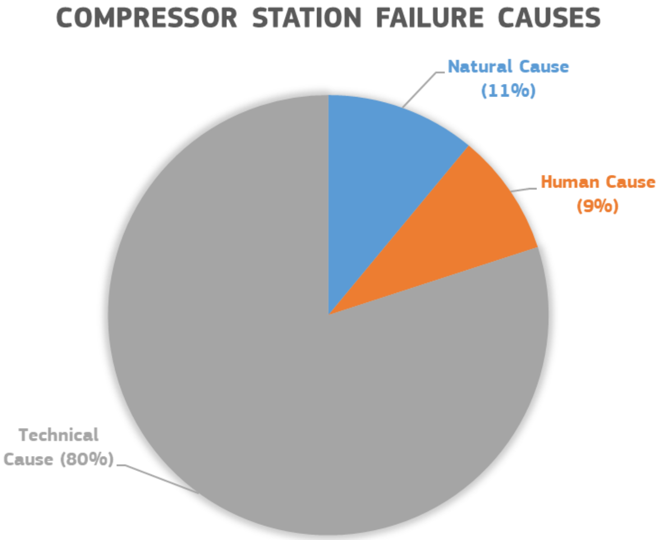
Figure 24 - Failure of components caused by natural hazards.



Source: PHMSA, 2014.

In total, 206 reports have been filed for compressor stations. In Figure 25 they are subdivided based on their cause. This diagram underlines that the contribution of natural causes to the total number of failures is relatively small compared to that of technical failures, and quite similar to that induced by incorrect operations or other human intervention. Analysing in detail how natural events affected the entire gas transmission system provides very useful indications regarding the different vulnerability of compressor stations to different natural events, compared to that of the entire system.

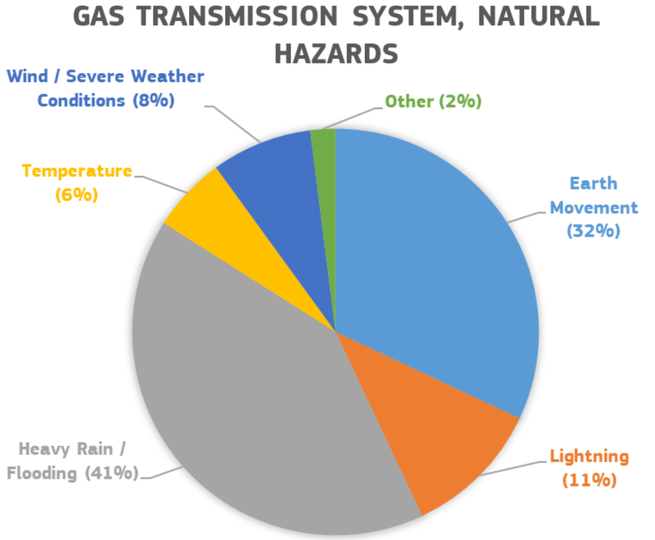
Figure 25 - Failure of compressor stations induced by different causes.



Source: PHMSA, 2014.

Most of the 293 failures of gas transmission systems have been caused by soil displacement (Figure 26), largely in the form of landslide, mudslide or subsidence. Only one reported case was explicitly attributed to an earthquake; it is however possible that earth movements identified as cause of incidents might have been caused themselves by earthquakes without specification.

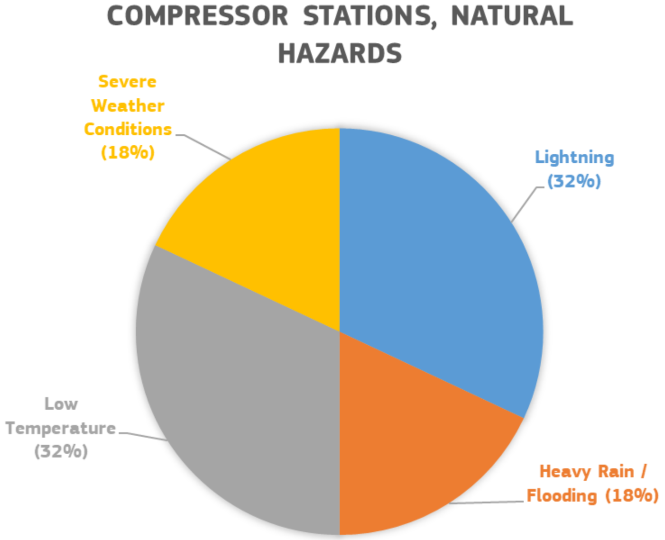
Figure 26 - Failure of compressor stations induced by different causes.



Source: PHMSA, 2014.

Compressor stations (22 reported cases) appear to have failed for quite different causes. In particular, lightning strikes and low temperature have been responsible together for over 60% of the filed reports (Figure 27).

Figure 27 - Failure of compressor stations caused by natural hazards.



Source: PHMSA, 2014.

The category labelled as "severe weather conditions" includes those reports for which it has not been indicated a specific cause and may regard strong winds, heavy rain, flooding or a combination of them. The review of articles and publications confirmed the difference in vulnerability between compressor stations and the rest of the transmission system.

Several researches have been conducted on seismic hazards. Based on observation of past events, compressors do not appear to be very vulnerable and generally have performed well. Most problems were usually caused by weak anchorage to the supporting foundations, insufficient tie-down of equipment, falling debris and failure of electrical supplies (United States Federal Emergency Management Agency, 1992). A study conducted by the American Lifelines Alliance (ALA) on almost 130 compressors indicated no signs of failure to the compressor units themselves (American Lifelines Alliance, 2005). Other references (Pipeline and

Hazardous Materials Safety Administration, 2014) confirm the fact that gas compressor stations are designed and constructed conservatively, after proper site selection. Transmission pipelines, however, cross large areas and often through zones of potentially unstable soils. These same reasons justify the lower number of cases reported as caused by heavy rain and flooding. While pipelines are often laid in proximity of water streams or have to cross them, compressor stations can be positioned in adequately selected sites, where the flooding hazard is lower.

The results appear to indicate that the emergency shutdown and relief systems are subjected to frequent failure. In particular, lightning hazards impacted on the ESD system, inducing spurious intervention of the valves, or interrupting supplies of electrical power to the system and causing its intervention.

Low temperatures, have been responsible for the incorrect functioning of the system's valves which have either been held blocked in closed position or induced to open by ice build-up. It must be pointed out however, that these incidents might have been avoided with better facility design or maintenance intervention to prevent liquid accumulation inside the equipment. The weather conditions should not be accounted as primary cause whenever evident flaws in the design, improper operations or pre-existing damage conditions were present.

The reports which include shutdown and restart times for incidents caused by lightning and low temperatures, indicate downtime shorter than five hours for all cases. In all cases manual intervention was required to re-establish normal functioning.

In conclusion, the historical analysis and literature review revealed that gas transmission systems are mostly affected by seismic, flooding and lightning hazards. For compressor stations statistics are poor (22 accidents due to natural hazards); the cases of compressor station impairment due to natural hazards is a small percentage of the total number of accidents due to natural causes that have damaged the whole gas transmission system (8% of the cases) with a prevalence of flooding, lightening, low temperatures, severe weather conditions. Low temperatures, as discussed here above, do not represent the initiator of the accident but such climate conditions acted as the triggering condition in presence of previous design or maintenance errors. For what concerns extreme weather conditions, most of the accidents involve flooding conditions.

4.2.2 UGS Sites

The considerations made for gas pipeline's compressor stations have been considered to be applicable also to underground gas storage facilities, regarding the impact of natural events on them. A research has been conducted to assess the impact of compressors failure on the functioning of the entire UGS facility.

Important information regarding past experience was found in a study conducted by the British Geological Survey for the Health and Safety Executive (Evans, 2007). The incidents reported in the study are summarized in Table 14. Only one reported incident was caused by the failure of compressor units, not triggered by a natural event. The impact of the compressor system seems, at least regarding incidents of important entity, negligible.

Table 14 - Documented incidents or problems at UGS facilities – Natural Gas Storage.

Cause of accident	Storage type			TOTAL
	Depleted reservoir	Aquifer	Salt cavern	
Well, casing failure	5	2	3	10
Valve, pipes, wellhead, compressor failure	3	--	--	3
Repair, testing, maintenance	--	2	--	2
Inadvertent intrusion	1	1	--	2
Overpressure, overfilling	--	--	--	0

Geology related	6	12	5	23
Other, not determined	1	--	--	1
TOTAL	16	17	8	41

Source: British Geological Survey, 2007.

Intense seismic activity damaged the well infrastructure or the geological integrity of the underground system. Geology-related incidents often caused gas migration to the surface, either through rock discontinuities, faults or failure of the cavity roof or salt creep. The failure rate due to reservoir formation damage in UGS facilities has been estimated in the order of 10-5 failures per well year (UK Health and Safety Executive, 2008). The consequence of this type of failure is the release of stored gas with a mass discharge rate of 10-4 kg/s over an estimated area of hundreds of square meters. In major hazard terms this equates to a risk that can be considered negligible.

A much larger risk is posed by the failure of the well that connects the cavity to the surface, having similar failure rate but a mass discharge rate estimated in the order of 250-550 kg/s (Watson, Metcalfe, & Bond, 2008).

Most incidents registered worldwide in depleted oil and gas fields, took place in California (69 %). This is largely due to the ongoing seismic activity and to the vast number of wells drilled in the past to produce the reservoir now used for storage. Therefore, these results can be relevant to underground gas storage in those areas of Europe where high seismic activity is met, i.e. Italy and Balkans. It should be noted that underground gas storage activity has been documented to trigger induced seismicity and subsidence. The recorded events have usually been of low intensity and unable to damage the facilities, however operations have sometimes been interrupted due to concerns of the surrounding community.

In conclusion, in accident reports and data there is no evidence of significant failure/unavailability of the UGS due to compressor failures depending on natural events. No other data source were found regarding the role of gas compression failures for UGS. It is safe to assume that the conclusions reached from the historical analysis performed for compressor stations installed along pipelines can be extended to these facilities.

4.2.3 LNG Facilities

The research for historical data lead to a study conducted by GIIGNL (International Group of Liquefied Natural Gas Imports), an association born in 1971 with 19 member companies and now counting 75. GIIGNL collects and analyses safety incidents which happen on facilities controlled by its members, but also those in the public domain concerning companies which are not directly taking part in the survey. The aim of the survey was to identify incidents of natural gas release and other incidents of concern for both liquefaction and regasification facilities, their severity and potential consequences, and finally to indicate under what circumstances and how frequently they occur. 328 incidents have been reported for the period 1965 to 2007, corresponding to a cumulative operation time of 1320 site-years (International Group of Liquefied Natural Gas Importers, 2016).

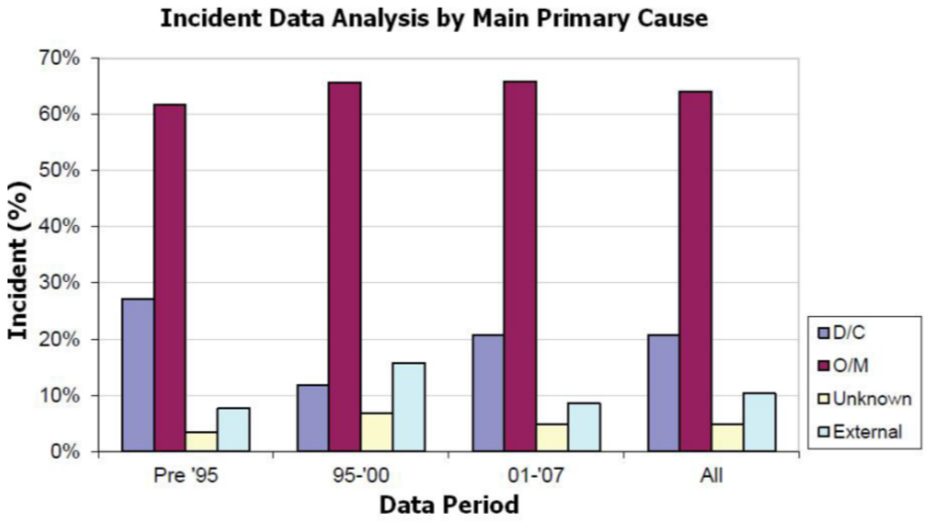
Table 15 - Historical Incidents Frequencies.

Period	Incidents	Operating site-years	Frequency
1965 - 1974	15	44	0,34
1975 - 1984	52	179	0,29
1985 - 1994	94	327	0,29
1995 - 2000	85	191	0,45
2001 - 2007	82	579	0,14
TOTAL	328	1320	0,25

Source: GIIGNL, 2016.

The incidents have been aggregated as induced by main primary causes, defined as design/construction (D/C), operation/maintenance (O/M), external and unknown. Incidents caused by problems with the initial design and installation of the equipment were grouped under design/construction. Those caused by equipment failure during operation, operator error, poor procedures and poor maintenance under operation/maintenance. Figure 28 shows the major impact of design/construction and operation/maintenance groups on the overall number of incidents. It is evident how external causes, including natural ones, contribute for about 10% of the total. Similarly to what was found for compressor stations, most incidents appear to be triggered by technical or human-caused failures.

Figure 28 - Incidents by cause.



Source: GIIGNL, 2016.

The survey contains information on incidents of any proportion, with around 60% of them reported to have resulted in a gas release of less than 100kg.

Concerning the effects of natural hazards on LNG plants the following considerations can be drawn considering that only seismic and Tsunami impacts have been reported. LNG facilities are located close to the coastline, hence the design must take into account, among others, the possibility of a tsunami triggered by an offshore earthquake or massive subsea landslides. A number of very large and large earthquakes have occurred with epicentres in areas that could potentially affect LNG facilities. Of the 16 very large earthquakes reported, only 3 caused significant damage.

Table 16 - Damage due to earthquakes.

Type	Location and Year	Terminal	Description	Damage to Facilities
Very large earthquakes	Japan 2011	Minato LNG	Magnitude: 9.0 PGA: 0.615g	Stretching of tie rod of gas holder. Tsunami damage
	Japan 1995	Senboku, Himeji	Magnitude: 7.3 PGA: 0.818g	Small sinkage of foundations due to soil liquefaction
	Chile 2010	GNL Mejilones	Magnitude: 8.8 PGA: 0.78g	No reported damage
	Chile 2010	GNL Quintero	Magnitude: 8.8 PGA: 0.78g	Occurred during construction of LNG tanks, which had seismic isolators. Tanks undamaged. Only slight damage to one cargo unloading arm, counterweight plates required to be adjusted
	Chile 2012	GNL Quintero	Magnitude: 6.5	Regasification operations resumed same day after power was restored
	Samoa 2009	Eastern Australia, US West Coast	Magnitude: 8.1	LNG facilities not yet operational when earthquake occurred
	Sumatra 2007	Indonesia, Japan, South Korea, India	Magnitude: 8.5	No reported damage
	Sumatra 2005	Indonesia, Japan, South Korea, India	Magnitude: 8.6	No reported damage
	Sumatra 2004	Indonesia, Japan, South Korea, India	Magnitude: 9.1	No reported damage
	Alaska 1964	Kenai	Magnitude: 9.2	LNG facilities not yet operational
Large earthquakes	US (Virginia) 2011	Cove Point, Savannah	Magnitude: 5.8	No reported damage
	Spain 2011	Barcelona, Huelva, Cartagena	Magnitude: 5.1	No reported damage
	Alaska 2011	Kenai	Magnitude: 6.8	No reported damage
	Italy 2009	La Spezia	Magnitude: 6.3	No reported damage
	Italy 2009	Rovigo	Magnitude: 6.3	LNG facilities not yet operational
	China 2008	East and south coastal terminals	Magnitude: 7.9	No reported damage

Source: GIIGNL, 2016.

Several events of major relevance have not caused any damage, however it should be noticed that earthquake magnitudes refer to epicentres and therefore the effects felt at the facilities located at a certain distance may have been less severe according to seismic attenuation. Some of these earthquakes have generated Tsunamis. Only one of the three reported cases resulted in damage to LNG facilities. In this case the marine LNG unloading facilities and the inland LNG storage tank were undamaged. Secondary pipe supports with shallow foundations and many instruments have been affected. The positive response of Minato plant to a flooding event of such extent confirms the effectiveness of Tsunami design resistance.

Table 17 - Damage due to Tsunami.

Name	Terminal	Description	Damage to Facilities
Japan 2011	Minato	4 meter over usual tide level for 1 hour	Facilities not supported by pile foundations greatly damaged.
Sumatra 2004	Osaka	1m over usual tide level	No damage
Chile 2012	Mejilones	0,5m over usual tide level	No damage. Unloading operations interrupted

Source: GIIGNL, 2016.

In conclusion this survey appears to provide very positive feedback regarding the resistance of LNG plants. Even very large earthquakes or the associated tsunamis have never caused incidents able to significantly compromise LNG facilities operations. Seismic design standards appear to properly include safety margins and Tsunami resistance design has proven quite effective in protecting facilities from flooding by placing sensitive systems above the potential flood level or behind adequate walls. The report does not contain specific comments on compression and pumping systems, furthermore, no incidents caused by other than seismic activity or tsunamis have been reported. It is safe to assume that naturally induced incidents involving compressors or pumps did not or occur or produced damage unable to affect operations.

4.3 Lessons Learned

Literature review provided a preliminary overview on the vulnerability of the gas transmission system, including that of compressor stations. The table presented below, extracted from a report presented by the American Lifelines Alliance, shows the degree of vulnerability for equipment and components of gas transmission systems for different natural hazards (American Lifelines Alliance, 2005). In particular it provides complete information for earthquake shaking and flooding.

Based on the historical analysis, it has been concluded that the analysis should be performed on hazards involving earthquakes, flooding and lightning strikes. The historical analysis contained reports about incidents related to hurricanes, however this type of hazard has not been taken into consideration as Europe is not historically hit by such events. Other hazards such as external fires, air pollution, extreme hail or snow precipitation have been considered to have negligible impact on the unavailability of compressor stations across Europe and have therefore not been included in the study. Risk assessments specific to the single facility should be performed whenever additional hazards are present.

Table 18 - Degrees of vulnerability of gas transmission system components: H=High, M=Moderate and L=Low.

Natural Hazards	Degree of Vulnerability							
	Pipeline	Comp. Stations	Processing Facilities	Storage Tanks	Control Systems	Maintenance and Operation Buildings and Equipment	Regulation/ Metering Stations	Service Lines/ Connections
Earthquake Shaking	L	M	M	H	M	H	L	M
Earthquake Permanent Ground Deformation (fault rupture, liquefaction, landslide and settlement)	H	-	-	L	-	-	L	M
Ground Movements (landslide, frost heave, settlement)	H	-	-	L	-	-	L	M
Flooding (river, storm surge, tsunami)	L	H	H	M	H	H	H	M
Wind (hurricane, tornado)	L	-	-	-	L	L	-	-
Icing	L	-	-	-	-	-	-	-
Collateral Hazard: Blast or Fire	M	H	H	H	M	L	L	M

Source: ALA, 2005.

4.3.1 Expert judgement

An industry expert in design and operation & maintenance of natural gas compressor stations in Italy owned by the main Transmission System Operator, and with more than 30 years of in the field, confirmed the results obtained regarding the vulnerability of compressor stations to seismic, flooding and lightning hazards. In particular he reported how the two earthquakes which occurred in Northern Italy in 2012, of magnitude 5.9 and 5.8, caused no damage to compressor stations located in the region. He however reported that compressors have been briefly shut down as a precaution. Regarding flooding, he recalled that in some occasions temporary protection had been put in place, to avoid water reaching sensitive parts of the facility. Facilities built in areas particularly exposed to flooding hazard are built on elevated foundations. Lightning strikes have been reported as relatively frequent and potentially able to induce damage, for instance igniting gas being vented.

4.4 Natural Hazard classification in EU

For flooding, seismic and lightning hazards a survey on European classification, in terms of severity and recurrence intervals, has been performed. The effects on the studied installations of phenomena characterized by different severity and recurrence interval thresholds commonly used in Europe were evaluated. For reference, also data referred to not European Countries have been considered.

4.4.1 Seismic

Earthquakes are seismic movements of the solid earth that are mainly caused by tectonic activities. Most of the world's earthquakes occur in areas where large tectonic plates meet but may also occur within plates. Earthquakes can also occur because of impacts such as the collapse of underground cavities. Human-induced explosions, like tunnelling works, can also create local earthquakes, meaning that earthquakes can occur in all terrestrial and submarine areas. Earthquakes can also trigger other hazards, such as landslides, tsunamis and avalanches.

Seismic events are arguably foremost in minds when geological hazards are mentioned, so the earthquake hazard is relatively well known and is usually represented by hazard curves that relate seismic parameters such as peak ground acceleration or spectral acceleration to the related exceedance probability for a given period of exposure and for a certain location.

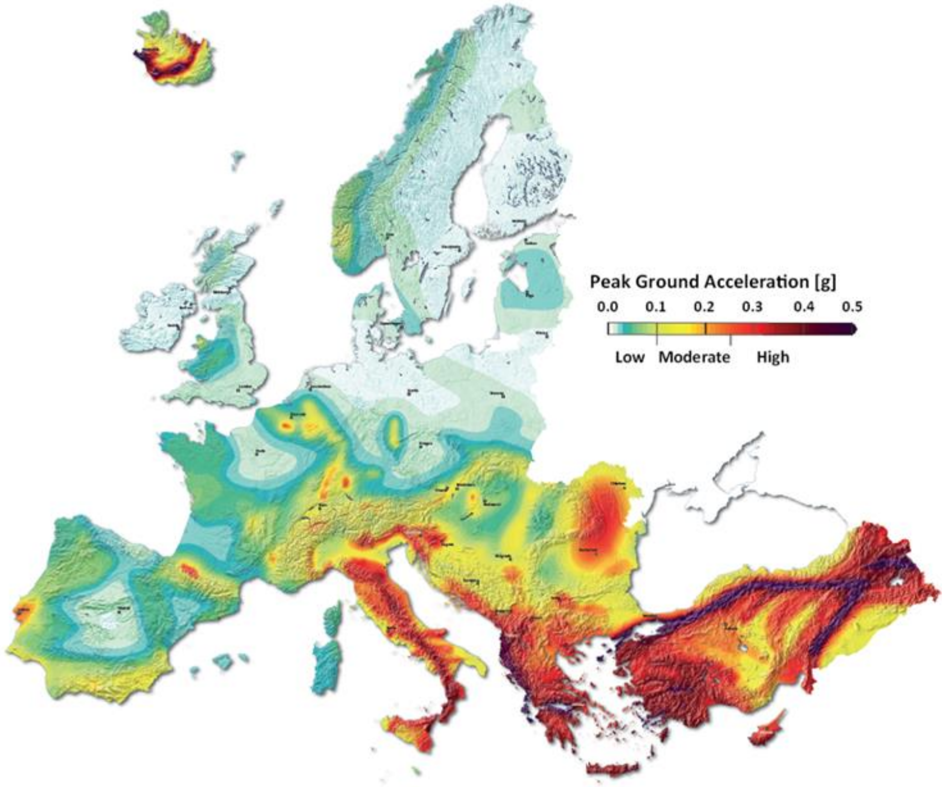
Peak Ground Acceleration (PGA) is a measure of the maximum acceleration recorded by instrumentation at the surface of the ground during an earthquake, while Spectral Acceleration (SA) is an index which allows a better evaluation the effects of earthquakes on buildings. The natural vibration period of a building indicates how vulnerable it is to ground motion of a certain period and tall buildings, characterized by longer natural vibration periods, are not greatly affected by short period seismic waves. In the same way, short buildings are not largely damaged by long period waves (United States Geological Survey, 2014).

The seismic hazard is usually described for each country by National agencies with zonation maps which subdivide the national territories into seismic zones based on the local hazard, and the EU has funded dedicated projects to develop methodologies and models able to evaluate earthquake hazard in Europe, to provide a homogeneous input for the correct seismic safety assessment for critical industry.

The Global Seismological Hazard Assessment Project (GSHAP) produced maps showing the maximum PGA values to be expected in a 50 year period, based on historical earthquake locations, frequency and magnitudes as well as known fault lines. A hazard risk map was published in 2004, identifying the NUTS 3 regions most at risk, with FP7 project SHARE (Seismic Hazard Assessment in Europe) aiming at improving earthquake hazard maps by taking into account the latest research and observations (SHARE, 2014).

SHARE produced a unified framework with a computational infrastructure and an integrated probabilistic seismic hazard assessment model which resulted in over sixty time-independent European Seismic Hazard Maps. Results are available for return periods between 73 and 4975 years and at least twelve different spectral PGA values, covering the whole Euro-Mediterranean region, including Turkey. The construction of these maps, such as the one illustrated in Figure 29, involved focusing on the geologic knowledge for the description of events with longer time horizons and seismological data for shorter ones (SHARE, 2014).

Figure 29 - Peak ground acceleration, 10% exceedance probability in 50 years, 475 years return time.



Source: SHARE, 2014.

The EN1998 Eurocode 8 “Design of structures for earthquake resistance” regulation intends to regulate earthquake proof building design in Europe (Lubkowski & Duan, 2001). In order to evaluate consequences on infrastructures, the suggestions contained in Eurocode 8 on which return times should be appropriately considered can be followed, standard EN 1998 defining three states of damage: “near collapse”, “significant damage” and “damage limitation”.

- Near Collapse (NC) - The structure is heavily damaged, with low residual lateral strength and stiffness, although vertical elements are still capable of sustaining vertical loads. Most non-structural components have collapsed. Large permanent drifts are present. The structure is near collapse and would probably not survive another earthquake, even of moderate intensity.
- Significant Damage (SD) - The structure is significantly damaged, with some residual lateral strength and stiffness, and vertical elements are capable of sustaining vertical loads. Non-structural components are damaged, although partitions and infills have not failed out-of-plane. Moderate permanent drifts are present. The structure can sustain after-shocks of moderate intensity. The structure is likely to be uneconomic to repair.
- Damage Limitation (DL) - The structure is only lightly damaged, with structural elements prevented from significant yielding and retaining their strength and stiffness properties. Non-structural components, such as partitions and infills, may show distributed cracking, but the damage could be economically repaired. Permanent drifts are negligible. The structure does not need any repair measures.

The appropriate level of protection against the exceedance of the three states is achieved by associating to each a return period value (T_r) for the design seismic action. Eurocode 8 suggests T_r specific values of respectively 2475, 475 and 225. To better understand the damage which can be associated to a certain PGA, it might be useful to refer to intensity scales. Many have been created over the years to describe earthquake effects and correlate them to PHA values. The Modified Mercalli Intensity Scale does not have a mathematical basis but instead describes earthquakes based on observed effects. It is evident that for the same seismic event, the identified intensity may be different based on factors such as construction standards (United States Geological Survey, 2014).

Table 19 - Correlation of PGA values [%g] and Modified Mercalli Intensity Scale.

MMI	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Richter (1958)	0,1	0,1	0,3	0,7	1,4	3,1	6,5	14,1	30,1	64,3		
Medvedev & Sponheuer (1969)				1,2 – 2,5	2,5 - 5	5 - 10	10 - 20	20 - 40	40 - 80			

Source: USGS, 2014.

Table 20 - Modified Mercalli Intensity scale.

Intensity	Shaking	Description / Damage
I	Not Felt	Not felt except by a very few under especially favourable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very Strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Severe Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

Source: USGS, 2014.

While the seismic hazard is well known, consequences are more difficult to assess. Earthquakes can trigger secondary effects (like landslides), for which specific knowledge is necessary. Furthermore, in order to assess infrastructure vulnerability, further knowledge is required, including the location and structural engineering parameters of buildings, the applicable zoning and building codes, and the level of compliance with the codes, this data being generally unavailable at national or European level. Ultimately, some properly justified assumptions will always be necessary when conducting the vulnerability assessment.

4.4.2 Flooding

Floods are here defined as occurrences where water overflows its natural or artificial banks onto normally dry land, such as a river inundating its floodplain, occurring at more or less regular intervals. In Europe floods occur most often in springtime, when the winter snow and ice is melting. Strong floods happen irregularly, in so-called re-occurrence intervals of 10, 50 or 100 years. However, these intervals are only statistical averages, for example the Rhine/Mosel areas were hit by 100-year return period floods at the end of 1993 and in the beginning of 1995. Heavy summer rainfalls can also lead to floods. Floods have become an increasing problem for the built-up environment since human beings have started to change, straighten and relocate river beds, and also by settling in low lying areas close to rivers, often in natural flood prone areas. Also, increased soil sealing leads to a higher flood hazard, as rainwater runs off directly into the streams and the water mass inflow to rivers is no longer delayed by natural soil retention. Flash floods can contribute to river floods, or can be caused by river floods, if, for example, an embankment collapses. Flash floods can occur all over the European territory but are mostly bound to catchment areas and are thus integrated into the map of large river floods in Europe (European Parliament and Council, 2007).

Storm surge is seawater that is pushed toward the shore by the force of the winds of a strong storm. This rise in water level can cause severe flooding in coastal areas, particularly when the storm tide coincides with the normal high tides. In northern Europe, many coastal areas lie just above or even below the mean sea level and the danger from storm surges is very high. Storm surges may appear in European areas, but due to the high winter storm probability, some parts of the North Sea and Baltic Sea shore- lines being especially vulnerable to this hazard. Storm surges are often closely linked to winter storms. Due to the influence of the coastal geology and morphology on the actual storm surge hazard, the areas with a high storm surge hazard are mostly located in the western, southern and eastern North Sea shores, as well as the western, northern and eastern Baltic Sea shores (European Exchange Circle on Flood Mapping, 2007).

European directive 2007/60/EC “Directive on the assessment and management of flood risks” required Member States to perform preliminary flood risk assessments by 2011 and prepare flood hazard and flood risk maps by 2013. Flood hazard maps should show the extent of the flooded area, the expected water depth and where appropriate, the flow velocity, in low, medium (return period ≥ 100 years) and high probability scenarios.

Almost all countries have released flood maps of some kind. Some have published maps containing historical flood data and most countries have provided maps containing information regarding flood extent, usually for two or three return periods, at least for the areas most exposed to flooding hazard. Flood depth maps are reported by several countries while only very few countries provided maps comprehensive of flow velocity. In some cases a combination of probability, depth and velocity is used to elaborate a danger map. Each country used its own methodology to produce these maps, often omitting technical details of the calculations done for their creation. As a result, it is impossible to create a coherent European map by aggregating the already existing ones released by each country.

JRC has been working on pan-European flood hazard and risk maps for various years. These maps are available at a spatial scale of 100 m resolution and provide a harmonised, regional overview on flood hazard and risks across Europe. However, due to the spatial scale as well as to the incomplete or unavailable baseline data required to produce such maps, the pan-European maps cannot provide the same spatial detail and preciseness as the maps that will be (or have already been) produced by the Member States.

JRC started working on approaches to generate a flood hazard map for Europe in 2007 and in 2012, an updated flood hazard map was produced using a cascading models approach, which currently represents the latest, state-of-the-art approach to generate a high resolution flood hazard map at large scales. The pan European flood hazard map has a 100m x 100m pixel resolution and is available for return periods of 5, 20, 50, 100 and 200 years return period flood events. Flood risk assessment requires the integration of the physical impact results (flood inundation extent and depth) with information on exposure and vulnerability or impact. Vulnerability is appraised using flood depth-damage functions that represent the absolute amount of damage as a function of flood inundation depth. For different recurrence intervals, direct damage estimates can therefore be obtained by overlaying the flood water depth map with the land use map linked with the corresponding depth-damage functions. By linearly interpolating damages between different return periods, damage probability functions can be constructed for each grid cell. The integral of this function represents the expected annual damage (EAD) at the particular location due to flooding (Schmidt-Thomé & Kallio, 2006).

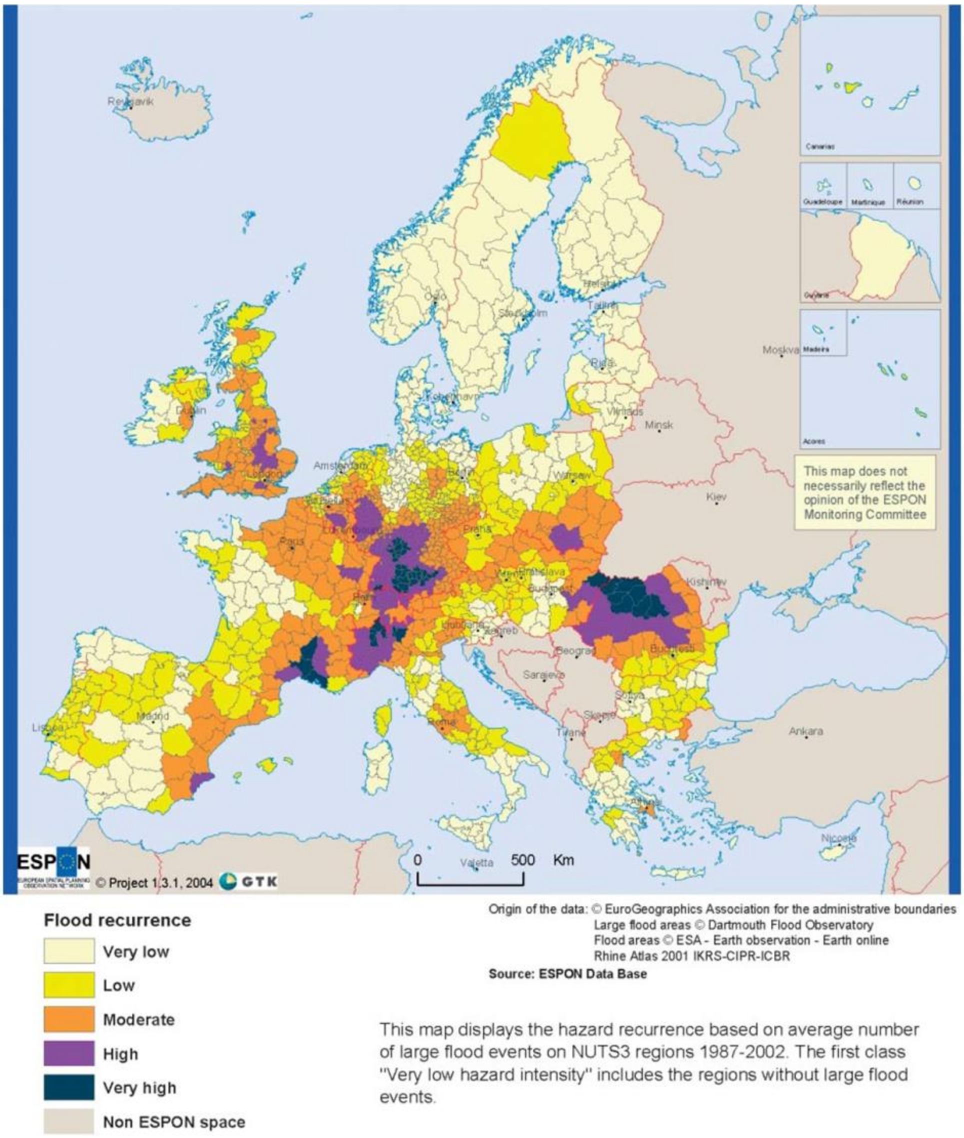
As an example of criteria to be adopted to assess flooding hazards, the current Italian situation is described. Italy has started implementing directive 2007/60/EC by adopting Legislative Decree D. Lgs. 49/2010, which requires that depth, flow rate and velocity are reported for the given return times (Gazzetta Ufficiale No. 77, 2010).

Table 21 - Return times proposed by Italian Legislative Decree 49/2010.

Likelihood	Directive 2007/60/CE	D.Lgs. 49/2010	DPCM 1998
Low	-	$T_r \leq 500$ years	$300 \leq T_r \leq 500$ years
Medium	≥ 100 years	$100 \leq T_r \leq 200$ years	$100 \leq T_r \leq 200$ years
High	-	$20 \leq T_r \leq 50$ years	$20 \leq T_r \leq 50$ years

Source: Italian Legislative Decree 49/2010, 2010.

Figure 30 - Flood Hazard in the EU.



Source: Schmidt-Thomé and Kallio, 2006.

The proposed depth intervals to be included in the maps should increase in 0.5 meter steps starting from 0.

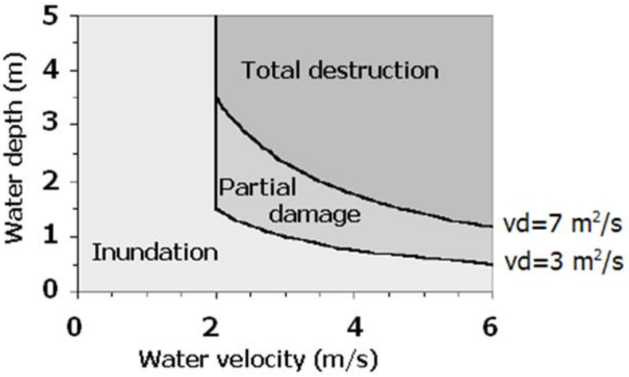
Table 22 - Depth intervals proposed by Italian Legislative Decree 49/2010.

h (m)	h < 0.5	0.5 ≤ h < 1	1 ≤ h < 1.5	1.5 ≤ h < 2	h ≥ 2

Source: Italian Legislative Decree 49/2010, 2010.

The proposal takes in consideration a combination of flood depth and flow velocity to define three classes of damage to buildings, total destruction, partial damage and inundated (Clausen & Clark, 1990). The damage corresponding to each point in Figure 31 is identified by the product of water depth (d) and water velocity (v).

Figure 31 - Damage as function of water depth and velocity.



Source: Clausen and Clark, 1990.

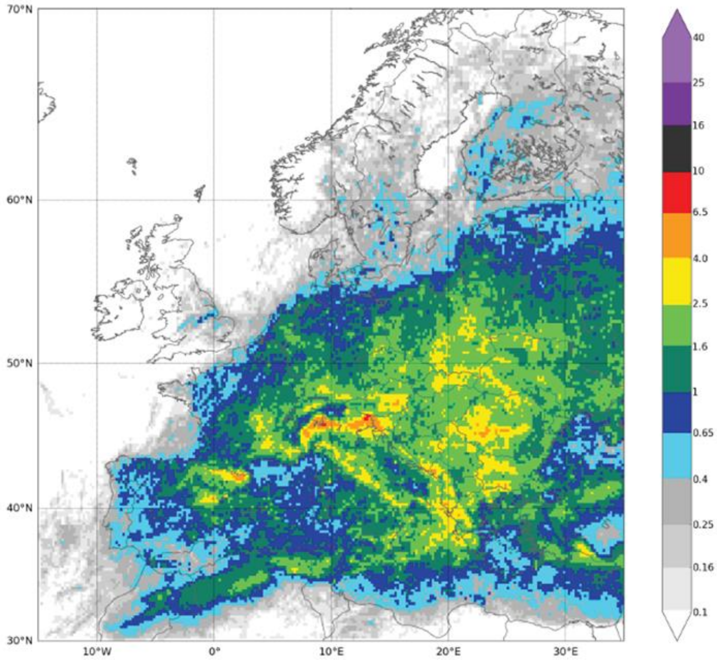
Whenever this information is available, it provides very useful additional information on the impact of flooding on facilities, allowing the assessment of the additional potential damage caused by debris transportation and water erosion.

4.4.3 Lightning

As mentioned above consultations with various experts with field experience resulted in the conclusions that the only real damage caused by hydrometeorological phenomena comes as expected from flooding but also, unexpectedly, from lightning. Given the relatively high number of events reported in the historical incident data bank a research on mapping of lightning density is available. Illustrated in Figure 32 is the average number of flashes observed during the period 1 January 2008 and 31 December 2012 by the Arrival Time Differing NETwork (ATDnet), showing the number of flashes per km2 per year (Anderson & Klugmann, 2014).

Most European countries are equipped with a lightning location system, providing high detection efficiency and location accuracy. For each lightning strike the main parameters are recorded: the time of event, the impact point, the current intensity and polarity, and the number of subsequent strikes. The information recorded is integrated within the EUCLID network which archives all the lightning information into its database (EUCLID, 2014).

Figure 32 - Annual detected lightning flash density (flashes per km^2 per year)



Source: Euclid, 2014.

4.5 Estimation of worsening factors

A correlation between the severity of natural hazard and the expected damage to natural gas installations was sought. The idea behind this method is to first evaluate the hazard level present at a certain location starting from the maps discussed above. This information can then be used, knowing the compressor station's vulnerability to each hazard, to estimate the potential unavailability of the plant. The vulnerability of compressor stations has been estimated based on existing fragility curves when available or historical analysis and technical evaluations in other cases.

4.5.1 Model

In general, the unavailability of a station at a certain location due to a natural event is calculated multiplying the yearly probability of occurrence of the event by the vulnerability of the plant to its effect, expressed in terms of time of lost functionality (RT – Repair Time).

For seismic hazards the calculation is made by the following formula:

$$Q_{\text{seismic}} = \sum_{i} f_{\text{seismic}_i} \cdot RT_i$$

where Q_{seismic} is the unavailability due to earthquakes that is given by the product of the event frequency (f_{seismic}) and of the repair time (RT), summed on the *i* classes of return period of the seismic event.

A similar formula has been set for flooding. Regarding lightening, the formula is simpler:

$$Q_{\text{lightning}} = f_{\text{lightning}} \cdot RT_{\text{lightning}}$$

The vulnerability of each facility to each hazard might be different, based on adopted standards of construction and presence of mitigation devices, such as vibration dampers to attenuate seismic impacts, water dykes to decrease vulnerability to water flooding or lightning protection systems. Given the vast number of stations a unified method is proposed, designed to provide realistic or slightly conservative results for all stations. The sum of the obtained results provides the unavailability caused by natural hazards (Q_{nat}). This value should be summed to the unavailability of 0% Flow Damage Class, for each configuration calculated earlier (Q_{tech}) to determine the total unavailability (Q_{TOT}) of the system.

$$Q_{\text{nat}} = Q_{\text{seismic}} + Q_{\text{flood}} + Q_{\text{lightning}}$$

$$Q_{TOT} = Q_{nat} + Q_{tech}$$

In all cases a 0% nominal flow Damage Class has been assumed to be present during the entire restoration time. This assumption is reasonable and produces conservative results, since in some cases other classes, such as bypass or 50% nominal flow, might be reached before full recovery of the system's functionality. In particular, in case of seismic activity it is safe to assume that the flow is stopped as a precaution, and especially considering the high vulnerability of pipelines to ground deformations and the likely consequent gas leakage. Similarly, in presence of flooding hazard the preventive shutdown of machines has been assumed given the high vulnerability of machines and electrical control equipment to water. Regarding lightning strikes, the assumption finds support in the historical analysis which described how lightning activity has caused spurious intervention of the emergency shut-down system, and gas has been vented to the atmosphere.

The proposed methodology can be applied to compressor stations placed along gas transmission pipelines and in underground gas storage sites. LNG facilities showed to have much greater resistance to the effects of both seismic and flooding hazards. The contribution of natural events on the unavailability of their compression or pumping systems can be safely be considered negligible if compared to that caused by technical failures.

4.5.1.1 Seismic

The unavailability of a station at a certain location due to seismic activity is calculated multiplying the yearly probability of occurrence of seismic events by the vulnerability of the plant to their effects. As described above, the first step involves consulting hazard maps to know the seismic activity in the area of interest.

The hazard maps available on the European Facility for Earthquake Hazard and Risk portal (www.efehr.org) allow to estimate the PGA values in a certain area for a given return period. The return periods (Tr) for which maps are available are 73, 102, 475, 975 and 2475 years (EFEHR, 2014).

Table 23 - Return periods and expected annual probability of exceedance.

T_r	P_i
73	0,013605
102	0,009756
475	0,002103
975	0,001025
2475	0,000404

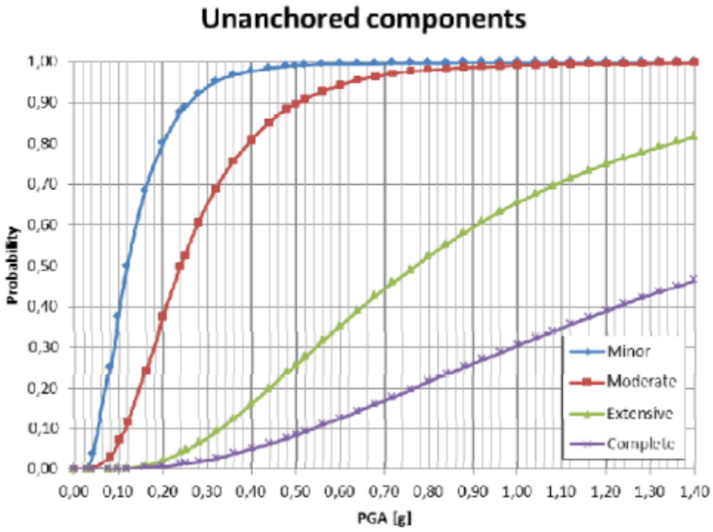
Source: EFEHR, 2014.

The annual probability of exceedance can be calculated as $P=1-e^{(-1/Tr)}$ and can otherwise be approximated by $P=1/Tr$.

When available, information for all return periods should be used. Neglecting part of it may lead to underestimated results of unavailability. The application of at least three classes is recommended when data are available. Table 23 will be used, here below, to estimate the frequency of occurrence of each return period class. The calculation of the resulting damage, expressed as repair time is estimated as follows.

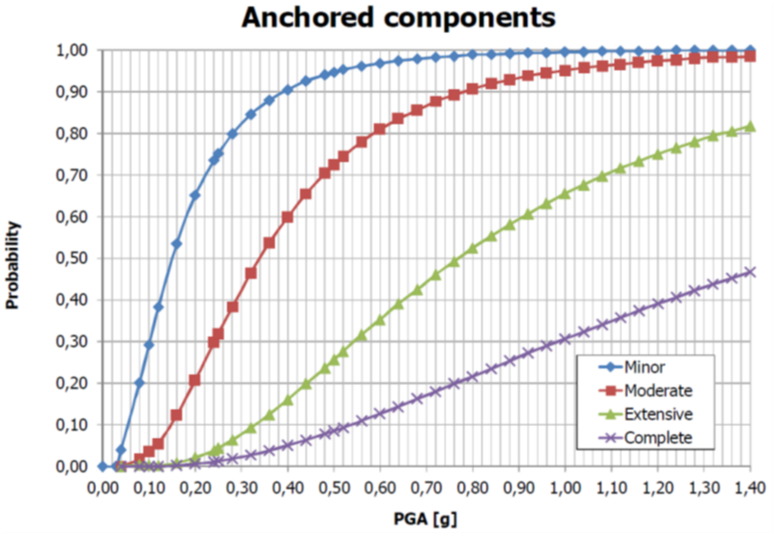
The functionality of compressor stations, in case of seismic events, has been evaluated based on fragility curves developed by the Applied Technology Council in the ATC-13 report and found in the FEMA's HAZUS earthquake technical manual (Hazus, 2012). These curves show the probability that a certain damage state is reached or overcome as function of PGA values, for anchored components, designed with special seismic tie downs and tiebacks, and unanchored ones with normal requirements. It should be noted that the manual contains curves built for water pumping equipment and later suggests that they can be considered valid also for both oil pumping and gas compression systems. Figures 33 and 34 illustrate the probability to suffer a certain damage depending on the magnitude of the earthquake, respectively for unanchored and anchored components.

Figure 33 - Probability of damage state exceedance, for unanchored components, as function of PGA.



Source: Hazus, 2012.

Figure 34 - Probability of damage state exceedance, for anchored components, as function of PGA.



Source: Hazus, 2012.

Restoration functions are provided by the Hazus® 2012 report in terms of mean and standard deviations.

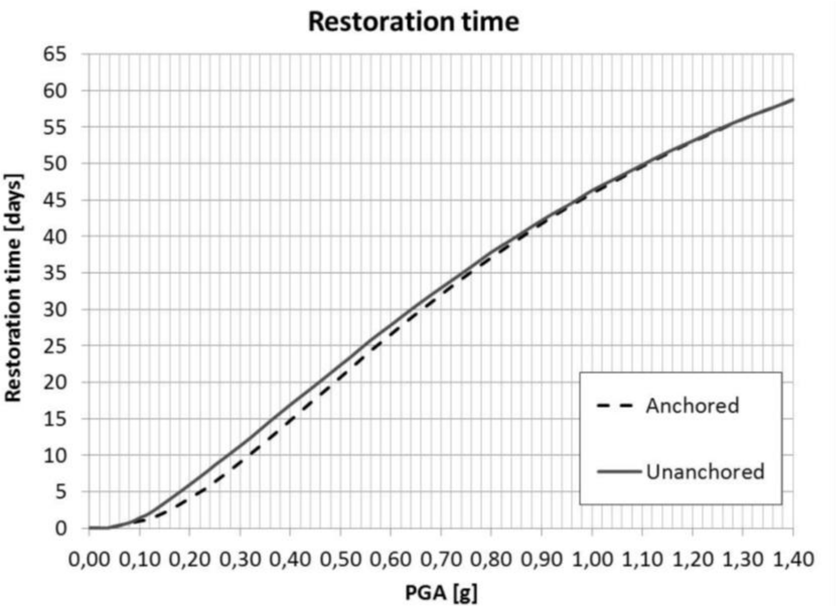
Table 24 - Restoration functions for compressor stations.

Damage State	Mean [days]	σ [days]
slight/minor	0,9	0,3
moderate	3,1	2,7
extensive	13,5	10
complete	35	18

Source: Hazus, 2012.

The expected restoration times RT_i for each damage state have been estimated as the sum of the mean plus three standard deviations, in order to estimate the time for a complete recovery of the functionality. From the probability of damage reported in Figure 33 and Figure 34, and according to the above method to estimate the restoration time, based on data reported in Table 24, Figure 35 can be drawn.

Figure 35 - Restoration time as function of PGA for anchored and unanchored components.



Source: Tractebel, 2016.

Curves for unanchored components have been used in the method presented in this report to obtain more conservative results. This is a good approximation and allows a simplification in the approach, since curves for anchored components only differ for minor and moderate damage states (that result in the shortest repair times), while curves referred to extensive and complete damages are the same of unanchored components. Also the difference in restoration time, calculated for large and very large earthquakes, between anchored and unanchored components, is negligible as reported in Figure 35.

Coupling the probability to suffer a certain damage depending on the magnitude of the event with the repair time for each damage state evaluated through Table 24, Table 25 can be derived, showing how each event magnitude is related to system restoration time, the restoration time has been evaluated as the mean value in the considered interval; for PGA values exceeding 1g a restoration time superior to 1110h has been considered. Each damage state has been associated to a range of PGA values.

Table 25 - Restoration time for different PGA intervals.

PGA Intervals [g]	Restoration time (RT_i) [h/ev]
<0,1	11
0,1-0,25	121
0,25-0,5	376
0,5-1	829
>1	>1110

Source: Tractebel, 2016.

The restoration time required to restore functionality of the facilities has been multiplied by the probability of exceedance (P_i-P_{i+1}) obtained for each return period interval *i*, corresponding to the frequency of occurrence of the event characterised by a certain magnitude (PGA). The probability for each return period interval *i* (P_i-P_{i+1}) has been calculated as the probability for a certain return period P_i minus the probability of the successive period P_{i+1}, to avoid overestimation in the final calculation of unavailability. In other words, P_i-P_{i+1} represents the probability per year of exceeding a given PGA value and not exceeding the next PGA considered.

Table 26 - Probability of exceedance (P_i-P_{i+1}) for each period interval *i*.

i	T_r [years]	P_i	P_i-P_{i+1}
1	73	0,013605	0,00385
2	102	0,009756	0,00765
3	475	0,002103	0,00108
4	975	0,001025	0,00062
5	2475	0,000404	0,0004

Source: Tractebel, 2016.

The found probability values have been multiplied by the restoration time values estimated above to obtain the following table.

Table 27 - Unavailability (Q_{seismic}) as function of return time and PGA intervals.

		PGA Intervals [g]				
T_r [years]	Interval P (P_i-P_{i+1})	<0,1	0,1-0,25	0,25-0,5	0,5-1	>1
73	0,0038	4,6E-06	5,3E-05	1,7E-04	3,6E-04	>4,9E-04
102	0,0077	9,2E-06	1,1E-04	3,3E-04	7,2E-04	>9,7E-04
475	0,0011	1,3E-06	1,5E-05	4,6E-05	1,0E-04	>1,4E-04
975	0,0006	7,5E-07	8,6E-06	2,7E-05	5,9E-05	>7,9E-05
2475	0,0004	4,9E-07	5,6E-06	1,7E-05	3,8E-05	>5,1E-05

Source: Tractebel, 2016.

To clarify how Table 27 was derived from data above reported let us consider, for instance, the 1.1 E-04 value obtained for T_r = 102 years and PGA between 0.1 and 0.25g. It is calculated as:

Q_i = 0,0077 [ev/year] x 121 [h/ev] / 8760 [h/year] = 1,1E-04

The first figure (0.0077) is directly reported in the second column of Table 27, while the second (121) is taken from Table 25 for the considered PGA interval (0.1g - 0.25g) and the third is from the conversion of RT from [h/event] into [years/event]. It must be pointed out that in Table 25 values have been rounded whereas in calculation of Table 27 they have been adopted without rounding.

The PGA values for each return period should be extracted from maps and located within PGA intervals. The values of unavailability should be identified corresponding to each return period (line) and PGA interval (column). They should then be summed, to obtain the total potential unavailability caused by seismic hazard.

$$Q_{\text{seismic}} = \sum_i f_{\text{seismic}_i} \cdot RT_i$$

After extracting the expected PGA from the seismic maps, for each return period the corresponding unavailability can be found. These unavailability values must be summed for all the return periods available in the maps in order to obtain $Q_{seismic}$.

NOTE: when the number of T_r classes is less than the five used in the method described here, Table 27 must substituted by the following Table 28 that is less precise but conservative in the final results:

Table 28 - Unavailability as function of return time and PGA intervals –Approximate method.

		PGA Intervals [g]				
T_r [years]	Interval P (P_i-P_{i+1})	<0,1	0,1-0,25	0,25-0,5	0,5-1	>1
73	0,013605	1,6E-05	1,9E-04	5,8E-04	1,3E-03	>1,7E-03
102	0,009756	1,2E-05	1,3E-04	4,2E-04	9,2E-04	>1,2E-03
475	0,002103	2,5E-06	2,9E-05	9,0E-05	2,0E-04	>2,7E-04
975	0,001025	1,2E-06	1,4E-05	4,4E-05	9,7E-05	>1,3E-04
2475	0,000404	4,9E-07	5,6E-06	1,7E-05	3,8E-05	>5,1E-05

Source: Tractebel, 2016.

4.5.1.2 Flooding

The influence of flooding has been evaluated following the analysis conducted on hazard mapping. In the present study, similarly to the approach suggested by the Italian Legislative Decree 49/2010, three return periods have been considered. Using the same criterion as for seismic events, the annual probability of exceedance is calculated as $P=1-e^{(-1/Tr)}$ and can be approximated by P=1/Tr.

Table 29 - Return periods as per the Italian proposal.

i	T_r [year]	P_i
1	50	2E-02
2	200	5E-03
3	500	2E-03

Source: Italian Legislative Decree 49/2010, 2010.

Table 29 will be used to estimate the frequency of occurrence of each return period class. The calculation of the resulting damage, expressed as repair time RT_i is estimated as follows.

A research to find pre-existing fragility curves as function of water depth, and of restoration time as function of damage states tables has been conducted without finding any result. An evaluation based on engineering expertise has been performed. All equipment sensitive to water has been reasonably assumed to be elevated from the ground level, hence the short downtime associated to the lowest water depth interval. The restoration time for larger water depths has been estimated keeping into account also that debris flow would likely occur and potentially impact on the station, and that surrounding infrastructure might be damaged as well, delaying maintenance and repair operations. The effects of flooding are strongly dependent on the territory in which the facility is located. The presence of physical barriers, natural or man-made, has in fact a major impact in the way water reaches the station site. Therefore this study provides a method that can be applied to any station based on the characteristics associated to its location on a large scale, however to have more detailed results a specific research for each site should be performed.

The damage caused by flooding has been expressed in terms of time necessary for the facility to return to functional status and the results are expressed in Table 30. A shutdown time of two days has been estimated for water depth up to half a meter. The level of damaged caused by a certain flooding event may differ greatly, based on how much equipment is raised above ground level and whether dykes are in place or not. For this reason an engineering estimation has been performed to correlate water depth to damage.

Table 30 - Damage caused by water for various depth intervals.

Water Depth [m]	Shutdown Time – RT_i [day/event]	Shutdown Time – RT_i [h/event]
h <0,5	2	48
0,5≤h<1	7	168
1≤h<1,5	21	504
h≥1,5	42	1008

Source: Tractebel, 2016.

Table 30 provides the final damage in terms of recovery time for each water depth. The restoration time of the facilities will be multiplied by the probability of exceedance obtained for each return period interval, corresponding to the frequency of occurrence of the event characterised by a certain water depth, in order to estimate the unavailability of that water depth. The probability for each return period interval has been calculated as the probability for a certain return period Pi minus the probability of the successive period P_{i+1}, to avoid overestimation in the final calculation of unavailability. In other words, P_i-P_{i+1} represents the probability per year of exceeding a given water depth and not exceeding the next water depth considered.

Table 31 - Probability of exceedance for each period interval *i*.

i	T_r [year]	P_i	P_i-P_{i+1}
1	50	2E-02	1,5E-02
2	200	5E-03	3E-03
3	500	2E-03	2E-03

Source: Tractebel, 2016.

The water depth values for each return period should be extracted from maps and located within water depth intervals. The values of unavailability should be identified corresponding to each return period (line) and water depth interval (column). They should then be summed, to obtain the total potential unavailability caused by flooding hazard. Data for each return period appears to be relevant as it shows values of orders of magnitude comparable to those of technical failures.

Table 32 - Unavailability as function of return period and water depth intervals.

		Water Depth Intervals [m]			
T_r [years]	Interval P (P_i-P_{i+1})	h <0,5	0,5≤h<1	1≤h<1,5	h≥1,5
50	0,015	8,2E-05	2,9E-04	8,6E-04	1,7E-03
200	0,003	1,6E-05	5,8E-05	1,7E-04	3,5E-04
500	0,002	1,1E-05	3,8E-05	1,2E-04	2,3E-04

Source: Tractebel, 2016.

Unavailability due to flooding for a certain return period is estimated by the product of the probability to have a specific water depth and the repair time related to the same water depth.

$$Q_{flooding_i} = Interval\ P_i \,.\, RT_i$$

The total contribution of flooding can be estimated by summing the contribution of all return periods by the following formula:

$$Q_{\text{flooding}} = \sum_i Q_{flooding_i} = \sum_i Interval\ P_i \ .\ RT_i$$

After extracting the expected water depth from the flooding maps, for each return period, the user can find the corresponding unavailability in Table 32. These values must be summed for all the return periods available in the map in order to obtain the Q_{flooding}.

NOTE: when the number of T_r classes is less than the three used in the method here described, Table 32 must substituted by the following Table 33 that is less precise but conservative in the final results:

Table 33 - Unavailability as function of return period and water depth intervals – Approximate method.

		Water Depth Intervals [m]			
T_r [years]	Interval P (P_i-P_{i+1})	h <0,5	0,5≤h<1	1≤h<1,5	h≥1,5
50	0,015	1,1E-04	3,8E-04	1,2E-03	2,3E-03
200	0,003	2,7E-05	9,6E-05	2,9E-04	5,8E-04
500	0,002	1,1E-05	3,8E-05	1,2E-04	2,3E-04

Source: Tractebel, 2016.

4.5.1.3 Lightning

The impact of lightning on the system's unavailability has been estimated for facilities of different extension and for different lightning activity.

The expected number of lightning strikes per year can be estimated by multiplying the plant extension by the number of flashes per year per area unit, obtained from the maps. The table below shows the results of a sensitivity analysis done for three different plant extensions and a range of lighting activity. It should be noted that the annual density of flashes across Europe is of the order of 0.1-4 flashes per km^2 per year (Anderson & Klugmann, 2014).

Table 34 - Expected strikes per year as function of plant extension.

	Plant extension [m^2]		
Flashes per km^2 per year	10000	20000	40000
1	0,01	0,02	0,04
2,5	0,025	0,05	0,1
4	0,04	0,08	0,16
6,5	0,065	0,13	0,26
10	0,1	0,2	0,4
40	0,4	0,8	1,6

Source: Tractebel, 2016.

Table 34 provides the annual frequency of occurrence of lightening ($f_{lightning}$) for different plant extensions and different flashes densities. Concerning the expected damage ($RT_{lightning}$), a shutdown time of 2 hours per strike has been assumed, compatible with what found from the historical analysis. The unavailability due to lighting strikes has been calculated, as shown in Table 35, as the product of the expected strikes per year by the 2 hours shut down time.

$Q_{lightning} = f_{lightning} . RT_{lightning}$

After extracting the flashes density for the examined location from a lightening flash density map and considering the plant extension, the user can find the contribution of lightening to the unavailability of the station $Q_{lightning}$.

Table 35 - Expected unavailability due to lightning strikes.

	Plant extension [m^2]		
Flashes per km^2 per year	10000	20000	40000
1	2,3E-06	4,6E-06	9,1E-06
2,5	5,70E-06	1,10E-05	2,30E-05
4	9,10E-06	1,80E-05	3,70E-05
6,5	1,50E-05	3,00E-05	5,90E-05
10	2,30E-05	4,60E-05	9,10E-05
40	9,10E-05	1,80E-04	3,70E-04

Source: Tractebel, 2016.

4.5.2 Example of application

The following example has been made to better clarify how to use described methodology.

Supposing that seismic hazard maps provide PGA values showed in the table:

Table 36 - Example of PGA values obtained from maps.

T_r [year]	PGA from maps [g]	PGA Intervals [g]
73	0,05	<0,1
102	0,09	<0,1
475	0,2	0,1-0,25
975	0,4	0,25-0,5
2475	0,7	0,5-1

Source: Tractebel, 2016.

The resulting unavailability values from seismic impact can be directly found on the table as follows.

Table 37 - Unavailability as function of return time and PGA intervals.

		PGA Intervals [g]				
T_r [years]	Interval P (P_i-P_{i+1})	<0,1	0,1-0,25	0,25-0,5	0,5-1	>1
73	0,0038	4,6E-06	5,3E-05	1,7E-04	3,6E-04	>4,9E-04
102	0,0077	9,2E-06	1,1E-04	3,3E-04	7,2E-04	>9,7E-04
475	0,0011	1,3E-06	1,5E-05	4,6E-05	1,0E-04	>1,4E-04
975	0,0006	7,5E-07	8,6E-06	2,7E-05	5,9E-05	>7,9E-05
2475	0,0004	4,9E-07	5,6E-06	1,7E-05	3,8E-05	>5,1E-05

Source: Tractebel, 2016.

The total unavailability will be the sum of all the highlighted values:

$$Q_{seismic} = 4{,}6E\text{-}06 + 9{,}2E\text{-}06 + 1{,}5E\text{-}05 + 2{,}7E\text{-}05 + 3{,}8E\text{-}05 = 9{,}38E\text{-}05$$

The impact of flooding events can be calculated as follows supposing the hazards maps provide the water depths listed below.

Table 38 - Example of water depth values obtained from maps.

T_r [year]	Water Depth from Maps [m]	Water Depth Intervals [m]
50	0,2	h <0,5
200	0,6	0,5≤h<1
500	0,8	0,5≤h<1

Source: Tractebel, 2016.

The resulting unavailability values from flooding impact can be directly found on the table as follows.

Table 39 - Unavailability as function of return period and water depth intervals.

		Water Depth Intervals [m]			
T_r [years]	Interval P (P_i-P_{i+1})	h <0,5	0,5≤h<1	1≤h<1,5	h≥1,5
50	0,015	8,2E-05	2,9E-04	8,6E-04	1,7E-03
200	0,003	1,6E-05	5,8E-05	1,7E-04	3,5E-04
500	0,002	1,1E-05	3,8E-05	1,2E-04	2,3E-04

Source: Tractebel, 2016.

The total unavailability will be the sum of all the highlighted values:

$$Q_{flood} = 8{,}2E\text{-}05 + 5{,}8E\text{-}05 + 3{,}8E\text{-}05 = 1{,}78E\text{-}04$$

The impact of lightning can be estimated as follows supposing a plant extension of 20000m^2 and a number of flashes per km^2 per year obtained from hazard maps.

Table 40 - Expected unavailability due to lightning strikes.

	Plant extension [m^2]
Flashes per km^2 per year	20000
1	4,6E-06
2,5	1,10E-05
4	1,80E-05
6,5	3,00E-05
10	4,60E-05
40	1,80E-04

Source: Tractebel, 2016.

The estimated unavailability caused by lightning strikes will be:

$$Q_{lightning} = 1{,}8E\text{-}05$$

As mentioned in the model description the total unavailability caused by natural hazards will be:

$$Q_{nat} = Q_{seismic}+Q_{flood}+Q_{lightning} = 9{,}38E\text{-}05 + 1{,}78E\text{-}04 + 1{,}8E\text{-}05 = 2{,}90E\text{-}04$$

This value, summed to one of those calculated for technical failure (0% Damage Class), provides the total unavailability.

Supposing that the here examined compression station can be modelled by configuration N-TUCO-RP and selecting a Logistic Delay Time of 24h its unavailability (for technical failures) for the described Damage Class is Q_{tech}=6,58E-06. With these hypotheses, natural events largely contribute to the total unavailability of the compressor station.

$$Q_{TOT} = Q_{nat} + Q_{tech} = 2{,}90E\text{-}04 + 6{,}58E\text{-}06 = 2{,}97E\text{-}04$$

The relatively high value of unavailability from natural causes is justified by the conditions assumed in the example. The represented station would be located in an area subject to intense seismic activity, exposed to significant flooding hazard and hit by a number of lightning strikes that corresponds to the upper limit of the average range for the European territory.

Moreover the N-TUCO-RP configuration (3 compressors, one compressor in standby) is characterised by a low technical unavailability in 0% Damage Class (6.58E-6). If the station was a 1-TUCO-RN (one compressor, no redundancy) the unavailability due to technical failure (0% Damage Class, 24h Logistic Delay Time) would be 3.06E-4, of a magnitude comparable to that of the unavailability for natural events in the example considered here.

4.6 Results and conclusions

After historical analysis, literature review and discussion with an expert in gas transmission systems, seismic, flooding and lightning hazards have been identified as able to cause significant unavailability to gas compression stations. LNG facilities emerged as scarcely vulnerable to any of the natural events considered in the study. The contributions to the overall unavailability of these systems caused by natural events can thus be considered negligible. The compressors present in UGS facilities can be treated similarly to those that are part of gas transmission pipeline systems.

The order of magnitude of unavailability caused individually by each natural hazard appears to be comparable to those of technical unavailability calculated earlier. Therefore all contributions from natural events to the overall unavailability of compressor stations should be taken into account, with particular reference to flooding hazards. In particular, earthquakes may contribute significantly to the final result in those areas in which events of medium to high intensity are expected with relatively short return periods. The results have been reached making conservative assumptions, considering that seismic impact may concern very large areas and in most cases without any warning signal which would enable the adoption of mitigation measures.

Flooding occurrences might also lead to substantial effects. However, unlike for seismic activity, the effects of this hazard are strongly influenced by the characteristics of the territory at a very small scale and they may easily result in an overestimation of the induced unavailability if the station has been specifically designed to withstand flood events of vast proportions. In all cases using data relative to as many return periods as available is suggested.

Despite the short compression station downtimes associated to the event, lightning strikes might impact the station’s functionality in an appreciable way, due to their relatively high frequency of occurrence.

5 Conclusions

A taxonomy of compressor stations of the EU gas transmission network has been developed. This taxonomy is definitely a simplified taxonomy due to the lack of access to a full census of CS. Nevertheless, this is a valid first step to develop in the future a more comprehensive taxonomy. The two key elements affecting the taxonomy have been the layout of the facility (number of compressors in parallel, existence or not of back-up in standby) and the type of compressor, typically turbocompressor or motorcompressor.

A Fault Tree methodology has been used to estimate the reliability magnitudes addressed in this study: unavailability, expected number of failures per year, downtime and average downtime. This has been estimated for each element of the taxonomy, each damage class and for three types of logistic delays (1 hour, 1 day and 1 week). Significant differences between estimates arise from the different logistic delays.

The authors of this report think that, in the absence of facility (CS) specific reliability data, results delivered in this report may be used as adequate proxies for the different reliability magnitudes, provided that the layout of the CS under consideration does not differ much from some the one considered as reference from this document.

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List of abbreviations and definitions

CS - Compressor Station

ECS - Equivalent Compressor Station

ENF - Expected Number of Failures

FR - Failure Rate

HAZID - HAZard IDentification

LNG - Liquefied Natural Gas

MTTR - Mean Time to Repair

NO – Normally Open Valve

NC – Normally Closed Valve

PFD - Process Flow Diagram

PGA - Peak Ground Acceleration

TSO - Transmission System Operator

UGS - Underground Gas Storage

List of figures

List of tables

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