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Data-driven condition-based maintenance for LNG transport systems via pipeline

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Abstract

This work presents an integrated approach to Condition-Based Maintenance (CBM) for natural gas pipelines, focusing on the Hassi R'Mel network in Algeria. Combining Bowtie analysis, interval Principal Component Analysis (PCA), and finite element simulation using ABAQUS, the study offers a comprehensive framework for failure prevention. Bowtie analysis identifies critical causes and consequences of faults; interval PCA detects anomalies from pressure, temperature, and flow data; and finite element analysis models the mechanical behaviour of corroded sections under overpressure. Results highlight the importance of continuous pressure monitoring and material integrity assessment. This methodology enables early fault detection, informed decision-making, and improved safety in pipeline operations, significantly reducing the risk of unexpected failures.

Keywords: CBM, pipeline, LNG, Bowtie, PCA, FEA, failures analysis

Résumé

Ce travail propose une approche intégrée de la maintenance conditionnelle (CBM) pour les réseaux de pipelines de gaz naturel, en se concentrant sur le réseau de Hassi R'Mel en Algérie. En combinant l'analyse nœud de papillon, l'analyse en composantes principales par intervalles (ACP) et la simulation par éléments finis effectuée avec ABAQUS, l'étude offre un cadre complet de prévention des défaillances. L'analyse nœud de papillon identifie les causes critiques et les conséquences des incidents ; la ACP par intervalles détecte les anomalies à partir des données de pression, de température et de débit ; et l'analyse par éléments finis modélise le comportement mécanique des sections corrodées soumises à une surpression. Les résultats soulignent l'importance d'une surveillance continue de la pression et d'une évaluation de l'intégrité des matériaux. Cette méthodologie permet une détection précoce des défauts, une prise de décision éclairée et une amélioration de la sécurité des opérations de pipeline, réduisant significativement le risque de défaillances imprévues.

Motsclées : MC, pipeline, GNL, ACP, AEF, analyse des défaillances

الملخص :

هذا البحث يقدم نهجًا متكاملاً للصيانة المعتمدة على الحالة لأنابيب الغاز الطبيعي، مع تركيز خاص على شبكة حاسي الرمل في الجزائر. ويقوم المنهج على دمج تحليل (Bowtie) لتحديد الأسباب الجوهرية وعواقب الأعطال، وتحليل المكونات الرئيسية(Interval PCA) لاكتشاف الشذوذات في بيانات الضغط ودرجة الحرارة والتدفق، بالإضافة إلى محاكاة تحليل العناصر المحدودة باستخدام برنامج (ABAQUS) لنمذجة السلوك الميكانيكي للأجزاء المتآكلة تحت تأثير الضغط الزائد. تُظهر النتائج أهمية المراقبة المستمرة للضغط وتقييم سلامة المواد، مما يتيح الكشف المبكر عن الأعطال واتخاذ قرارات مبنية على البيانات، ويُعزّز السلامة في عمليات النقل ويقلّص بشكل ملحوظ مخاطر الفشل المفاجئ.

الكلمات المفتاحية: الصيانة الشرطية, خط الانابيب, غاز طبيعي مسال, تحليل المكونات الرئيسية, تحليل العناصر المحدودة, تحليل الاعطال

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General introduction

General Introduction

Maintenance is a fundamental pillar for ensuring the efficiency and sustainability of operations in industrial and processing sectors. It plays an important role in reducing breakdowns, extending equipment lifecycle, and enhancing productivity (SRAOUI & AGDI, 2024). The petroleum sector stands at the forefront of these industries in terms of strategic importance, particularly in Algeria, where it constitutes a primary source of national income, making it a vital and strategic sector both locally and internationally.

Among the key challenges facing this sector is the issue of transportation. Pipeline transport is considered one of the most effective methods when compared to trucks or trains, due to its high operational efficiency and safety (Wafia, 2021). However, these pipeline networks are exposed to various technical failure and risks such as corrosion, leaks, blockages, and pressure drops, all of which can lead to significant financial losses and severe environmental damage if not addressed through efficient and proactive maintenance(HAMMOUYA et al., 2025).

The problem lies in the limited effectiveness of traditional maintenance strategies, whether based on fixed scheduling or reactive interventions after failure (Bouami, 2019). These approaches often lack the flexibility required to balance cost and reliability. Consequently, modern strategies such as Condition-Based Maintenance (CBM) have emerged. CBM relies on real-time monitoring using smart sensors, enabling the early detection of degradation indicators and optimize intervention timing (SRAOUI & AGDI, 2024).

This methodology increasingly incorporates artificial intelligence techniques, including Principal Component Analysis (PCA), which is used to extract hidden trends and detect anomalies from vast volumes of sensor data (Ait Izem Tarek, 2018). However, these techniques are not sufficiently effective unless integrated into a comprehensive framework that includes conventional analytical methods and field-based validation to anticipate and mitigate failure scenarios.

In response to these challenges, this research proposes a structured intelligent maintenance methodology for to LNG pipeline systems, with a case study focusing on the Hassi R'mel region. The proposed approach integrates failure analysis tools, such as the Bowtie method (including Fault Tree Analysis and Event Tree Analysis) (de Ruijter & Guldenmund, 2016), AI-based techniques like PCA, and numerical simulation using ABAQUS software (DJAARIRI & BAKHOUCHE, 2024), in order to construct a predictive and holistic maintenance system.

The primary aim of this study is to improve the efficiency of maintenance systems, reduce unplanned downtime and associated losses, and ensure operational continuity while preserving industrial and environmental safety.

The work is organized into several parts. It begins with a general introduction, which outlines the context, importance, objectives, and methodology of the study. This is followed by a State of the Art chapter that reviews the existing literature on maintenance strategies and diagnostic techniques, with a particular focus on condition-based maintenance and intelligent monitoring systems.

The first core chapter presents an overview of hydrocarbon pipeline transport, identifying the key degradation mechanisms and operational failures and risks affecting pipeline infrastructure.

The second chapter is dedicated to the methodology adopted in this study. It details the integrated approach combining the Bowtie method (including Fault Tree and Event Tree Analyses), Principal Component Analysis (PCA), and numerical simulation via the ABAQUS software.

The third chapter focuses on the practical application of this methodology to a real-world case study involving the LNG pipeline network in the Hassi R’mel region. It discusses the results obtained and evaluates the effectiveness of the proposed approach in enhancing maintenance planning and mitigation barriers.

Finally, the thesis concludes with a synthesis of the findings, highlighting the scientific contributions and suggesting potential directions for future research.

State of the Art

State of the Art

0.1. Introduction

The evolution of industrial maintenance has shifted from reactive and time-based approaches to more advanced, predictive and condition-based strategies. Modern methods integrate intelligent diagnostic tools to detect and address faults proactively. Diagnosis techniques are typically classified into model-driven, data-driven, and hybrid approaches, each offering unique strengths depending on system complexity and data availability. This chapter explores the state-of-the-art in maintenance and diagnosis, outlining the major categories of methods in use today, and highlighting how these approaches are applied to monitor, analyze, and maintain complex systems.

0.2. General concepts

Error: An error is defined as a deviation between the actual behavior of a system and its intended or expected behavior. It may be caused by human mistakes, system design flaws, or incorrect input data. Errors are precursors to faults and failures and may remain latent before manifesting (DJ Smith, 2021).

Fault: A fault is a defect or anomaly in a system's physical or logical structure that causes incorrect behavior under certain conditions. It is typically the root cause behind errors and may persist without immediate detection (B. S. Dhillon, 2006).

Failure: A failure is the point at which a system or component loses its capacity to fulfill its required function within the specified limits, often as a result of accumulated faults or errors over time (K. S. Trivedi & A. Bobbio, 2017).

Breakdown: A breakdown refers to a sudden and complete stop of a system's operation, typically requiring immediate corrective action. It is an overt form of failure that disrupts performance entirely(I. Setiawan et al., 2021).

Availability: Availability describes the likelihood that a system will be operational and accessible when needed. It reflects both how reliable the system is and how quickly it can be repaired after failure(K. S. Trivedi & A. Bobbio, 2017).

Reliability : Reliability is the probability that a system or component will perform its intended functions correctly over a given period, without unexpected interruptions, under stated operating conditions(B. S. Dhillon, 2006).

Maintainability: Maintainability refers to the ease and efficiency with which a failed system can be diagnosed, repaired, and restored to operational status. It plays a key role in minimizing downtime(B. S. Dhillon, 2006).

Safety: Safety is the ability of a system to operate without causing unacceptable risk of harm to people, property, or the environment, even in the presence of faults or failures(B. S. Dhillon, 2006).

0.3. Maintenance

Maintenance first emerged in the manufacturing sector in the late 1970s and, from the 1990s onward, extended into the service industry (Amel & Dhaker Ellah, 2022). It refers to the actions or processes involved in keeping something in a proper or functional condition.

According to the British Standards Institution (BSI, 1984), maintenance is defined as “a combination of all technical and associated administrative activities required to keep equipment, installations, and other physical assets in the desired operating condition or restore them to this condition” (*BSI, BS 3811:1984 – Glossary of Maintenance Management Terms in Terotechnology*, 1984) . Similarly, the French standard NF X60-010 describes maintenance as “the set of actions aimed at maintaining or restoring an asset to a specified state or to a condition in which it can perform a required function”(AFNOR, n.d.) . The European standard NF EN 13306 further refines this by defining maintenance as “the combination of all technical, administrative, and managerial actions during the life cycle of an asset, intended to maintain or restore it to a state in which it can perform the required function”(François & Claude, 2019) .

0.3.1. Maintenance Types

Maintenance is generally categorized into several types based on its timing, purpose, and method of application. Each type plays a crucial role in ensuring the reliability and safety of systems throughout their operational life.

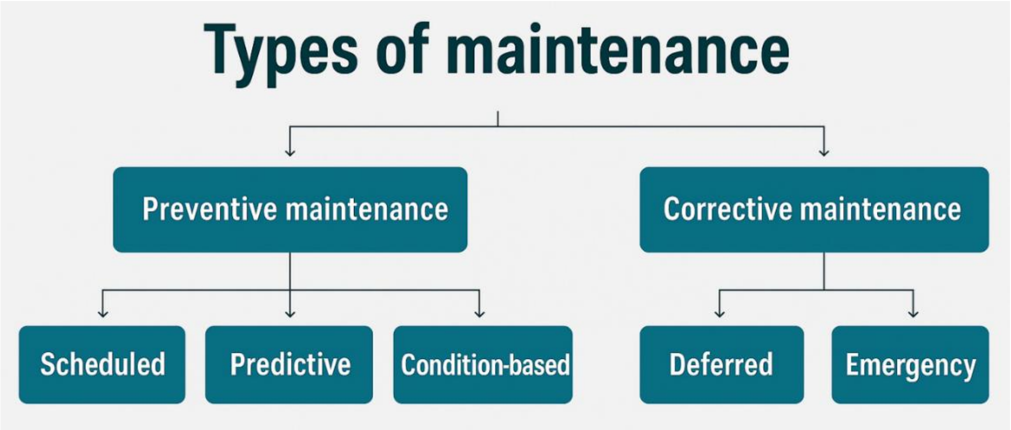


Figure 0.1 :Types of maintenance(N. Terrier, 2001)

0.3.1.1. Corrective Maintenance (CM)

a. Deferred Corrective Maintenance

Deferred Corrective Maintenance refers to failure repair tasks that are postponed and planned rather than executed immediately. This is a valid approach for non-critical failures that do not compromise operational safety or availability [2]. It helps balance workload and reduce costs, but excessive reliance can lead to operational risks if prioritization is weak (Erik Hupjé, n.d.).

b. Emergency Maintenance

Involves urgent, unscheduled repair after a significant or dangerous equipment failure. It is disruptive, labor-intensive, and typically the most expensive maintenance type. Studies suggest emergency maintenance can cost 3 to 5 times more than well-planned preventive tasks. Organizations aim to minimize emergency maintenance to less than 2% of total maintenance activity, promoting safer and more predictable operations(Erik Hupjé, n.d.).

0.3.1.2. Preventive Maintenance (PM)

a. Scheduled maintenance

Scheduled maintenance is the practice of performing preventive maintenance tasks at fixed, predetermined intervals either time-based (e.g., every quarter) or usage-based (e.g., after a set number of operating hours) without prior inspection of equipment condition, with the aim of reducing unplanned downtime and optimizing asset reliability and life-cycle cost(N. Terrier, 2001).

b. Predictive Maintenance (PDM)

Predictive Maintenance (PdM) is a proactive maintenance strategy that uses condition-monitoring technologies, machine learning, and historical data to predict when equipment failure might occur. This allows maintenance to be scheduled at the optimal time, minimizing downtime and reducing unnecessary maintenance costs(M. Achouch et al., n.d.).

c. Condition-Based Maintenance (CBM)

Condition-Based Maintenance (CBM) is a maintenance strategy that involves performing interventions only when physical or functional signs of degradation are detected. These signs may include changes in parameters such as vibration, temperature, pressure, or lubricant quality.

As a strategy, CBM focuses on identifying tangible indicators that a failure is occurring or is likely to occur. This broader perspective highlights CBM's applicability beyond traditional condition monitoring methods typically associated with rotating equipment(Erik Hupjé, n.d.).

A key concept within CBM is the P-F curve, illustrated in the figure below, which represents the time between the point when a potential failure can first be detected (P) and the point of functional failure (F), P-F curve is shown in the figure below.

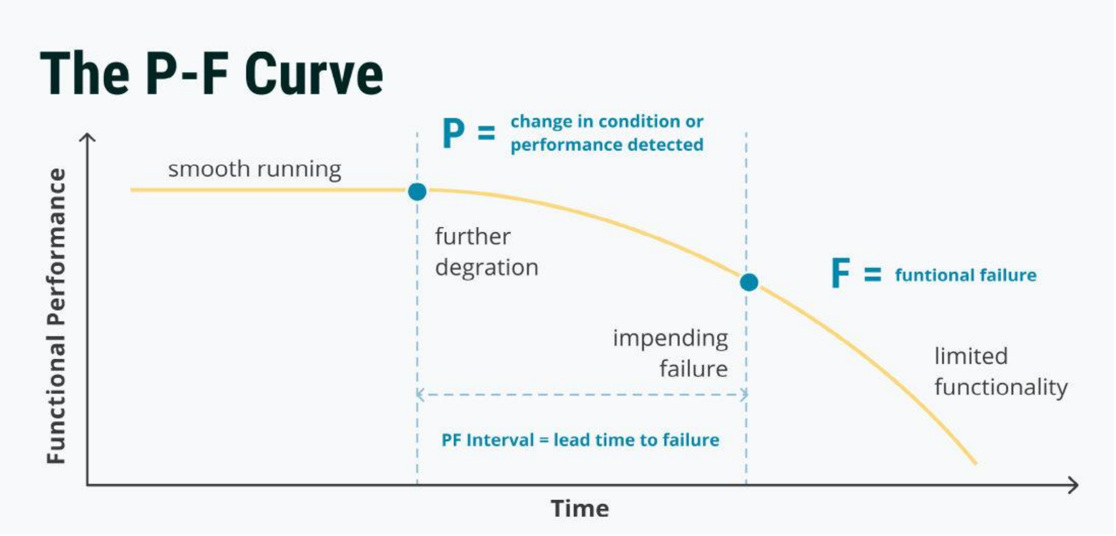


Figure 0.2 : The P-F curve(Erik Hupjé, n.d.)

The P-F interval the time between potential failure detection (P) and actual failure (F) is critical for planning interventions. CBM does not prevent failure but enables timely action to reduce downtime and cost. Its effectiveness depends on having a sufficiently long and predictable P-F interval, along with efficient systems for monitoring, analysis, and response. CBM is less suitable when failures occur suddenly or unpredictably.

0.4. Monitoring

Monitoring in Condition-Based Maintenance (CBM) involves real-time tracking of equipment conditions using advanced sensors and diagnostic technologies. Key parameters like vibration, temperature, pressure, and lubrication quality are measured to detect anomalies and predict failures before they occur. This approach enables maintenance activities to be performed only when needed, reducing costs and preventing unplanned downtime. Additionally, data-driven models enhance fault detection and prognosis, extending equipment life and improving operational safety(S. Kumar et al., 2022).

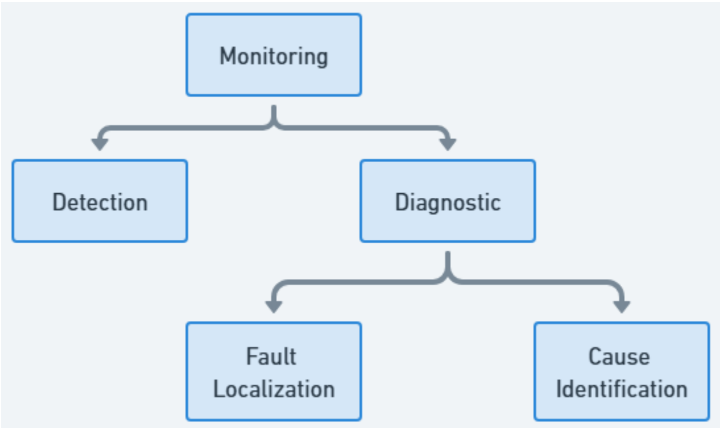


Figure 0.3: Components of Industrial Monitoring

0.5. Diagnosis

0.5.1. Definition

Fault diagnosis in Condition-Based Maintenance (CBM) is the process of identifying, isolating, and assessing equipment failures or irregularities based on real-time monitoring data. Accurate fault diagnosis enables maintenance teams to detect potential problems early, preventing unexpected breakdowns and extending equipment life [15].

0.5.2. Diagnosis steps

The diagnosis of an industrial system requires a series of steps. These steps may vary depending on the context and the specific characteristics of the system being diagnosed. Moreover, the diagnostic process can be iterative, incorporating feedback loops to enhance the accuracy and reliability of the results (Benslim, 2021; SRAOUI & AGDI, 2024).

A. Data Acquisition

CBM monitoring begins with data acquisition, where sensors are strategically placed on equipment to collect real-time data. These sensors measure key operational parameters such as vibration, temperature, pressure, noise, and oil condition.

B. Data Processing and Analysis

The collected raw data is processed and analyzed using advanced algorithms to detect patterns indicative of wear or malfunction. Machine learning models further enhance anomaly detection and predict the Remaining Useful Life (RUL) of components.

C. Localization

After detecting a fault, the localization phase focuses on pinpointing which specific subsystem is at fault whether it’s a sensor, an actuator, a control unit, or a particular process.

D. Decision-making

Once a system malfunction has been identified, the decision-making phase kicks in to ensure the installation continues to meet its performance goals. During this stage, corrective actions are devised and potentially executed under the oversight of a human operator to restore normal operation of the system.

0.5.2.1. Diagnosis methods Classification

The main classification of fault diagnosis methods can be based on the type of modelling used to represent the system or extract diagnostic insights. These methods are grouped into three major families:

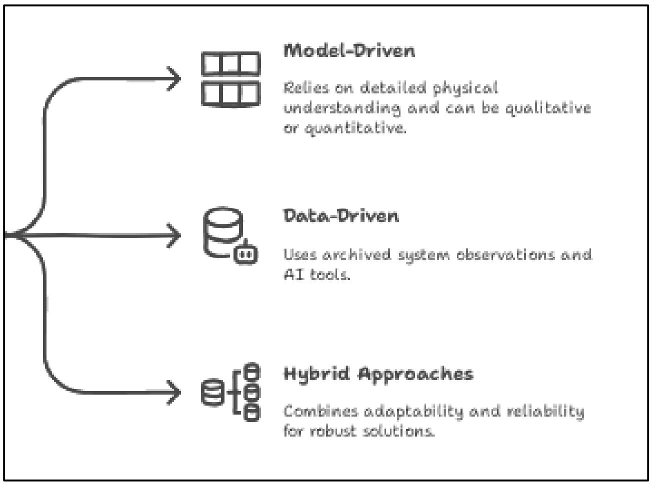


Figure 0.4: Classification of Diagnostic Methods

❖ **Model-Driven Diagnosis Methods**

Model-based diagnostic methods draw on a detailed physical understanding of the process being monitored and can be either qualitative or quantitative. Qualitative approaches represent the system’s input-output behavior using high-level functions focused on specific process units typically organized into either causal models, which describe cause-and-effect relationships, or hierarchical models, which structure behavior at multiple levels of abstraction. Quantitative methods, by contrast, rely on analytical state-space representations of the system’s dynamics. In these approaches, diagnostics are performed by generating residuals fault-indicating signals obtained by comparing the system’s actual observed behavior with the behavior predicted by the model(S. Benmoussa, 2013).

❖ Data-Driven Diagnosis Methods

Data-Driven Methods: Also called history-based approaches, these techniques leverage archived system observations to identify features that characterize both normal and abnormal operation. They fall into two categories quantitative and qualitative. Quantitative approaches use artificial intelligence (AI) tools such as neural networks and Bayesian networks, or statistical methods like Principal Component Analysis (PCA). Qualitative approaches typically involve expert systems or Qualitative Trend Analysis (QTA). Because data-driven diagnostics depend exclusively on information stored in databases historical records, rule sets, or forms they don't require detailed analytical or structural models of the physical system. However, accurately capturing the various operating modes of the physical system from the available data remains highly challenging(S. Benmoussa, 2013).

❖ Hybrid Approaches

The limitations of pure data-driven and model-driven methods have led to the development of **hybrid approaches**. These combine the adaptability of data-driven methods with the reliability of model-driven techniques, resulting in more robust diagnostic solutions.

An example of this is the **hybrid-driven diagnosis of axial piston pumps**, where both model-based simulations and data-driven anomaly detection are used to improve reliability and fault detection accuracy. In **power generation systems**, hybrid methods are used to monitor the health of turbines by combining physical modeling with real-time sensor data, enhancing predictive maintenance capabilities [3].

Comparison

The following table provides a comparative overview of the main fault diagnosis methods, highlighting their key advantages and limitations:

Table 0.1: Fault diagnosis methods advantages and limitations.

Fault diagnosis methods	**Advantages**	**Limitations**
Data-Driven	-High adaptability to different systems and configurations. -Ability to detect complex, non-linear relationships in data. -Scalable across large industrial setups.	-Requires large datasets for training and accuracy. -Lack of transparency and explainability compared to model-based methods.
Model-Driven	-High accuracy and reliability in well-understood systems. -Better interpretability due to the use of physical models. -Effective in low-data environments where historical data is limited.	-Less flexible when system dynamics change or are highly non-linear. -Building accurate models requires domain expertise and extensive system understanding.
Hybrid Approaches	-Improved fault detection accuracy. -Enhanced adaptability to dynamic system changes. -Better balance between interpretability and predictive power.	- Can be complex to implement and integrate. - May require significant computational resources and multidisciplinary expertise.

0.6. Conclusion:

This chapter has presented a comprehensive overview of the current state of the art in industrial maintenance and fault diagnosis. By grounding maintenance practices in core reliability principles, organizations can effectively implement preventive, predictive, and condition-based strategies to optimize operational uptime and reduce costs. The integration of advanced diagnostic techniques significantly enhances early fault detection, enabling targeted interventions before failures escalate. Collectively, these elements establish a robust framework for ensuring the safety, reliability, and efficiency of industrial infrastructure.

Chapter 1: General Overview of Hydrocarbon Transport via Pipeline

Chapter 1: General Overview of Hydrocarbon Transport via Pipeline

1.1. Introduction

Hydrocarbons play a fundamental role in the global energy landscape, and their efficient transport from production sites to consumption areas is a critical aspect of the oil and gas industry. Among the various transportation methods such as rail, road, and maritime, the pipeline system stands out for its safety, reliability, and economic efficiency over long distances.

This chapter explores the importance of pipelines in energy logistics. From installation and maintenance to innovations and management strategies, we look at how these essential infrastructures support the modern energy industry.

1.2. Hydrocarbons-general overview

1.2.1. Definition of hydrocarbons

Hydrocarbons are organic compounds composed exclusively of carbon (C) and hydrogen (H) atoms. The Carbon atoms can form linear chain or ring bonds. The general molecular formula for hydrocarbons is C_nH_m.

An exception to this rule is found in heterocyclic hydrocarbons, which include atoms other than carbon and hydrogen within their rings (Frédéric Élie, 2022).

1.2.2. Definition of LNG

Liquefied Natural Gas (LNG) is natural gas that has been cooled to approximately -162°C (-260°F), transforming it into a liquid state. This liquefaction process reduces its volume by about 600 times, making it highly efficient for storage and long-distance transportation. LNG primarily consists of methane, along with minor amounts of other hydrocarbons, and is widely used in power generation, industrial applications, and transportation (Z. C. Kab & K. Kemassi, n.d.).

1.2.3. Hydrocarbon Transportation means:

The transportation of hydrocarbons is carried out using a variety of means, each selected based on technical, economic, and logistical criteria such as transport distance, volume, terrain, and the physical state of the product. These means include:

- **Pipelines**
- **Railway systems**
- **Road tankers**
- **Maritime transport**

Each of these methods contributes to an integrated supply chain, linking production sites to processing facilities or export terminals.

The hydrocarbon transportation network in Algeria, which incorporates all these transportation means, is illustrated in (Figure 1.1).

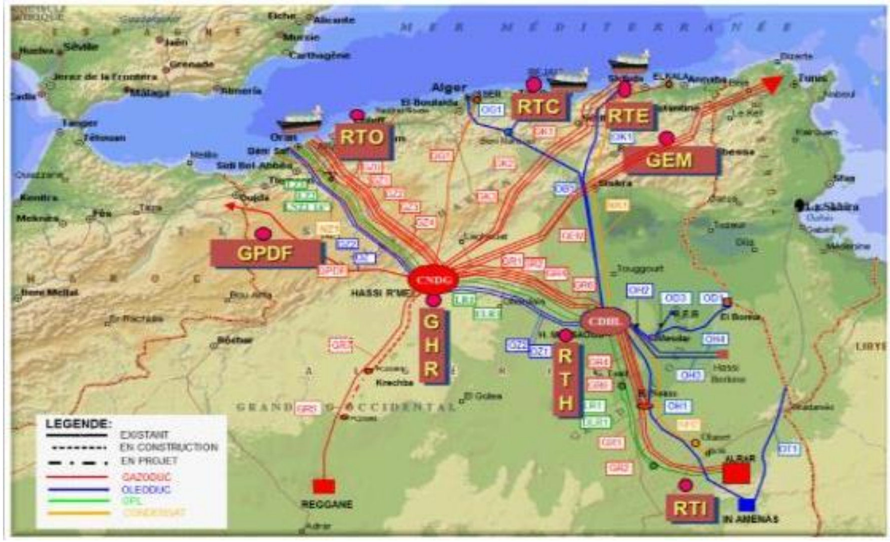


Figure 1.1 : The Algerian Hydrocarbon Transportation Network Map (MINISTERE DE L'ENERGIE, 2018)

Each of these transportation means presents a distinct set of advantages and limitations. The table below provides a comparative overview of these methods:

Table 1.1 : Advantages and Disadvantages of Hydrocarbon Transportation Means(A. Hart, 2014; A. Saniere et al., 2004)

Transportation Mean	**Advantages**	**Disadvantages**
Pipeline Transport	- Highly cost-effective for moving large volumes over long distances. - Continuous, automated operation - Produces fewer emissions compared to other transportation methods. - Reduces road traffic and improves supply security - Long service life with proper maintenance	- High initial investment - Inflexible routing once built -Vulnerable to leaks and cyber threats - Requires ongoing monitoring and corrosion control
Rail Transport	- Does not require fixed infrastructure. - Offers moderate flexibility in route selection. - Suitable for medium-volume transport needs.	- Higher accident risk - More expensive on a per-unit basis than pipeline transport. - Requires specialized tanker cars for safe transportation.
Marine (Tanker) Transport	- Economical for long-distance and global transport - Can handle large, diverse hydrocarbon volumes	- Risk of spills with severe ecological impact - Slower and affected by maritime conditions - Exposed to piracy/weathe
Road (Truck) Transport	- Highly flexible and ideal for short distances or remote access - No need for dedicated infrastructure	- High fuel consumption and emissions - Greater traffic and safety risks

1.3. Pipeline Transportation:

Pipelines are essential infrastructures for the large scale transport of fluids whether liquid, liquefied, or gaseous over both long and short distances. They offer high flow capacity while operating discreetly, and have consistently proven to be the safest and most environmentally sustainable method for transporting hydrocarbons(Cécil, n.d.). Most pipelines are used to convey oil or gas from extraction sites to areas of consumption, storage or export. The total length of pipelines worldwide is estimated at around one million kilometers equivalent to two trips between the Earth and the Moon. Most underground pipelines are typically buried at a depth of approximately one meter (1 m) in populated areas. In contrast, they are often installed at ground level in desert regions or on solid terrain, and may also be laid underwater in marine environments (Hulkak, 1997).

1.3.1. Types of Pipeline Transportation:

The designation and type of a pipeline are determined by the physical properties of the transported substance as well as the specific operational and safety conditions required. We note for example:

- **Natural gas** is transported through a gas pipeline, commonly referred to as a “gazoduc” in French;
- **Crude oil or petroleum products** are transported via an oil pipeline, known as an “oléoduc” in French;
- **Water** is conveyed through an aqueduct;
- **Saltwater** (brine) is transported using a saumoduc;
- **Oxygen** is delivered via an oxygen pipeline, referred to as an “oxyduct.” Or “oxygénoduc” in French;
- **Hydrogen** is transported through a hydrogen pipeline, known as a “hydrogénoduc” in French(Senagria Zakaria, 2022).

Figure 1.2: Gas pipelines(Senagria Zakaria, 2022)

Figure 1.3: Oil pipelines(Senagria Zakaria, 2022)

1.3.2. The Algerian Pipeline Network for Hydrocarbon Transportation

1.3.2.1. History of the network

The development of Algeria’s hydrocarbon transport networks is closely linked to the country’s pursuit of sovereignty over its natural resources. Following the establishment of SONATRACH in 1963, Algeria initiated the construction of major infrastructure projects, such as the Hassi Messaoud–Béjaïa oil pipeline, which symbolised the nation's growing energy independence. The nationalisation of hydrocarbons in 1971, underscored by President Boumediene's iconic speech, marked a turning point: the state reclaimed ownership of pipelines and gas distribution networks, while SONATRACH emerged as the central actor in transportation and export operations.

During the 1980s, Algeria expanded its influence with the development of transcontinental gas pipelines, including the Transmed pipeline to Italy and, subsequently, the Maghreb–Europe pipeline to Spain, reinforcing its role as a key energy supplier to Europe. Despite gradual sectoral reforms in the 1990s and 2000s that allowed for limited foreign participation, SONATRACH retained its strategic control over infrastructure. Today, Algeria operates a network exceeding 15,000 km of pipelines, complemented by historic LNG terminals in Skikda and Arzew, consolidating its position as a major regional and global energy player (Mekideche, M, 2008).

1.3.2.2. National Network Overview

Algeria boasts an extensive pipeline network for hydrocarbons, including crude oil, condensate, natural gas, and LPG. This network consists of 21 Pipeline Transport Systems (STC) spanning roughly 19,623 km. In addition, a new natural gas pipeline system, called STC GR5, is under construction to handle future production from the southwestern fields, connecting Reggane to HassiR'mel.

Dispatch centers play an important role in SONATRACH's operations by collecting and routing hydrocarbons from production areas to various destinations. The Liquid Hydrocarbons Dispatch Center (CDHL) at Haoud El Hamra in Hassi Messaoud manages liquid hydrocarbons, while the National Gas Dispatch Center (CNDG) in HassiR'mel oversees natural gas collection and its transport via pipelines to consumption centers, processing facilities, and export terminals(M. H. Hayes, 2004; Z. Bilal, 2018).

Algeria exports gas to Europe via three main pipeline routes: the Enrico Matei pipeline, which connects Algeria to Italy through Tunisia; the Pedro Duran Farrel pipeline, linking Algeria to Spain through Morocco; and the HassiR'Mel to Béni-Saf pipeline, which connects Algeria to Spain via Medgaz. The lifecycle of these pipeline projects includes the design, construction, and operation phases (Figure 1.4)(M. H. Hayes, 2004).

It is important to note that pipelines serve a vital role in ensuring the safe and efficient transport of hydrocarbons in Algeria, thereby contributing to the country's economic development and its exports to other regions(Z. Bilal, 2018).

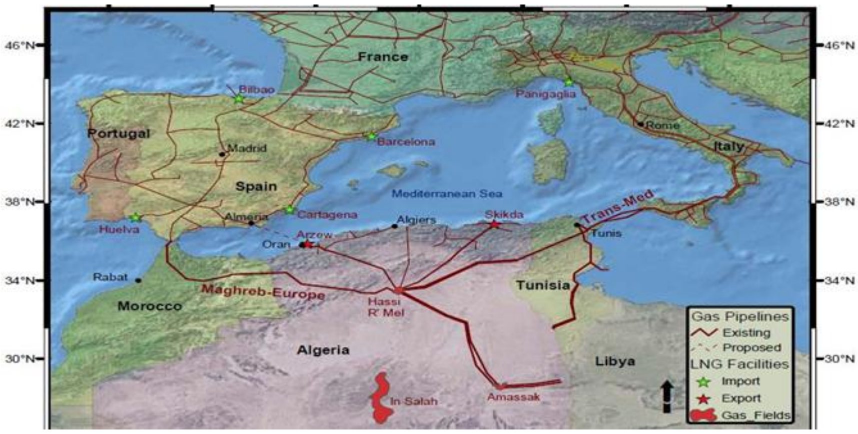


Figure 1.4: Algerian Gas Pipeline Network(M. H. Hayes, 2004)

1.3.2.3. Components of Pipeline Transportation Networks

The primary components in pipeline networks are the operational zones and the pipeline segments. Operational zones can include distribution centers, ports, or refineries, and they are connected by one or more pipeline segments through which various fuels are transferred.

a. **Injection or Departure Stations:** These serve as the entry points into the transportation network. Depending on their design and geographic location, they can function as terminals or entry stations.
b. **Compression Stations (for gases) or Pumping Stations (for liquids):** These stations are strategically located along the network to maintain the required pressure and flow rate of the fluids within the pipelines.
c. **Delivery Stations :** These facilities ensure that the transported materials are delivered to intermediate or final recipients(Guellal Z'hor & Gaci Yacine, 2016).

1.4. Technical Characteristics of Pipeline

1.4.1. Types of Steels Used:

The steel grades typically used in pipeline construction are defined by two API (American Petroleum Institute) specifications that have been in use by the U.S. oil industry since 1992(Nekkaa Bahria, 2019).

• 5L for standard quality.

• 5LX for high-strength quality.

Table 1.2 :The most commonly employed steel grades exhibit the mechanical properties outlined in(Belkhamgani Mohamed Amine & Bendehnoun Khalil, 2018)**.**

API specification	Grade	Limit of elasticity (Kg/mm^2)	Resistance to repturing (Kg/mm^2)
5L	A	21	34
5L	B	25	42
5LX	X42	29	42
5LX	X46	32	45
5LX	X52	37	47
5LX	X56	39	52
5LX	X60	41	55
5LX	X65	46	56
5LX	X70	48	56

1.4.2. Diameters and wall thickness

Most pipelines are made of steel, although plastic and aluminum are sometimes used for natural gas distribution networks. Steel pipelines are constructed by welding short pipe sections (typically 20 meters long) together. After radiographic inspection of the welds, the pipeline is coated with a protective layer before being buried. Every pipeline under goes rigorous inspection and pressure testing before being put into operation(Mechernene .A, 2013).

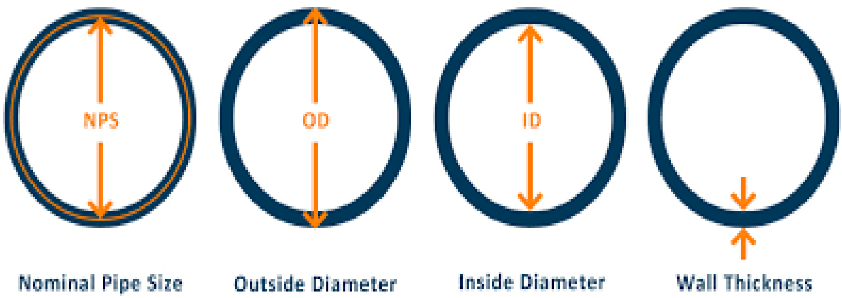


Figure 1.5: Pipe Dimensions (*Understanding Nominal Pipe Size (NPS)*, n.d.)

The design of a pipeline, including its diameter, wall thickness, steel grade, construction specifications, and operating conditions, is carefully determined based on regulatory standards and detailed engineering calculations. The pipeline diameter is selected by considering the flow rate, viscosity, and density of the transported product, aiming to balance the energy required for pumping or compression with the overall investment cost. Diameters typically range from 50 mm (2 inches) to 1400 mm (56 inches). Regulatory authorities in each country closely oversee these parameters to ensure public safety and environmental compliance.

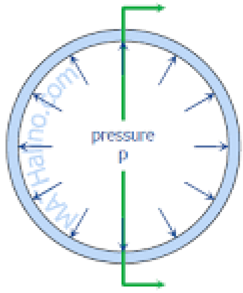


Figure 1.6: Pressure Distribution in Pipe

General construction guidelines typically cover maximum service pressure, safety factors, inspection protocols, pressure testing procedures, and specialized leak prevention measures, particularly in high-risk areas. In essence, pipelines are long-distance systems operating under high pressure (often reaching up to 100 bars) with large diameters and wall thicknesses ranging from 6.35 mm to 30 mm or more. They are usually buried at depths between 0.6 m and 1 m, depending on factors such as the pipeline's age, location, and the surrounding environment.(Hulkak, 1997; Mechernene .A, 2013).

1.4.3. Norms and standards in pipeline fabrication

Pipeline fabrication is a critical process in the oil, gas, and petrochemical sectors, requiring strict adherence to international standards to ensure safety, efficiency, and durability. The ASME (American Society of Mechanical Engineers) and API (American Petroleum Institute) provide key guidelines for material selection, welding, and inspection. API 5L specifies pipeline materials, while ASME B31.3 governs design and fabrication procedures(M. Sambasivan & S. Gopal, 2018).

Carbon steel is the most commonly used material, with stainless steel and composites employed in corrosive environments. Welding processes are regulated by API 1104, and quality is ensured through Non-Destructive Testing (NDT) methods such as ultrasonic and radiographic testing (K. H. Dhandha et al., 2011).

Emerging technologies like automated welding and digital inspection tools enhance fabrication reliability and regulatory compliance.

1.5. Pipeline manufacturing Process

The diversity in pipeline diameters and wall thicknesses, along with advancements in manufacturing techniques, has significantly shaped the structure of hydrocarbon transport networks in Algeria. The primary production methods include:

1.5.1. Spiral Welded Tubes

Modern facilities are used to produce high-quality spiral-welded pipes, especially for high-pressure applications. This process involves bending steel strips into a helical tube and welding the edges together. The manufacturing procedure follows several stages, as illustrated in Figure 1.7. The raw material typically consists of steel plates specifically designed for spiral welding (A. Bouziane, 2008).

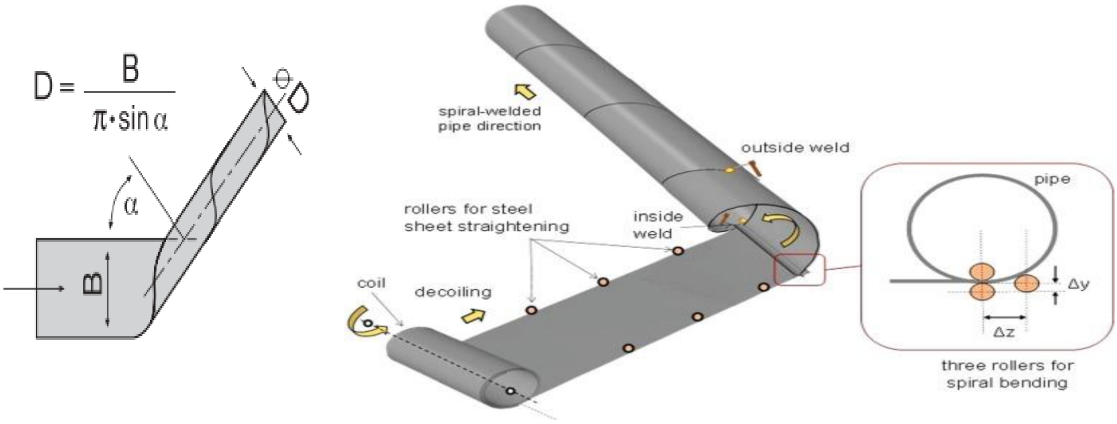


Figure 1.7: Manufacturing technique for spiral welded tubes(J. F. Kiefner & M. J. Rosenfeld, 2012)

The forming of the spiral tube is carried out by inclining the entry angle of the strip, which is calculated according to the following relationship:

$$\boldsymbol{D} = \frac{\boldsymbol{B}}{\boldsymbol{\pi sin} \propto} \quad (1.1)$$

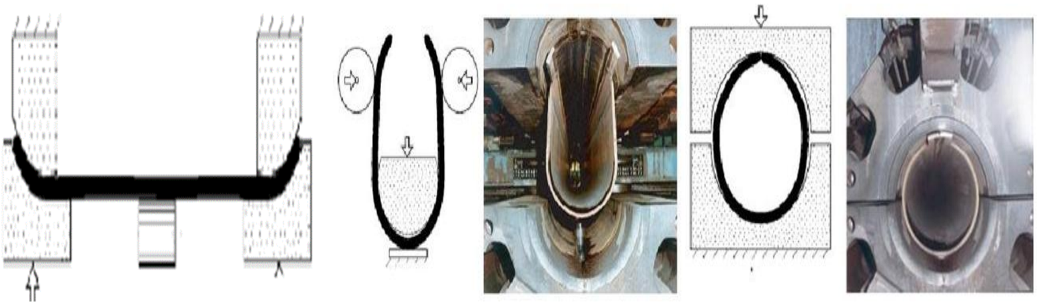
Where:
D: the tube diameter
B: the strip width
α: the entry angle

1.5.2. Longitudinally Welded Tubes

The manufacturing process for longitudinally welded tubes typically relies on cold forming of the steel plate using the UOE process, and it is specifically designed for tubes with diameters exceeding 406.4 mm (16 inches). This technique involves three main stages:

a. Bending and Forming

The steel plate is initially bent at its edge to ease the subsequent bending operations. Following this preliminary step, the single sheet is processed using two types of presses: the first press shapes the plate into a "U" form, while the second press transforms it into an "O" form (see the following figure).



Initial Bending U-Shape Forming O-Shape Forming

Figure 1.8: Longitudinally welded tubes bending and shapes forming(M.RAMDANI, 2008)

b. Tube Welding

Submerged Arc Welding (SAW) is used to join the tube edges. Two passes are performed: one external and one internal, staggered by half a rotation along the seam.

Figure 1.9: Tube Welding(M. Nahal, 2016)

c. Expansion and Calibration :

The primary objective of this operation is to produce tubes with a perfectly circular cross section. The diameter is increased by approximately 1 to 1.5% to meet dimensional accuracy standards (Figure 1.10).

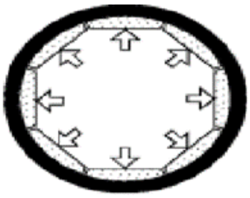


Figure 1.10: Expansion(H.P.Bloch & Geitner.F.K, 2012)

1.5.3. Seamless Tubes

Seamless tubes are forged steel tubular products manufactured without a weld seam. They are produced from a cylindrical billet through hot metal working (rolling) to achieve the required shape, dimensions, and mechanical properties. These tubes are generally limited to smaller diameters, usually less than 450 mm.

The manufacturing process is based on forming the metal so that it is contained between the die and the mandrel, resulting in a monobloc seamless tube. A common variant is needle-nose drawing, where the mandrel remains stationary during the forming process.

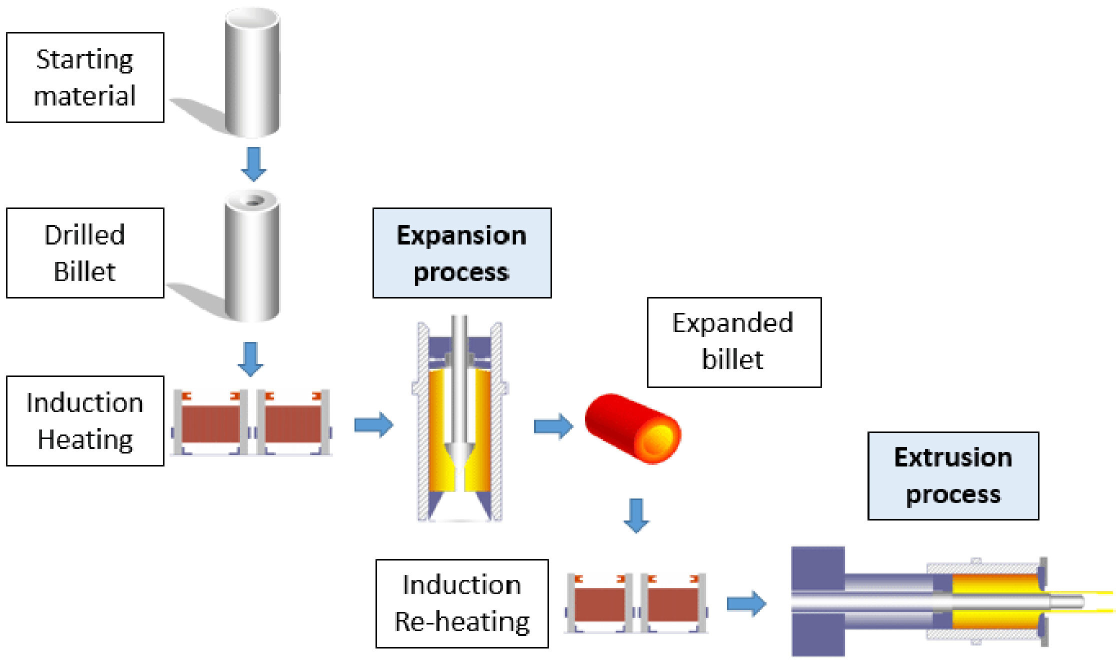


Figure 1.11: Seamless pipe manufacturing process chain(S. Hansson & M. Fisk, 2010)

1.6. Pipeline Damage

Although the transportation of hydrocarbons via pipelines is generally considered a reliable method, these systems can deteriorate over time. Such degradation may lead to leaks, ruptures, or other safety hazards. Consequently, it is essential to identify any failures to enhance reliability, ensure continuous availability, and maintain the safety of the transportation network, thereby reducing risks and guaranteeing an uninterrupted supply of petroleum products.

1.6.1. Corrosion

Corrosion is one of the most common issues affecting pipelines. It occurs due to chemical reactions between the pipeline material and environmental elements such as water, oxygen, and other corrosive agents. This process may affect both the interior and exterior surfaces of the pipelines. Common causes include moisture, aggressive soils, the presence of chemical and electrolytic contaminants, as well as design or installation flaws(sahraoui Yacine, 2014).

The main types of corrosion observed in pipelines include(Abdelkader KESSAB & Nour El Houda MOKTAR, 2020):

- Internal/external corrosion
- Uniform corrosion
- Localized corrosion (including pitting and galvanic corrosion)
- Electrolyte-induced corrosion
- Microbiologically influenced corrosion (caused by sulfate-reducing bacteria, acid-producing bacteria, or bacteria oxidizing iron and manganese)

1.6.2. Cracks

Cracks in pipelines can develop due to various factors, including the quality of the materials used. They generally occur in areas subjected to significant stress. Potential causes include bacterial corrosion, excessive mechanical loads during the loading and unloading of products, and fabrication defects such as faulty welds, among others (TOUGGUI Youssef & HOUASNIA Imed, 2016).

1.6.3. Wear

Wear results from the continuous friction between particles carried in the transported fluid and the internal surfaces of the pipelines. These particles may include sediments, impurities, chemical compounds, or abrasive materials. Over time, wear leads to thinning degradation of the pipeline's internal walls, increasing the risk of leaks or ruptures. Factors contributing to wear include the nature of the transported materials, the velocity of the gas flow, and the roughness of the pipeline's internal surfaces [19].

Scratches represent a particular form of wear, occurring when a foreign object contacts the pipeline surface, removing material. These are similar to notches and are typically defined by a length greater than their width. Scratches are often caused by tool impacts or equipment parts, such as bucket teeth, and are frequently unnoticed or unreported(Julien CAPELLE, 2008; T. NATECHE, n.d.).

1.6.4. Denting

Denting in a pipeline occurs when the circular wall undergoes a permanent plastic deformation following an impact with a foreign object, potentially affecting its structural integrity and operation. This can be caused by the bucket of a construction machine for buried or ground-laid pipelines, or by boat anchors for submerged pipelines. Denting is characterized by a change in the curvature of the pipeline wall without any alteration in its thickness. The depth of the dent is measured as the maximum reduction in the pipe's diameter relative to its original diameter(Julien CAPELLE, 2008).

1.6.5. Mechanical Damage

Mechanical damage can be caused by shocks, vibrations, impacts, or external deformations of the pipelines. Such damage may result from construction activities, excavation work, soil movement, external loads, earthquakes, or collision related accidents. These impacts can lead to permanent deformations, cracking, or even ruptures in the pipelines(HAMMOUYA, 2023).

1.6.6. External Interferences

External interferences refer to damage caused by human activity or natural events occurring near pipeline systems. These can include unauthorized excavations, nearby construction work, soil movements, landslides, floods, erosion, or impacts from wildlife. Such interferences can compromise the pipeline's integrity and increase the risk of failure.

1.6.7. Construction Defects

Construction defects arise from errors during the manufacturing, assembly, or installation of the pipelines. These problems can include defective welds, poorly executed joints, coating flaws, design errors, or material quality issues.

a.Crack(E. Casas et al., 2024)

b.Denting(C. Alexander & K. Brownlee, 2007)

c.Weld porosity(M. Lassoued et al., 2017)

d.Internal Corrosion(M. Askari et al., 2019)

Figure 1.12: Different Types of Pipeline Damage

1.7. Pipeline Maintenance

Pipelines are critical infrastructures for transporting fluids such as oil, natural gas, and water. Their reliable operation depends on well-designed maintenance strategies that ensure safety, efficiency, and long-term performance. Effective maintenance not only reduces the probability of accidents occurring, and minimizes repair costs but also optimizes the overall management of these vital infrastructures.

Recent studies highlight that integrating Industry 4.0 technologies, such as IoT, artificial intelligence, and advanced data analytics, into pipeline maintenance significantly improves real-time monitoring and anomaly detection. These innovations contribute to more proactive and efficient management of critical infrastructure (J. E. Naranjo et al., 2022).

1.7.1. Preventive Maintenance

1.7.1.1. Non-Destructive Testing (NDT)

Non-destructive testing methods are used to assess the internal integrity of pipelines without causing any damage. Commonly employed techniques include radiography, ultrasonic testing, magnetic particle inspection, eddy current testing, and thermography. These methods are essential for detecting corrosion, welding defects, cracks, or other structural anomalies(H. Amel & H. Dhaker Ellah, 2022).

- **Visual Inspection**

Regular visual inspections are used to detect signs of deterioration, corrosion, leaks, or other visible anomalies on the pipeline surface. This process can be carried out using cameras, drones, or visual patrols along the pipeline route (HAMMOUYA, 2023).

- **Radiography**

Industrial radiography employs low-wavelength X-rays or gamma rays that can penetrate materials. As these rays pass through an object, their intensity is altered depending on whether they encounter solid material or defects. A radiographic detector positioned behind the object records these variations, producing an image or film that highlights differences in density or contrast. This method is used to detect corrosion, locate obstructions within pipes or accessories, and verify the position of components such as valves(T. NATECHE, n.d.).

- **Ultrasonic Testing**

Due to safety requirements and the challenges associated with deep-sea operations, automated ultrasonic testing is increasingly used to inspect the circumferential welds of pipelines, gradually replacing radiographic methods. This technology measures the travel time of ultrasonic waves that travel perpendicularly through both the conveyed fluid and the tube's metal. By analysing the time delay and the reflections from the internal and external surfaces, the system calculates wall thickness. However, the precision of this method relies heavily on the cleanliness of the pipeline interior (HAMMOUYA, 2023).

Figure 1.13: Ultrasonic testing

1.7.1.2. Real-Time Monitoring

Ensuring the integrity of pipelines requires continuous, real-time monitoring of key parameters such as pressure, temperature, and flow rate. These metrics are vital for early detection of potential failures, optimizing system performance, and implementing predictive maintenance strategies.

- **Pressure Monitoring:** Tracking pressure fluctuations enables the identification of leaks, structural weaknesses, or excessive stress that could compromise pipeline safety.
- **Temperature Monitoring:** Changes in temperature can affect material expansion, fluid properties, and overall pipeline durability, making constant tracking essential to prevent damage.

- **Flow Monitoring:** Variations in flow rate may signal blockages, leaks, or pump inefficiencies, ultimately impacting operational performance(Khan, F., Thodi et al., n.d.)**.**

1.7.1.3. Hydrostatic Testing

Hydrostatic testing is a procedure used in pipeline maintenance to assess the strength and integrity of the pipelines. The test involves filling the pipeline section under inspection with water and applying a pressure that exceeds the normal operating level. This process helps verify the pipeline's ability to withstand increased pressure and detect potential leaks or structural weaknesses.

However, hydrostatic testing has certain limitations. It requires a temporary shutdown of the pipeline, which can disrupt product supply. Additionally, obtaining sufficient water for the test can be challenging, especially in areas where water is scarce. After the test, fully drying the pipeline can be difficult, potentially promoting corrosion. Furthermore, hydrostatic testing only provides a snapshot assessment of the pipeline's condition and may not detect evolving or latent defects(T. NATECHE, n.d.).

1.7.1.4. External Protection

External protection is vital for preventing pipeline corrosion and extending the service life of infrastructure. It typically involves a combination of surface preparation, protective coatings, and cathodic protection.

- **Sandblasting**

Sandblasting is an industrial technique used for cleaning surfaces. It involves propelling an abrasive powder such as hard oxides, corundum, or alumina at high speed onto the surface with compressed air and a nozzle. This process removes contaminants, deposits, or existing coatings from the material. After sandblasting, it is common practice to apply a protective film or a primer layer to safeguard the treated surface from damage or further contamination(SAHRAOUI Aboubakr, 2021).

Figure 1.14: Pipeline sandblasting

- **Protective Coatings in Pipelines :**

Protective coatings are essential for extending the life of pipelines by preventing corrosion and surface degradation. Pipelines are frequently exposed to moisture, soil, chemicals, and varying temperatures, all of which contribute to corrosion and material breakdown. Protective coatings act as barriers, shielding the metal surface from environmental elements and minimizing maintenance costs. Common types of protective coatings are Fusion-Bonded Epoxy (FBE), which is highly resistant to moisture and chemicals, Polyethylene Coatings for strong mechanical protection, and Polyurethane Coatings for durability in extreme conditions. These coatings not only enhance the structural integrity of pipelines but also contribute to safety and environmental protection by reducing the risk of leaks and failures(E. A. Yatsenko et al., 2024).

- **Cathodic protection :**

Cathodic protection (CP) is a critical electrochemical method used to prevent corrosion in buried or submerged pipelines by maintaining the metal structure as a cathode, thereby suppressing oxidation reactions. This is achieved through two primary systems: sacrificial anode and impressed current cathodic protection. Sacrificial anode systems rely on metals such as magnesium or zinc, which corrode preferentially to the pipeline, as demonstrated in field studies (J. A. Smith, 2018). Impressed current systems use inert anodes connected to an external power source to deliver a controlled protective current. Recent advancements in monitoring technologies, such as wireless sensor networks and real-time data analytics, have significantly improved the accuracy of CP performance assessments, particularly in addressing challenges like coating degradation and soil resistivity variations (M. Elboujdaini & R. W. Revie, 2020). Integrating CP with robust pipeline coatings and regular inspections remains essential to mitigate stray current interference and ensure long-term structural integrity.

1.7.2. Corrective Maintenance

1.7.2.1. Internal Cleaning and Inspection of Pipelines Using a Pig

A pipeline pig is a cylindrical device used for the internal cleaning and inspection of pipelines. It moves along the pipeline using the fluid flow or an internal force and scrapes away deposits with its brushes. Additionally, it can be equipped with sensors to detect issues like corrosion, cracks, or coating defects, while also gathering data on flow, pressure, and temperature. This information helps assess the pipeline's integrity and plan maintenance work. However, pigs may not be suitable for all pipelines, such as those with small diameters, sharp bends, or low pressure and flow conditions, which might require alternative inspection methods(H. Amel & H. Dhaker Ellah, 2022; T. NATECHE, n.d.).

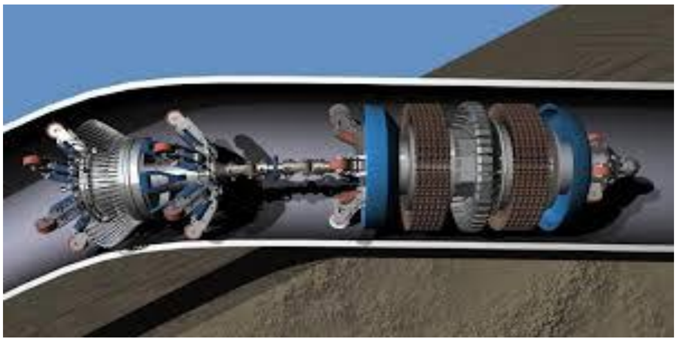


Figure 1.15: Pipeline Pigging

1.7.2.2. Sandblasting and Coating

Sandblasting and coating are essential for the corrective maintenance of pipelines, ensuring durability and corrosion protection. Sandblasting removes rust and old coatings, improving adhesion for new protective layers. Proper rehabilitation through sandblasting has been shown to reduce maintenance costs and operational risks, while effective surface preparation is emphasized for extending coating lifespan and enhancing corrosion resistance(F. B. Azevedo et al., 2024; J. A. Kehr, 2003). Implementing these techniques improves pipeline safety, minimizes downtime, and optimizes long term performance.

1.7.2.3. Welding

Welding is an essential method used in corrective maintenance of pipelines to fix damages such as cracks, corrosion, or leaks. It helps restore the pipe's strength without needing full replacement, saving both time and cost. In maintenance, common welding techniques like shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) are chosen for their reliability in different conditions. Careful control of welding procedures is important to

avoid issues like residual stress, which can weaken the repaired area. Modern methods also use automated welding and testing to improve safety and durability of the repairs(I. Zakharova, 2024).

1.8. Conclusion

Pipelines are a vital component of hydrocarbon transportation, offering a safe and efficient means to supply these essential resources over long distances. Supported by advanced technology and strict regulations, they minimize risks compared to other bulk transport methods. This chapter reviewed the entire lifecycle of pipelines from design and construction to ongoing maintenance highlighting their strategic role in ensuring energy security and economic stability. It is crucial that these infrastructures continue to evolve to meet both present and future energy demands.

Chapter 2: Work Methodology

Chapter 2: Work Methodology

2.1. Introduction

This chapter presents the study's methodology in a structured and systematic manner. It begins with an in-depth case study and the data collection process. The methodology is based on a diagnostic approach using the Bowtie Method to analyze the causes and consequences of pipeline failures. Next, Principal Component Analysis (PCA) is described, outlining an interval-based procedure for fault detection. The chapter concludes with an overview of the mechanical behavior study using the Finite Element Method (FEM) through the Abaqus software, which allows for precise simulation based on accurate geometry and material properties.

2.2. Methodology of work

In this work, a structured hybrid diagnosis methodology was adopted to analyze potential failures in a hydrocarbon transport system. The process began with the application of the Bowtie Method, which was used to identify possible causes of pipeline failures and to map their potential consequences. This step facilitated the definition of fault scenarios and the identification of both preventive and mitigative barriers.

Once these failure scenarios were established, the Principal Component Analysis (PCA) by interval was applied to detect early signs of abnormal behavior. This technique allowed for the selection of the most informative primary sensors, ensuring that meaningful operational data could be monitored for deviations.

To evaluate the mechanical consequences of these deviations, particularly those related to overpressure, a detailed structural analysis was conducted using the Finite Element Method (FEM) in Abaqus. The simulation focused on a corroded pipeline section subjected to varying stress conditions, providing insights into its mechanical response.

This integrated methodology offers a reliable framework for fault detection, and the implementation of effective corrective and preventive actions.

2.2.1. Case study

As part of our undergraduate training, we had the opportunity to undertake an internship at Sonatrach's operational facilities in **Hassi R'mel**, Algeria's largest natural gas field and a cornerstone of the country's energy infrastructure.

Situated in the heart of the Sahara Desert, approximately 550 km south of Algiers, between the towns of Laghouat and Ghardaïa, Hassi R'mel lies in a relatively flat region of the northern Sahara at an average altitude of 750 meters. The region experiences an arid climate, with low annual rainfall (140 mm), summer humidity of 19%, and 34% in winter. Temperatures can range from –10°C in winter to +50°C in summer, with prevailing northwesterly winds(Djamel & Kahina, 2011).

Spanning an area of nearly 1,200 km², the Hassi R'mel field serves as a vital hub in Algeria's gas network, significantly contributing to national production. It not only meets substantial domestic demand but also supports exports to Europe via key international pipelines such as Transmed, Maghreb_Europe, and Medgaz(ETIEVANT et al., 2007).

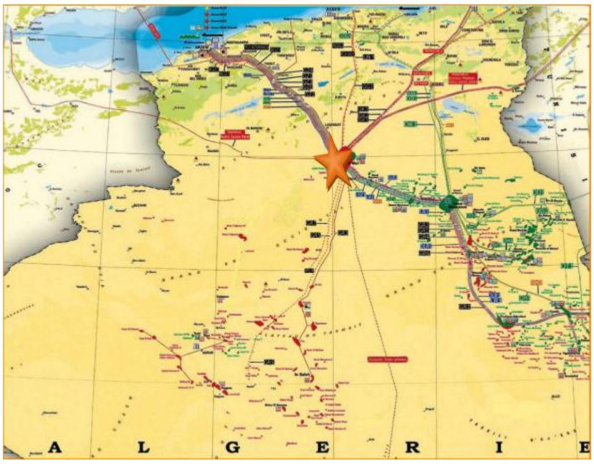


Figure 2.1 : Location Map of the Hassi R'mel Gas Field(SAOUDI & BOUGDAH, n.d.)

The Hassi R'mel field is organized into three principal zones: North, Central and South (see Figure 2.2) Each zone is equipped with essential gas infrastructure, including gas-processing modules, compressor stations, oil-treatment centers, units for removing industrial effluents, and a domestic wastewater treatment plant.

Module 3, a depropaniser unit, and a compression station are included in **the North sector**. In **the Central sector**, Modules 0, 1, and 4 are found, along with the Central Storage & Transfer Facilities (CSTF), the Oil Treatment Centre (CTH), and Phase B, which is recognized as a major processing unit. **The South sector** is comprised of Module 2, an additional compression station, the Djebel Bessa facility, and the HR South unit (Ferhat Amhis., 2011).

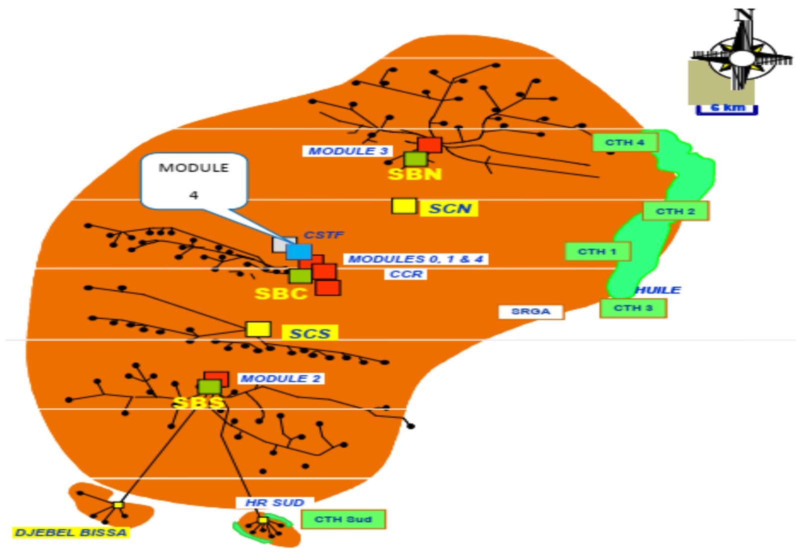


Figure 2.2 : Map of the main production zones at Hassi R'mel (*Rapport d'activité de La Direction d'exploitation*, 2007)

Gathering gas through long pipelines, especially over hills, around bends, or across rough terrain, reduces its pressure. At the same time, the reservoir naturally depletes as it is produced, and liquids such as water or condensate can accumulate in the lines, further hindering the flow.

To maintain an optimal and uninterrupted flow from the wellhead to the export systems and LNG trains, Sonatrach has installed a series of midstream compression stations, also known as boosting centers. Strategically located across the field (usually every 80–120 km)(Djamel & Kahina, 2011; Oumechouk, 2012), these stations:

- Boost wellhead pressure (typically from 40 bar to about 70 bar),
- Prevent fluid build-up and pressure drop,
- Support long-distance pipeline transport efficiency.

Each station is equipped with multi-stage centrifugal compressors driven by gas turbines, ensuring robust performance even under harsh desert operating conditions. This infrastructure plays a vital role in ensuring that Algeria meets both its domestic energy needs and its international export commitments.

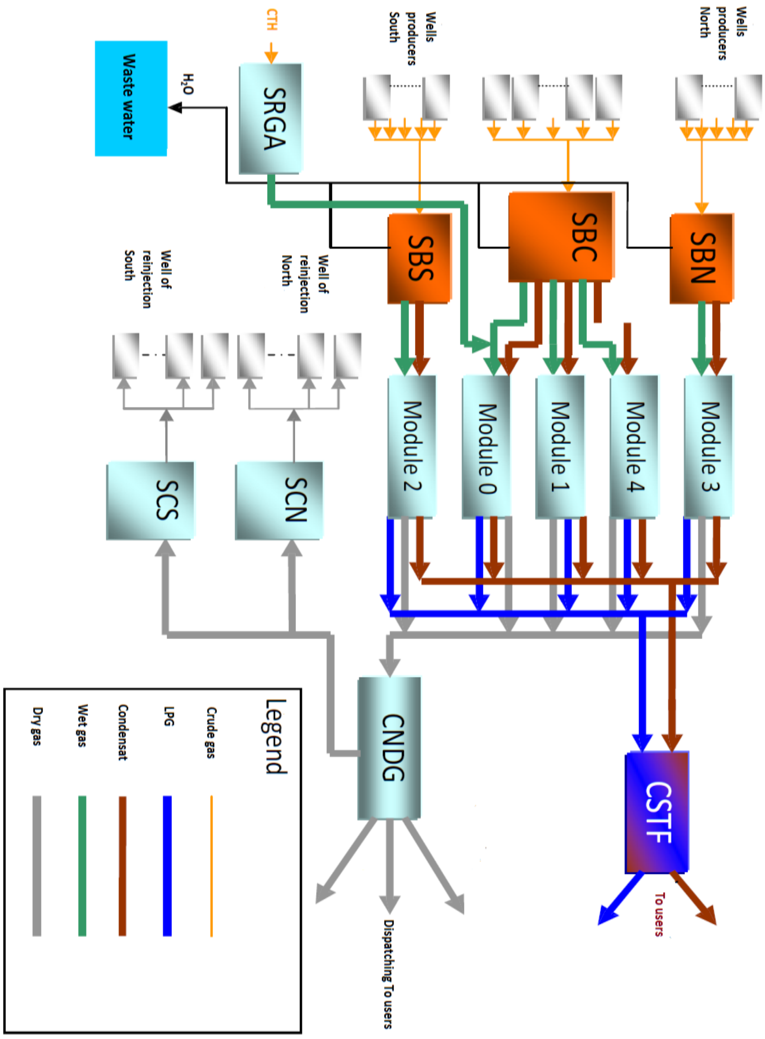


Figure 2.3 : Diagram of industrial processing at HASSI R'MEL(*Rapport d'activité Des Operateurs, Module IV HASSI R'mel*, 2006)

2.2.2. Data collection

During the internship at Sonatrach's Hassi R'Mel facility, operational parameters were collected and validated from Boosting Centre 3 (SBC3), which functions as a central collection and pressure-raising hub within Sonatrach's midstream network at Hassi R'Mel.

The boosting process is monitored and managed from the control room, which is equipped with computer systems operating in synchrony with programmable logic controller (PLC) cabinets. These controllers are supervised by an intelligent SCADA (Supervisory Control and Data Acquisition) system, which enables real-time monitoring and control of the process. The boosting system is instrumented with various sensors to measure temperature, pressure, and flow rate, ensuring accurate data acquisition (see Figure 2.4).

Any deviation in these parameters can compromise downstream equipment, trigger relief systems, or lead to pipeline failures. Therefore, maintaining both inlet and outlet pressures within their design limits is essential for safe, efficient, and reliable operation.

Pression sortie SBC3	Pression sortie SBC2	Pression entrée SBC3	Pression Entrée SBC2	T°(C°)	Débit refoulement
58,23	104,7	35,02	57,4	46,1	101,4
58,1	104,4	35,38	57,2	45	103,5
58,02	103,8	34,77	57,2	48,1	102,8
58,21	105	35,58	57,3	48,01	102,7
58,15	104,7	35,29	57,3	47,98	102,2
58,17	104,3	34,81	57,4	51,39	103,4
58,13	105,3	35,3	57,3	49	103,2
58,14	105,6	35,27	57,4	49,45	103
58,23	105,1	35,2	57,3	47,7	103,3
58,23	105,3	35,2	57,3	50,46	103
58,27	105,9	34,25	57,4	50,5	103
58,29	105,5	35,4	57,4	50	103
58,18	104,8	35	57,4	50	103
58,22	104,1	33,8	57,3	46,5	103
58,32	103,5	33,98	57,4	47	103
58,16	103,4	34,04	57,3	48	103
58,23	103,3	33,71	57,3	44,26	103,5

Figure 2.4: Example of Data collected from station Boosting Centre 3

2.3. Bowtie Method

The Bowtie Method is a visual failure and risk analysis technique that combines aspects of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) to evaluate and manage hazards in a comprehensive manner. Developed initially in 1971 by Nielsen and further refined during the 1990s, this method focuses on understanding failures and risks in terms of their causes, consequences, and the associated safety barriers for prevention and mitigation(Hammouya, 2025).

At the center of the diagram lies the Top Event, representing the critical incident or feared event. On the left side of the diagram, potential threats or initiating causes are identified, while the right side outlines the possible consequences. These are flanked by preventive barriers on the cause side and mitigative barriers on the consequence side. The resulting shape resembles a bowtie, hence the name.

This structured visual representation allows organizations to clearly identify how failure develop and how they can be effectively controlled or minimized. Through barrier analysis, the Bowtie Method facilitates decision-making in maintenance and safety management by highlighting both vulnerabilities and existing safeguards (A. de Ruijter & F. Guldenmund, 2016; M. Omidvar et al., 2022).

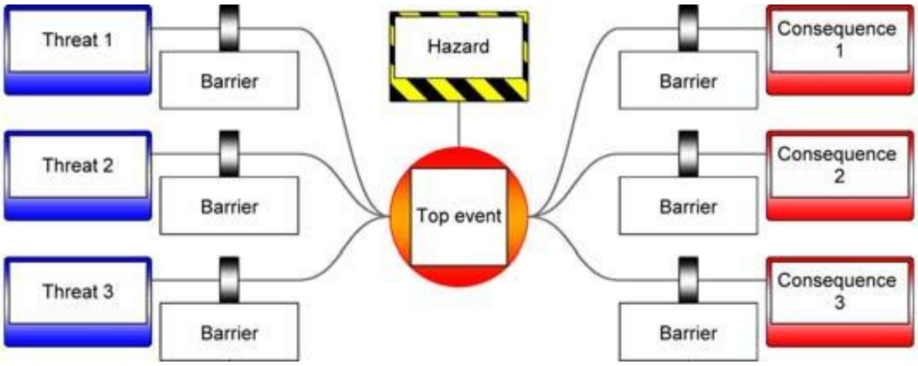


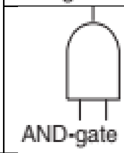
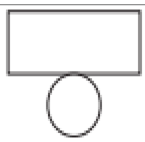
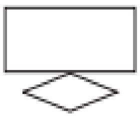
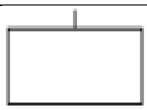
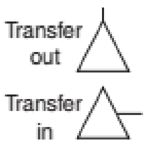
Figure 2.5 : Bowtie diagram (HAMMOUYA et al., 2021)

2.3.1. Fault Tree Analysis Method

Fault Tree Analysis (FTA) is a probabilistic and deductive method initially developed by H.A. Watson and M.A. Mearns in 1961. It was first applied in the field of U.S. military aviation systems. This method is primarily used to identify the underlying causes that may lead to an undesirable event, by breaking down the contributing factors into their most basic and indivisible elements(HAMMOUYA et al., 2025b).

The fault tree is a schematic, logic-based diagram that illustrates the principle of multiple causation by detailing every event branch that might result in an accident or failure using various symbols, labels, and logic gates (such as AND, OR) (Siddiqui, 2016) (see table 2.1).

Table 2.1 : Fault tree symbols(Marvin Rausand, n.d.)

Logic gates		The OR-gate indicates that the output event occurs if any of the input events occur
		The AND-gate indicates that the output event occurs only if all the input events occur at the same time
Input events (states)		The basic event represents a basic equipment failure that requires no further development of failure causes
		The undeveloped event represents an event that is not examined further because information is unavailable or because its consequences are insignificant
Description of state		The comment rectangle is for supplementary information
Transfer symbols		The transfer-out symbol indicates that the fault tree is developed further at the occurrence of the corresponding transfer-in symbol

Even then, variations of these symbols may be encountered in practice. Fault tree diagrams are typically constructed from the top down. They begin with the undesired event of interest (the "top event," since it is placed at the top of the diagram). The next step is to determine logically and illustrate the immediate contributing fault conditions that lead to this event. Each of these conditions may, in turn, stem from additional faults, and the process continues. Although this could potentially be endless, it ultimately stops at the primary failures. The most challenging aspect of the method is establishing the initial sequence of failure dependencies.

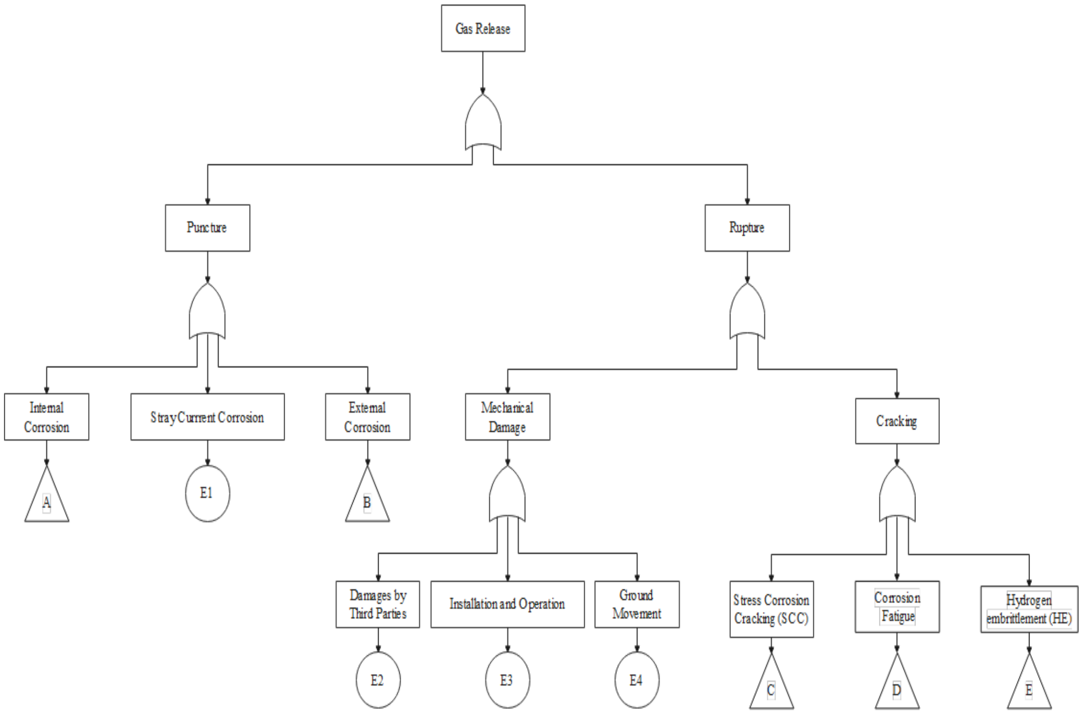


Figure 2.6 : Example of FTA diagram(Sabará, M. A et al., 2025)

2.3.2. Event Tree Analysis method

Event Tree Analysis (ETA), also known as the Tree of Consequences, is an inductive method. It was first used in the 1970s in nuclear power plants in the United States(HAMMOUYA et al., 2025a).

As the second part of the Bowtie method, Event Tree Analysis focuses on mapping out the sequence of events that may follow an initiating event, such as a component failure. This approach allows us to understand and mitigate the potential consequences of an undesirable event, rather than aiming to prevent it entirely. In essence, it resembles observing the ripple effect after a single splash, helping us plan effective responses.

ETA is generally conducted in four stages:

- Defining the initiating event;
- Identifying the safety functions and controls in place;
- Constructing the event tree;
- Analyzing and interpreting the resulting consequences(Hammouya, 2021).

Event trees can be constructed in several formats, but they typically use Boolean (binary) logic gates, representing decisions or outcomes in two states: success/failure, yes/no, or on/off. The diagram usually starts on the left with the initiating event and branches to the right, with each branching point referred to as a node. In simpler systems, the event tree may be presented at a higher level to summarize key sequences without going into detailed branching (Siddiqui, 2016).

Below is a general example of how an event tree may be structured.

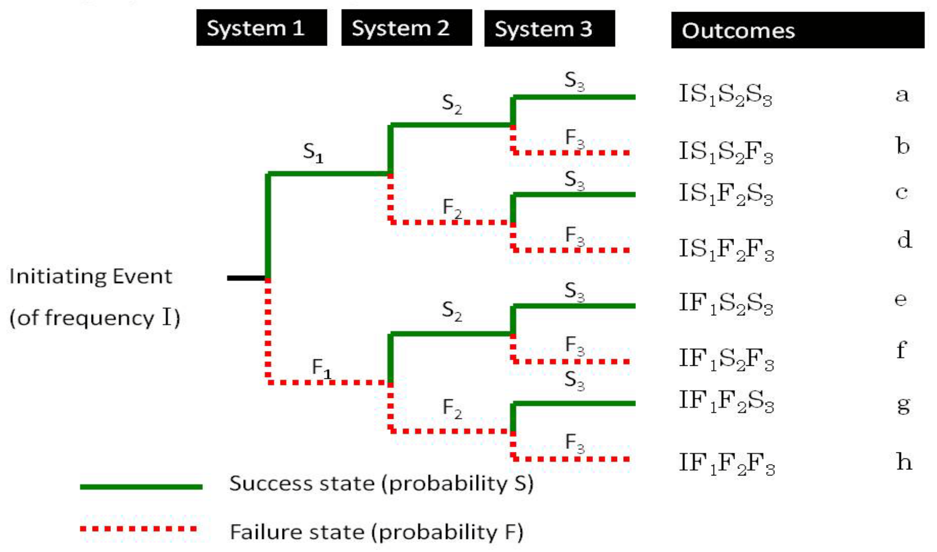


Figure 2.7 : Example of ETA diagram(Siddiqui, 2016)

2.4. Fault Diagnosis Using Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a well-established numerical technique in data processing used to reduce the dimensionality of a system's representation. Linear PCA serves as a modeling tool for the linear relationships among the various variables that characterize a process; it uncovers inter variable relationships without any a priori structural assumptions. In practice, PCA implicitly constructs a model of the system from data collected during normal operation. This descriptive technique can be regarded as a complete system-identification method in its own right. Model identification proceeds in two stages: first estimating the model parameters, then determining its structure. Once the PCA model is established, residuals are generated by comparing observed behavior to that predicted by the reference PCA model. These residuals enable both the detection and localization of any faulty variables(Benslim, 2021).

2.4.1. The steps of PCA

The main steps of PCA involve gathering the data, normalizing it, calculating either the covariance or correlation matrix, determining the eigenvectors and their corresponding eigenvalues, projecting the data onto the axes defined by the principal components of the model, and finally detecting and isolating any faults(Ait Izem Tarek, 2018; HAMMOUYA, 2023; SRAOUI & AGDI, 2024).

2.4.1.1. Data Normalization

Normalization means putting all the variables on the same scale, so that those with larger ranges don't dominate the analysis. This is usually done by centering and scaling the data basically adjusting it so that each variable has a mean of zero (M = 0) and a standard deviation of one (σ = 1).

Let's say we have a system with ***m*** sensors (or variables), and each sensor records ***n*** measurements at every time point ***k***. The data collected during normal operation when there are no faults can then be organized into a data matrix $X^g R^n$*m (Equation *2.1*).

$$X^g = \begin{pmatrix} x_{11} & . & x_{m1} \\ . & . & . \\ x_{1n} & . & x_{mn} \end{pmatrix} \tag{2.1}$$

Each variable XjX_j in the newly normalized matrix XX is calculated as follows:

$$X_j = \frac{X_j - M_j}{\sigma_j} \tag{2.2}$$

Here, Mj is the mean of all observations in column j, and σj is the standard deviation of those observations.

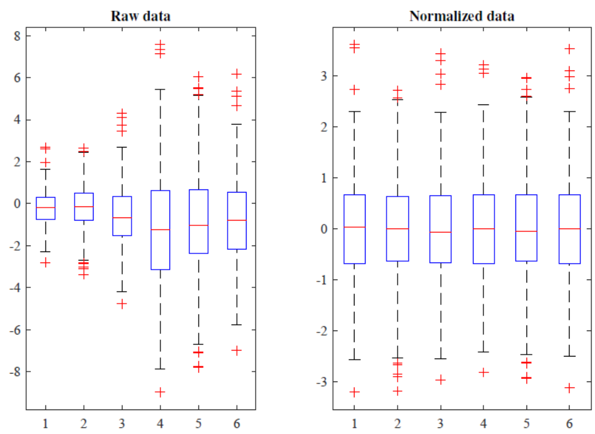


Figure 2.8: Data normalization Example

2.4.1.2. Checking Correlations

Once our data is normalized, the next step is to compute the covariance (or correlation) matrix Σ. This matrix captures the linear relationships between variables, helping us understand how they depend on each other and quantify the strength of those correlations. If Σ shows no meaningful relationships among the variables, then PCA isn't a suitable method for this dataset.

The covariance matrix is defined as:

$$\Sigma = \frac{1}{N-1} XX^T \tag{2.3}$$

2.4.1.3. Calculating Eigenvalues and Eigenvectors

Next, we break down the covariance matrix Σ to find its eigenvalues Λ and eigenvectors P. In formula form, this looks like:

$$\Sigma = P \Lambda P^T \quad (2.4)$$

Here's what's happening:

- **Eigenvalues (Λ)**: These go into a diagonal matrix, with values sorted from largest to smallest ($\lambda 1 \geq \lambda 2 \geq \cdots \geq \lambda_n$). Each λ_i tells you how much "information" or variance is captured by the corresponding principal component.

$$\Lambda = \begin{bmatrix} \lambda_{l \times l} & 0 \\ 0 & \lambda_{(n-l)(n-l)} \end{bmatrix} \quad (2.5)$$

- **Eigenvectors (P)**: These are the directions of the principal components. You can think of each column p_i P=[p1 p2 … pm] as pointing along one principal axis in the data space.

Together, Λ and P let us see which directions carry the most variance and therefore which components are most important for reducing dimensionality.

2.4.1.4. Selecting Principal Components

In this step, we select the most significant principal components $\widehat{P}$, based on the eigenvalues Λ. The goal is to choose a reduced number of components ($l < m$) that capture the majority of the total variance in the data. To do this, we partition the eigenvector matrix P as follows:

$$P = [\widehat{P}\widetilde{P}] \quad (2.6)$$

This split lets us express the data in a lower-dimensional principal space $\widehat{T}$ using the first l eigenvectors $\widehat{P}$ that capture the most meaningful variation. The remaining ($m-l$) eigenvectors $\tilde{P}$ make up the residual space $\tilde{T}$ holding whatever variation wasn't captured by the top components.

Accordingly, we can break our original data X into two parts:

- $\hat{X}$: the portion explained by the first ***l*** eigenvectors (the principal subspace)
- $\tilde{X}$: the residual portion explained by the remaining eigenvectors (the residual subspace)

$$\hat{X} = X\hat{P}\hat{P}^T = X\hat{C}^{(l)} \quad (2.7)$$

$$\tilde{X} = X - \hat{X} = X(1 - \hat{C}^{(l)}) \quad (2.8)$$

$$\hat{C}^{(l)} = \hat{P}\hat{P}^T \quad (2.9)$$

2.4.1.5. Determining the Number of Principal Components

Here, we use the cumulative variance criterion to decide how many components to keep. First, we calculate the fraction of total variance each principal component explains, then add these fractions up in order. By setting a threshold say 80% or 90% we pick the smallest number of components needed to reach that level of explained variance. This way, we retain most of the information from the original data while effectively cutting down on dimensionality. The cumulative variance percentage is given by:

$$PCV(\ell) = 100\left(\frac{\sum_{j=1}^{\ell} \lambda j}{\sum_{j=1}^{m} \lambda j}\right)\% \qquad (2.10)$$

2.4.1.6. Projecting Data onto Principal Components

Once the principal components have been selected, the data is projected onto them in the new, reduced-dimensional space (Figure 2.9). This projection allows us to represent the data more compactly while preserving the essential information. The optimal transformation of the data matrix X is given by:

$$X = TP^t \qquad (2.11)$$

$$T = P^t X \qquad (2.12)$$

Where:
T∈Rn×mT is the matrix of principal components.

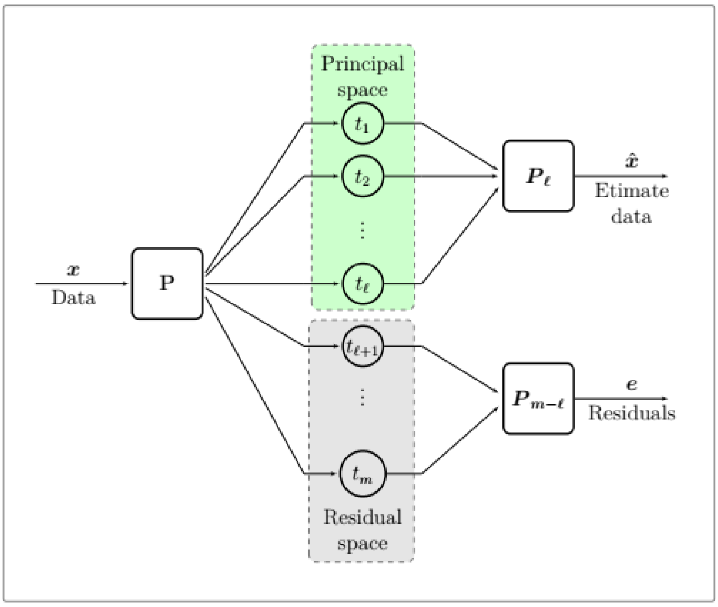


Figure 2.9 : Mapping and Inverse Mapping Using Linear PCA(Ait Izem Tarek, 2018)

Figure 2.9 Shows that PCA transforms the original data into two parts: the principal part and the residual part. The principal part contains the main patterns and important information in the data, helping to simplify and understand the overall structure. The residual part holds the smaller details or variations that are not as significant. This way, PCA helps reduce the complexity of the data while still keeping the most useful information.

2.4.2. Interval-based PCA

Interval PCA, when applied using the center-radius approach, helps overcome the challenges typically faced in analyzing interval data. These challenges mainly come from the difficulty of computing covariances and performing eigenvalue and eigenvector decomposition on interval-based data. By representing interval data in terms of centers and radii, this method simplifies the statistical analysis, making the data easier to process and interpret.

2.4.2.1. MRPCA Model

The MRPCA (Multi-Range Principal Component Analysis) model is designed for interval-based measurements, where data is represented using lower bounds (LB) and upper bounds (UB). For each variable j and each observation iii, the interval values are expressed as $[\underline{x}j(k);\ \overline{x}j(k)]$.

The center of the interval, xcj(k) is calculated as the average of LB and UB. The radius of the interval xrj(k) is computed as half the difference between UB and LB.

$$x_j^c(k) = \frac{\underline{x}_j(k) + \overline{x}_j(k)}{2} \tag{2.13}$$

$$x_j^r(k) = \frac{\underline{x}_j(k) + \overline{x}_j(k)}{2} \tag{2.14}$$

The standard form of the interval can then be reconstructed from its center and radius as follows:

$$[x_j(k)] = [x_j^c(k) - x_j^r(k)\ , x_j^c(k) + x_j^r(k)] \tag{2.15}$$

The MRPCA (Multi-Range Principal Component Analysis) approach is a hybrid method that builds upon the center-based CPCA approach by also incorporating the radius information of the data. In practice, MRPCA is applied using the center matrix $\mathbf{X^c}$, the radius matrix $\mathbf{X^r}$, and the relationship between the two. According to the literature [6], two separate PCAs are independently applied to these two matrices. The solutions are derived from the following eigenvalue problems:

$$X^c {\textstyle\sum_c^{-1}} P^c = \Lambda^c P^c \tag{2.16}$$

$$X^r {\textstyle\sum_r^{-1}} P^c = \Lambda^r P^r \tag{2.17}$$

Λ^c: eigenvalues of the covariance matrix of the centers, Σc
Λ^r: eigenvalues of the covariance matrix of the radii, Σr
P^c: eigenvectors of the center covariance matrix Σc
P^r: eigenvectors of the radius covariance matrix Σr

To achieve a consistent statistical representation of the data based on the MRPCA model, a rotation is applied to the coordinates of the radii. These rotated radii are then overlaid onto the principal component coordinates of the centers as additional data points. This rotation can be done either by maximizing Tucker's congruence coefficient between the centers and radii [7], or by using a rotation matrix A= QP [6], which is obtained through the following singular value decomposition (SVD):

$$X^{c^T} X^r = P \Lambda^{cr} Q^T \tag{2.18}$$

The identification of the MRPCA model can be broken down into the following steps:

1. Perform a PCA on the center matrix XcX_cXc.
2. Perform a PCA on the radius matrix XrX_rXr.
3. Compute the rotation matrix A=QPA = QPA=QP.

4. Construct the interval principal component vectors [t(k)] by projecting the rotated radius components $t_r(k)$ onto the coordinates of the center components $t_c(k)$:

$$\begin{cases} T^c = X^c P^c P^{cT} \\ T^r = X^r P^r P^{rT} \end{cases} \quad (2.19)$$

5. create the interval estimate vectors $[\hat{X}(k)]$ .To do this, we take the rotated radius estimates $\hat{X}^r(k)$ and project them onto the coordinates of the center estimates $\hat{X}^c(k)$, yielding:

$$\begin{cases} \hat{X}^c = X^c \hat{P}^c \hat{P}^{cT} \\ \hat{X}^r = X^r \hat{P}^r \hat{P}^{rT} \end{cases} \quad (2.20)$$

6. Next, we calculate the interval residuals by taking the difference between the original data and their estimates:

$$[\tilde{x}(k)] = [x(k)] - [\hat{x}(k)] \quad (2.21)$$

Here, $[\tilde{x}(k)]$ represents the lower and upper residuals for each observation interval, showing how far the estimated intervals deviate from the actual data.

2.4.3. Fault Detection

There are several metrics for spotting faults; here, we'll use the SPE (Squared Prediction Error) index. SPE flags unusual conditions by looking at the residual space. It's calculated from the estimation error ***e*** using this formula:

$$SPE(k) = \| e(k) \|^2 = e^T e \quad (2.22)$$

Under normal operation when there's no fault the SPE value stays within a certain range. If a fault occurs, the SPE statistic jumps outside that range, causing its value to rise noticeably.

-absence de défaut $\quad SPE(k) \leq \delta_\alpha^2 \quad$ (2.23)

-présence d'un défaut $\quad SPE(k) > \delta_\alpha^2 \quad$ (2.24)

In interval PCA, the ISPE (Interval Squared Prediction Error) index is calculated from the interval norm of the residuals. It's defined as follows:

$$ISPE(k) = \| [\tilde{x}(k)] \|^2 = \sum_{j=1}^{m} \| [\tilde{x}j(k)] \|^2 \quad (2.25)$$

Where $\| [\tilde{x}(k)] \|^2$ represents the squared interval bound of the residuals:

$$\| [\tilde{x}j(k)] \|^2 = \frac{1}{3}\left(\underline{\tilde{x}}_j^2(k) + \overline{\tilde{x}}j(k)\underline{\tilde{x}}j(k) + \overline{\tilde{x}}_J^2(k)\right) \quad (2.26)$$

The SPE control limit at a confidence level ${\delta_\alpha}^2$ is given by:

$$\delta_{\alpha}{}^{2} = \theta_1 \left[\frac{h_0 C_{\alpha} \sqrt{2\theta_2}}{\theta_1} + 1 + \frac{(\theta_2 h_0)(h_0 - 1)/}{\theta_1^2} \right]^{1/\mathrm{h0}}$$
$$\theta i = \sum_{j=l+1}^{m} \lambda_j^i. \text{ Pour j} = 1,2,3 \tag{2.27}$$

$$h_0 = 1 - \frac{2\theta_2\theta_3}{3\theta_2^2} \tag{2.28}$$

$$C_{\alpha} = \theta_1 \frac{\left(\frac{\| e \|^2}{\theta_1} \right)^{h0} - 1 - \frac{\theta_2 h_0 (h_0 - 1)}{\theta_1^2}}{\sqrt{2\theta_1 h_0^2}} \tag{2.29}$$

2.5. Finite Element Method (FEA)

The Finite Element Analysis (FEA), also known as the Finite Element Method (FEM), is a computational technique employed to derive approximate numerical solutions for boundary value problems encountered in engineering. A boundary value problem refers to a class of mathematical problems where dependent variables must satisfy a governing differential equation across a defined domain of independent variables while adhering to prescribed conditions on the domain's boundaries. Widely utilized software platforms such as ANSYS and ABAQUS are prominent in FEA due to their comprehensive capabilities for diverse engineering simulations and analyses(ISMAIL BIN ISMAYATIM, 2009).

2.5.1. Abaqus module:

Abaqus is a powerful finite element analysis (FEA) software suite developed by Dassault Systems under the SIMULIA brand. It is widely used in engineering and scientific industries for solving problems related to structural mechanics, heat transfer, fluid dynamics, and multiphysics interactions.

Abaqus offers a comprehensive environment called Abaqus/CAE (Complete Abaqus Environment), designed for model creation, analysis, and post-processing (Dassault Systèmes, 2016)(Dassault Systèmes, 2025; Dhaker Ellah, 2022).

Abaqus consists of two major solvers:

- **Abaqus/Standard:** for static, dynamic, and thermal analyses using implicit methods.
- **Abaqus/Explicit :** for solving highly nonlinear, dynamic problems using explicit time integration(K.-J. Bathe, 2014).

The modular architecture of Abaqus/CAE allows users to focus on specific tasks efficiently through dedicated modules, each specialized for a part of the simulation process.

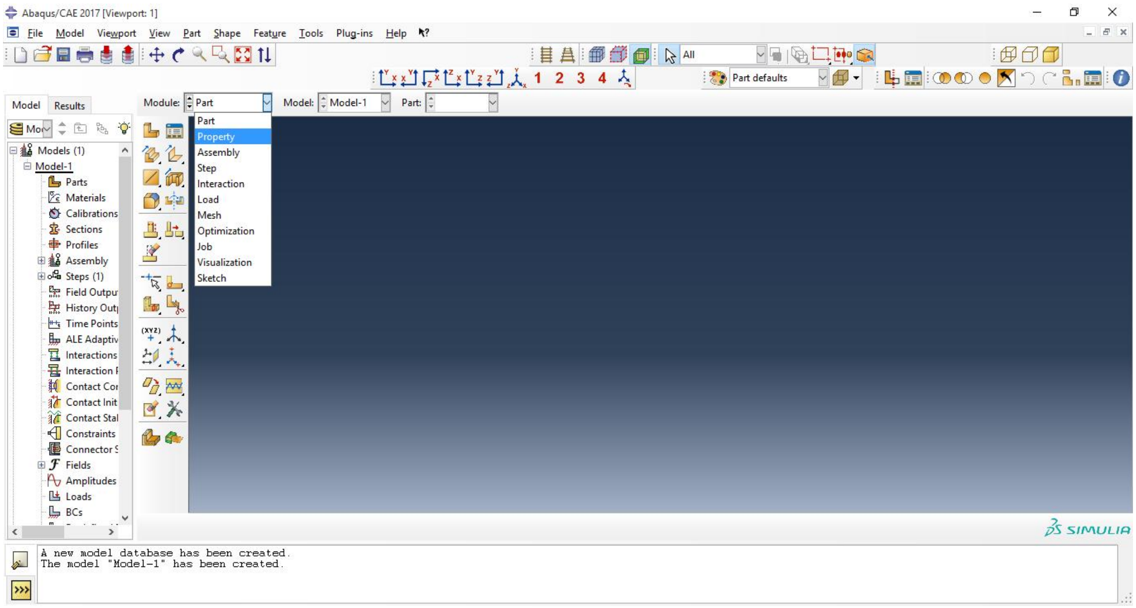


Figure 2.10: Main window of the ABAQUS software

2.5.2. Abaqus modules

Abaqus is structured around a series of interconnected modules, each dedicated to a specific stage of the simulation process. These modules guide the user through a logical sequence, from geometry creation to results visualization(DJAARIRI & BAKHOUCHE, 2024).

2.5.2.1. Part Module

The Part Module in Abaqus/CAE is used to create geometric models, known as parts, which represent the physical bodies under investigation. It provides tools for creating solid, shell, beam, and axisymmetric models. Sketching features, extrusion, revolution, and Boolean operations allow complex part development.

This module also supports importing geometry from CAD files like STEP and IGES.

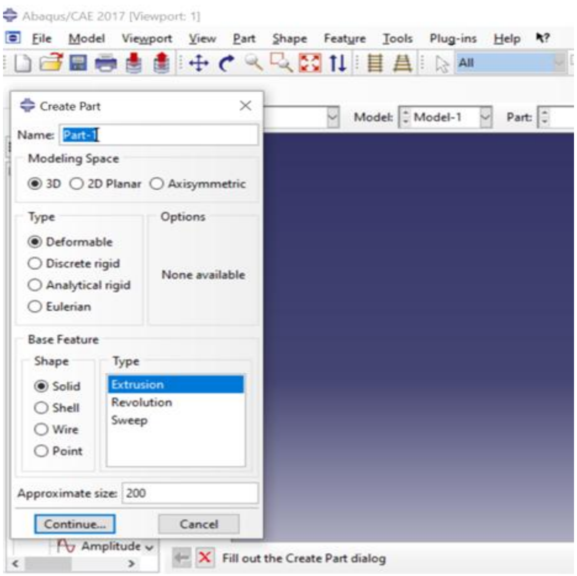


Figure 2.11: Part Module

2.5.2.2. Property Module

In the Property Module, users define material models and section properties.Materials can exhibit linear elastic, plastic, viscoelastic, hyperelastic, or user-defined behavior. Sections are then assigned to parts, connecting material definitions with geometric regions .Composite layups, shell thicknesses, and beam profiles are also specified here.

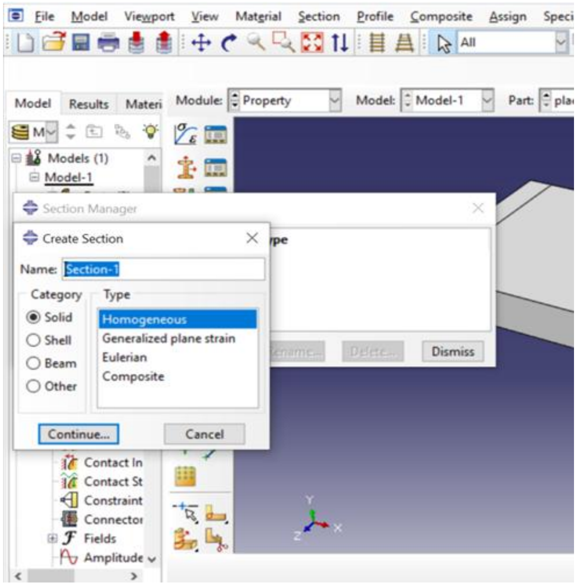


Figure 2.12 : Property Module

2.5.2.3. Assembly Module

The Assembly Module allows users to position and connect parts to form the complete model, referred to as an assembly. Positioning can be done manually or with constraints (e.g., mating surfaces) .Instances of parts can be independent or dependent; dependent instances replicate the part geometry exactly, saving computational resources.

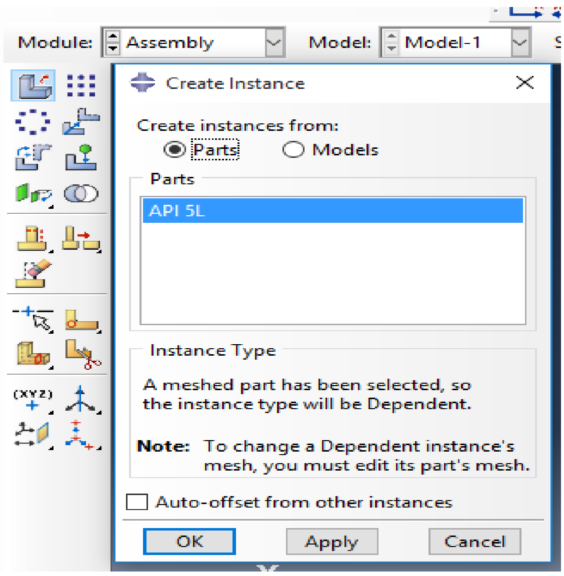


Figure 2.13: Assembly Module

2.5.2.4. Step Module

The Step Module organizes the sequence of analysis events.Each step defines a time period, loading conditions, and solver settings.

Typical steps include static general, dynamic explicit, heat transfer, frequency extraction, or user-defined procedures.

Load application, contact activation, and boundary condition changes are managed through steps.

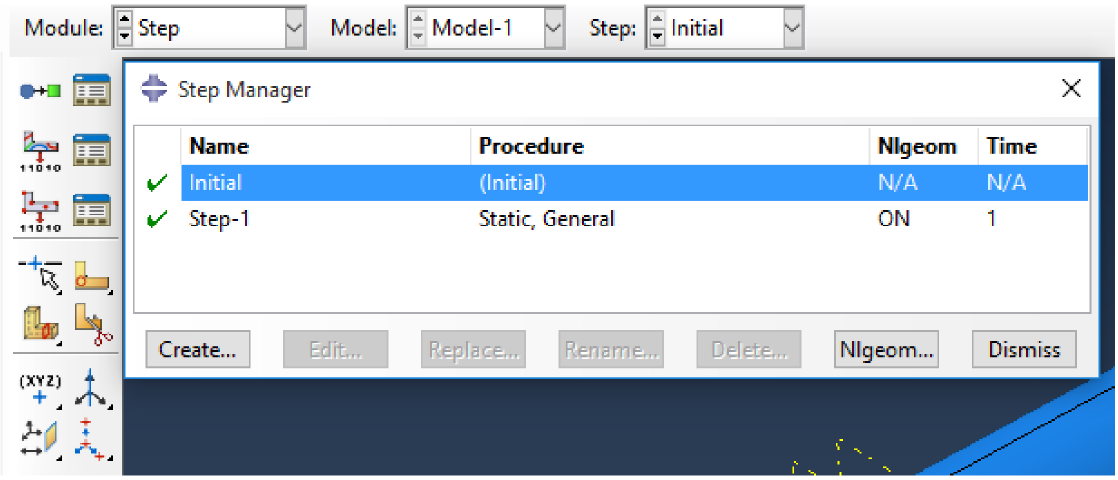


Figure 2.14: Step Module

2.5.2.5. Interaction Module

In the Interaction Module, users define interactions between model components Including contact (surface-to-surface, general, or node-to-surface), constraints (tie, coupling), and connectors (springs, dampers).

Sophisticated algorithms like surface smoothing and contact stabilization can be applied.

2.5.2.6. Load Module

The Load Module provides capabilities to apply external effects to the model, such as forces, pressures, moments, temperatures, prescribed displacements, and electromagnetic fields.

Boundary conditions like fixed supports, symmetry, and roller supports are also defined here.

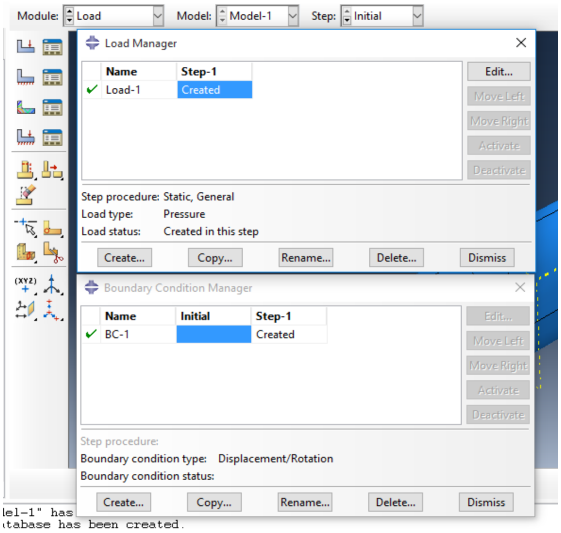


Figure 2.15: Load Module

2.5.2.7. Visualization Module

The Visualization Module (Abaqus/Viewer) offers tools for post-processing analysis results.It provides contour plots, deformed shape visualizations, animations, X–Y plots, and field output reports.

Users can perform operations such as cutting planes, probing results, and calculating derived quantities like reaction forces.

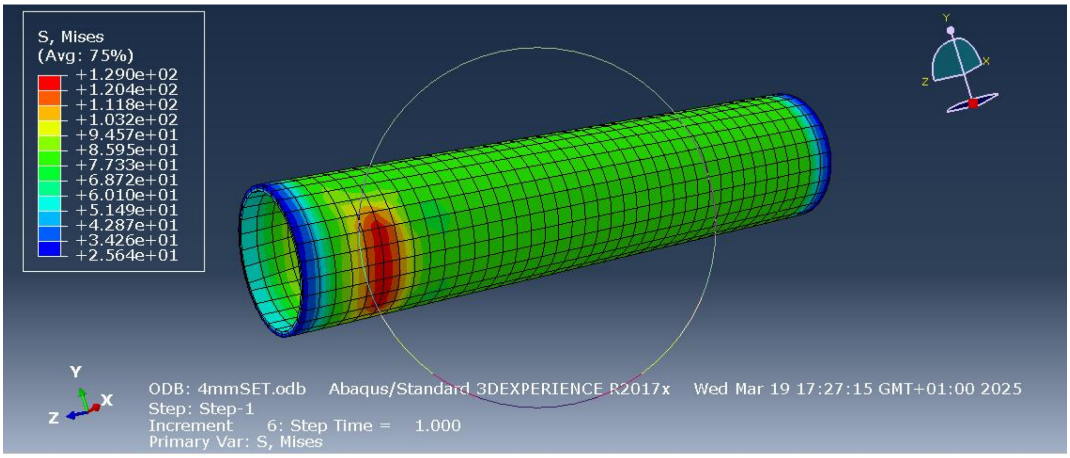


Figure 2.16: Visualization Module

2.5.3. Geometry & Material Definition

The following table shows the parameters used to simulate the corroded part of a pipeline under overpressure.

Table 2.2: Simulation parameters

Parameters	
Material	*API 5L GrB*
External diameter	***219***(mm)
Thickness	***8***(mm)
Length	1000 (mm)
Corrosion section (L*w*t)	143.8*50*6
	143.8*50*4
	143.8*50*2

The API 5L Grade B (GrB) is a type of carbon steel pipe commonly used for oil and gas transmission pipelines. It is classified by a minimum yield strength of 245 MPa (35,500 Psi)(*API 5L Grade B Pipe Specification (PSL1, PSL2, SOUR)*, n.d.).

2.6. Conclusion

This chapter has presented an integrated methodology that combines failure analysis, fault diagnosis, and structural simulation to facilitate a comprehensive investigation of pipeline failures. It began by presenting the case study context and the process of data collection at Hassi R'Mel. The Bowtie Method was then introduced to analyze potential causes and consequences of failures, followed by the implementation of an interval-based PCA approach for effective fault detection and diagnosis. Finally, the use of finite element modelling (FEM) through Abaqus was demonstrated to assess the mechanical behavior of compromised pipeline sections.

Together, these techniques significantly enhance the accuracy of failure prediction and support the development of informed, preventive maintenance strategies. The methodological framework established in this chapter provides a solid foundation for the in-depth analyses, results, and recommendations presented in the chapters that follow.

Chapter 3 : Results and discussion

Chapter 3: results and discussion

3.1. Introduction

This chapter presents the key findings from the analysis of pipeline failures using the structured maintenance methodology introduced in the previous chapter. It applies three complementary approaches, the Bowtie method, Principal Component Analysis (PCA), and finite element analysis using ABAQUS, to a national case: the natural gas pipeline system in the Hassi R'mel region, one of Algeria's most critical energy infrastructures.

The aim of this chapter is to assess the operational condition of the pipeline, identify potential failure scenarios, and demonstrate how data-driven insights combined with failureanalysis can support effective and proactive maintenance decision-making.

3.2. Failure Analysis Using the Bowtie Method

In pipeline infrastructure projects, Bowtie analysis offers a structured approach to link potential causes, through Fault Tree Analysis (FTA), and possible consequences, through Event Tree Analysis (ETA), centered on a critical top event: pipeline failure. This section investigates the primary causes and consequences associated with failure in our case study, aiming to identify key contributing factors and support the development of effective mitigation strategies.

3.2.1. Causes of Pipeline Failure

As the first step in the Bowtie method, we construct a Fault Tree to develop a clear, hierarchical representation of the potential pathways leading to pipeline failure. This approach enables a comprehensive identification and logical organization of root causes. The following figures illustrate the results of the Fault Tree Analysis (FTA).

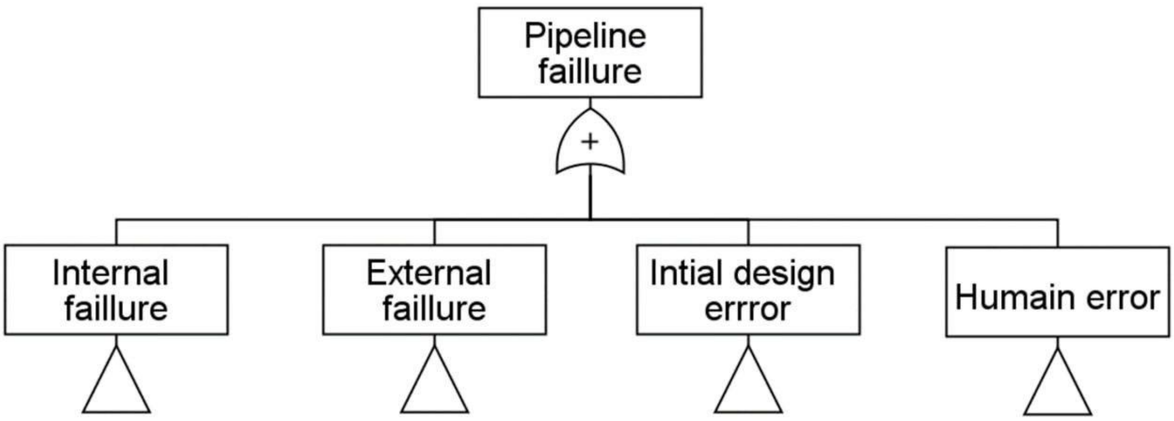


Figure 3.1: Pipeline fault tree analysis diagram

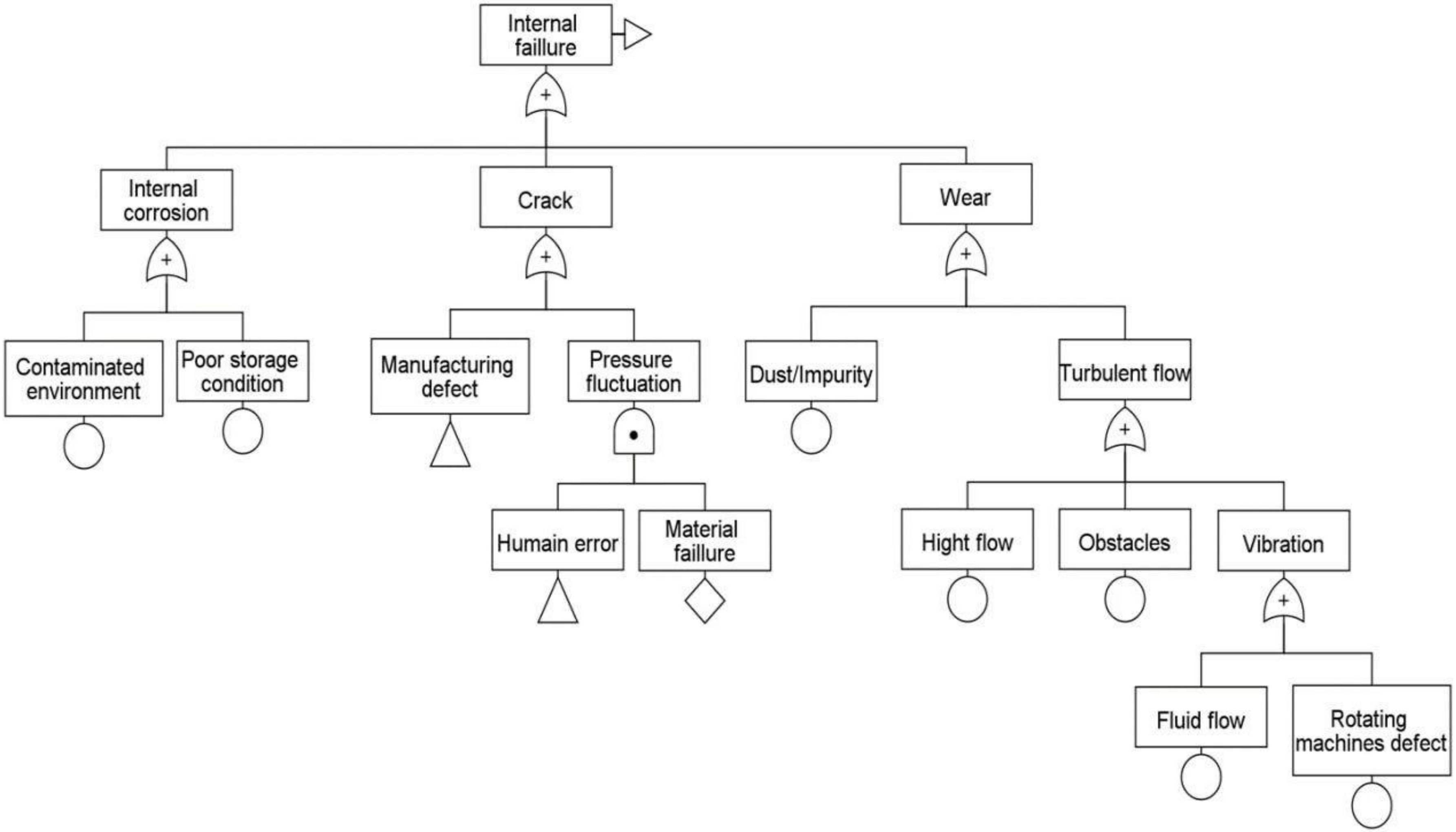


Figure 3.2: Pipeline internal failure fault tree analysis diagram

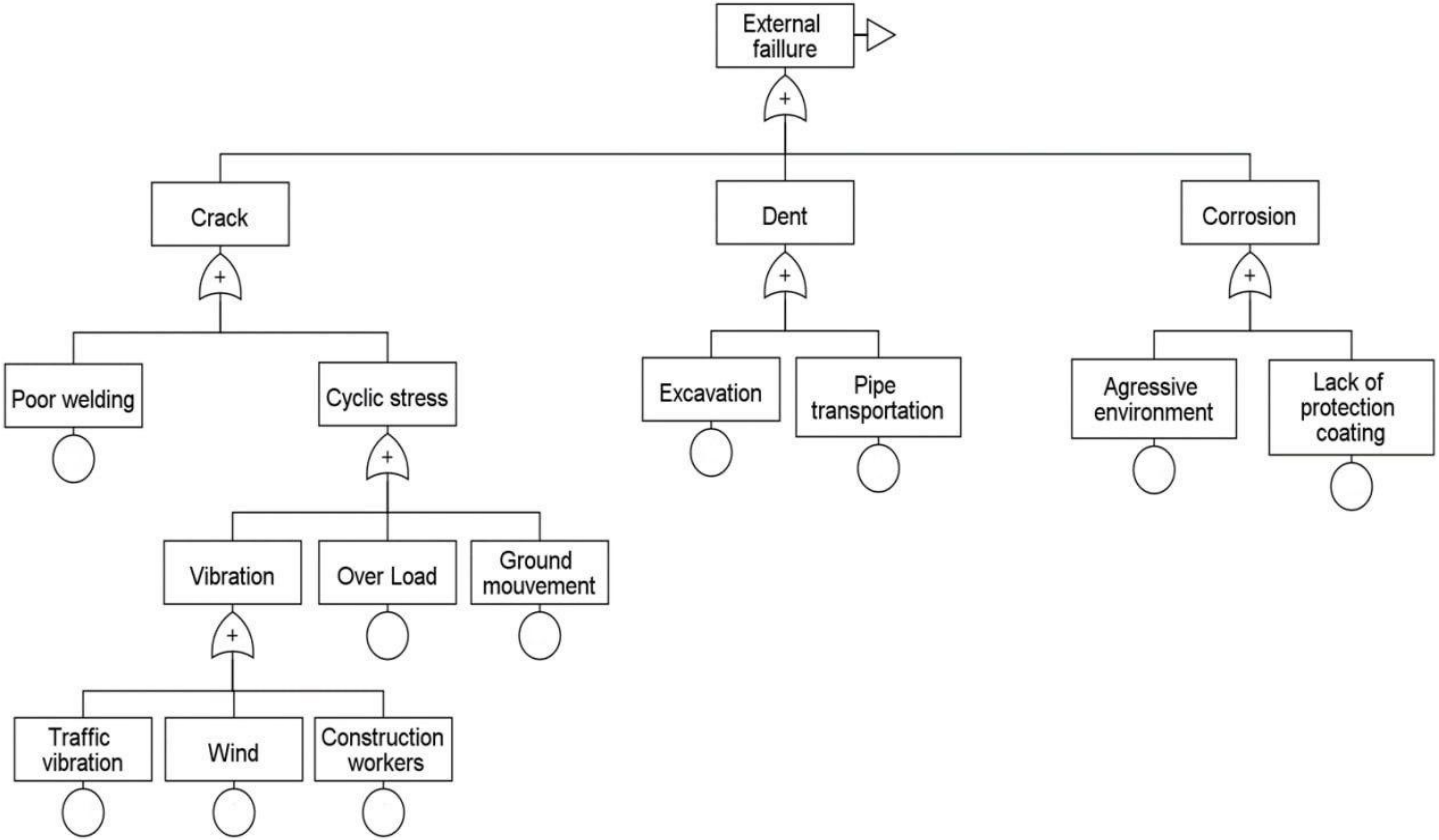


Figure 3.3: Pipeline external failure fault tree analysis diagram

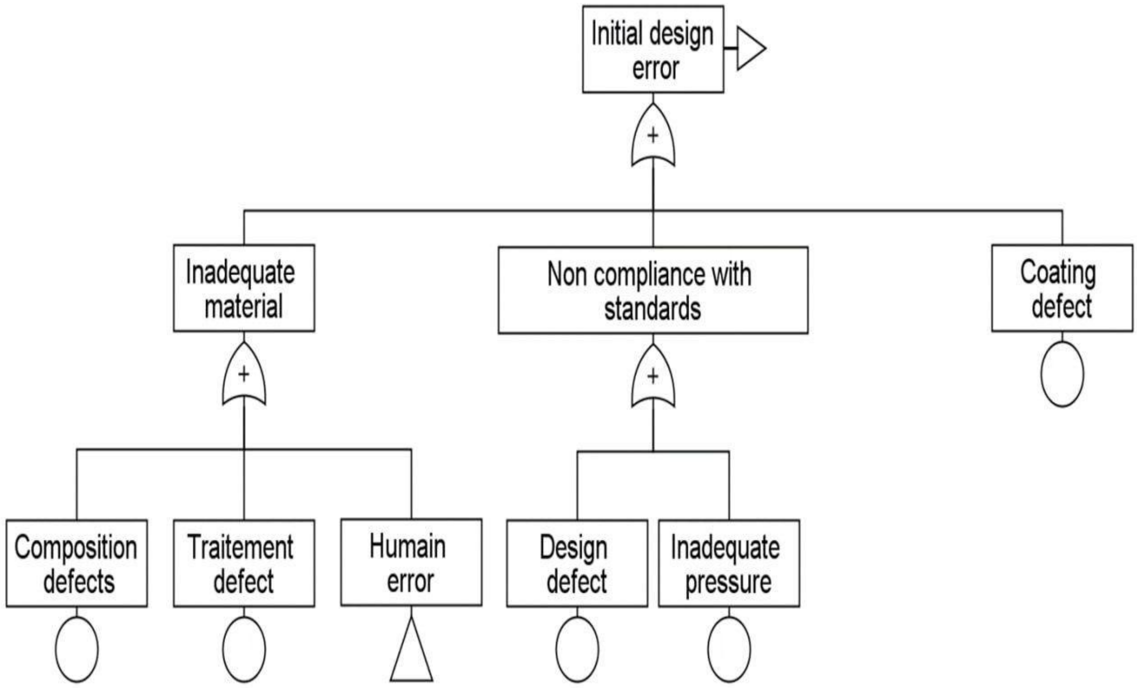


Figure 3.4: Pipeline initial design fault tree analysis diagram

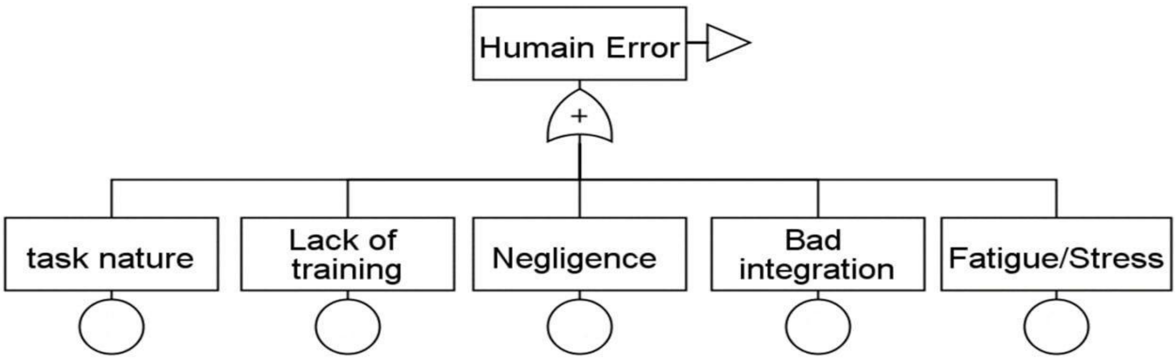


Figure 3.5: Fault tree analysis diagram of the impact of human errors in pipeline failure

The Fault Tree Analysis (FTA) performed in this section provides a systematic breakdown of the primary causes contributing to pipeline failure, classified into internal, external, design-related, and human-induced factors. The hierarchical structure of the diagrams allows for a detailed understanding of the origin and interaction of failure modes:

- **Internal failures** (Figure 3.2) mainly stem from corrosion, crack, and wear due to poor manufacturing defect and fluid properties…
- **External failures** (Figure 3.3) are driven by crack, environmental corrosion, and ground movement.
- **Design flaws** (Figure 3.4) include improper material selection and coating defect...
- **Human errors** (Figure 3.5) are linked to poor training, maintenance lapses, and psychological causes...

3.2.2. Consequences of Pipeline Failure

After identifying and structuring the majority of potential root causes of pipeline failure using FTA, we will move to Event Tree Analysis **(ETA)** to examine the range of possible consequences that may unfold after the failure event to map out the possible consequences that may arise after a pipeline failure has occurred.

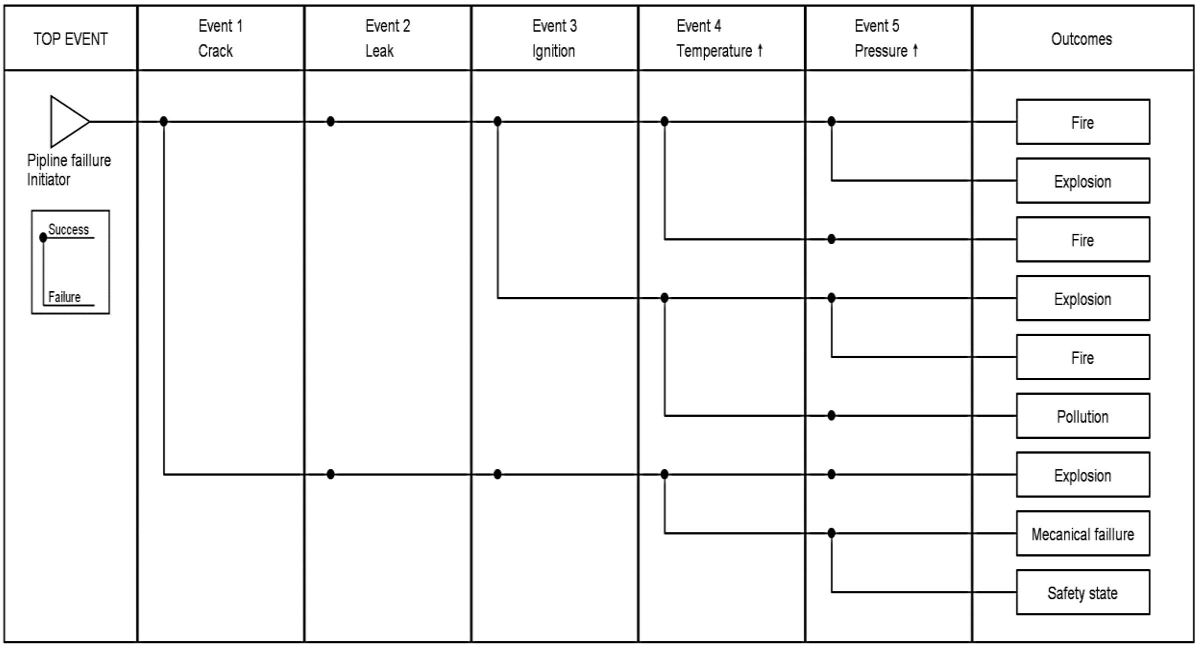


Figure 3.6: Pipeline failure event tree analysis

This event tree clearly outlines the key escalation stages following a pipeline failure (crack, leak, ignition, temperature rise, and pressure increase) to show different combinations of success or failure possible outcomes. By progressing step-by-step from left to right, the diagram makes it easy to see how a small leak that goes undetected can escalate into an ignition and overpressure scenario, or how a prompt detection and valve closure can stop the sequence early and preserve the “safety state”. Essentially, the event tree serves as a simplified roadmap of how failures unfold and the potential consequences, enabling precise identification of where improved detection, isolation, or suppression measures are required.

3.2.3. Preventive and Protective Measures in Pipeline Failure Management

In the context of pipeline integrity management, effective response to failure risks necessitates a dual approach: preventive measures, aimed at avoiding the occurrence of faults, and protective measures, designed to mitigate consequences once a failure has occurred. The following table categorizes key interventions to be implemented before and after fault occurrence:

Table 3.1: Measures proposed to follow before and after fault in a pipeline failure

Preventive Measures	Protective Measures
- Pressure and temperature regular monitoring - Use high-quality materials - Apply proper welding and inspection - Control corrosion - Install pressure relief valves - Flexible joints + early warning systems - Use GIS mapping and ground markings - Apply epoxy coatings, cathodic protection - Implement phased-array ultrasonic testing - Enforce stringent welding standards - Install vibration dampers and conduct regular monitoring	- Emergency shutdown systems - Composite reinforcement sleeves - Rapid isolation valves - Spill containment basins - Explosion-proof enclosures - Water deluge/fire suppression - Emergency venting - Active cooling or heating systems - Pressure relief valves activation

3.3. Fault diagnosis using interval PCA

Following the identification of potential failure scenarios through the Bowtie method, which highlighted the critical need for early anomaly detection and system monitoring, this section presents the diagnostic approach adopted using interval-based Principal Component Analysis (PCA). The objective in this section is to apply PCA to the collected operational data from the case study in order to detect latent anomalies and deviations in key monitoring parameters, such as pressure, temperature, and flow rate, before they evolve into actual faults. This method enables the extraction of underlying patterns from large datasets, even in the presence of uncertainty, offering a robust foundation for predictive maintenance decisions.

3.3.1. Data description

The dataset employed in this analysis comprises sensor readings acquired from the monitoring system of the Station Boosting Centre (SBC), a critical facility within Sonatrach's gas compression and transport infrastructure located in Hassi R'Mel. This station serves as a strategic node responsible for gas collection and pressure augmentation within the national pipeline network. The collected data were sourced from six sensors, categorised into three key operational parameters: pressure, temperature, and flow rate. These parameters are essential for evaluating the dynamic behaviour of the pipeline system and serve as the input variables for the interval PCA diagnostic model. A detailed inventory of these sensors appears in (Table 3.1).

Table 3.2: Used sensors information

Sensors	Sensor's type	Measurement unit
P1SBC2	Output pressure transmitter	Kg/cm^2
P1SBC3	Output pressure transmitter	bar
P2SBC2	Input pressure transmitter	Kg/cm2
P2SBC3	Input pressure transmitter	Kg/cm2
TSBC3	Temperature transmitter	C°
FSBC	Discharge flow transmitter	$MMSM^3/J$

3.3.2. Interval-Based PCA Implementation

After normalizing the interval data, we compute the covariance matrices for both the interval centers and the interval radii, and then extract their eigenvalues and eigenvectors. To construct the PCA model for the process, the next step is to decide how many principal components should be retained.

3.3.3. Selecting the Number of Principal Components

In this step, we determine how many principal components to retain by applying the PCV (Percentage of Cumulative Variance) criterion, as illustrated in the figure below:

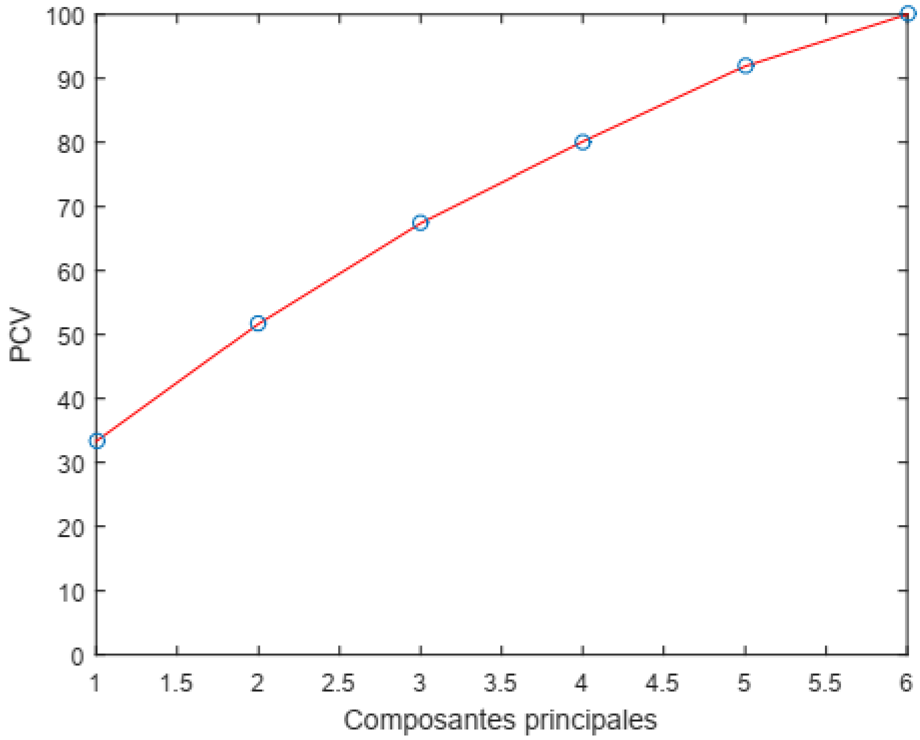


Figure 3.7: Principal Components Retained According to the PCV Criterion

Based on Figure 3.7, five dominant principal components (l = 5) have been retained, representing 95 % of the total variance. This finding highlights the need to focus on the five corresponding sensors to ensure reliable system performance, as they capture the majority of the informational content.

To validate the PCA model, we reconstruct the system's sensor data using these five components and compare the estimates against the original measurements.

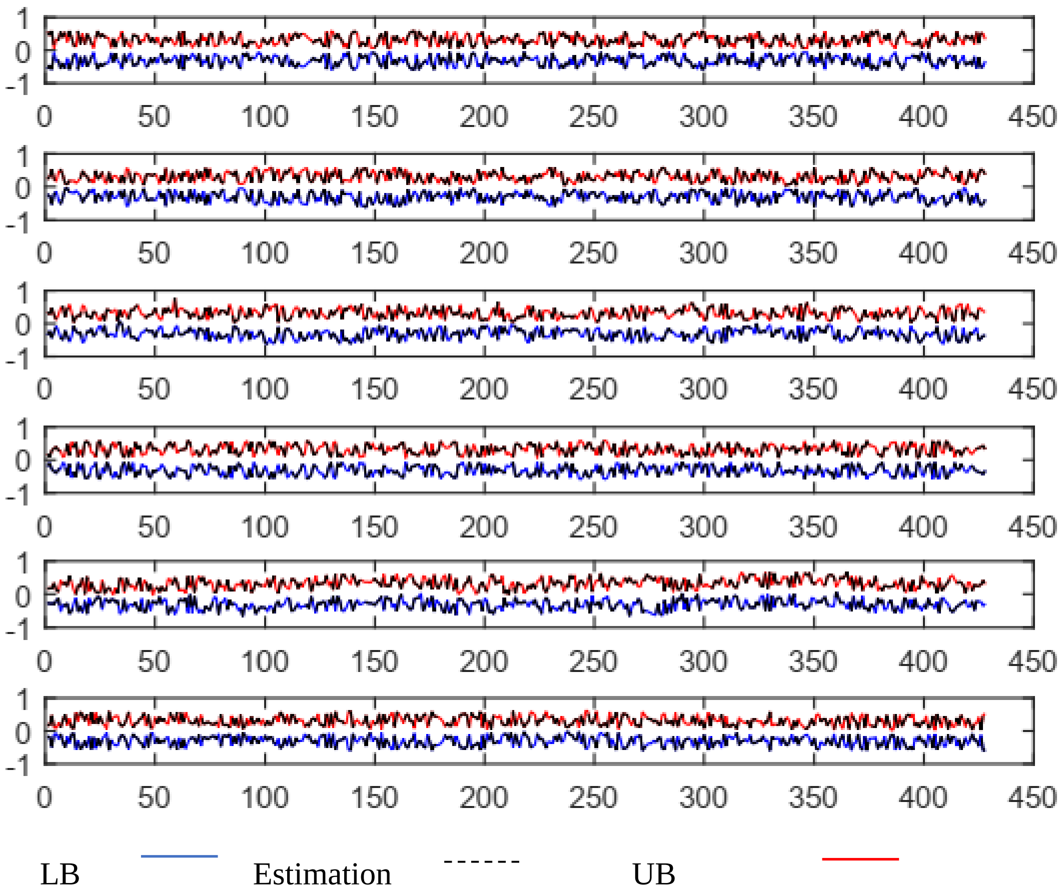


Figure 3.8: Comparison of Estimated versus Measured Data

Figure 3.8, illustrates that the interval-based PCA model delivers an outstanding fit to the data, which validates our choice of principal components. The close alignment between the model's estimates and the original measurements proves that this method effectively captures the system's behavior.

3.3.4. Fault Detection

In the next phase of our study, we compute a statistical fault‑detection index based on our interval PCA model to assess potential defects in the pipeline system. Specifically, we'll use the interval squared prediction error (ISPE). First, we calculate ISPE under healthy operating conditions using the five retained principal components to establish the detection threshold, then we apply the interval PCA model to a dataset that includes two fault scenarios one artificially injected into the data and one arising from an actual control-valve failure in the system.

- **Case 1**: **Fault‑Free System**

Figure 3.9 depicts the ISPE values for the healthy operating condition. These values are calculated using equation (2.25) to establish the 95 % detection threshold. By examining the resulting curves, we can define a clear boundary between normal and abnormal observations, thus enabling reliable identification of defects in the pipeline system.

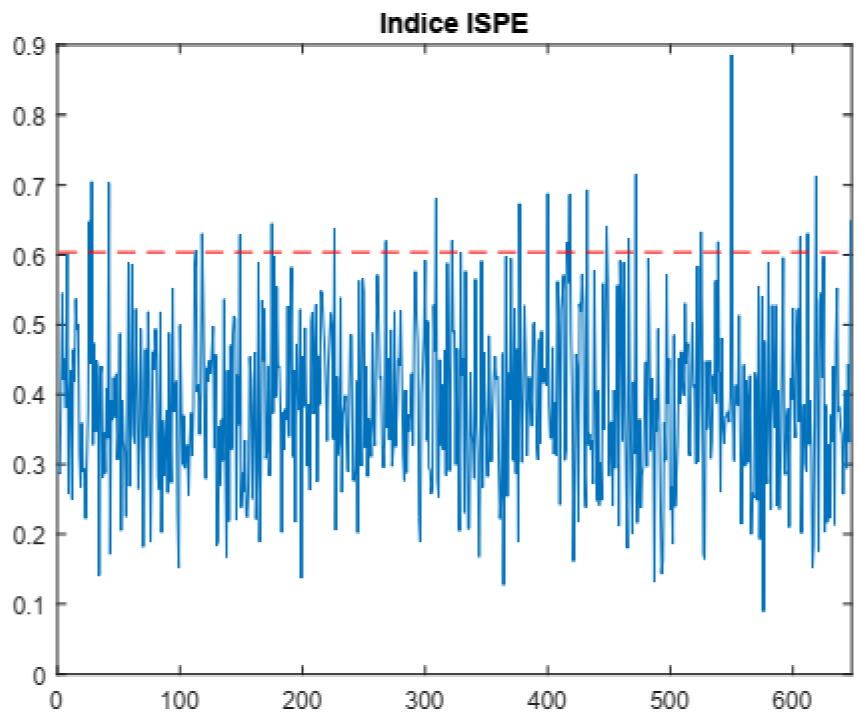


Figure 3.9: Interval-Based ISPE Index under Fault-Free Conditions

Analysis of Figure 3.9, reveals occasional false alarms arising from modeling inaccuracies. These spurious alerts are largely driven by the system's inherent dynamic behavior. It is important to emphasize that these outliers do not indicate actual faults, but rather normal operational fluctuations.

- **Case 2: System with a Fault**

In Case 2, the interval PCA model is applied to a dataset containing two types of faults: one artificially injected, and another resulting from an actual control valve malfunction in the system. The goal is to assess the model's ability to detect both abrupt and evolving anomalies based solely on its statistical reconstruction capabilities.

To evaluate fault occurrence, we compute the Interval Squared Prediction Error (ISPE) and compare the results to the 95 % confidence thresholds established during normal operating conditions. This provides a quantitative measure of how well the current sensor data aligns with the baseline model derived under healthy conditions.

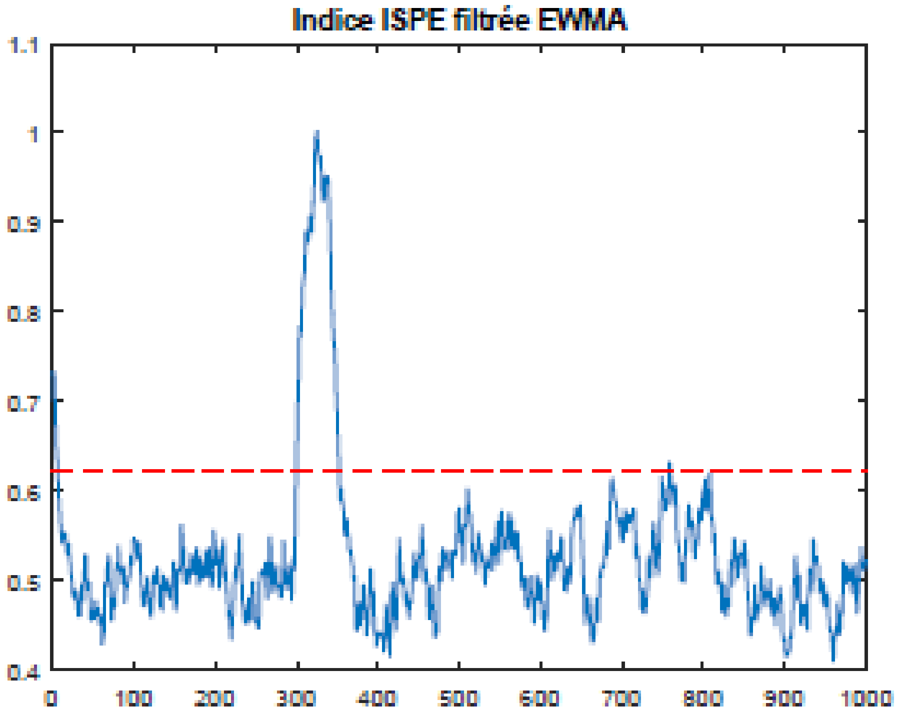


Figure 3.10: ISPE$_f$ Index for a Synthetic Fault Injection

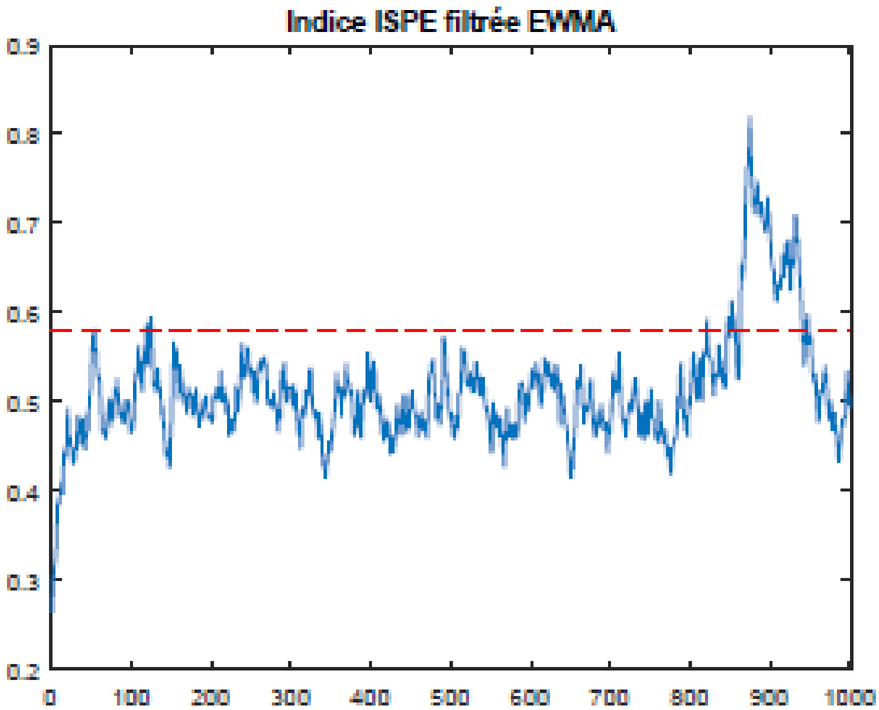


Figure 3.11: ISPE$_f$ Index for an Actual Control-Valve Failure

Figure 3.10 shows the ISPE index for the dataset with a synthetic fault introduced around sample 300. A clear and sharp increase in the ISPE is observed, significantly exceeding the control threshold. This spike highlights the model's high sensitivity to sudden abnormal deviations and confirms its ability to flag short-term disturbances.

Figure 3.11 illustrates the ISPE behavior during a real control valve failure, which begins to manifest around sample 850. In contrast to the synthetic case, the ISPE rises more gradually, indicating a slow-developing fault. Nonetheless, the index clearly breaches the threshold, demonstrating the model's robustness in tracking both abrupt and progressive fault patterns.

These results confirm that the interval PCA model, even without the use of smoothing filters such as EWMA, is capable of accurate and timely fault detection. It successfully distinguishes between normal system variability and abnormal events, making it a reliable tool for early warning diagnostics in pipeline infrastructure monitoring.

3.4. Mechanical Behavior of a Failed Pipeline

In scenarios where monitoring systems fail to detect defects in a pipeline system, it becomes essential to understand the mechanical response of the pipeline under fault conditions. To this end, a numerical simulation was conducted to analyze the effect of overpressure on a corroded section of a natural gas pipeline.

The simulation was carried out using **ABAQUS/CAE**, a leading finite element analysis (FEA) software. This involved the structured application of several modules to build a realistic model of the corroded pipeline segment. The objective was to accurately capture the mechanical and structural behaviors under critical loading conditions, such as internal pressure build-up due to operational faults or delayed detection.

3.4.1. PART Module

In the PART module of ABAQUS/CAE, the geometric representation of the corroded pipeline section was carefully constructed. The corroded zone was modelled to reflect its irregular surface profile and non-uniform wall thickness, accurately simulating real-world material degradation. This geometry was sketched and refined within ABAQUS to enable precise control over critical parameters, such as pipe diameter, wall thickness, and defect morphology (see Figure 3.12).

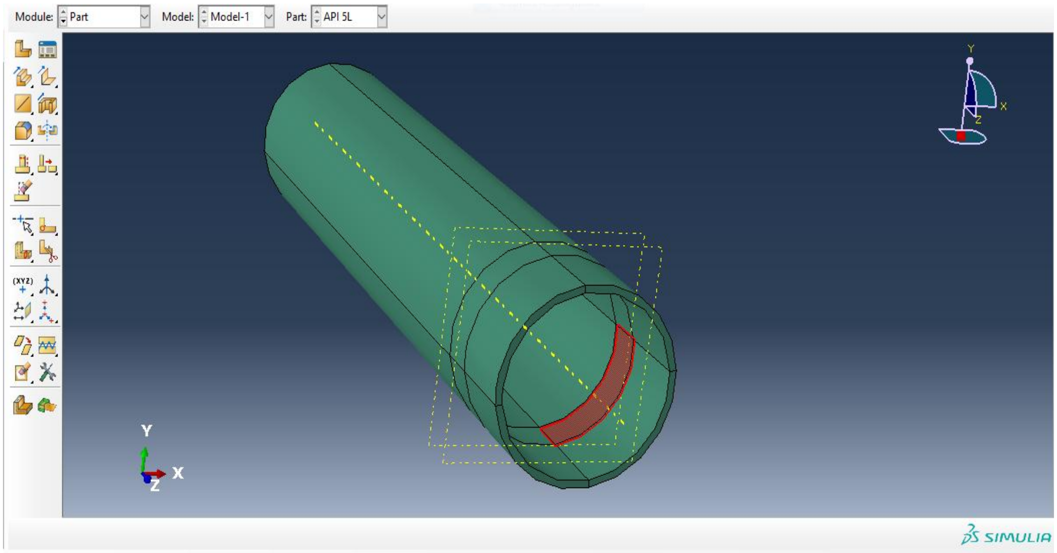


Figure 3.12: Corroded pipe modelled in the Part module

3.4.2. PROPERTY Module

Within the PROPERTY module, the material characteristics of the pipeline were defined. This included specifying the mechanical properties such as Young's modulus, Poisson's ratio, and yield strength of the steel, as well as any adjustments for material degradation due to corrosion. These properties were very important for capturing the stress-strain response of the corroded metal under simulated overpressure conditions (see Figure 3.13).

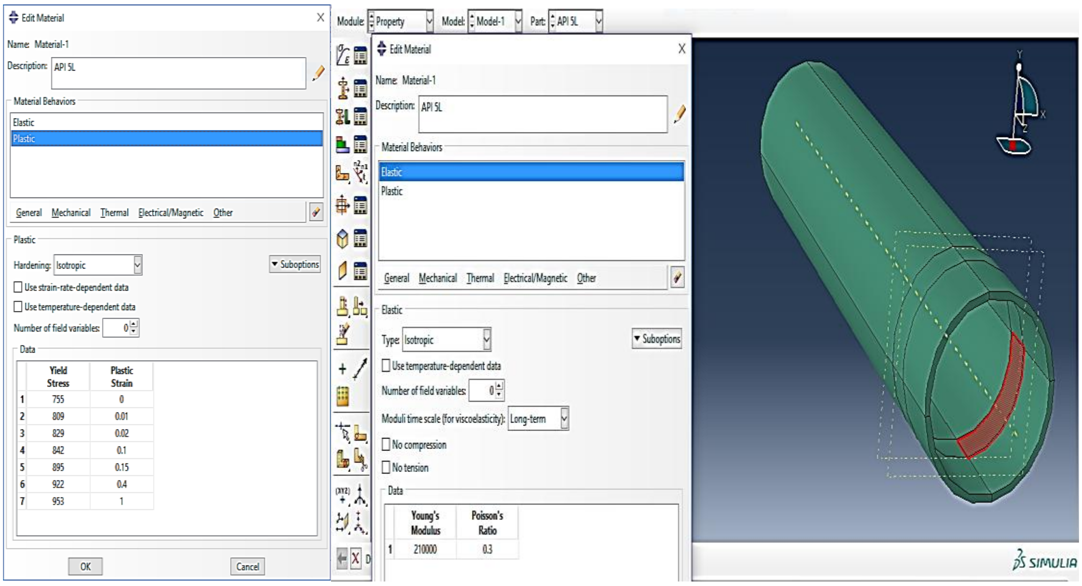


Figure 3.13: Model's mechanical properties

3.4.3. LOAD Module

The LOAD module was employed to define the boundary conditions and applied loads that replicate realistic operational and failure scenarios. Internal pressure was applied uniformly along the inner surface of the pipeline to simulate overpressure conditions, representing potential extreme events that could compromise the structural integrity of the corroded section (see Figure 3.14).

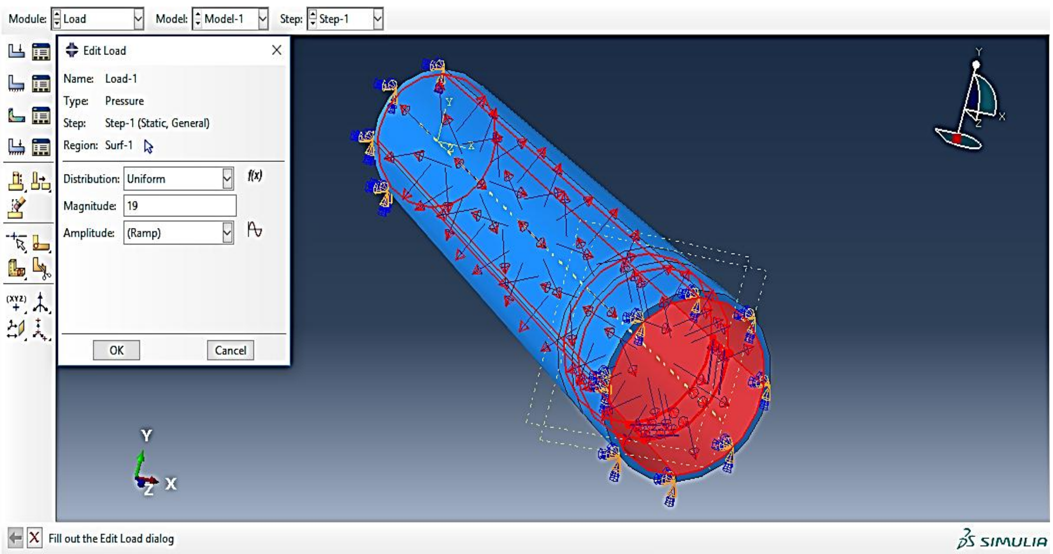


Figure 3.14: Applied boundary conditions

3.4.4. MESH Module

In the MESH module, a structured meshing strategy was implemented to enhance the accuracy of stress and deformation predictions in the corroded area. Fine mesh elements were concentrated around the corroded region to capture localized stress concentrations (see Figure 3.15).

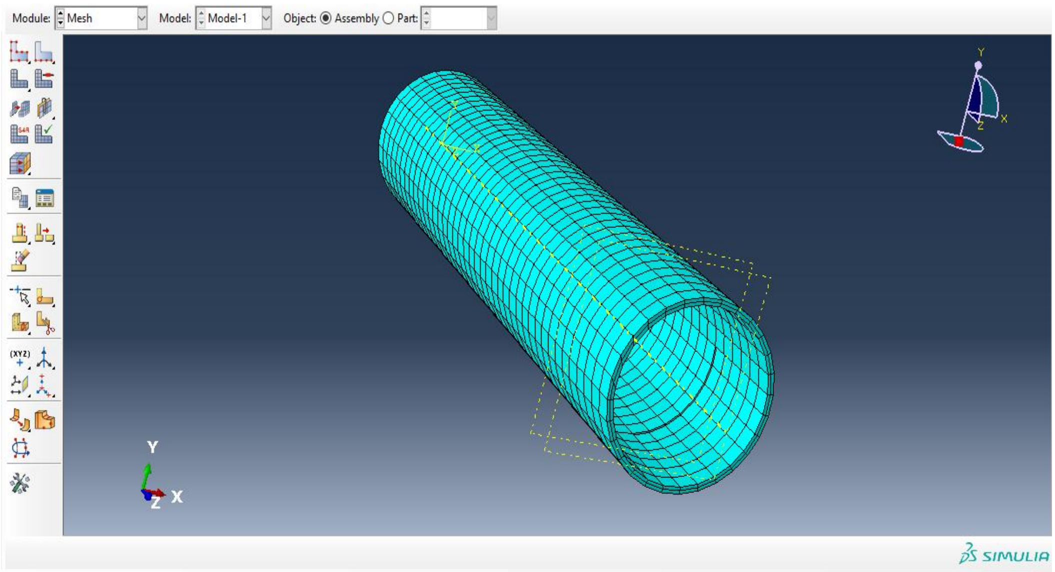


Figure 3.15: Meshing of the parts

3.4.5. Numerical Results

- **Stress and strain investigation**

The primary goal of the simulation was to investigate the behavior of a corroded pipeline segment under overpressure. Post-processing the ABAQUS output revealed that both stress and deformation peaked in the most highly loaded region precisely where the corrosion defect is located. These maximum values are clearly illustrated in Figures 3.16 and 3.17, highlighting the critical vulnerability of the corroded section under excessive internal pressure.

These results correspond to an internal pressure of 19 MPa applied to a pipeline segment featuring a 6 mm wall thickness at the corroded region.

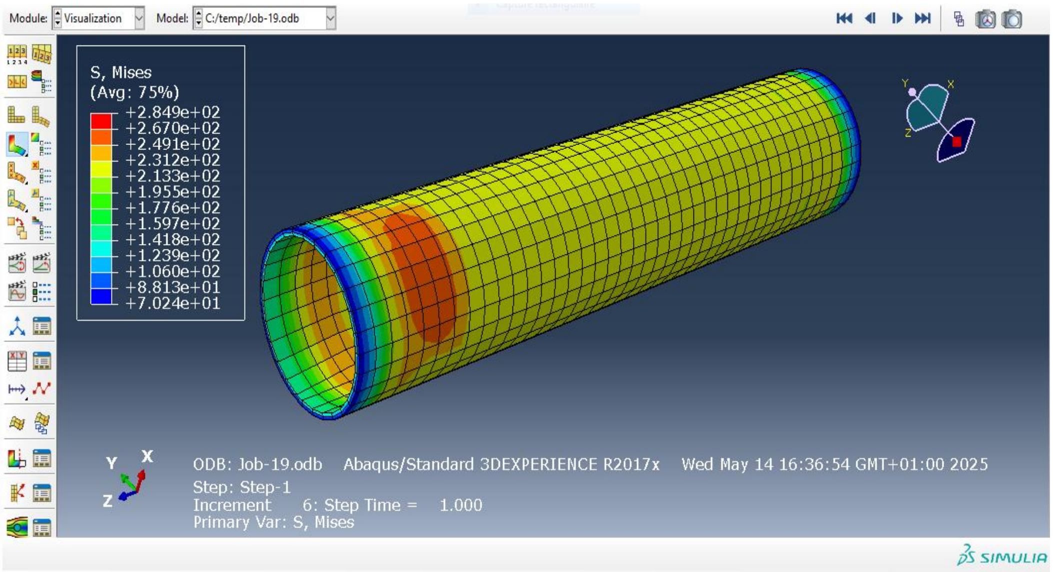


Figure 3.16: Visualization of stresses

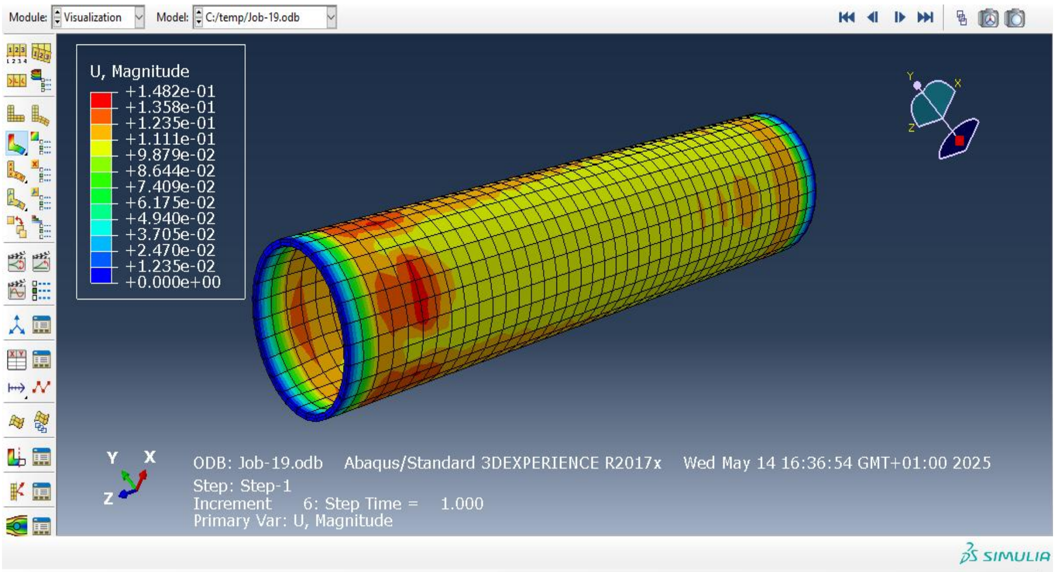


Figure 3.17: Visualization of displacements

According to the simulation results, the maximum stress value observed was 284.90 N/mm² (Figure 3.16), which remains below the material's yield strength. This suggests that the pipeline material is approaching the plastic deformation domain, though it still operates within the elastic limit. Regarding displacement (Figure 3.17), the deformation was found to be in the order of millimeters, which is consistent with the expected elastic response under the given loading conditions.

- **Variation investigation**

To assess the worst-case scenarios and enhance the robustness of our analysis, a parametric study was conducted. This involved systematically varying two key parameters:

- Internal pressure, from nominal levels up to extreme overpressure values;
- Residual wall thickness, to reflect progressive corrosion and material loss.

Each simulation case was designed to represent increasingly severe corrosion states, and the resulting maximum stress and displacement values were recorded. The numerical results are summarized in Table 3.3 and illustrated graphically in Figure 3.18 and Figure 3.19.

Table 3.3: Effect of Internal Pressure and Corrosion-Induced Wall Loss on Stress and Displacement in an 8 mm Pipeline

Pressure (MPA)	Corrosion-affected area thickness (mm)	Von Mises stress MAX (MPA)	Displacement (mm)
2	6	58.63	0.045
	4	36.86	0.023
	2	30.10	0.015
4	6	117.2	0.090
	4	73.72	0.047
	2	60.18	0.031
7	6	205.1	0.16
	4	129	0.083
	2	105.2	0.055
9	6	263.6	0.202
	4	165.9	0.106
	2	135.2	0.070
11	6	322.0	0.246
	4	202.8	0.129
	2	165.2	0.085
14	6	407.9	0.313
	4	258.2	0.164
	2	210.1	0.109
19	6	555.6	0.422
	4	350.4	0.223
	2	284.9	0.148

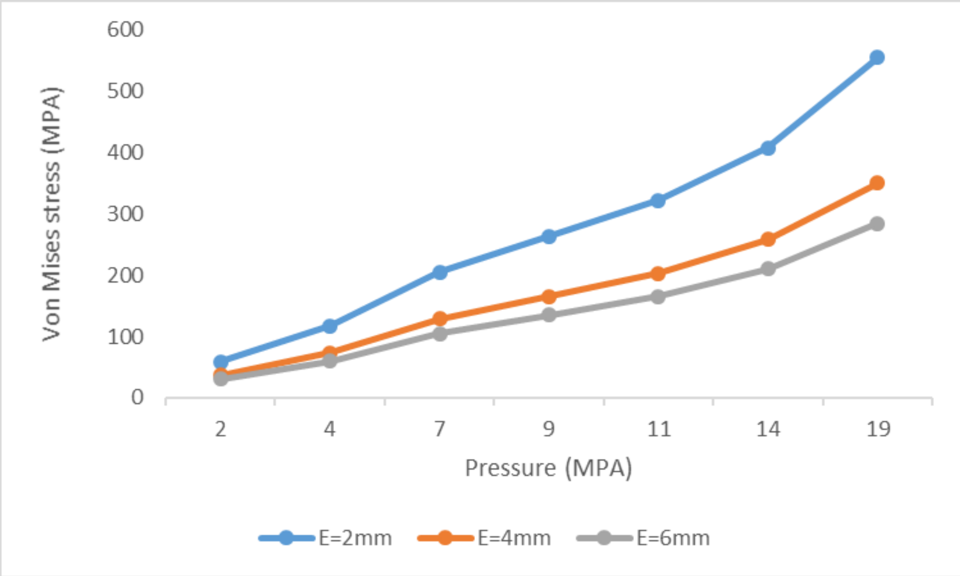


Figure 3.18: Von Mises Stress Distribution

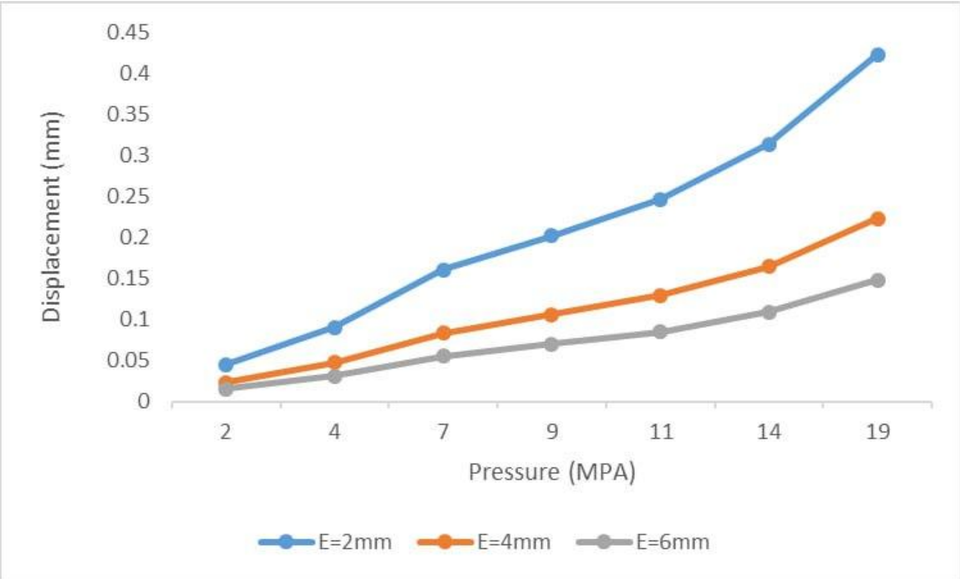


Figure 3.19: displacement Distribution

The results presented in Table 3.3, Figure 3.18 and Figure 3.19 clearly demonstrate that the structural integrity of a corroded pipeline is highly sensitive to both internal pressure and the remaining wall thickness at the corrosion site. As pressure increases, the von Mises stress and displacement values rise significantly, especially in areas where wall thickness has been reduced. For example, at 19 MPa, a wall thickness of 6 mm leads to a maximum stress of 555.6 MPa and a displacement of 0.422 mm, while the same pressure applied to a 2 mm section results in a stress of 284.9 MPa and a displacement of 0.148 mm. Although the stress is lower for the thinner wall, it approaches the material's yield strength, indicating a high risk of failure. These results highlight the dangerous amplification of stress due to corrosion-induced thinning and underscore the importance of maintaining sufficient wall thickness (typically above 4 mm) to ensure mechanical stability under high-pressure conditions. The findings confirm the need for rigorous monitoring and timely intervention in corroded zones to prevent structural failure.

3.1 Conclusion

This chapter demonstrated a comprehensive, multi-method analysis of pipeline failure mechanisms within the natural gas network of the Hassi R'Mel region, integrating fault diagnosis and mechanical behavior simulations.

Overall, the chapter underscores the value of integrating diagnostic analytics with mechanical modelling to support intelligent maintenance strategies. This approach provides a holistic framework for predicting failures, optimizing intervention, and enhancing the safety and reliability of gas pipeline systems.

General Conclusion

General Conclusion

This thesis has explored the application of data-driven approaches to Condition-Based Maintenance (CBM) in Liquefied Natural Gas (LNG) transport systems, with a particular emphasis on the pipeline network of the Hassi R'mel field in Algeria. These pipelines, which form a cornerstone of the nation's energy infrastructure, are continuously exposed to various forms of degradation that pose substantial operational and safety challenges. Current limitations in traditional monitoring techniques further highlight the pressing need for more intelligent and adaptive maintenance strategies.

To address this, we have proposed and implemented an integrated intelligent maintenance methodology designed to enhance the reliability and resilience of natural gas pipelines. Our approach brings together three complementary pillars: structured failure analysis using the Bowtie method, fault detection via interval-based Principal Component Analysis (PCA), and detailed mechanical simulation using the ABAQUS software suite.

The Bowtie methodology offered a clear and systematic way to identify the root causes and consequences of pipeline failures, leveraging both Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). This enabled the mapping of escalation scenarios and the evaluation of existing safety barriers, providing vital insight into where intervention is most effective.

The interval PCA model demonstrated its robustness in detecting system anomalies by analyzing multi-dimensional sensor data, successfully differentiating between normal fluctuations and both sudden and progressive faults. This data-driven diagnostic tool proved instrumental in facilitating early fault detection, which is essential for reducing the likelihood of severe incidents and costly downtime.

In parallel, finite element simulations using ABAQUS enabled a detailed examination of the mechanical behavior of corroded pipeline sections subjected to varying internal pressure levels. The findings revealed that wall thinning caused by corrosion significantly amplifies localized stress concentrations, especially under elevated pressure conditions. These results underscore the critical need for continuous and precise monitoring of internal pressure as a primary indicator of pipeline integrity. Accurate pressure surveillance, combined with material degradation assessments, is essential not only for detecting early signs of structural vulnerability but also for triggering timely maintenance interventions. Such measures are vital to prevent the escalation of minor defects into catastrophic failures.

Together, these methodologies constitute a robust and scalable framework for predictive maintenance. By integrating real-time monitoring, anomaly detection, and structural analysis, the proposed approach empowers decision-makers to anticipate failures and risks, optimise intervention strategies, and allocate maintenance resources more effectively. This not only improves safety and system reliability but also contributes to environmental protection and cost-efficiency.

Looking ahead, this work lays the foundation for further research into digital twin technologies, AI-enhanced diagnostics, and the extension of this methodology to other sectors reliant on high-risk, high-value infrastructure.

Bibliography

Bibliography

A. Bouziane. (2008). *Contribution à la détermination des critères de qualité des tubes soudes soumis à une pression intérieure* [Thèse de Doctorat]. Université de Boumerdes.

A. de Ruijter & F. Guldenmund. (2016). The bowtie method: A review,. *Safety Science*, *88*, 211–218.

A. Hart. (2014). Journal of Petroleum Exploration and Production Technology. *A Review of Technologies for Transporting Heavy Crude Oil and Bitumen via Pipelines*, *4*(3), 233–241.

A. Saniere, I. Hénaut, & J. F. Argillier. (2004). Oil & Gas Science and Technology – Revue d'IFP Energies nouvelles. *Pipeline Transportation of Heavy Oils, a Strategic, Economic and Technological Challenge*, *59*(5), 455–466.

Abdelkader KESSAB & Nour El Houda MOKTAR. (2020). *Corrosion des pipelines: Applications au tronçon Haoud ElHamra*. Université Abdelhamid Ibn Badis Mostaganem.

AFNOR. (n.d.). *NFX60-010 Maintenance—Concepts et définitions des activités de maintenance*. Afnor EDITIONS. Retrieved May 19, 2023, from https://www.boutique.afnor.org/fr-fr/norme/x60010/maintenance-concepts-et-definitions-des-activites-de-maintenance/fa039463/56989

Ait Izem Tarek. (2018). *Diagnosis of Uncertain Systems using Principal Component Analysis* [These de doctorat]. UNIVERSITE BADJI MOKHTAR ANNABA.

Amel, H., & Dhaker Ellah, H. (2022, December). *Maintenance conditionnelle basé sur l'analyse vibratoire d'un compresseur axial*. the 2nd National Symposium on Process Safety and Sustainable Development, oran.

API 5L Grade B Pipe Specification (PSL1, PSL2, SOUR). (n.d.). https://www.octalsteel.com/resources/api-5l-grade-b-pipe/

B. S. Dhillon. (2006). *Maintainability, Maintenance, and Reliability for Engineers*.

Belkhamgani Mohamed Amine & Bendehnoun Khalil. (2018). *Evaluation de la réparation Par composite d'une pipe soumise à un chargement de pression* [Mémoire de master en Génie Mécanique, option : Energétique]. Universitaire d'Ain-Temouchent.

Benslim, M. (2021). *Data driven approach for photovoltaic shading fault detection*. UNIVERSITE BADJI MOKHTAR ANNABA.

BSI, BS 3811:1984 – Glossary of Maintenance Management Terms in Terotechnology. (1984).

C. Alexander & K. Brownlee. (2007, Nashville, Tennessee). Methodology for Assessing the Effects of Plain Dents, Wrinkle Bends, and Mechanical Damage on Pipeline Integrity. *Proceedings of the NACE International Corrosion 2007*.

Cécil, A. (n.d.). *L'inspection des pipelines par racleurs instrumentés*. Société du Pipeline Méditerranée-Rhône.

Dassault Systèmes. (2025). *Abaqus Documentation. Dassault Systèmes*.

Dhaker Ellah, H. (2022). *Etude du comportement mécanique en flexion 3 points de deux composites stratifiés Verre/Epoxy [04] et [0/902/0]* [Memoire de master]. BADJI-MOKHTAR-ANNABA UNIVERSITY.

DJ Smith. (2021). *Reliability, Maintainability and Risk: Practical Methods for Engineers, 9th ed.*

DJAARIRI, A., & BAKHOUCHE, O. (2024). *Analyse du comportement mécanique des matériaux composites* [Memoire de master]. ABBES LAGHROUR university.

Djamel, K., & Kahina, L. (2011). *Modélisation séquentiel et conception d'une solution de supervision de la séquence de lancement du turbo compresseur de la station Boosting de SONATRACH à HASSI R'MEL* [PhD Thesis, Université Mouloud Mammeri]. https://www.ummto.dz/dspace/bitstream/ummto/7994/1/KoufiDjamel.pdf

E. A. Yatsenko, W. Li, A. I. Izvarin, & B. M. Goltsman. (2024). Review of protective coatings for pipelines. *International Journal of Hydrogen Energy*, *50*(09), 4802–4818.

E. Casas, L. Ramos, C. Romero, & F. Rivas. (2024). A review of computer vision applications for asset inspection in the oil and gas Industry. *Journal of Pipeline Science and Engineering, Art, 100246*.

Erik Hupjé. (n.d.). *9 Types of maintenance: How to choose the right maintenance strategy*. Reliability Academy.

ETIEVANT, C., LECHEVALIER, S., BELHAMEL, M., MAHMAH, B., CHADER, S., M'RAOUI, A., & HAROUADI, F. (2007). PROJET MAGHREB–EUROPE: PRODUCTION D'HYDROGENE SOLAIRE PHASE I: ETUDE D'OPPORTUNITE ET DE FAISABILITE DU PROJET. *2nd International Workshop Hydrogen*, 27–29. https://www.cder.dz/wih2/communication/c02.pdf

F. B. Azevedo, C. Gudme, & E. Nunes. (2024). Pipeline Coatings. In *Handbook of Pipeline Engineering, Springer*.

Ferhat Amhis. (2011). *Étude et simulation de DCS I /A Séries de FOXBORO sur le four rebouilleur H101* [Mémoire de Fin d'Etudes En vue de l'obtention du diplôme D'Ingénieur d'Etat en Automatique]. Université Mouloud MAMMERI, Tizi-Ouzou.

François, M., & Claude, K. (2019). *Maintenance, Outils, méthodes et organisations efficientes* (5e ed.). Dunod.

Frédéric Élie. (2022, December). *Les hydrocarbures*. 13.

Guellal Z'hor & Gaci Yacine. (2016). *Optimisation du transport de gaz naturel Par Le Gazoduc GZ1 Hassi R'mel-Arzew TRC-SONATRACH: Recherche Opérationnelle et Mathématique de gestion (ROMAG*. Université de Boumerde.

H. Amel & H. Dhaker Ellah. (2022). *Maintenance conditionnelle basé sur l'analyse vibratoire d'un compresseur axial* [Présenté à the 2nd National Symposium on Process Safety and Sustainable Developmen].

Hammouya, A. (2021). *Contribution à l'amélioration des barrières de sécurité dans un système industriel*. badji mokhtar annaba university.

HAMMOUYA, A. (2023). *Contribution au diagnostic des défauts d'un système industriel (gazoduc Berrahal)*. BADJI-MOKHTAR-ANNABA UNIVERSITY.

Hammouya, A. (2025). *ANALYSE ENVIRONNEMENTALE ET SÉCURITAIRE DES RISQUES LIÉS AU REJET D'HYDROCARBURES : IMPACTS ET PRÉVENTION*. THE THIRD

INTERNATIONAL CONFERENCE ON MATERIALS, ENERGY & ENVIRONMENT (MEE-2025), El Oued.

HAMMOUYA, A., CHAIB, R., VERZEA, I., & HAMMOUYA, D. E. (2021). STUDY OF THE HUMAN WHOLE-BODY VIBRATION TRANSMISSION (CASE STUDY). *ACTA TECHNICA NAPOCENSIS - Series: APPLIED MATHEMATICS, MECHANICS, and ENGINEERING*, *64*(2). https://atna-mam.utcluj.ro/index.php/Acta/article/view/1604

HAMMOUYA, A., REDJIL, A., BENHAMLAOUI, W., & CHAIB, R. (2025a). *Advanced Engineering Approach to Analyse Pipeline Failure Consequences*. The IV. International Van Scientific Research Congress(ASES CONGRESS'25), turkie.

HAMMOUYA, A., REDJIL, A., BENHAMLAOUI, W., & CHAIB, R. (2025b). *Contribution to the study of environmental risks associated with pipeline failures*. THE THIRD INTERNATIONAL CONFERENCE ON MATERIALS, ENERGY & ENVIRONMENT (MEE-2025), El Oued.

H.P.Bloch & Geitner.F.K. (2012, January). *Machinery Failure Analysis and Troubleshooting*.

Hulkak. (1997). *High strength large diameter pipe plate from standard production to X80/X100.* (Niobuim information 13/1997). CBMM/NPC.

I. Setiawan, A. Bahrudin, M. M. Arifin, W. I. Fipiana, & V. Lusia. (2021). Analysis of preventive maintenance and breakdown maintenance on production achievement in the food seasoning industry. *OPSI*, *14*(2), 253–261.

I. Zakharova. (2024). Welding processes in the restoration of industrial and energy facilities," Machinery & Energetics. *Machinery & Energetics*, *15*(1), 56–64.

ISMAIL BIN ISMAYATIM. (2009). *Finite Element Analysis of Corroded Pipelines* [Dissertation submitted in partial fulfillment of the requirements for the Bachelor of Engineering (Hons)]. Universiti Teknologi PETRONAS.

J. A. Kehr. (2003). Rehabilitation of Pipeline Coatings Can Reduce Cost and Risk. *3M, USA*.

J. A. Smith. (2018). *Field Application and Challenges of Cathodic Protection in Buried Pipelines* [Ph.D. dissertation, Dept. Eng]. Univ. Manchester.

J. E. Naranjo, G. Caiza, R. Velastegui, & M. Castro. (2022). *A scoping review of pipeline maintenance methodologies based on industry 4.0* (Vol. 14).

J. F. Kiefner & M. J. Rosenfeld. (2012). *Spiral-Welded Pipe Manufacturing Process, in Oil and Gas Pipelines: Integrity and Safety Handbook* (1st ed).

Julien CAPELLE. (2008). *Étude de la nocivité d''un défaut de type éraflure sur une conduite destinée au transport de gaz naturel soumise à une pression d''hydrogène* [Thèse de Doctorat]. Université Paul Verlaine de Metz.

K. H. Dhandha, A. D. Bhathena, & M. Ghosh. (2011). Fabrication and NDT Requirements for Pressure Vessel, Boiler, Piping, Structure & Nuclear Component Manufacturing with Respect to Various Codes & Standards. *In Proceedings of the NDE India Conference*.

K. S. Trivedi & A. Bobbio. (2017). *Reliability and Availability Engineering: Modeling, Analysis, and Applications* (Cham, Switzerland).

Khan, F., Thodi, Thodi, P, Imtiaz, S, & Abbassi, R. (n.d.). *Real-time monitoring and management of offshore process system integrity* [Current Opinion in Chemical Engineering].

K.-J. Bathe. (2014). *Finite Element Procedures, 2nd ed.*

M. Achouch, M. Dimitrova, & K. Ziane. (n.d.). *On predictive maintenance in industry 4.0: Overview, models, and challenges*. *12*(16), 2022.

M. Askari, M. Aliofkhazraei, & S. Afroukhteh. (2019, November). Journal of Natural Gas Science and Engineering. *A Comprehensive Review on Internal Corrosion and Cracking of Oil and Gas Pipelines*, *71*, 102971.

M. Elboujdaini & R. W. Revie. (2020). Advances in Cathodic Protection Monitoring. *Materials Performance*, *59*(4), 34–39.

M. H. Hayes. (2004, May). Algerian Gas to Europe: The Transmed Pipeline and Early Spanish Gas Import Projects. Working Paper #27. *Geopolitics of Natural Gas Study*, 9‑11.

M. Nahal. (2016). *Etude mecano-fiabiliste des pipelines destines aux hydrocarbures* [Thèse de Doctorat]. Université Badji Mokhtar–Annaba.

M. Omidvar, E. Zarei, B. Ramavandi, & M. Yazdi. (2022). Linguistic Methods Under Risky and Uncertain Conditions. *Fuzzy Bow-Tie Analysis: Concepts, Review, and Application*, 27–48.

M. Sambasivan & S. Gopal. (2018). *Handbook of Oil and Gas Piping: A Practical and Comprehensive Guide*. Taylor & Francis.

Marvin Rausand. (n.d.). *Chapters 3 and 4 Fault Tree Analysis*. RAMS Group Department of Production and ality Engineering NTNU.

Mechernene .A. (2013). *Étude du comportement en fatigue des aciers pour pipelines* [Mémoire de master, option: ingénierie des systèmes mécanique productiques]. université de Tlemcen.

Mekideche, M. (2008). *Le secteur des hydrocarbures en Algérie (1958-2008): Problématiques, enjeux et stratégies.*

MINISTERE DE L'ENERGIE. (2018). *BILAN DES REALISATIONS DU SECTEUR DE l'ENERGIE ANNEE 2018*.

M. Lassoued, R. Ben Khalifa, N. Ben Yahia, & A. Zghal. (2017, November). Contribution de la classification des défauts de soudage semi‑automatique par un système neuronal. *Conference Paper*.

M.RAMDANI. (2008). *Etude mécano fiabiliste sur le comportement en corrosion localisée des aciers API -5L- X60 pour pipeline: Modèle basé sur la ténacité* [Thèse de magister en génie mécanique option : science des matériaux]. Université ABOU BEKR BELKAID Tlemcen.

N. Terrier. (2001). *Maintenance systématique* [M.S. thesis]. Univ. Angers, Angers, France.

Nekkaa Bahria. (2019). *Réparation d'un gazoduc corrodé par un système composite stratifié* [Thèse doctorat, Option : Construction]. université d'Oran.

Oumechouk, H. T. (2012). *Modélisation et performances d'un gazoduc algérien évaluées avec l'équation de SOAVE-REDLICH-KWONG* [PhD Thesis, Ecole Nationale Polytechnique]. https://www.pnst.cerist.dz/detail.php?id=74310/

Rapport d'activité de la direction d'exploitation. (2007). région HASSI R'mel.

Rapport d'activité des operateurs, module IV HASSI R'mel. (2006).

S. Benmoussa. (2013). *Approche Bond Graph pour la détectabilité et l'isolabilité algébriques de défauts composants* [These de doctorat]. L'université Lille 1.

S. Hansson & M. Fisk. (2010). Simulations and measurements of combined induction heating and extrusion processes. *Finite Elements in Analysis and Design*, *46*(10), 875–885.

S. Kumar, R. Gupta, & A. Singh. (2022). *Advanced Monitoring Techniques for Predictive Maintenance in Industrial Applications*.

Sabará, M. A, Ponciano Gomes, J. A. da C, & Bueno, A. H. S. (2025). Development of a Fault Tree Analysis (FTA) for Structural Integrity Assessment of Gas Pipelines: A Literature-Based Approach,. *Rev. Gest. Soc. Ambient*, *19*(4), 1–22.

SAHRAOUI Aboubakr. (2021). *ETUDE DE LA CORROSION DES PIPELINES PETROLIERS* [Memoire de master, Mohamed Boudiaf]. University of M'sila.

sahraoui Yacine. (2014). *OPTIMISATION DES METHODES D'INSPECTION DES PIPES* [These de doctorat]. BADJI-MOKHTAR-ANNABA UNIVERSITY.

SAOUDI, J., & BOUGDAH, I. (n.d.). *Modélisation et analyse de performances de production des puits de gisement de HASSI R'MEL (cas de champ sud-2018-)* [PhD Thesis]. Retrieved May 14, 2025, from https://dspace.univ-ouargla.dz/jspui/handle/123456789/19347

Senagria Zakaria. (2022). *Analyse de risque de la station de pompage SP1 Bis par la méthode AMDEC* [Mémoire de Master]. Université Mohamed Khider de Biskra.

Siddiqui, A. (2016). FTA-Fault Tree Analysis Explained in Quality Management. *General Directorate of Health, Public Health Department*.

SRAOUI, O., & AGDI, A. (2024). *Contributions à l'analyse des principales défaillances D'un système industriel (ventilateur industriel)* [Memoire de master]. ABBES LAGHROUR university.

T. NATECHE. (n.d.). *Réhabilitation et Renforcement des Canalisations sous pression en présence des défauts de surfaces* [Universite des sciences et de la technologie Mohamed Boudiaf (Oran)].

TOUGGUI Youssef & HOUASNIA Imed. (2016). *Etude de la maintenance d'un pipeline dégradé par un type de fissure* [Memoire master]. Université SAAD DAHLEB Blida1.

Understanding Nominal Pipe Size (NPS). (n.d.). Piping Technology System. https://pipingtechs.com/understanding-nominal-pipe-size-nps/

Z. Bilal. (2018). *ANALYSE DU COMPORTEMENT DE SYSTEMES INDUSTRIELS PAR LES RESEAUX BAYESIENS POUR LA PREVENTION DES SCENARIOS INDESIRABLES* [These de doctorat]. UNIVERSITE BADJI MOKHTAR.

Z. C. Kab & K. Kemassi. (n.d.). *Technical and Economic Analysis of Natural-Gas Pipeline Infrastructure Use for Hydrogen Transport in Algeria* [Master's thesis]. Univ. Ouargla, Algeria, 2020.

Bibliographic Appendix

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Certificate of participation in oral and technical presentation, recognition and appreciation of research contributions IV. INTERNATIONAL VAN SCIENTIFIC RESEARCH CONGRESS held in Van, Türkiye, during March 21-23, 2025.

With the paper entitled: **“ADVANCED ENGINEERING APPROACH TO ANALYSE PIPELINE FAILURE CONSEQUENCES”**

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Echahid Hamma Lakhder University of El Oued – The Third International Conference on Materials, Energy and Environments (MEE - 2025) – Faculty of Exact Sciences Departement of Physics

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