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Review

Weather-Related Combined Effect on Failure Propagation and Maintenance Procedures towards Sustainable Gas Pipeline Infrastructure

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Abstract: Weather-related events are among the major causes of failure propagation in natural gas pipeline infrastructure. The interaction between multiple natural-force factors, such as temperature, precipitation, and wind, and their unpredictable simultaneous occurrence can intensify the vulnerability of pipeline infrastructure, increasing the likelihood of leaks, ruptures, and mechanical damage. This paper provides a comprehensive review of the combined effect of weather-related events on the failure propagation of pipelines, focusing on the impact of weather-related external force factors and climate change on sustainable pipeline integrity, including corrosion, erosion, and mechanical damage. Additionally, the paper examines various maintenance policies and strategies that can be implemented to mitigate the impact of weather-related failures. The review highlights gaps in existing knowledge and future research directions to enhance the understanding of weather-related failure propagation in natural gas pipeline infrastructure. This paper provides insights into the challenges and opportunities for improving the resilience and sustainability of pipeline infrastructure to weather-related failures.

Keywords: failure propagation; weather-related events; combined effect; natural gas pipeline; optimal maintenance; climate change impact

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1. Introduction

Natural gas, the most significant energy source for domestic and commercial activities, is supplied through a vast network of pipelines [1]. To transport this invaluable commodity, pipeline infrastructure plays a pivotal role in extracting, distributing, and delivering natural gas products [2]. The pipeline networks are spread around most countries to fulfill their ever-increasing energy requirements. The demand and supply define the dimensions and proportions of the pipeline. In the United States (US), over 2.6 million miles of complex pipeline network provides natural gas to end users. The US market has also decided to construct a new assembly to meet its future energy reserves by spending approximately USD 200 billion [3]. However, this vast infrastructure is also liable to risks and hazards due to natural or non-natural-force effects. Among the prominent risk factors, natural forces such as storms are the major pipeline failure intermediaries. Natural forces include all situations that adversely affect the system's reliability, such as hurricanes, floods, geological movements, humidity, inconsistent temperature variations, lightning, and thunder [4].

Weather conditions severely endanger pipeline infrastructure, risking their stability and disrupting the availability of natural gas for commercial and domestic use [5]. Weather-related factors threaten the safety of oil and gas fields and endanger environmental integrity and sustainability [6]. Extreme weather events, such as hurricanes, floods, heavy snowfall, or high winds, can trigger a cascade of pipeline failures, leading to widespread disruptions [7]. While temperature can pose risks to the stability of pipelines, it is crucial

to consider the potential for failure propagation scenarios. Past research indicates that pipeline failure due to extreme temperature conditions might not always occur directly, but it escalates other risk factors, leading to ultimate failure [8]. Pipelines buried in soil are vulnerable to heat conduction from the surroundings. Variations in external air temperature influence soil temperature dynamics, causing the expansion and contraction of pipelines, thus impacting pipeline integrity [9]. The temperature effects may cause stress corrosion cracking (SCC), which has a 50% share in gas pipeline failures [10]. In other scenarios, hurricanes, one of the unavoidable natural-induced disasters, also intensify the environmental hazards for the pipelines [11]. Studies have delved into the impact of hurricanes on pipeline integrity, revealing lateral and vertical displacements within the network [12]. Understanding the interactions between environmental factors like temperature and extreme weather events like hurricanes is vital for comprehensively assessing and mitigating the risks to pipeline infrastructure.

A thorough analysis of past research work is mandatory to maintain the integrality of the pipeline network and ensure a smooth natural gas supply. By viewing the data, regulatory bodies such as engineers, operators, and policy strategists will be able to inspect the reasons and rate of failures to mitigate the perils limiting the performance of pipeline infrastructure. These efforts will also guide the researchers in exploring the gaps in the associated field to develop more precise strategies to boost the overall structure's resilience. Their devoted attention will result in more accurate planned monitoring of pipeline systems, also known as condition-based monitoring (CBM), to reduce the real-time futilities and predict future incidents [13]. Technological advancement is no longer disconnected from the modern maintenance approaches of the pipeline structures unguarded by natural calamities using methods and tools equipped with artificial intelligence (AI)-based integration [4].

Restrepo et al. analyzed the causes and related impacts of pipelines using the PHMSA data of three years and identified weather-related incidents, equipment failures, external and internal corrosion, and operational errors as major contributors to failures [14]. Silver-Evans et al. studied the PHMSA data for forty years (1968–2009), covering more than 40,000 incidents. The research outlines the causes and impacts leading to human and property losses. The results mentioned that a major share of accidents led to property damage (43%), while a small share resulted in fatalities or injuries (32%) [15]. Kumari et al. presented an integrated risk prediction model by taking data on failure incidents from PHMSA ranging from 2010 to 2019. The proposed model utilized ANN coupled with Bayesian analysis for corrosion-induced incidents by proving the model as an assessment tool for analyzing various failure attributes [16]. Xiao et al. explored various background factors on gas pipeline incidents and highlighted that 42.21% of the failure incidents are due to outside force damage. The study also established that incidents in pipelines with larger diameters and higher pressures have severe consequences, causing more fatalities and injuries [17]. Shen and Zhou used the natural gas pipeline database of the Canada Energy Regulator (CER), ranging from 1995 to 2016, to analyze the leading causes of pipeline failures. The research concluded that the annual rupture rate of pipelines varies from 3.5×10^{-5} to 4.5×10^{-5} [18]. Ilincă C presented findings from a case study of a ruptured buried gas pipeline that exploded, resulting in fire. The research emphasized the benefits of assessing the structural integrity of pipelines through finite element analysis [19]. Using an AI-based prediction model, Mammadov et al. analyzed failure incidents due to human errors. Based on data from 1184 incidents, the study underscored the need for hazard awareness due to improper vehicle operation and proper site supervision to mitigate these incidents [20]. Awuku et al. utilized an AI-based prediction algorithm to analyze the gas pipeline failure caused by natural force by integrating climate change data. The PHMSA database from 2010 to 2022 was used, and after processing and feature selection the model achieved 92.3% accuracy. The research highlighted the need to understand the pipeline–climate interactions to refine the infrastructure monitoring and maintenance practices [4].

This paper explains the weather-related combined failure effects on pipeline infrastructures, along with the consequences of these vulnerabilities hindering the running fluency of the natural gas pipeline assembly. The paper also provides insight into the procedures and mechanisms developed to resolve the problems and complications to guarantee the smooth operation of the system. By reviewing the previous contributions in the area, this piece of literature outlines the improved ideas and tools to enhance the precision of failure forecasting models and perspectives to achieve the maximum efficiency of the natural gas pipeline organization. The primary purpose of the study is to highlight the combined effects of weather-related degrading of the lives of these critical assets and operations, decreasing their proficiency. The study might also encourage policymakers and researchers to design well-equipped policies to analyze and solve the rising issues of poor pipeline performance. This paper underlines the weather-related degradation of key assets and operations, leading to reduced pipeline efficiency. The following review addresses these issues by providing a comprehensive overview of recent advancements in the field. After identifying the research gaps in the study, this review article also presents a comprehensive outlook of significant augmentation in the sphere. The insights and findings derived from this study will inform the development of strategies that ensure the safe and reliable operation of sustainable pipelines under diverse weather conditions.

Following this introduction, the rest of the paper is structured as follows. Section 2 delves into the propagation and mechanisms of pipeline failures, distinguishing between weather-related and natural-force damages, and offers an overview of weather-related incidents. In Section 3, this paper examines current research efforts regarding predictive models for weather-related failures. Section 4 explores maintenance policies and procedures crucial for ensuring pipeline operational safety. Continuing in Section 5, we review ongoing research and future directions concerning the combined effects of weather-related failures. Finally, Section 6 provides a conclusion to the review.

2. Gas Pipeline Failure Propagation

The concept of "pipeline failure propagation" refers to the spreading out of a pipeline failure from its initial position, having a more significant and noticeable impact on the pipeline infrastructure [21]. The US boasts an extensive network of regulated natural gas pipelines, facilitating the delivery of approximately 27.6 trillion cubic feet (Tcf) of natural gas to approximately 77.7 million consumers [22]. However, the scale of these pipelines has presented significant environmental risks, contributing to substantial damage to local communities and considerable environmental pollution [23]. Although the decision to switch from using other fuels to natural gas is appreciable, it is unexpectedly associated with increased greenhouse gas emissions, such as methane [24]. Many of these issues stem from aging and deteriorating infrastructure, which can lead to leaks, ruptures, and other pipeline failures [25]. The Pipeline and Hazardous Materials Safety Administration (PHMSA) reported almost 5750 pipeline damage incidents in the US from 2001 to 2020, laying a USD 10.7 billion burden on the economy [26].

Root cause analysis plays a pivotal role in this context, as it seeks to identify the underlying causes of pipeline failures and environmental hazards. Figure 1 provides a summary of root cause analysis for natural gas pipeline failure, where engineering faults, accidental failures, third-party damage, corrosion and cracking, different equipment failures, failures due to human errors, construction failures, natural-force failures, incorrect operations, defects, and deterioration play a part in causing the natural gas pipeline to potentially fail [27]. Addressing these challenges necessitates a comprehensive understanding of the factors contributing to the degradation of pipeline infrastructure.

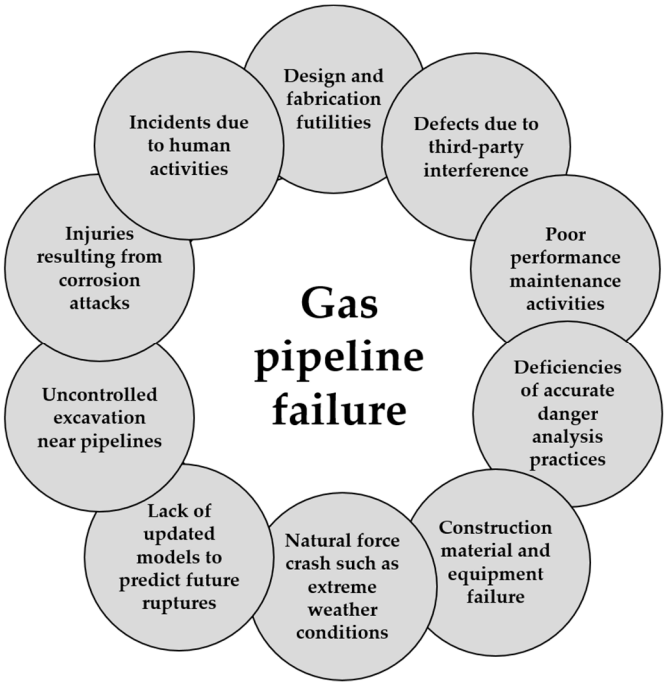


Figure 1. A detailed analysis of natural gas pipeline failure causes [27].

The subsequent sections will thoroughly examine these general root causes contributing to pipeline failures, explicitly emphasizing the role of weather-related and natural-force damage. By identifying and understanding these combined root causes linked to weather-related incidents, enhanced approaches for the maintenance and enhancement of pipeline systems can be formulated to mitigate risks to local communities and the surrounding environment.

2.1. PHMSA Failure Causes

PHMSA is a US government agency under the Department of Transportation (DoT) responsible for ensuring the safe transportation of gas and hazardous materials by pipelines and other modes of transportation. PHMSA categorizes the common causes of failures into several causal types, which are corrosion (external and internal corrosion), excavation damage, natural-force damage, other outside force damage, material/weld failure, equipment failure, and incorrect operation [28]. Based on the past 20 years of PHMSA data, 436 and 414 failure incidents are caused by excavation damage and other outside force damage, respectively. After these two prominent factors, other causes, such as other outside force damage, material failure of pipe/weld, natural forces, and incorrect operation, accounted for approximately 90 incidents. On the other hand, equipment failure and corrosion have emerged as the least frequent contributors to failures in the natural gas pipeline network over the last two decades. The relationship between incident cause and occurrence ratio is depicted in Figure 2, showing the frequency of incidents over the past 20 years in the United States, totaling 1320 reported events [4].

Excavation activities threaten safe pipeline operations by potentially compromising pipeline integrity through unintentional hits or insufficient backfilling [29]. This damage encompasses various types, from surface coating impairment to direct punctures into the pipeline, raising concerns about operational disruptions and risks to public safety and the environment [30]. There are several modes through which excavation damage can lead to catastrophic failures, including subway construction or tunneling processes leading to nearby pipeline failures, consequently resulting in many ground deformations [31]. Dent-cracking, as a combined effect, is more harmful to the pipeline assembly than a single dent or crack effect, challenging the pipeline's gas-carrying capacity [32]. The latter scenario involves accelerated corrosion due to coating damage, which, combined with physical

harm to the pipe, amplifies the risk of future leaks or catastrophic failure. Tragically, injuries and even fatalities can result from such excavation damage [33].

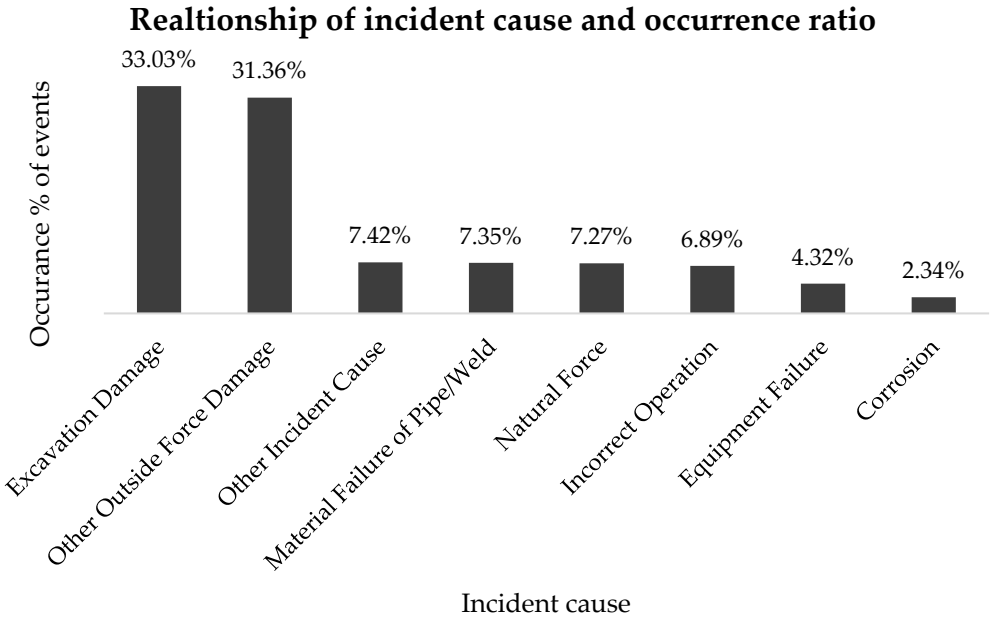


Figure 2. Cumulative incidents, occurrence percentage over a 20-year PHMSA record [4].

Additional forms of other outside force damage encompass factors beyond the pipeline infrastructure, including vehicle collisions or third-party interference (vandalism, sabotage, and terrorism) that can lead to pipeline damage and subsequent failures [34]. Pipelines that exhibit high susceptibility to other incident causes are facilities situated above ground, particularly near highways, where they face considerably more operational pressure, densely populated areas, or industrial centers. The observations have disclosed that 41.21% of injuries originated from external activities, with the cost rate being 1.043×10^{-4} and the injury rate being 1.728×10^{-4} [17].

In addition, material defects of the pipelines also make them weaker and less capable of bearing natural or external stress. Faulty manufacturing procedures may consist of impure construction material, metal defects, improper use of tools, or low expertise of the manufacturer [35]. Pipelines transporting natural gas or hazardous materials possess multiple weld joints along their whole lengths. Flaws in the welding process also initiate pipeline defacing. Dents appearing on the weld points, such as smooth or kinked dents, also escalate the degradation process. The cracks on the inner or outer surface of the welds additionally pose a threat to pipeline integrity [35,36]. Studies have utilized the implementation of computational fluid dynamics (CFD) and X-ray detection methods of the defects to analyze weld cracking [36]. Natural disasters are the largest source of pipeline ruptures, making their structure vulnerable to long-lasting, uninterrupted power supply—these range from landslides to earthquakes, including debris flow and rock mass movements [37]. Failure caused by natural agents is observed as more catastrophic than non-natural factors. For instance, severe weather conditions not only degrade the infrastructure of the pipelines but also intensify the probability of failure occurrences [38]. The reason for this lies behind the unpredictable trends of these calamities. Technologies have served the field in foreseeing such occasions, but crucial steps must still be taken to minimize their consequences [39].

Pipeline failure incidents can also arise from incorrect operations or operational errors, including improper pressure control, inadequate maintenance, or neglect of safety protocols [40]. Given that numerous aspects of pipeline operations depend on worker actions, situations occasionally emerge where human errors become possible, potentially leading to accidental pipeline releases [41]. Moreover, the fluid flow in pipelines becomes at risk

due to malfunctioning sensors, leakages, and blockages in the structure due to corrosion or other infrastructure preservation deficiencies, resulting in the degradation of the whole system [42]. Equipment failures of valves, pumps, or monitoring systems can also compromise the safe operation of pipelines. The wreckage of the critical parts of machinery during the operation or transportation and the mishandling of tools by engineers also cause the system to fail [43]. Additionally, corrosion may cause gas pipeline failures and can occur externally due to environmental factors or internally when certain gases react with other gases in the pipeline. Gases like carbon dioxide (CO_2), hydrogen sulfide (H_2S), and often oxygen (O_2) raise the chances of corrosion [44]. The potential of hydrogen (pH) and the presence of hydrocarbons can be factors that can cause corrosion [45]. Stress corrosion cracking (SCC), a specific type of corrosion, occurs when there is tensile stress and a corrosive environment, leading to cracks in the pipeline [46]. SCC primarily affects the welds in pipelines due to impurities in the weld material, resulting in localized corrosion [47].

2.2. Understanding Weather-Related and Natural Forces in Pipeline Failure Propagation

Although natural-force and weather-related damages denote dual terms, they have similar effects and consequences by adverse impacts on the pipeline networks, threatening the environment and human safety [48]. "Weather-related damages" refers to failures due to weather-related factors such as hurricanes, lightning, extreme temperatures, precipitation, or high winds [49]. On the contrary, "natural-force damage" has a broader scope, encompassing destruction caused by natural phenomena such as earthquakes, landslides, and geological events [50]. However, both terms converge when referring to the impact of extreme weather events on pipeline integrity. For example, an increase in the frequency of extreme high-temperature events may lead to the intensification of storms and a higher likelihood of flash floods, which could eventually jeopardize pipeline integrity. In a more expansive context, natural-force damage extends beyond the realm of weather to encompass a more comprehensive array of natural forces like extreme rainfalls, seismic activity, or geological shifts [51].

2.2.1. Weather-Related Failure Mechanism

Understanding the weather-related mechanisms of failures and their propagation in natural gas pipeline applications is essential for safeguarding infrastructure integrity and operational reliability. Figure 3 summarizes the prominent weather-related attributes associated with propagation failure, including corrosion, soil erosion, climate change, natural disasters, and temperature variations. These attributes may lead to the loss of structural integrity in gas pipelines through structural damage, soil movement, and thermal contraction and expansion.

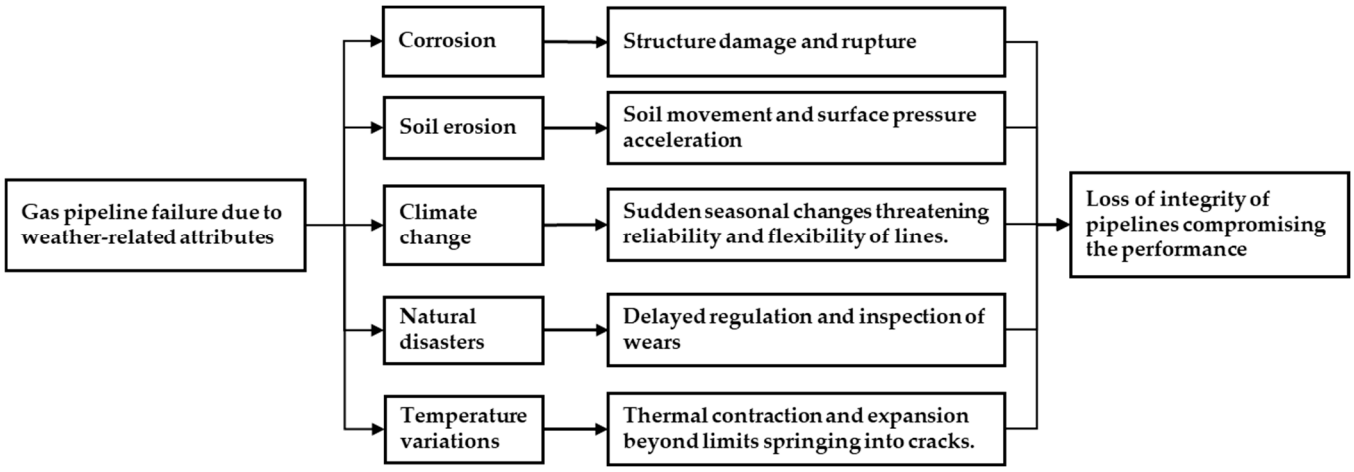


Figure 3. Prominent factors associated with weather-related propagation failures [29].

Weather-related failures cover a wide range of environmental factors and events that lead to structural degradation, leaks, ruptures, and other forms of damage, posing risks to public safety, environmental protection, and energy supply reliability [52]. Exposure to moisture, salts, and other corrosive elements in the atmosphere can lead to the degradation of pipeline materials, increasing the risk of failure. Other elements, such as humidity, can exacerbate corrosion, as internal factors related to the composition of the transported gas or contaminants within the stock may result in structural damage to the pipelines [53]. Corrosive soil also oxidizes the pipeline, which is why it is buried inside the Earth. In this environment, the exterior surface acts as both anode and cathode at a time. Thus, these regions form an electrochemical cell that accelerates the corrosion process [54]. Multiple factors accelerate the corrosion rate of the pipeline, such as moisture content, increased oxygen levels in the soil, and the pH value of the soil. Some macro parameters are pipeline topography, soil temperature values, and soil type in direct contact with the pipeline [55]. The flow chart in Figure 4 explains the conditions accelerating the corrosion rate.

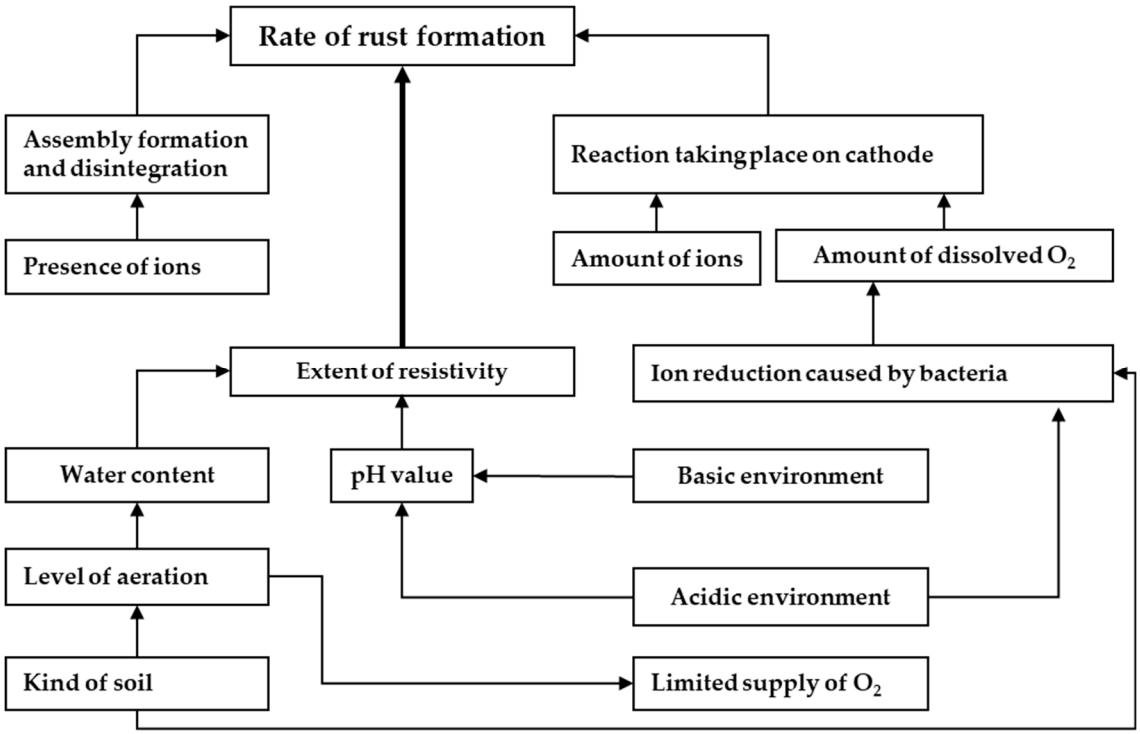


Figure 4. Relationships between corrosion-provoking conditions [55].

The key elements responsible for corrosion propagation are as follows: (i) The concentration of the chloride ions present in varying amounts in the soil [56]. They constitute the survival mechanism of corrosion-enhancing bacteria. A higher amount of chloride ions means an elevated rate of activity taking place inside the electrochemical cell. (ii) In the same context, moisture content is also worth examining [57]. A higher humidity level is the root of enhanced bacteria production. However, water content above a specific brim stops accelerating the surface oxidation phenomenon [58]. Moreover, (iii) resistivity is an inherent characteristic and a micro-corrosion-advancing property. Low-resistive natural gas pipelines are more prone to damage at acidic or basic pH [59]. However, this heterogeneous factor is hard to predict compared to the other dominating contributors. Resistivity meters help forecast the corrosion measurement of the under-observed soil [60]. The corrosion weakens the structural integrity of pipelines over time, making them more susceptible to failure [61].

2.2.2. Natural Hazards and Temperature Variations Failures Mechanism

In pipeline integrity, the interplay between natural hazards and temperature variations is critical in understanding the mechanisms behind pipeline failure propagation. Figure 5 shows an interconnected relationship between two natural or weather phenomena, concluding with pipeline failures. The progression starts with warmer temperatures due to climate change, leading to increased evaporation rates from water bodies like oceans, lakes, and rivers (Stage 1). For every one-degree centigrade rise in temperature, 7% evaporation happens from the water sources [62]. High temperature stimulates more evaporation due to the increased kinetic energy of water molecules converting into heavy clouds and precipitation (Stage 2) [63]. Higher temperatures lead to greater atmospheric instability by enhancing the development of thunderstorms and intense rainfall events (Stage 3). Excessive rainfall is the sequel to the phenomenon showing a pipeline failure threat. Intense rainfall and storms induce soil movement and expansion, leading to massive landslides threatening pipeline integrity, resulting in leaks or ruptures.

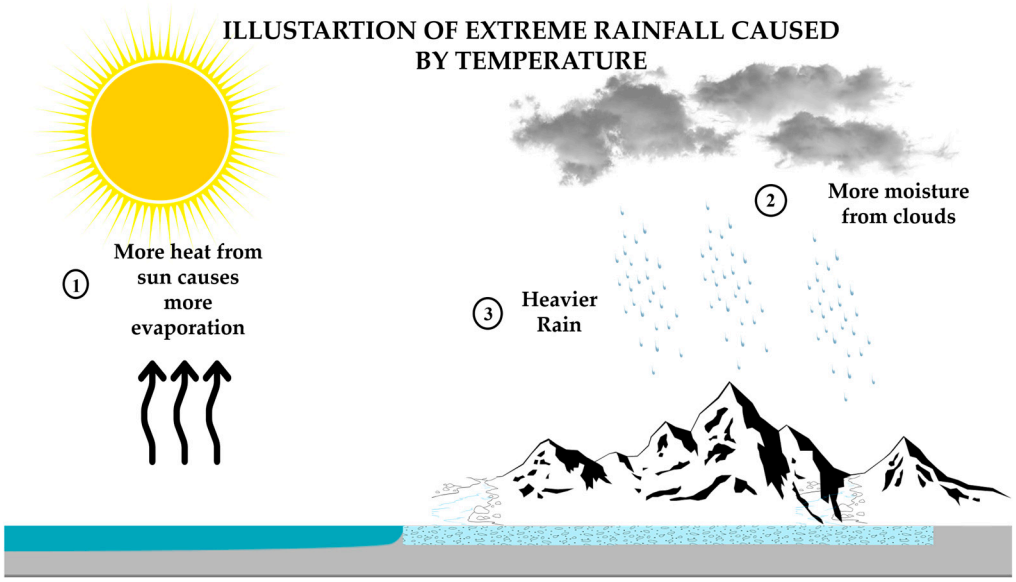


Figure 5. Relationship between extreme rainfalls due to extreme hot temperatures [63].

Temperature uplift can produce unlimited stress on the pipeline structure, initiating cracks that lead to ruptures [11]. Extreme temperatures prove precarious for pipeline integrity, and lower temperatures give rise to frost heave under the soil surface [64]. Frost heave occurs when ice forms beneath the topsoil, expanding into crystals with the aid of cold-water seeping through porous soil. This growth process poses challenges to pipeline integrity [65]. Low temperatures may also harm the pipeline's thermal stress due to snow or ice piles increasing the pressure loads on the pipeline surface [66]. During summer months, the soil stiffness surrounding the pipelines intensifies when the temperature rises beyond the limit. It has been observed that elevated temperature results in a decrease in soil mobilization lying against pipelines, thereby lowering their coaxial resistance [67]. The situation also compels the structure towards degradation. Furthermore, the pipeline's position on the ground thrives towards versatile external environments such as local communities, buildings, trees, and nearby habitats, propelling the pipeline organization to attacks due to their risk negligence and ignorance practices [68]. Mechanical damage, such as cracks in the pipe's structure, is another significant concern, often resulting from severe weather events such as storms, floods, landslides, and earthquakes. These calamities can be triggered by natural elements such as higher external temperatures, sudden and extreme weather changes, and an immediate wind range [69].

The mechanical factors provoke structure leakages, which may lead to expanded devastation. This scenario also underscores the potential for dangerous phenomena, such

as fires and explosions, due to uncontrolled gas release from pipeline damage [70]. This is particularly relevant in mechanical damage, emphasizing the threat posed by ground deformations, such as those caused by mining subsidence, to buried gas pipelines [71]. It is also crucial to discuss the impacts of the released natural gas from a hole due to mechanical agents such as excavator gadgets and equipment [72]. The released gas due to any tragedy poses a severe danger to the residents and surrounding property. The gas leakage often turns into a large-range explosion, expanding to far-off places, hampering their normal activities [73]. It was reported that a 0.5 m diameter and 5 MPa pressure pipeline led to 200 m wide damage [29]. Gas particles start ignition after exposure to the atmosphere, and ignition expands in the form of an explosion in the area, bringing social, economic, and biological resources to a halt [74]. When exploring the past literature to identify more reasons for weather-related pipeline failures, we encountered a specific example of the impact of water jetting from a failed water pipe on the erosion and subsequent failure of a steel natural gas pipeline [75]. The cause of the failure of two natural gas pipelines, named SDR 17 and NPS 8, made of polyethylene was determined. It was concluded that the erosive slurry affected the other two lines by making their bodies susceptible to failure [76].

It can be concluded that when natural gas pipelines face severe climate or weather conditions, the risk of leakage or rupture tends to increase manifold, affecting their operations and future working abilities [77]. These factors also negatively impact the country's economy, hindering industrial share growth. The subsequent damage also cut off the energy supply to commercial as well as residential users, interrupting their daily routine activities. Moreover, identifying the rate of failure and its repair processes is also time-consuming and costly [78]. When combined, all these attributes present abnormal weather conditions as unbearable catastrophes that are nothing but vandalizing human societies and industrial growth [79]. It is essential to develop maintenance policies by considering all perspectives of its breakdown so that proper preventive measures can be adopted to combat these detrimental effects. Therefore, a detailed analysis is mandatory to understand these weather-related failures of natural gas pipelines to combat their negative impacts on the environment and humans [80]. These insights will also facilitate the fabrication and integration of failure precision models, leading to the development of more accurate and boosted approaches to compensation strategies. Techniques known as weather-resistant coatings, such as anti-corrosive coatings made of composite polymer, have proven very effective in the corrosion prevention of pipelines, transforming rust into stable compounds. When these techniques were adopted after reviewing the contribution in the field, they directed operational practices towards refined preventive measures against nature-propagated failures [81].

2.3. Historical Pipeline Failure Propagation Incidents

An in-depth analysis of natural hazard factors affecting onshore regions in the United States, portrayed in Figure 6, sheds light on critical considerations encompassing meteorological, geological, hydrological, and climate factors.

Meteorological factors involve studying Earth's atmosphere and short-term weather phenomena, including temperature, atmospheric pressure, wind patterns, cloud formation, and precipitation. Geological factors focus on the Earth's crust, including rocks, minerals, landforms, faults, earthquakes, volcanoes, and plate movements. Hydrological factors such as precipitation, evaporation, runoff, groundwater flow, and surface water flow concern water movement and quality. Climate encompasses long-term weather patterns like temperature, precipitation, and wind from years to decades. While climate and meteorological factors primarily deal with weather-related conditions and patterns, hydrological and geological factors encompass broader aspects related to water movement and the Earth's geological processes. These factors uniquely contribute to understanding and assessing natural hazards and their impacts on onshore pipeline failure propagation incidents.

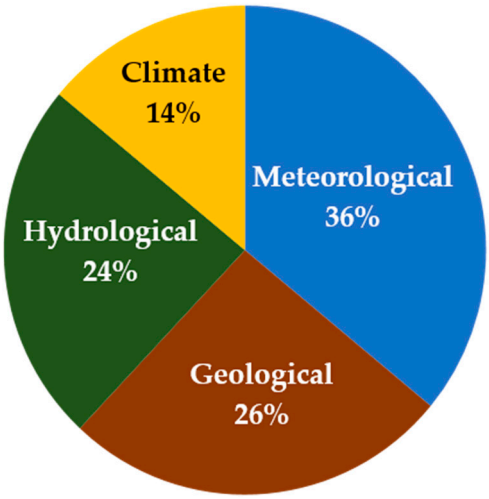


Figure 6. Natural hazard factors on onshore incidents in the United States [82].

Weather-related damage due to unexpected climate changes are a critical agent against the pipelines' resilience [83]. Several case studies illustrate the impact of weather-related failures and the importance of preventive measures towards pipeline integrity. One such effect was observed in February 2021 in Texas, USA, due to four continuous days of snowfall that sparked a winter storm. The unusual weather variations further intensified grim conditions. Another notable incident involved a natural gas pipeline, 7.2 mm thick, API 5L X52 DSAW, exploding in a region of the US, unleashing flames that soared 30 m high [84]. In September 2010, a gas pipeline explosion, named the Line 132 blast, happened in Crestmoor residential near San Bruno City and resulted in multiple fatalities and significant property damage, highlighting the importance of pipeline safety and maintenance. Various casualties were recorded due to mishandling of the supply complex or natural assaults [85]. The investigation revealed that the event was not known at the time of the explosion, and losses reported due to the blast included 8 deaths, 58 injuries, and 38 home destructions. The residents of the nearby area reported noticing a gas smell just one day before the event. The California Public Utilities Commission (IPR 2011) and the National Transportation Safety Board (NTSB) investigation (NTSB 2011g) were responsible for the maintenance of the complex and investigation of the tragedy [86]. One notable case study of a weather-related failure in a natural gas pipeline is the San Bruno pipeline Burst, which was investigated using the PLP [87]. The findings revealed that outcomes were stated to not adhere to the classic distribution of events. Still, a specific pattern was analyzed between the size and magnitude of outcomes and their periodicity. The report showed the occurrence pattern of the event after every 40 years [86]. The failure was accredited to poor management of the gas supply in relation to extreme weather conditions such as heavy rainfall, ground movements, elevated humidity levels of the environment, and debris stress [88]. The impact of the incident caused the regulatory bodies to have a critical check on the inception and maintenance strategies of the industry to ensure a fast and valid assessment of impending hazards [89].

In August 2005, Hurricane Katrina destroyed much of the Gulf Coast and seriously affected energy infrastructure in the region; almost all-natural gas production facilities in the Gulf of Mexico were evacuated and shut down. The strong winds, storm surge, and flooding triggered by the hurricane caused problems for facilities producing natural gas, causing power outages in gas pipelines from Gulf Coast refineries, leading to capacity vanishing and marked supply disruptions. A disaster with huge losses makes it evident that these invaluable infrastructures are vulnerable to harsh weather conditions, hence the need for robust and emergency response strategies to manage disruptions [90]. On 9 February 2011, a natural gas explosion in Allentown, Pennsylvania, resulted in five fatalities when a blast from a crack in a 12-inch cast-iron gas main shook Allen Street. Investigators

found the pipe had suffered heavy external corrosion, with almost 80% wall loss. The investigations pointed out that, in 1991, the NTSB recommended that all pipeline operators identify and replace pipelines that could pose a threat to public safety. This accident highlighted the risks associated with aging pipeline infrastructure and the importance of following safety recommendations and replacement programs. The external corrosion was primarily due to weather-related factors, such as moisture and temperature fluctuations, which accelerated the material's degradation over time [91]. On 17 April 2015, a natural gas pipeline exploded in Fresno, California, when a backhoe struck a 12-inch gas line. One person was killed and eleven others received injuries from the explosion. According to an investigation by the California Public Utilities Commission, Fresno County Public Works failed to properly survey the dig site before excavation. The gas pipeline was owned by Pacific Gas and Electric Company, which had warned companies and residents about the pipeline. The explosion blew out a part of the pipe 34 feet from the epicenter of the explosion and caused close to USD 2.8 billion in losses for PG&E. The incident happened due to mechanical damage from excavation activities [92].

Table 1 summarizes the comparative analysis of different impacts, with specific data showing the effects of weather-related factors. This incident serves as a reminder of how weather-related conditions can exacerbate infrastructure maintenance and operations risks.

Table 1. Comparative analysis of various weather-related factors with specific data.

Weather-Related Factors	Impact on Pipelines	Incident Location and Year	Specific Data
Corrosion	Reduces the strength of the structure	Allentown, Pennsylvania (2011)	External corrosion caused 80% wall loss
Corrosion	Reduces the strength of the structure	Hurricane Katrina (2005)	Moisture and temperature fluctuations enhance the impacts of corrosion.
Erosion	Results in material loss.	Hurricane Katrina (2005)	Floods and heavy rain greatly increase erosion, which in turn inflates maintenance and repair costs.
Mechanical Damage	Causes ruptures and leaks	Fresno, California (2015)	An explosion caused by mechanical damage from excavation.
Mechanical Damage	Causes ruptures and leaks	Texas Winter Storm (2021)	Mechanical failures caused by extreme weather.
Mechanical Damage	Causes ruptures and leaks	San Bruno, California (2010)	Faulty welds and over-pressurization caused an eruption.

A US onshore liquid pipeline incident due to natural hazards was analyzed to understand its environmental impacts and to obtain preventive measures for related future risks recorded through the PHMSA database [93]. The analysis was made by observing an overview of the previous causes of such hazards. Although the available data were not consistent with the causes of the incident, their quality was also challenging. Keeping in view that the data available from 1986 to 2012 were sorted and analyzed, the findings revealed that most of the damages resulted from natural-force factors, causing property loss of 1 million USD. The overall report of pipeline failures in the United States presented that 36% of incidents were caused by meteorological conditions and 26% by geological situations, respectively, involving subsidence and frost-heave as the significant risk factors, as shown in Figure 6. Among various natural circumstances, climate and hydrological conditions made up 24% and 14%, respectively. The most prominent participants in the meteorological hazards were reported to be lightning and heavy rainfall, making up 58% and 20%, respectively. The other factors, such as windstorms and tornadoes, were not significant. Overall, a share of 81% is credited to hydrological happenings such as floods, and the remaining part is due to stream flow conditions giving rise to scouring. These studies

collectively highlight the importance of considering weather conditions and corrosion in developing preventive measures for natural gas pipelines [82].

3. Weather-Related Failure-Prediction Models

Weather-related failure-prediction models are integral to evaluating the susceptibility of pipeline infrastructure to environmental conditions. These models rely on comprehensive datasets encompassing various environmental parameters for their effectiveness. Ongoing research endeavors are dedicated to refining and enhancing the accuracy of these models. Numerous predictive models have been developed and deployed to assess the risk of weather-related incidents. Leveraging historical data, environmental variables, and risk assessment methodologies, these models forecast potential failure events and prioritize mitigation strategies. In this section, we delve into the data requirements essential for developing robust prediction models, explore current research efforts to enhance predictive capabilities, and examine different failure-prediction models utilized in practice.

3.1. Data Requirements

Understanding the intricacies of weather-related failure-prediction models begins with thoroughly examining the data requirements necessary for their development and implementation. Various types of data, as listed in Table 2, need to be collected to identify the combined causes of failures in pipeline systems. This includes pipeline structure data, capturing segment identifications (IDs), geometry details, and port locations [94]. Pipeline behavior data involves monitoring physical phenomena, utilizing state equations to describe the system's behavior, and documenting transitions between operational states. Pipeline operation data focuses on detailed procedures, unit procedures, and steps with pre- and post-conditions. Materials data involves understanding material properties and identifying the materials involved in operations. Degradation or deterioration data categorize failure modes, symptoms, causes, consequences, and behavioral equations. Environmental impact data considers weather conditions and potential natural disaster effects [37]. Collecting and analyzing these data provides valuable insights for developing effective failure-prediction models and maintenance strategies to enhance pipeline integrity and reliability.

Table 2. Data to identify combined causes of failure in the pipeline system.

Type of Data	Description
Pipeline structure	Segment IDs, geometry (length, diameter, wall thickness), ports (locations of connections, valves, etc.) [94].
Pipeline behavior	Phenomena (pressure changes, temperature fluctuations, flow rates, corrosion, erosion), state equations (mathematical models of fluid dynamics, structural mechanics, material degradation), and transitions (between operational states or phases) [10,42,55].
Pipeline operation	Procedure (protocols for pipeline operations), unit procedure (individual steps or actions within a method), operation (specific operation being conducted, e.g., pumping, transportation), phase (corresponding phase of the operation), steps (detailed steps involved in each operation), formula (calculations employed), pre and post conditions (necessary for successful operations) [40].
Materials	Material properties (tensile strength, corrosion resistance, thermal expansion coefficient, fatigue characteristics), materials involved in each operation/behavior (pipe materials, coating materials, sealing materials) [55,81].
Degradation/ deterioration	Failure class (failure modes or types observed in the pipeline system), symptoms (indications or signs of potential failures or degradation), causes (factors contributing to the occurrence of failures or deterioration), consequences (impact or effects resulting from failures or degradation), behavioral equations of failure (mathematical models of failure or degradation behavior over time [95,96].
Environmental impacts	Weather conditions (weather conditions and their potential effects on the pipeline system) and natural disaster impact (potential impacts of natural disasters such as earthquakes, floods, or landslides on the pipeline system) [37].

3.2. Current Research Efforts

A weather-related combined effect is defined as a term that describes how weather and climate factors affect the system. Different types of extreme weather have recently been recorded to have significantly impacted pipeline health [97]. Some of the latest studies have described the methodology used and the results obtained, highlighting the role that weather had in the spread of the failure. Computational fluid dynamics (CFD) is a powerful simulation technology in various engineering applications, including pipelines. CFD technology analyzes and models fluid flow and heat transfer in complex geometries. In the context of pipelines, CFD can be employed to study the behavior of fluids (liquids or gases) as they flow through the pipeline, enabling engineers to gain valuable insights into the system's performance [98]. Table 3 shows the recent research on weather-related combined effect failure propagation or maintenance procedures.

In research by Jiang et al., a Bayesian neutral network (BNN) model was employed to study various weather-related failures in distribution systems. Compared with other advanced models, the BNN model outperformed in assessing and managing failure risk, demonstrating its accuracy [99]. In 2020, Zahid et al. described the interactions of landslides by utilizing COMSOL Multiphysics® Software version 5.5 Modeling to propose an analytical technique for calculating pipeline axial strain during pipeline landslide scenarios. The study considered slope angle, soil cohesion, temperature gradients, and material selection, offering practical solutions and design insights [100]. To investigate long-term pipeline operation, Vilkys et al. used the finite element method and ANSYS approach, generating pressure projections for potential failure and considering the actual properties of the pipeline's metal [101]. Mahmood et al. used a hybrid fuzzy Bayesian network (HFBN) by combining historical data and expert elicitation, including weather-related and natural hazards. The study concluded that third-party interference is a major cause of pipeline failure [102]. Kakoudakis et al. addressed natural gas pipeline disruptions with artificial neural network (ANN) and evolutionary polynomial regression (EPR) models. These models segmented networks by pipe diameter and age, enabling the estimation of annual failure rates [103]. Zhang, J. et al. used an empirical approach that provided empirical formulas for forecasting strain and denting levels in buried pipelines, particularly emphasizing the increased risk of pipelines within rock layers due to the reflection of explosion waves [104]. Table 3 is the collection of the related contributions in the field.

Table 3. Compilation of findings on weather-related combined effect failure propagation.

Author, Year	Failure Cause	Methods	Findings
Mahmood, 2024 [102]	Natural-force damage, weather-related factors, equipment, mechanical and operational errors	Hybrid fuzzy Bayesian network integrated with expert elicitation	External force, especially third-party interference, is a major cause of pipeline failures, emphasizing the implementation of necessary mitigation strategies.
Jiang, 2021 [99]	Wind speed, rainfall intensity, lightning days in a week	Bayesian neural network (BNN) in forecasting weather-related failure risk in distribution systems	The BNN weather-related failure risk prediction model outperformed six other models, covering failure risk exceptionally. Valuable prediction uncertainty and estimation for utility companies, enhancing maintenance decisions and distribution system resilience.

Table 3. *Cont.*

Author, Year	Failure Cause	Methods	Findings
Umer Zahid, 2020 [100]	Landslide	Assessing underground gas pipeline strains during landslides for safety compliance.	The study developed a simplified analytical method for assessing underground gas pipeline strains during landslides, ensuring safety code compliance, and providing efficient results for long pipeline systems.
Tadas Vilkys, 2018 [101]	Fractures in pipeline	Evaluation of the impact of mechanical damage on pipelines	The study investigated the mechanical damage to gas pipes, classifying forms of damage, identifying cracks, and simulating damage using the finite element method.
Konstantinos Kakoudakis, 2018 [103]	Failure in distribution lines	Predicting pipe failures in water networks due to weather using artificial neural networks (ANN) and evolutionary polynomial regression (EPR)	Artificial neural networks (ANN) and evolutionary polynomial regression (EPR) were used to predict water distribution network pipe failures, highlighting low temperatures' link to increased failures and aiding utilities in managing water loss and costs.
Zhang J. et al., 2018 [104]	Buckling failure due to ground explosions	Evaluating ground explosions' effects on buried pipeline safety using empirical methods	Ground explosions impact buried pipelines differently in soil and rock layers, affecting deformation, stress, and safety, with empirical prediction formulas developed.
Seleznev, 2007 [98]	Design, technological, and operational constraints of network equipment	Numerical simulation of gas pipeline network operation using high-accuracy computational fluid dynamics (CFD) simulators, tailored to model the unsteady, non-isothermal processes of gas mixture flow through long, branched, multi-section pipelines.	The practical application is illustrated by the comparison of computation results with gas flow parameters measured on-site at a gas transmission enterprise, to demonstrate the efficacy of numerical simulation to manage gas transmission networks.

3.3. Failure-Prediction Models

Various studies have explored prediction measures for weather-related failures in natural gas pipelines. Researchers have developed optimal preventive maintenance models for the pipelines based on these measures, focusing on the cost of internal and external failure factors [105]. Natural gas pipelines, being midway to supplying energy requirements for users, derive the attention of manufacturers and resistance against external threats and enhance the design of the complex to forecast future incidents better [106]. Still, there is a need to develop a regular optimized strategy to counter the effects of mechanical as well as weather-related propagation failures [107]. The European Gas Pipeline Incident Data Group (EGIG) recorded almost 1366 events from 1970 to 2016 per 1000 km average range [83]. The system demands updates as the need arises due to outdated infrastructure. Therefore, engineers must apply preventive measures to protect the environment from the hazardous effects of duct explosions [108,109]. The studies collectively highlight the importance of considering weather conditions and corrosion in the development of preventive measures for natural gas pipelines [110]. Furthermore, advancements in predictive modeling and data analytics are helping improve the industry's ability to anticipate and respond to weather-related risks, allowing for more proactive maintenance and infrastructure upgrade initiatives [111]. Additionally, advancements in pipeline materials and construction techniques, such as the use of corrosion-resistant alloys and advanced welding technologies, are helping to improve the integrity of pipeline infrastructure and reduce the potential for weather-related failures [112,113].

Pipeline integrity management (PIM) defines the systematic approach, identifies the possible risks, and applies preventive methods [114]. Advancements have been made in integrating machine learning (ML) and PIM for the maintenance, inspection, and analysis of cracks from pipeline failures, and preventing corrosion in pipelines [115]. The functionalization of ML techniques in the weather-related propagation failures of pipelines is a field of attention and interest in the modern era. The reason behind the technical shift is the precise computation of the variables with an accelerated rate of determination. Weather risk assessment of pipeline failures using ML was adopted in the study by employing techniques to locate the cracks in ducts. This work performed PIM in two steps: classification of failure and regression to finalize the size and amount of failure. The classifiers used for the analysis are typically a support vector machine (SVM), a decision tree, or Naive Bayes. The SVM is the primary classifier in evaluating the risk management of pipeline injuries. It includes data collection and screening processes along with further methodologies to help find the risks [116,117]. It can also be described using the following equation [116]:

$$C_i((z * y_i) + d) = 1. \quad (1)$$

In Equation (1), C_i is the ith data value representing class, y_i represents the ith data value input vector, and d denotes any term found to be biased in the analysis.

Further, the decision tree classifier functionalizes a tree-like structure showing the relationship between selected attributes and outcomes. The distribution continues until enough output of data is obtained for risk forecasting [118]. It can be shown by the following equation [116]:

$$G_i = S - [A_w * k]. \quad (2)$$

Here, G_i is gain in information, S is entropy value, A_w is average weight, and factor k is an associate with entropy. Entropy denotes any purity or impurity measurement utilized during decision tree generation. By considering the futility caused by different elements, such as the age of the pipeline, the location of the pipe network, and the material of construction, a decision tree can be assimilated to find the damage.

The Naive Bayes classifier is based on the Bayes theorem, which prompts the finding of the failure hazard using priority features. The model best suits large and versatile datasets by giving consistent and reliable results. It prioritizes one of the risk forecast's contributing elements [95]. The study considered the relative risk score (RRS) algorithm as the most functional proposed ML model for estimating and maintaining the integrity of the pipelines. The model is based on an indexing phenomenon in which different attributes are associated with the numeric points as scores [95]. The following relationship shows the calculation of RRS [116]:

$$RRS = \sum \text{indexes}/L_{IF}. \quad (3)$$

Here, L_{IF} is leakage impact factor, and the sum of indexes includes the addition of the corrosion index, third-party index, incorrect operation, and design index. The RRS methodology focuses on qualitative risk estimation and involves various factors, such as soil movements and other weather conditions, to maintain the health of the infrastructure [119]. Each element is analyzed separately, followed by the calculation of RRS by dividing the index sum and the impact factor of the leakage. Here, the impact factor is the product of dispersion value, leakage volume, product hazard, and receptor value.

A stochastic modeling process can be utilized to remove the impairment of the design. Two repairing modeling processes are homogeneous and non-homogeneous Poisson processes [96]. The homogeneous Poisson process (HPP) is a promising model for forecasting the rate of natural gas pipeline failures [120]. HPP helps determine the reliability of the pipeline network, which is necessary to ensure a stable energy supply and is dependent on the maintenance of operational equipment [121]. The model toils the non-variable intensity function by acting as the null set against which the comparison for spatial value arrangement is made. However, this model is equipped with limitations as it cannot maintain its reliability depending on time. Therefore, there is a risk to employing it to examine

the time-dependent pipeline failure. The rate of failure (λ) can be evaluated by using the equation as follows [96]:

$$\lambda = A(N_{obs})/B_E B_(exposed) * N_{obs}, \quad (4)$$

where A is the sum of the failures noticed during the observation at a time "N" and B_E is the total length dimension of the line exposed to the risk and analyzed in time "N".

The non-homogeneous Poisson process (NHPP) is a promising method widely employed to estimate gas pipeline injuries that can be repaired and compensated over time. Although it operates on the same principle as the HPP, it toils variable intensity function [96]. Moreover, NHPP precisely represents the likelihood of events or frequency of incidents by comparing them with their past distribution [122]. The failure rate can also be determined for the systems that continue boosting performance over time. The process can also be utilized for the reliability analysis of the pipelines undergoing shock process damage, also known as two-step failure [123].

The power law process (PLP) is the alternative or particular form of the NHPP, also known as the Weibull process [124]. The reason behind the reference is the similarity in operational function form between both. The intensity function of the PLP can be represented in the following way [96]:

$$\lambda(t) = (\alpha)/\beta[(t/\beta)]\gamma(\alpha - 1), \quad (5)$$

where α and β are both assumed to be greater than zero.

The structured methodology for analyzing and predicting pipeline failure incidents can be completed in five steps, as shown in Figure 7. It involves several steps to collect, classify, model, and predict pipeline failure data.

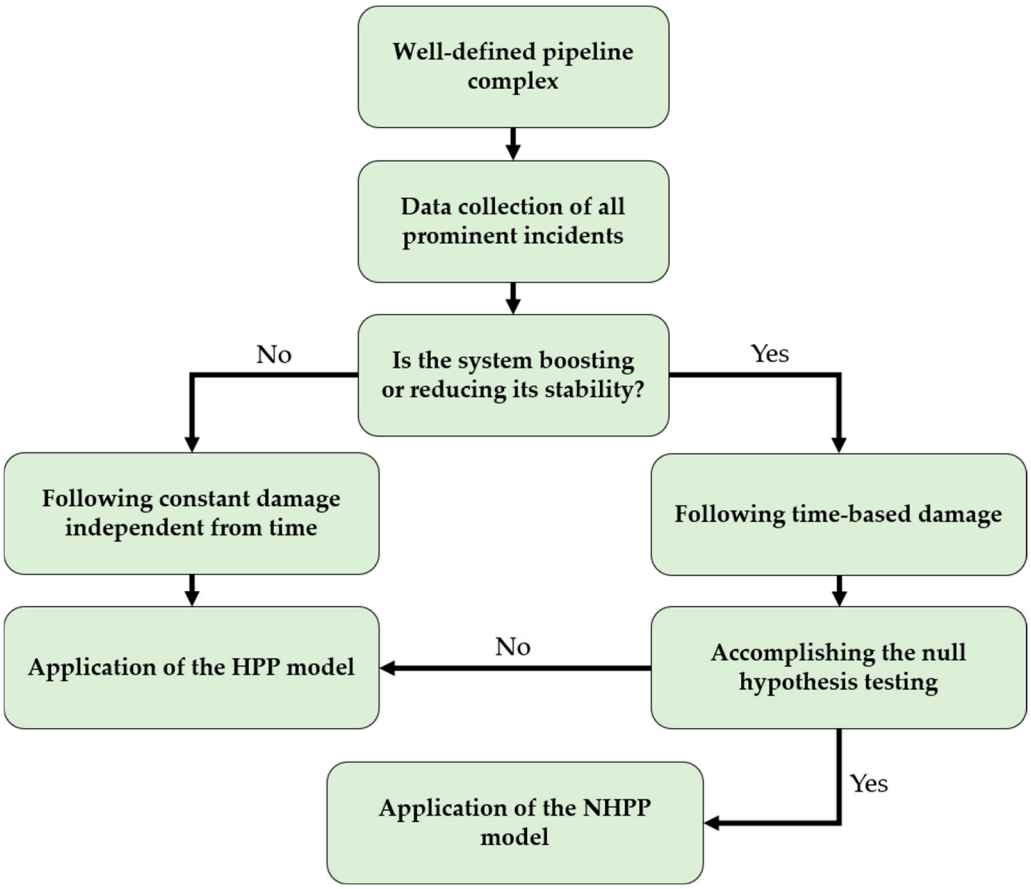


Figure 7. Working principle of damage rate-determining process [96].

The initial phase involves precise sample collection, sourcing data from databases like the PHMSA or other relevant sources that detail pipeline operations and failure incidents. These data are then subjected to a classification process, which accounts for pipeline characteristics such as diameter, construction materials, and types of damage. Subsequently, the second stage entails assigning an intensity function, achieved through the utilization of either the HPP or NHPP modeling approach, with selecting the most suitable model based on the provided data. The third step compares the priority method with alternative methodologies to determine the optimal choice. Following this, the fourth stage evaluates confidence intervals and power law attributes for NHPP or expected damage rates for HPP. Finally, the last step entails forecasting the total expected damages, along with their intensity functions and associated confidence intervals. This process can be further utilized as a framework for assessing the risk of pipeline failures, identifying potential vulnerabilities, and implementing preventive measures to enhance pipeline safety and reliability.

4. Maintenance Procedures for Pipeline Infrastructure

The sheer scale of the pipelines makes it challenging to oversee and maintain the infrastructure effectively. As pipelines often transport flammable or toxic fluids, and even during maintenance shutdowns residual fuel can be present, complicating repair and maintenance procedures. Extreme caution must be exercised to avoid destabilizing the pipeline contents during maintenance activities. Another complexity arises from pipelines passing through multiple jurisdictions, requiring compliance with different regulatory standards for the same pipeline. Additionally, pipelines traversing politically unstable regions further complicate maintenance [125]. Several maintenance procedures are frequently used in this situation, including corrective, preventive, predictive, and proactive maintenance. From the 1940s to the 2010s, the asset maintenance policies and their implementation changed occasionally.

4.1. Corrective and Preventive Maintenance

Corrective maintenance (CM) is a cost-efficient approach for implementing maintenance actions. CM tasks detect repair failures, reinstall, and resume facility output. It is reactive and entails quick responses in the event of equipment failure. CM tasks detect the failure that could be caused by any component and repair it to reinstall the equipment and resume the facility's output [126]. This type of maintenance is conducted as needed to restore the pipeline's proper functioning. On the other hand, preventive maintenance (PM) takes a proactive approach by scheduling regular maintenance tasks at predetermined intervals. These tasks include inspections, cleaning, lubrication, adjustments, and minor repairs. The aim is to prevent potential failures by addressing issues before they escalate into significant problems. The scientific data analysis methodology serves as the foundation for the PM policies. The PM policies include operation research techniques for consistent decision-making [127]. In addition, most industrial preventive maintenance procedures rely on the knowledge of industry professionals and advice from original equipment manufacturers (OEM) [128,129]. In addition, the PM policies have been divided into three groups according to pipeline age, length of use, and number of repairs or failures [40]. However, in comparing the costs and advantages of CM and PM provided by Christer Stenström, PM is more reliable in the long run [38].

4.1.1. Age-Dependent Policies

The commonly employed policy is based on a straightforward concept of replacing the component at a pre-determined age limit, denoted as T* [127]. The choice between maintenance and replacement under policies based on age is made when the component reaches age T*, or earlier in the event of failure. Two possible ways exist for the component to either be replaced early, even if it still works, or replaced when it stops functioning [130,131]. Sometimes, this type of maintenance is referred to as weak maintenance with repair proce-

dures like welding cracks and inserting sleeves. Although studies have merged models of age-dependent policy with unit replacement policies at age T*, the age of the unit is the most important element. The NHPP model, proposed by Barlow and Hunter in 1960, is a cost model used in modeling repairable system failures and earthquake occurrences [132] and examining cost-efficient maintenance strategies for pipeline systems [133,134]. This model aims to improve the system's cost per unit of time during its lifespan. Equation (3) demonstrates that the variable T* represents the optimal replacement time, which reduces the system's overall maintenance cost [133]:

$$T^* = C_P/(\beta - 1)C_f^{1/\beta}. \quad (6)$$

Here, C_p = System replacement cost, C_f represents the cost of a failure's minimal repair, and β = shape parameter of the model.

Age-based strategies received the most attention throughout the 1960s, but more extensive models were developed between 1990 and 2000. Table 4 displays these extended models [40].

Table 4. Types of maintenance policies for single units and pipeline assets [40].

	Policy Types				
Asset Types	**Age-Based Policies**	**Service Time Policies**	**Failure Limit-Based Policies**	**Condition-Based Policies**	**Risk-Based Policies**
Units/plants	✓	✓	✓	✓	✓
Pipelines	-	✓	-	✓	✓

4.1.2. Development of Asset Maintenance Policies

Time-based policies have been frequently used in repairable systems, with periodic preventive maintenance being a particularly prominent strategy within the "Time in service" framework, collecting significant focus and consideration [135]. Under the "Time in service" policies, Chaudhuri & Sahu (1977) established the imperfect maintenance idea. When a unit is repaired improperly, it fails to be considered brand-new and is instead expected to be older than before [136]. If system L is replaced at p after performing $(p - 1)$ PM interventions ($p > 1$), the replacement system will operate without further maintenance for a net period of t time units [129]. The cost of replacement at p will be:

$$B_p = C_1\left[1 + \left(T_L + t_p\right)r\right] + DS_L, \quad (7)$$

where B_p is the total cost of replacement at p, C_1 is the cost of a single preventive maintenance intervention, T_L is the total time the system has been in service, t_p is the time period for which the replacement system will operate without further maintenance, r represents the rate at which the cost of preventive maintenance increases with time, and DS_L is the cost of system downtime during the replacement.

To maintain a system's performance and minimize costs, replacing it when it reaches its maximum failure rate during a planning period may be necessary. Tam A et al. proposed a model in which installation time is taken to be constant, and maintenance is carried out when a system achieves its maximum failure rate. To keep the system within the allowable failure rate as it matures, downtime, downtime costs, and maintenance costs rise [129].

4.1.3. Failure/Repair Limit-Based Decision Policies

Bergman (1978) first proposed the idea of failure/repair limits policies, which combine imperfect and effective maintenance techniques [137]. The underlying principle of these policies is to conduct suboptimal maintenance activities until a specific predetermined threshold of failures or repairs is reached, upon which the equipment is replaced. Because of insufficient maintenance, the policy keeps the unit in service until the set level of reliability

and maintains an acceptable degree of reliability. The policy, which suggests replacing the unit when the anticipated repair costs exceed a predetermined economic threshold, was pioneered by Nakagawa and Osaki in 1974 [40].

4.2. Predictive Maintenance or Condition-Based Maintenance

A condition monitoring and inspection procedure is used in condition-based maintenance (CBM), also known as condition-based inspection and maintenance (CBIM), which was first developed in 1975 [138]. The primary goal of the CBM is to conduct a real-time evaluation of the equipment to increase its reliability and decrease unnecessary maintenance expenses [139]. In the CBM policy, the system's condition is typically checked out regularly. The condition analysis informs decisions about upcoming maintenance [140]. Diagnostic and prognostic maintenance choices fall under the CBM policy regulations. Finding the cause of the problem and its source requires going through the diagnostic process [141], whereas the prognostic approach uses predictive techniques to identify the reasons for failures. The diagnostic approach gives management an early indicator of failure. The performance of the equipment may appear satisfactory up until it completely fails, when it exhibits anomalous behavior, but there are no visible signs of failure. When a diagnostic technique is incapable of foreseeing a failure, a prognostic strategy may forecast the failure in advance if it occurs. The prognostic strategy can be more economical since it enables accurate planning, increases the efficiency of the equipment, and prevents unexpected failure [127].

4.3. Proactive Maintenance or Risk-Based Maintenance

Risk management is an organized method for assessing system risk, lowering the probabilities of potentially hazardous incidents, and/or minimizing the adverse effects of those events that occur [142,143]. Using risk-based inspection and maintenance (RBIM), developing a condition-based maintenance policy is a more innovative method of monitoring pipeline integrity. An inspection and maintenance plan can be prioritized using the need-based risk assessment method, which enables managers to conduct proficient testing and inspection without endangering public safety [144].

Techniques for assessing risk can be categorized into three categories: semi-quantitative, qualitative, and quantitative. Quantitative approaches need a significant amount of input data, some of which may not be available to pipeline operators. With sufficient input data, the output will offer concrete mitigation and inspection alternatives and requirements. For upstream pipes, these techniques are neither efficient nor economical. Simple decision matrix techniques are used in qualitative research. These techniques rely heavily on industry standards and professional judgment. These techniques work incredibly well in classifying pipeline risk [145]. Risk assessment procedures can use qualitative and quantitative techniques, as adopted by Arunraj and Maiti (2007), which include frequency assessment and consequence assessment. Both methods evaluate the risk of failure due to various causes, such as operational errors, corrosion, or third-party damage. Both assessment methods can be used, qualitative and quantitative, because qualitative techniques require expert judgment and risk matrices to rank the relative consequences of failure [146]. In contrast, quantitative techniques require statistical and mathematical analysis to calculate the consequences of failure. The main benefit of these procedures is that they can provide an objective and systematic approach to assessing the risk as well as evaluating the risk reduction measures [147,148].

4.4. Comparison of Maintenance Procedures for Weather-Related Failures Scenarios

Different maintenance policies have varying levels of effectiveness in preventing pipeline failures. Another previous study described the optimization strategy for a pipeline system that uses historical data to predict the probability of failure and impacts, emphasizing risk assessment and maintenance optimization [149]. While maximizing total cost, it reduces hazards to human and environmental safety. Figure 8 outlines the steps in

optimizing a pipeline system's maintenance strategies. These steps include choosing segments; defining attributes; defining failure modes; identifying hazards; calculating failure probability; quantifying the consequences for the economy, the environment, and safety; and aggregating total risk. While selecting maintenance choices, potential risk reduction is identified. The decision-making process is constrained by risk acceptability and maintenance budget, aiming to improve risk-minimization tactics while maximizing resource allocation. Corrective maintenance involves fixing assets only after they fail. It can be suitable for low-cost or non-essential assets but may result in significant downtime and repair costs for critical assets. On the other hand, preventive maintenance entails scheduled maintenance tasks regardless of asset condition, offering the potential to reduce failures and extend asset life. Still, it can become wasteful and costly if performed too frequently. Figure 8 summarizes the maintenance framework of the pipeline network.

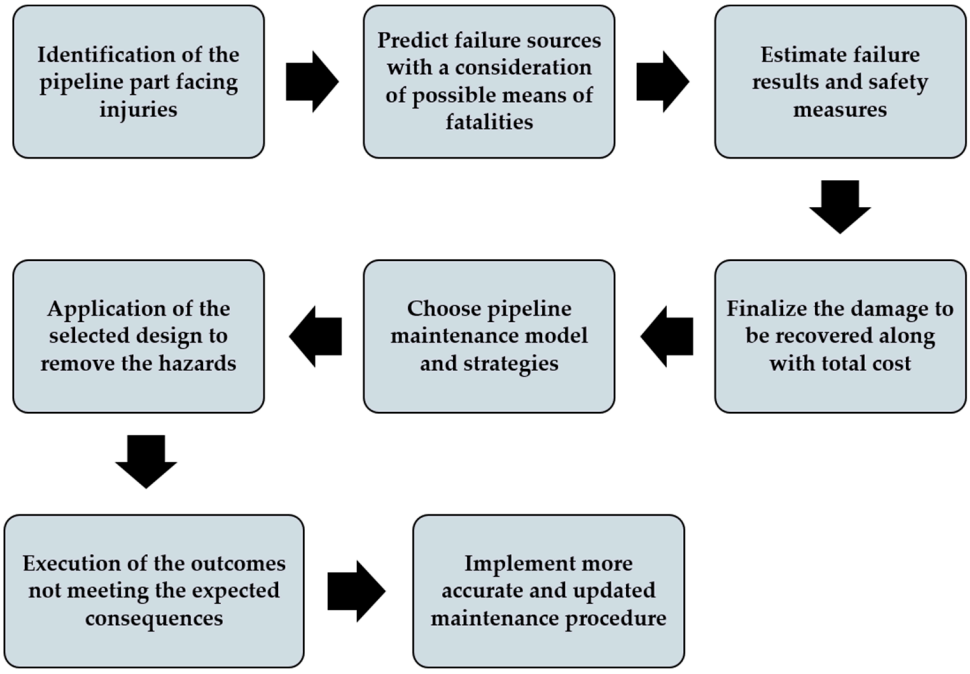


Figure 8. A pipeline system maintenance optimization framework [149].

According to a case study on train infrastructure, CM accounts for 79–90% of the entire cost, while PM maintenance accounts for 10–30%. The research is based on past information for inspection costs, maintenance costs, repair costs for functional failures, and production loss costs. Condition-based maintenance relies on intelligent asset performance monitoring, allowing maintenance tasks to be performed only when necessary. This policy can optimize maintenance interventions and facilitate early failure detection, but it relies on accurate and reliable data collection and analysis. Lastly, risk-based maintenance involves estimating the possibility of failure and its effects to prioritize maintenance tasks accordingly. This strategic policy can allocate maintenance resources to critical assets but requires a comprehensive understanding of failure modes and their impacts [150]. Table 5 compares all the above policies for maintenance from the perspective of a natural gas pipeline.

Table 5. Comparison of all the above policies for maintenance from a pipeline perspective [40].

Policy	Assessment Criteria	Decision Criteria	Advantages	Disadvantages	Pipeline Compatibility
Corrective maintenance policy	Complete failure	Knowledge about failure	Suitable in terms of cost	Increased downtime	Inappropriate for the pipelines
Preventive maintenance policy	Predetermined periods, such as age and service	Opinion of an expert, historical industrial practice, most recent repair	Reduced the occurrence, effective in terms of cost reduction of a manufacturing loss	Decisions are highly subjective, and the pipeline's condition was not evaluated	Inappropriate for the severe consequences of pipelines
Predictive Maintenance/ Condition-based Maintenance policy	Condition-based assessment	Examining and evaluating the situation	Pipeline evaluation in real-time	High cost of inspection, uncertainties in the inspection process Decisions restricted to the condition assessment, difficulties in selecting the inspection intervals	Appropriate for pipelines
Proactive Maintenance/ Risk-Based Maintenance Policies	Considering the risk of failure and condition	Assessment of inspection and condition, risk, and need-based maintenance approach	Evaluation of pipelines in real-time reduces the likelihood of dangerous events and the adverse effects of the actual events	Variability and uncertainty in inspection data logical presumptions and decision-maker assessments are subjective	Most popular policy for pipeline infrastructure

5. Future Research Direction

Future research should focus on identifying gaps, exploring emerging technologies, and fostering collaborative efforts to enhance pipeline infrastructure resilience against weather-related combined effect failures. Three key directions can guide these efforts: understanding, developing, and improving.

- Understanding: Research should focus on recognizing pipeline infrastructure and developing suitable maintenance policies. This includes analyzing how failures propagate through interdependencies with power networks and inherent risk factors.
- Developing: Efforts should integrate approaches to forecast and mitigate casualties using advanced validation strategies and artificial intelligence-driven models. Improving data analysis techniques through sensor technologies can enhance prediction accuracy and system resilience.
- Improving: Enhancing current measures involves refining existing policies for greater flexibility and accuracy in failure determination. Optimizing integrity-supporting approaches and implementing faster risk response plans are critical steps toward consistent results. Collaboration with policymakers and stakeholders can drive innovation in management paradigms, including cost-effectiveness and real-time failure analysis.

Additionally, it is essential to establish a comprehensive database of pipeline events, their frequency, and classification (natural vs. non-natural hazards). This database will support the development of models and machine-learning techniques to effectively protect communities from weather-related threats. The following subsections outline potential research directions for studying the combined effects of weather on failure propagation and maintenance procedures in natural gas pipeline infrastructure.

5.1. Sustainable Development Goals for Weather-Related Pipeline Failure Propagation

Understanding the intricate interplay between weather-related combined effects and pipeline integrity is crucial for sustainable solutions. Safeguarding pipeline networks and minimizing environmental impact is increasingly essential [151]. Integrating sustainable development into gas networks facilitates the transition to sustainable energy. Research on failures from extreme weather and natural hazards is critical for addressing climate change [152]. The 3Rs (risk, reliability, resilience) concept is essential for sustainable gas infrastructure growth, identifying risks, implementing mitigation measures, and reducing downtime. This approach ensures safer, cost-effective operations and infrastructure longevity. Concepts like risk, resilience, and reliability are pivotal for managing disruptions from various sources [153]. While risk assessment and techniques minimize tangible losses, addressing reputation damage in pipeline propagation sequences is vital [154]. Prioritizing strategies to mitigate weather-related pipeline failures aligns with sustainable development goals, securing critical infrastructure and advancing broader sustainability objectives for resilient energy transport systems.

5.2. Data Analysis and Integration of AI Algorithms in Failure Prediction

From a technical perspective, AI-driven data analysis aims to efficiently predict, prevent, and recover network failures. The cluster–impute–classify (CIC) framework, a semi-supervised learning approach, achieves a 91% accuracy rate by leveraging existing datasets to fill in missing event reports and understand correlations [155]. Additionally, integrating acoustic emission (AE) systems with genetic algorithm (GA) and principle component analysis (PCA) enhances pipeline condition monitoring [156]. Challenges persist due to limited incident report data, complicating the development of robust data-driven failure assessment models [157]. Utilizing machine-learning models trained on in-line inspection data from ROSEN's Integrity Data Warehouse (IDW), future studies can also focus on factors like pipeline material, excavation types, burial depth, and environmental factors to predict external interference risks and prevent failures [158]. These advancements in data analysis and AI integration enable proactive maintenance strategies, ensuring the ongoing safety and reliability of pipeline infrastructure amidst evolving challenges.

5.3. Multi-Hazard Risk Assessment to Prioritize Maintenance and Mitigation Efforts

From a proactive standpoint, while eliminating the risk of pipeline collapse entirely is impossible, it can be significantly mitigated by adhering to the principle of minimizing risks to an "as low as reasonably practicable" level [40]. Risk management involves understanding current risks, implementing precautions to reduce the likelihood of adverse events, and minimizing potential consequences [159]. Pipeline risk assessment follows defined procedures, including hazard identification, frequency estimation, consequence assessment, and risk calculation. This process considers factors contributing to risk, predicts failure probabilities, and evaluates potential consequences [145,160]. Global pipeline accident data can be analyzed to develop effective mitigation strategies, identify root causes of incidents, assess system strengths and weaknesses, derive meaningful insights, and learn lessons for future improvements [40].

5.4. Sensor Integration for Real-Time Monitoring of Pipeline Operations

Effective pipeline monitoring and inspection are critical to prevent breaches, environmental damage, and costly repairs associated with pipeline failures [161]. Numerous techniques are used for pipeline inspection, including hydrostatic tests, in-line inspection instruments, prospective survey techniques, and tools for investigating non-piggable pipes, such as pipeline crawlers [162]. One of the methods for monitoring and inspecting pipelines is in-line inspection, commonly termed a "smart pig" in the oil and gas sector [163]. Four metrics are frequently used to assess in-line inspection performance: detection, identification, accuracy, and locating, with a typical probability of detection (POD) reaching 90%. By advancing sensor integration capabilities, future studies can contribute to developing more

robust and efficient pipeline monitoring systems, ultimately enhancing the overall safety, reliability, and sustainability of pipeline operations [160].

5.5. Materials and Construction Techniques to Brace for Potential Extreme Weather Events

From the inherent structure considerations and in anticipation of potential extreme weather events, efforts focus on enhancing pipeline infrastructure resilience through advanced materials and construction techniques. Nanomaterials and nanocomposite materials can be used as anticorrosion agents. Another study employed a nanocomposite covering demonstrating anti-corrosion solid qualities. The nanocomposite inner layer in the experiment demonstrated a suitable response for pipeline installation in inclement weather [164]. Applying welding methods that are effective in adverse conditions and using pipeline expansion joints should be considered [165]. Welding methods like flux-cored arc welding (FCAW) offer clean solutions suitable for adverse outdoor environments, despite associated health risks [166,167]. Utilizing pipeline expansion joints is also recommended to accommodate thermal fluctuations, vibrations, and misalignments, ensuring safe operation [168,169]. The utilization of nanoparticles and nanocomposite materials, in conjunction with efficient building methodologies, can bolster durability against weather challenges. However, further research is needed to optimize the efficacy and applicability of these technologies in practical scenarios.

6. Conclusions

The study concerning weather-related combined effect failure propagation in the sustainability of pipeline infrastructure has produced valuable findings, which are summarized as follows:

- Weather-related factors such as moisture, temperature variations, and extreme weather events escalate the risk factors. The failure incidents of Hurricane Katrina in 2005 and the Allentown, Pennsylvania explosion in 2011 clearly show how environmental conditions enhance material degradation and consequently lead to such catastrophic failures.
- Data from past records demonstrated that weather-related external corrosion caused an 80% wall loss in a cast-iron main in Allentown, subsequently leading to a fatal explosion. Similarly, Hurricane Katrina's storm surge and subsequent flooding caused widespread erosion and corrosion that seriously disrupted natural gas production, resulting in supply constraints and price increases across the country.
- Weather-related force agents such as wind speed, fluctuations in temperature, and sudden climate changes are distinct factors effecting the pipeline infrastructure, which is exposed to several attacks, such as erosion, excavation damage, corrosion, stress cracking, etc. The combined influence of the environmental intermediaries endangers the network by lowering its gas-carrying capacity and endurance against future disasters.
- Modern propositions, including artificial intelligence and other date-driven strategies, such as sensor-equipped automatic mechanization, guarantee the further amplification of system optimization in dealing with threat prognosis. The application of these advancements can certainly reduce the potential for pipeline deformations.
- It is also crucial to ensure the practical integration of all policies to sustain the health of infrastructure. If planned modifications in the construction materials, tool design, installation, and manufacturing process are functionalized, it might better prepare the system to face the weather adaptations meeting the market demands.

Thus, reviewing the concepts of natural-force damages is required to make primary decisions relating to consistent performance and sustainable infrastructure. The goals can be accomplished by adopting ameliorated technological evolution horizons. Besides all this, a realistic attitude towards the root of environmental degradation will support the execution of the above-mentioned transformations towards a more reliable and sustainable gas pipeline infrastructure network.

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