Failures Root Cause Analysis for Sewer Pipeline Network System

تحليل السبب الجذري لفشل نظام شبكة أنابيب الصرف الصحي

by

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ABSTRACT

Wastewater System is one of the most critical infrastructure systems. It is known that there are several types of Wastewater, and this dissertation is concerned with the Sewer type of Wastewater in particular. In addition, there are several systems of Sewer Wastewater as the dissertation is centered around Sewer Wastewater Pipeline Systems. Furthermore, there are two types of Sewer Wastewater Pipeline Systems: the gravity and pressure systems, and both systems will be discussed in this dissertation.

The Sewer Wastewater Pipeline System was chosen for several reasons, the most important of which is finding Sewer Wastewater Pipeline System failures that affect the Sewer Wastewater as a whole System. In addition, to the danger effects of Sewer Wastewater Pipeline System failures. These effects may reach the residents of the area where the Sewer Wastewater Pipeline System failures occur. Furthermore, there are very harmful environmental effects.

This dissertation aims to study the Sewer Pipelines system failures in an infrastructure organization in one of the Middle East countries. The period of data collected from 2014-2022. For studying and analyzing this topic, some techniques will be used Failure Rate, Pareto Chart, FMEA, and Fishbone Diagram.

The research findings are summarized as the failure rate of the Gravity Pipeline system is higher than the Pressure Pipeline system. Also, the most frequent system failures are Pipeline broken, joint dislocation, connection broken, and damage. In addition, the most important consequences of the sewage pipeline system effects are the health, environmental impact, and road collapse in some failure cases. Furthermore, the most critical root cause is Third Party, Water Hammer, and Groundwater movement.

الملخص

يعد نظام مياه الصرف أحد أكثر أنظمة البنية التحتية أهمية، مع العلم بأن هناك عدة أنواع من مياه الصرف، تعنى هذه الرسالة بنظام مياه مجاري الصرف الصحي على وجه الخصوص، بالإضافة إلى ذلك، هناك العديد من الأنظمة التي تعنى بها نظام الصرف الصحي، سيتم تناول ودراسة نظام خطوط أنابيب مياه الصرف الصحي في هذه الأطروحة، علاوة على ذلك، فإن هناك نوعين من نظام خطوط أنابيب مياه الصرف الصحي، وهما نظام الجاذبية ونظام الضغط، وعليه في هذه الأطروحة سيتم مناقشة كلا النظامين بشكل منفصل.

تم اختيار نظام خطوط أنابيب مياه الصرف الصحي لعدة أسباب، من أهمها: اكتشاف حالات فشل نظام خطوط أنابيب مياه الصرف الصحي تؤثر بشكل مباشر على نظام مياه الصرف الصحي بشكل كامل، بالإضافة إلى تلك الآثار الخطيرة لفشل نظام خوط أنابيب مياه الصرف الصحي، حيث أن هذه الآثار قد تصل إلى سكان المنطقة التي يحدث فيها فشل نظام خطوط أنابيب مياه الصرف الصحي، علاوة على ذلك، هناك آثار بيئية ضارة بشكل كبير من فشل النظام.

تهدف هذه الأطروحة إلى دراسة فشل نظام خطوط أنابيب مياه الصرف الصحي في مؤسسة بنية تحتية في إحدى دول الشرق الأوسط، كما أن فترة البيانات المجمعة هي 2014-2022، سيتم استخدام عدة تقنيات لدراسة وتحليل هذا الموضوع، حيث سيتم استخدام التقنيات التالية: حساب معدة الفشل، مخطط باريتو، تقنية حالة الفشل وتحليل التأثيرات، ومخطط هيكل عظم السمكة.

تم تلخيص نتائج الدراسة على النحو التالي: تبين أن معدل فشل نظام خطوط أنابيب الجاذبية أعلى من نظام خطوط أنابيب الضغط، أيضًا، وجد أن أعطال النظام الأكثر شيوعًا هي كسر خط الأنابيب، وخلع المفصل، وانقطاع الوصلات، والتلف لبعض الأجزاء، بالإضافة إلى ذلك، فإن أهم نتائج تأثيرات نظام خطوط أنابيب الصرف الصحي هي الآثار الصحية والبيئية وانهيار الطرق في بعض حالات الأعطال، علاوة على ذلك، فإن الأسباب الجذرية الأكثر أهمية يعتمد على المعلومات السابقة والطرف الثالث ومطرقة المياه وحركة المياه الجوفية.

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Chapter 1 Introduction

1.1 Study Overview

1.1.1 Background in General

Wastewater is dirty water that is produced by rainfall runoff and human activity. There are many types of Wastewater, depending on the stage it is. It contains various kinds of water like Sewer Water, rainfall Water, and Irrigation Water. Some of the research they called Wastewater as Municipal Water. Wastewater treatment is critical for protecting our planet and the health of animals and people alike. When Wastewater is not adequately handled, it may pollute our water supply, harm the Environment, and cause significant diseases for humans (Koning et al. 2006; Junga 2022).

Each type of wastewater has a different stream, with its own pipes that do not mix with other types. As each type of wastewater has requirements for the types of pipes in terms of the type of manufactured material, the thickness of the pipes and other differences in requirements. It is also worth noting that the uses of wastewater differ from each other. Some of them are processed to produce organic fertilizer, others are used to irrigate plants, and sometimes rainwater is drained into the sea. In addition, the treatment and treatment method of wastewater are different from each other.

1.1.2 Wastewater

Wastewater is one of the infrastructure challenges in the whole world. Every type of Wastewater differs, and this difference lies in the style, composition of Wastewater, method of transporting water, uses of water, and methods of disposal. There are also different benefits that can be used for these different types of water, each of them according to what can be benefited from. Furthermore, many failures could happen in the system, effectively impacting humans and animals (Koning et al. 2006). The Sewer System is very harmful; it could affect any country, and it could affect the primary operations of the government. Also, it is prevalent and could affect the country's global reputation.

1.1.3 Sewer Wastewater System

The Sewer Wastewater system contains several systems, from exiting sewage water from homes to passing through lines and pipelines to pumping stations. After that, all the way to purification stations for converting water into irrigation water and extracting fertilizer for use in agriculture. Therefore, sewage pipelines are one of the most critical systems in the sewage system (Koning et al. 2006). Furthermore, it should also be noted that the sewage pipelines operate in two different ways: Gravity and Pressure pipeline systems.

1.1.4 Sewer Pipeline System

There are several components of each type of Pipeline Sewer Wastewater system. First, the Gravity pipeline system consists of Pipes, Joints, and Manholes. Second, the Pressure pipeline system consists of Pipes, Joints, Valves, Pumps, and Chambers. In addition, these Pipes are connected by Joints, whether Pressure or Gravity type. In Pressure types, there are Valves and Chambers connected for maintenance. On the other hand, in Gravity types, Manholes are connected for care.

1.1.5 Sewer Pipeline System Failures

There are many kinds of failures in the Sewer Pipeline System. Some of these failures are similar to each other in the Gravity system and the Pressure system, like Joint dislocation and leakage. On the other hand, some failures are different in each system because there are various components in each system. Furthermore, the effects of these failures could be similar or different depending on the type of system and the components.

1.2 Research Problem Statements

Wastewater system management is one of the most critical systems in the whole world, and affecting or stopping the wastewater service significantly affects countries. In this regard, some obstacles can occur, which states can deal with immediately to avoid spreading their effects on the residents (Yin et al. 2020a). Among the most important of these obstacles is the failure of sewage pipelines. Whereas Sewer pipeline system failures poses one of the

most significant challenge to urban infrastructure and public health in our region and current time.

This Study will focus on Sewer Pipeline system failures. It is worth noting that there are different reasons Sewer Pipeline system failures. As examples but not limited to, we can point to the following reasons: inadequate maintenance, aging sewer pipelines, and corrosive environments, resulting in frequent failures such as cracks, leaks, collapses, and blockages. There are various effects that may affect the failure of sewage pipes, including unpleasant odors and health problems that may affect the health of workers and employees in stations or on residents and residents next to the sites where this failure of sewage pipes occurs. One of the most important impacts that may be difficult to know at the time should not be overlooked, which is groundwater pollution. It is also worth noting the impact that it may have on the animal or plant environment or even on the outside air. These effects may be exacerbated depending on the size of the problems that may occur from sewage pipes. As it may rise to an emergency, crisis, or even disaster at the level of the country in which it occurs. Moreover, the economic burden of replacing, modifying, or repairing wastewater line pipes costs states a lot of money. Therefore, it is important that these problems are dealt with firmly and that the root causes behind the failure of wastewater pipes that may reoccur are investigated. Clear, long-term strategies must be developed to treat this problem.

Furthermore, the study will include both types of Sewer Pipelines system failures. While the previous research has studied other pipeline systems with different scopes, a gap was identified in investigating failures for the Sewer Pipeline system and identifying the root cause of the most critical subsystem.

1.3 Research Aim and Objectives

1.3.1 Research Aim

This Research aims to study the Sewer Pipelines system failures in an infrastructure organization in one of the Middle East countries. The root causes behind wastewater pipe failure will be studied and known through this research. This is to develop the wastewater pipeline system.

In this study, some techniques will be applied to reach the aim of the Research. Failure Rate, Pareto Chart, FMEA, and Fishbone Diagram are these techniques. By using these techniques in this research; Each technology has a different role to reach the goal in this study. First, Failure Rate will be used to compute the likelihood of pipeline system failures or components of the system over time. Second, Pareto chart will be used to find the most significant causes of sewer pipeline system failures. It assists in focusing sources and efforts on focusing the most critical pipeline system failures, resulting in more effective and capable problematic solving. Third, FMEA used to risk analysis tool in the pipeline system. Whereas, it includes analyzing possible Sewer Pipelines system failures types. Fourth, Fishbone Diagram will be used to examine the underlying Sewer Pipelines system failures causes or root causes.

1.3.2 Research Objectives

I. Calculate the Failure Rate for the whole system and each system severally to compare the results between both systems.
II. Determine the most critical Sewer Pipelines system failures by using Pareto Chart.
III. Find out the Effect of Sewer Pipelines system failures for each component's failures by using Failure Mode and Effects Analysis (FMEA).
IV. Identify the root causes of Sewer Pipelines system failures for each type of system.

1.4 Research Questions

This research will answer the following questions to the aim of studying the Sewer achieving the expected dissertation aim and objectives Pipelines system failures and achieving the desired objectives:

I. What is the failure rate of the whole system and for each system severally?
II. What are the differences between the two types of the system?
III. What are the most critical Sewer Pipelines system failures?
IV. What are the most critical effects of Sewer Pipelines system failures?
V. What are the root causes of Sewer Pipelines system failures for each type of system?

1.5 Research Significance

I. This research is the first study and analysis of Sewer Pipelines system failures in this area of organization in the whole Middle East region.

II. This study identifies the Sewer Pipelines system failures, which helps the organization proactively prevent these failures.
III. By knowing the Sewer Pipelines system failures, research helps save time, effort, and resources.

1.6 Research Limitations

I. Research data was collected not over a large period, which in turn partially affects the search results.
II. There is a lack of Papers research examining the Sewer Pipelines system failures in the rejoin of the Middle East.

1.7 Dissertation Organization

This dissertation is organized into five main chapters. This section's following lines will summarize each chapter's research content separately.

The first chapter briefly summarizes the study's excellent idea related to the Wastewater system and the failures of the Pipelines system. Also, the critical research guidelines that are adopted in the research.

The second chapter shows the types of Wastewater and the system of Wastewater, which is available literature to aid the complete understanding of the study. The chapter starts to give a brief idea of Wastewater and the types of Wastewater. Then, it presents Wastewater systems in general. After that, introduce the Wastewater system failures and the causes of these failures.

The third chapter in this dissertation presents the research methodology where the method of studying sewage pipeline system failures is explained. In addition, the methods by which the study of sewage pipeline system failures will be carried out have been clarified. Furthermore, how the analysis of the sewage pipeline system failures is conducted.

The fourth chapter presents the calculation of the data collected for Sewage Pipeline system failures. Also, analysis of these data to achieve the expected dissertation aim and objectives. In addition, give the summary of findings related to the data calculated.

The fifth chapter summarizes all the research outcomes and the link between the results findings and the dissertation objectives mentioned before from the beginning. Also, the most important recommendations are mentioned at the end of the research.

Chapter 2 Literature Review

2.1 Introduction of Wastewater

The development of a country is closely tied to water as it plays a central role in producing and preserving a range of advantages and benefits for both people and ecosystems. However, the combination of unsustainable development practices, the quick expansion of urban areas, and population growth will put significant pressure on water resources. It is estimated that global water demand will see an increase of approximately 55% by the year 2050. The expected rise in demand is projected to be propelled by more significant needs from various sectors, including manufacturing (which is predicted to increase by 400%), thermal electricity generation (expected to increase by 140%), and domestic consumption (predicted to increase by 130%) as found in the researches (Boretti & Rosa 2019; Colella et al. 2021) For these reasons, (Colella et al. 2021) discussed, as mentioned earlier, the World Economic Forum identified the water crisis and the associated risks as one of the most significant environmental risks on a global scale. The authors (Masi, Rizzo & Regelsberger 2018; Colella et al. 2021) mentioned that the issue of water scarcity is becoming more challenging, and wastewater management has been recognized as an essential factor in addressing it. This recognition is reflected in one of the seventeen Goals for Sustainable Development, known explicitly as SDG 6. Amongst other objectives, SDG 6 aims to boost water utilization efficiency throughout all divisions, guarantee sustainable withdrawal, and provide fresh water by 2030.

Moreover, the authors (Voulvoulis 2018; Smol, Adam & Preisner 2020; Colella et al. 2021) emphasized that safe and sufficient water supplies are closely related to wastewater management. Agriculture consumes nearly 50% of the world's freshwater through evapotranspiration in irrigated farmland, and the remaining 50% of this natural resource is discharged into the Environment as Wastewater. Water sources include effluent from municipalities and industrial facilities and agricultural drainage water. The consequences of this have far-reaching effects on economic productivity, as well as the productivity of human health.

According to (Anwar, Liu & Zhang 2022), municipal Wastewater comprises a combination of sewage from households, industries, and urban runoff, mainly consisting of water (over 95%) and various pollutants. The authors (Khadom, Hassan & Abod 2015; Anwar, Liu & Zhang 2022) presented that the Wastewater from households contains a variety of substances mentioned, encompassing a range of elements, from both pathogenic and non-pathogenic microorganisms, organic and inorganic chemicals, as well as suspended and dissolved elements, also other substances. (Anwar, Liu & Zhang 2022), discussed that Wastewater from industrial and commercial manufacturing facilities is generally more intricate and challenging to treat than domestic sewage. The authors (Srivastava et al. 2020; Anwar, Liu & Zhang 2022) found that the composition of industrial Wastewater contains hazardous elements such as organic compounds. These substances include oils, fats, alcohols, heavy metals, acids, and alkalis.

2.2 Wastewater System

(Yin et al. 2020a) reviewed the implementation of drainage systems has played a pivotal role in the development of humanity throughout history. Improving sanitation conditions has increased human longevity, particularly in densely populated areas where hygiene is essential in preventing widespread epidemics. Therefore, governing bodies allocate considerable financial resources and other assets to execute proactive maintenance procedures for sewer pipes. The main objective of this preventive maintenance practice is to detect and identify any structural or operational degradation of sewage pipes as early as possible. This will allow for the most effective corrective measures to be implemented. Also, this enables the most appropriate rectification work, such as minor repair, rehabilitation, or total replacement in case of highly damaged parts. The objective of the maintenance job is to keep the infrastructure in good condition to minimize operational disruptions and provide near-optimal levels of service.

(Junga 2022) emphasized that protecting the Environment by treating municipal and industrial Wastewater is crucial. The countries belonging to the European Union have pledged to protect the Environment by preventing negative consequences caused by the release of Wastewater into neighboring bodies of water. Implementing this Directive

involved improving the current wastewater treatment facilities and building new ones, which required significant financial resources. The total investment between 1990 and 2010 is estimated at 152 billion euros, with an additional 35 billion euros estimated for the new EU member states in 2010. The significant expenses associated with water management infrastructure are reasonable because untreated wastewater discharge primarily contributes to environmental contamination. Also, it poses a threat to water quality and increases the rate of biodiversity loss.

The authors (Moskvicheva, Sidyakin & Shitov 2016; Anwar, Liu & Zhang 2022) mentioned the wastewater sewage system that the process, which includes purifying Wastewater, conveying it through pipelines, and using intermediate pump stations, is critical to ensuring a clean, healthy, and uncontaminated water supply.

2.2.1 Wastewater Pipelines System

(Anwar, Liu & Zhang 2022) discussed that the sewer pipes that carry Wastewater have multiple sections connected to form more extended channels for transporting the Wastewater. The authors (Stanaszek-tomal & Fiertak 2016; Anwar, Liu & Zhang 2022) mentioned that treatment plants' sewage pipes and components face harsh environmental conditions. For example, exposure to acid, microbes, and Corrosion. This will ultimately lead to cause deterioration of the concrete.

The engineering community globally is showing more interest in being proactive and adopting preventive maintenance strategies for the maintenance of sewer pipes. This indicates a significant shift away from conventional reactive maintenance that addresses faults only after they occur, leading to unexpected failures that could significantly impact finances, society, and the Environment. Nevertheless, Numerous communities have yet to adopt efficient maintenance approaches that would reduce the likelihood of significant sewer pipe breakdowns. Such breakdowns may cause considerable disruption for local inhabitants and result in costly repairs or complete replacement. In recent years, maintenance and inspection methods for sewer pipes have been developed to enhance maintenance efficiency and reduce inspection expenses. One commonly used strategy to effectively maintain sewer pipes involves categorizing them as critical or non-critical. For instance, a risk-based model could be developed in a mid-sized city utilizing a risk matrix and a weighted sum multi-

criteria decision matrix to prioritize sewer pipes. In another approach, the probabilistic and weighted average methods are used to determine the probability and consequences of failure for sewer pipes, grouping them into various risk categories. Following the classification process, a maintenance timetable can be established accordingly, with more urgent attention being given to critical sewer pipes, as found in the research of (Yin et al. 2020a)

The study by (Anwar, Liu & Zhang 2022) presented that sewage effluents are gathered and conveyed via wastewater sewer pipelines to intermediate wastewater pumping stations. They are transported to treatment plants and subjected to various purification processes, including mechanical, biological, chemical, filtration, and sludge separation systems.

2.2.2 Wastewater Plant System

(Junga 2022) presented that Figure 1 shows a general layout of a municipal wastewater treatment plant (WWTP), but it cannot be assumed that this exact procedure will continually be used. Every wastewater treatment plant is distinct and must be customized to meet specific criteria, such as the location, type of sewer system, and other specifications. The initial phase of the treatment process involves mechanical pretreatment, which is intended to eliminate non-dissolved materials from the Wastewater and safeguard the subsequent stages. The second stage, biological or secondary treatment, is crucial to cleaning. It involves using aerobic conditions to break down organic matter in the Wastewater using microorganisms. This is done through an activation system that maintains a specific concentration of sludge biomass in the tank, allowing microorganisms to decompose organic substances into H2O and CO2 while obtaining energy.

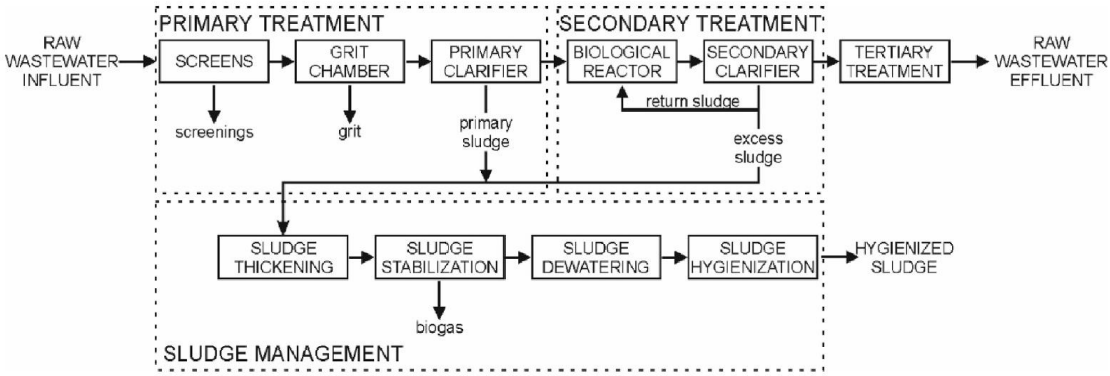

Figure 1: Generalized WWTP Scheme

(Junga 2022)

2.3 Wastewater System Failures

(Anwar, Liu & Zhang 2022) mentioned that acids, microbial, and corrosive material will subject the sewage pipelines and various structural components in treatment plants to robust hostile environmental conditions. (Junga 2022) presented the multiple objects of a wastewater treatment plant (WWTP) and the percentage of accidents occurring in each object (as shown in Figure 2). These objects are grouped into 13 categories. Table 1 presents the actual and proportional number of accidents across different types, while Figure 2 visually displays the percentage of accidents across various objects.

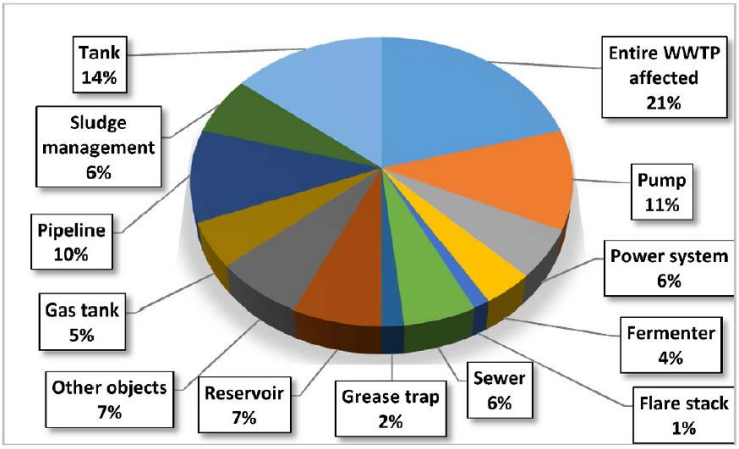

Figure 2: Percentage of Accidents in Individual WWTP Objects

(Junga 2022)

Table 1: Number of Accidents at Individual WWTP Parts *(Junga 2022)*

Object	*Absolute number (–)*	*Relative number (%)*
Entire WWTP affected	48	21
Pump	26	11
Power system	13	6
Fermenter	9	4
Flare stack	3	1
Sewer	13	6
Grease trap	4	2
Reservoir	16	7
Other objects	16	7
Gas tank	12	5
Pipeline	24	10
Sludge management	15	6
Tank	33	14

Table 2: Dominant Manifestation of Accident *(Junga 2022)*

Category	*Absolute number (–)*	*Relative number (%)*
Undesirable chemical reaction	9	4
Other	6	3
Poisoning	1	0.4
Environmental damage	134	58
Fire	22	9
Leak	50	22
Explosion	10	4

(Junga 2022) found that Figure 4 illustrates the categorization of accidents based on their severity. The incidents are classified into three levels of severity. The severity of an incident is determined based on its potential impact on the safety of people, property, and the Environment. Suppose an incident causes the shutdown of a unit but does not endanger life, health, property, or the Environment. In that case, it is considered a level-one severity incident and does not require rescue or liquidation operations. Suppose an incident poses a risk to life, health, property, or the Environment but can be managed by the workers on duty without rescue or liquidation operations. In that case, it is considered a level two severity incident. However, if an incident poses a significant threat to life, health, property, or the Environment and requires rescue or liquidation operations, it is considered a level three severity incident. In such cases, the staff or employees on duty may be unable to manage the incident, and external support may be required.

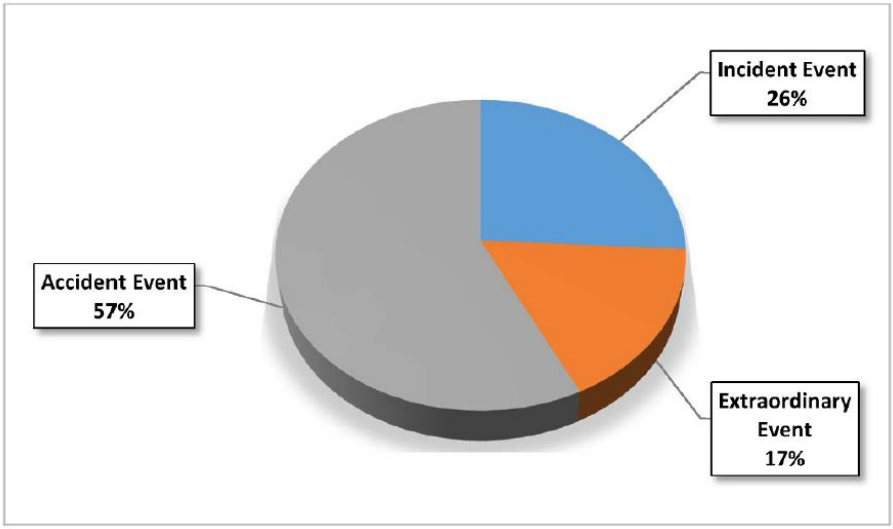

Figure 3: Classification of Events According to their Severity

(Junga 2022)

(Yin et al. 2020a) emphasized that over time, the sewage infrastructure becomes older. The rate at which the sewer pipes deteriorate varies depending on usage conditions. This is known as intrinsic conditions. In addition, external factors like the presence of trees with extensive roots or the volume of traffic passing over sewer lines (known as extrinsic factors) can deteriorate the sewer pipes. The structural integrity of the sewer pipes may be affected by both intrinsic and external factors working together. This fact has led to the widespread usage of closed-circuit television (CCTV) for inspection to assess the integrity of the underground infrastructure. Monitoring the drainage system regularly is critical, as replacement of such a system is very costly and highly disruptive to people's daily routines.

2.4 Causes of Wastewater System Failures

(Junga 2022) mentioned that the reasons behind accidents were classified into eleven categories, refer to Tables 1,2,3, and Figure 4. This categorization process involves some simplifications that are necessary due to various factors. One factor is limiting the cause categories to an acceptable number. Additionally, accidents can have multiple root causes, and for the sake of clarity, the leading cause was identified and assigned to the relevant category for each recorded accident. It is essential to remember that categorization is

subjective by nature, and there will be different opinions. Therefore, the types of causes of accidents in Figure 5 should be considered a general guide.

Table 3: Categories of Causes of Accidents *(Junga 2022)*

Category	Absolute number (–)	Relative number (%)
Ageing	6	3
Design Error	11	5
Human Error	22	9
N/A	28	12
Other	5	2
Extreme weather events	30	13
Malicious act	8	3
Incorrect procedure	2	1
Device or structure failure	104	45
External causes	14	6
Maintenance	2	1

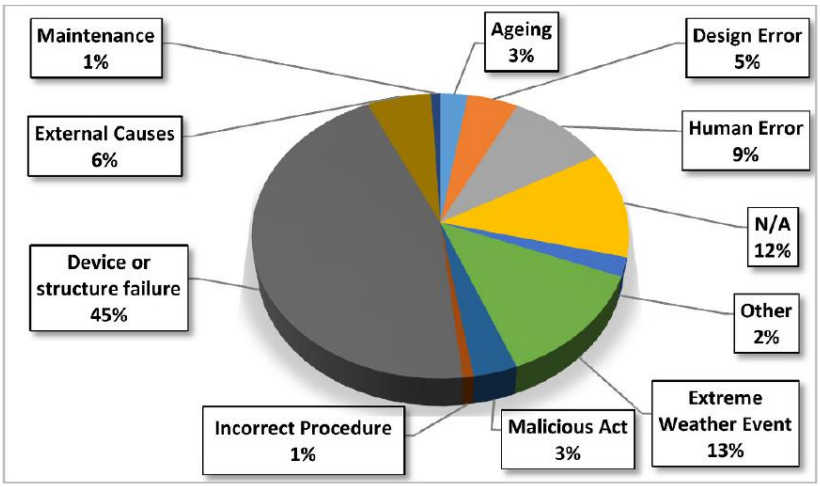

Figure 4: Percentage of Accident Cause Categories

(Junga 2022)

(Yin et al. 2020a) reviewed the pipelines have six categories of imperfections, which are broken, hole, deposits, crack, fracture, and root. Furthermore, (Junga 2022) reviewed the category that recorded the most accidents as "Entire WWTP affected," which encompasses incidents where the entire wastewater treatment plant was impacted. This could occur due to various reasons, such as a power outage affected by a blackout, fire, or explosion,

environmental disasters like floods or heavy rains, or outer factors such as the introduction of unusual chemicals.

(Junga 2022) presented that around 50% of all incidents fall under the category of "Device or structure failure," which encompasses various subcategories such as pump or fan technical malfunctions, filling hose ruptures, tank integrity loss, and more. It was sometimes challenging to identify the primary cause, as in the case of reservoir collapse, which was categorized as "Device or structure failure." The primary cause of this collapse was not evident from the records and could have been due to factors such as material Ageing or structural changes. Material corrosion is also a critical safety management concern, but only two records explicitly mention Corrosion as the cause of an accident. One record was classified as "Design Error," while the other was classified as "Ageing." However, there could be more incidents attributed to Corrosion. To provide a qualitative representation of accident causes, fishbone diagrams were created (see Figures 7 and 8), and specific cause categories will be further explored in subsequent subchapters.

- Ageing:

Equipment component ageing, technological obsolescence, decreased ability to adapt to external conditions, and other similar factors can lead to accidents. In chemical plants, for instance, Ageing is considered a primary concern in terms of process safety, as mentioned in the research (Gyenes & Wood 2016; Junga 2022)

(Gyenes & Wood 2016; Junga 2022) define that an ageing accident is an unexpected and unintentional incident that causes harm to people, the Environment, or property and occurs towards the end or after the intended lifespan of a system, structure, or component.

(Gyenes & Wood 2016; Junga 2022) mentioned four distinct types of Ageing: functional, technological, knowledge-based, and organizational. Six accidents that could be linked to "Ageing" were identified in the database. Based on the descriptions provided, functional Aging likely caused three incidents, such as material fatigue or Corrosion. The remaining three incidents resulted from practical and technological Ageing, reducing wastewater treatment efficiency at the WWTP.

- Design error:

(Junga 2022) presented that there was a total of 11 accidents in this category. Five cases were caused by design errors and related to biogas' handling and storage. In each case, leakage occurred, but no explosion or other catastrophic events occurred. The leakage was due to excessive condensate in the pipe, which initiated the safety burner to shut down. Taking precautions during the planning phase, such as selecting the proper location for the condensate trap and ensuring that the biogas pipe has adequate support and slope, will contribute to preventing the build-up of condensate.

- Human error:

This category of accidents usually results from human error, such as carelessness, lack of attention, or lack of knowledge about the correct equipment operating processes. This group had twenty-two cases, as mentioned in the research (Junga 2022).

(Junga 2022) presented that eleven accidents in this category resulted from human error, precisely mistakes in handling chemicals. This occurred when a chemical was mistakenly pumped into a tank containing another chemical, leading to an unexpected reaction. Both company employees and external personnel, primarily drivers, were responsible for these mistakes. Data from the database indicates that external personnel was at fault in five out of the eleven cases. To prevent these accidents from happening again, preventative measures such as employee training (for drivers and filling workers), a system of permissions for filling where drivers essentially request written approval from a spatialize person, clear labeling of chemical tanks, careful employee hiring practices, change management, and improvements in communication systems should be implemented.

In addition, (Junga 2022) mentioned that another group of accidents occurred because it was uncertain whether the shut-off fitting was in an open or closed position, leading employees to mistakenly close it when they thought they were opening it or vice versa. To prevent these accidents from happening again, measures such as installing shut-off fittings according to industry best practices, with clear indicators of whether the fitting is open or closed, should be taken.

According to (Junga 2022), two events involved a pipeline being damaged in a traffic accident, and in both instances, biogas leaked without any additional action being taken. One of the incidents happened when a mobile crane collided with an overhead pipeline, and the operator took preventive measures by setting up a protective frame, installing cameras on the mobile crane, and using a suitable escort vehicle. In the second occurrence, the operator was careless while dealing with the damaged overhead Pipeline, resulting in a comparable scenario.

Furthermore, (Junga 2022) reviewed it is challenging to anticipate the human element's behavior, so it is necessary to implement actions to mitigate the impact of significant incidents. It is crucial to prioritize the monitoring and implementation of measures.

- Extreme weather events:

(Junga 2022) highlighted that extreme weather conditions such as atmospheric electrical discharges, floods, heavy rainfalls, and long periods of drought caused the incident and resulted in decreased or complete stoppage of the WWTP's cleaning abilities. The number of incidents recorded was relatively high compared to other categories, which was 30. This shows that WWTPs can be pretty vulnerable to extreme weather events, and the issue is amplified by the ongoing problem of global climate change and its related impacts.

The reason the "Extreme weather events" category has a relatively large portion in the WWTP incident list could be attributed to the accident that frequently occurs in the author's database. The most common outcome of an accident appears to be "Environmental damage." Additionally, the incidents resulting in environmental damage are the most numerous (Junga 2022). In addition, according to (Ricci, Moreno & Cozzani 2021; Junga 2022) 53% of incidents cases resulted in environmental contamination. In 38% of cases, the substance that caused the contamination leaked without further consequences.

- Malicious act:

(Junga 2022) mentioned that municipal WWTPs are typically situated outside densely populated areas of cities, with little to no human traffic, particularly during the evening hours. Consequently, these facilities are highly susceptible to acts of vandalism or sabotage.

It is essential to consider the possibility of a terrorist attack on these facilities as well. According to the study, it indicates that out of a total of 232 incidents, only 6 were deliberate acts. Therefore, the percentage of intentional acts out of the total incidents is approximately 2.6%.

- Incorrect procedure:

(Junga 2022) highlighted that it was determined that two situations occurred due to a wrong approach. In the first instance, an explosion happened in the screw conveyor due to mishandling of the self-heated dried sludge. In the second occurrence, inappropriate handling led to a fire in the sludge drying room.

- Device or structure failure:

According to (Junga 2022) there were 104 incidents in this group, of which 15 were caused by pipeline leaks or ruptures, including filling hose ruptures. Additionally, ten occurrences resulted from the loss of integrity of concrete reservoirs, storage tanks, transport containers, or fermenters. Given the limited descriptions of these incidents, it is difficult to determine the reasons for the leaks, ruptures or collapses. Possible causes could include poor material choice, fatigue, or defects. In this study, unless explicitly stated otherwise in the accident report, the assumption was made that material defects caused the incidents and therefore categorized as "Device or structure failure." Although, it is essential to note that the substances used in WWTPs, such as chemicals, Wastewater, and biogas, are highly aggressive and can degrade construction materials relatively quickly, rendering them incapable of fulfilling their intended functions. In such cases, incidents resulting from material degradation could be considered in the "Ageing" category.

- External causes:

This category consisted of fourteen incidents. The incidents resulted from unpredictable external factors unrelated to the WWTP's operation. One such factor was infiltration, which can negatively impact the hydraulic system and the effectiveness of wastewater treatment.

As a result, operating costs can increase significantly directly to the higher energy intensity required to pump water and use chemicals (Junga 2022).

- Maintenance:

The "Maintenance" group contained two incidents. One involved hot particles that caused a fire while grinding metal material, and the other resulted from inadequate upkeep of the retention tank, as found in the research (Junga 2022).

- Other:

There were five incidents labeled as "Other." These incidents were linked to a blocked grease trap, a sewer at the inlet of the wastewater treatment plant, or a congested fitting. Due to inadequate information about these accidents, it was not feasible to identify the substance that caused the blockage. Nonetheless, it can be inferred that grease likely caused it (Junga 2022).

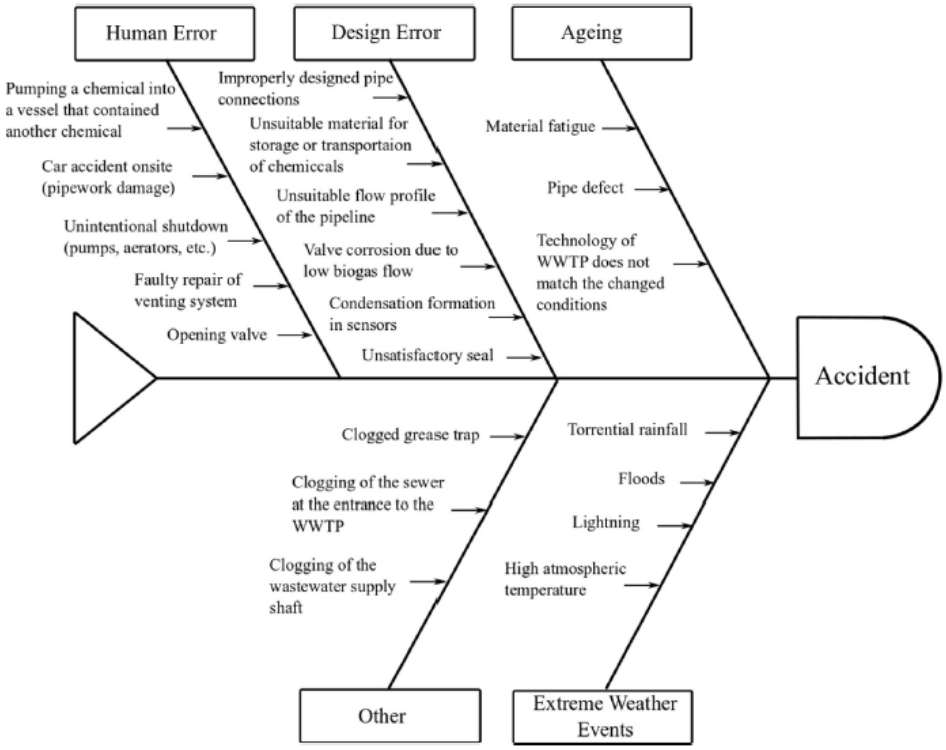

Figure 5: Fishbone Diagram (Causes of accidents part 1)

(Junga 2022)

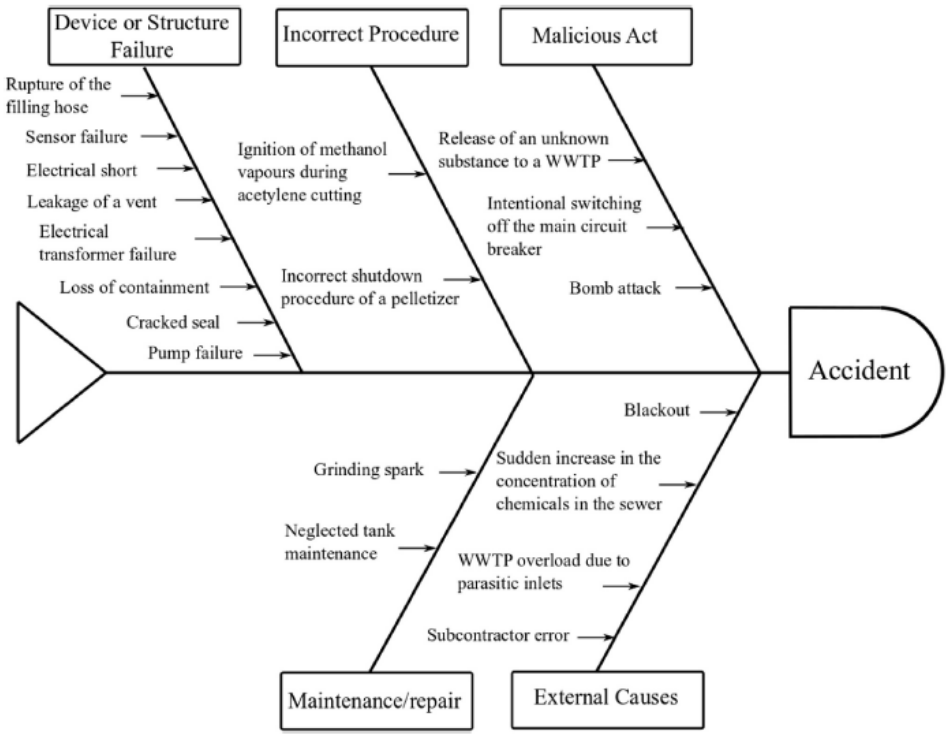

Figure 6: Fishbone Diagram (Causes of accidents part 2)

(Junga 2022)

2.5 Effects of Wastewater System Failures

The study by (Junga 2022) discussed that the Environment could be harmed through water, soil, or air damage. In incidents involving wastewater treatment plants, it was found that the aquatic ecosystem was impacted in most cases. Specifically, out of 232 recorded accidents in one study, 58% harmed the ecosystem. These accidents were typically caused by untreated Wastewater released directly into the Environment.

2.6 Risk management in the wastewater system

In the research conducted by (Magdalena & Zakrzewska 2020), a new risk assessment method was introduced based on historical data collected by sewage treatment plant operators. This study is among a small number of research carried out in this field. Another study by (Tušer & Oulehlov 2021) identified 58 risks, including biological and process risks

associated with employee injuries. The study by (Falakh & Setiani 2018) focused on risk assessment in the context of occupational health and safety.

According to (Junga 2022) ISO 31000 technical standards is the most reliable and up-to-date information that should be utilized to ensure a comprehensive risk assessment. According to ISO 31000:2018, the input for risk management should be based on the best available information, including historical and current data. Historical records of accidents play an essential role in risk assessment as it provides a better understanding and management of accidents. Additionally, the number of future accidents will be reduced.

2.7 Summary

In summary, the literature review has extensively acknowledged the significance of wastewater management worldwide. The world's population is also increasing, and their use of Wastewater is in increasing demand. Many consequences pose a threat to Wastewater. Some causes that may occur and affect public water have been addressed through the research (Gyenes & Wood 2016; Junga 2022). There are different causes, and for each cause, several effects differ from one cause to another.

Moreover, some triggers vary in frequency and occurrence to specific conditions and locations. Several papers by different authors have investigated the most important causes of the wastewater management system. They found the most repeated causes are Ageing, Design error, Human error, Malicious acts, Incorrect procedure, Device or structure failure, External causes, Maintenance, and some other causes, using the analytical tool fishbone diagram. The subject is extensive, and adopting a scientific approach to prioritize and manage the wastewater system effectively is essential. Sewage defects often lead to disasters that must be dealt with seriously, firmly, and correctly as failure to deal with it properly may exacerbate the disaster, which in turn may claim the lives of many residents next to the disaster.

According to the research of (Yin et al. 2020b; Junga 2022), it was decided to dig deeper into the sewage pipeline system in UAE. This choice comes due to the extreme importance of the effects resulting from these pipes. Especially when it was discovered that defects in sewage pipeline systems require an in-depth search for the root causes, which could affect

sewage pipeline system performance, the causes of sewage pipe defects will also be analyzed through the fishbone diagram tool. In addition, the highest cause among the group of causes will be identified so that appropriate solutions can be known to mitigate or remove it from the list.

Finally, According to (Carlson 2014; Hassan et al. 2022), using Failure Modes and Effects Analysis techniques is very important. FMEA is a generally used risk analysis tool in the pipeline system. In addition, it includes analyzing possible failure types such as the poor performance of a function, failure to achieve a function within identified limits, or accidental or undesired functions. Furthermore, According to (Fadeyi et al. 2016), a fishbone diagram is a tool used to identify and examine the underlying causes or root causes of a failure or problem. It can be an effective tool to find the underlying causes and the factors that impact these failures.

Chapter 3 Research Methodology

3.1 Introduction

This chapter aims to examine some of the applications of the method in previous papers that study and define the adopted research approach in this study. The chapter examines the usual research methods, which consist of quantitative, qualitative, and mixed techniques. The qualitative approach comprises conducting surveys and reviewing the literature. On the other hand, the quantitative method involves using simulation and computer science algorithms of real data from the field. The mixed approach is a blend of both quantitative and qualitative methods. In addition, in this chapter part, the methodology employed in the dissertation is explained in depth. This includes describing how data will be gathered, analyzed, and interpreted to produce results.

This project will follow the methodology illustrated in Figure (7):

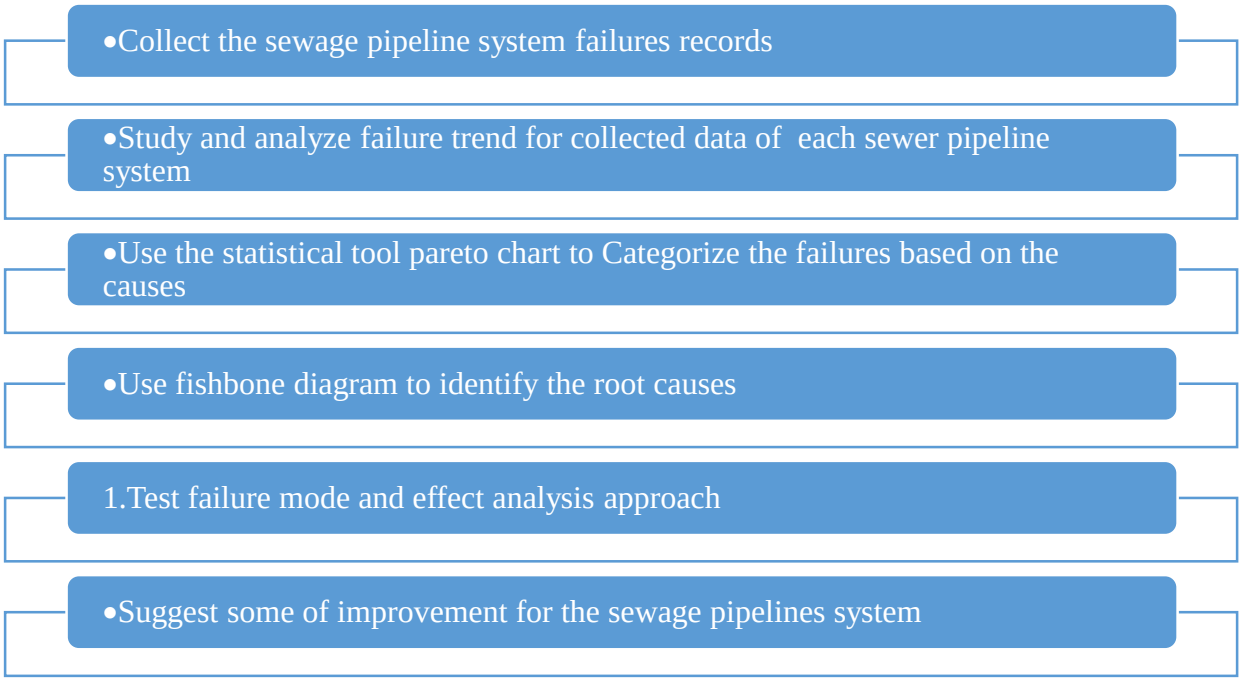

Figure 7: Research Methodology Steps

3.1.1 Qualitative and Quantitative Analysis

According to (Antwi et al. 2015), pure quantitative research involves gathering numerical data and is focused on hypothesis and theory testing using the confirmatory scientific method. The researchers state their ideas and then collect empirical data to confirm or reject them. On the other hand, pure qualitative research collects non-numerical data such as words and images. It uses the experimental scientific method to describe local observations, generate new hypotheses and theories, and discover more about a topic. This approach is used when little is known about a phenomenon. Mixed research combines both methods, using exploratory and confirmatory methods in one study.

This research study will use quantitative and qualitative analysis techniques to get the best recommendations for improvement for the sewage pipeline system failures.

3.2 Data Collection

(Elizabeth 2016) describes case study research as thoroughly examining and analyzing individual or group cases to comprehend the subject's intricacies. The case study methodology is closely linked to fundamental values and purposes and is characterized by its specificity, detailed description, and exploratory nature. Additionally, some writers consider case study research design an exhaustive and practical exploration of a recent occurrence in its real-life setting.

In this research, a case study of sewer pipe system failure will be presented. The data will be collected from UAE based system in the middle east region for the last six years. Also, the research will examine the causes of these failures and the root causes for each failure. In addition, the study will consider the location, weather, and pipe size for all sewer pipeline systems.

3.3 Analysis Steps

3.3.1 Failure Rate:

Like other types of pipelines, wastewater pipelines are subject to various failures, which can result in environmental contamination, property damage, and public health risks.

The failure rate used for wastewater pipelines can vary depending on several factors of the Pipeline and the quality of its design. Proper materials, installation, and maintenance of wastewater pipelines system will help reduce failures and ensure a safe and reliable wastewater pipeline system (Li et al. 2019).

According to the approach of (Lam, Engineer & Zhou 2016; Li et al. 2019), studying the past data on Sewer Pipeline system failures requires a complete and thorough database of pipeline failures. The collected data must be organized and classified based on its intended use. To obtain the most correct and objective failure rate for the sewer pipeline system, the information is categorized based on the causes of failures. The information gathered for each category can be further segmented based on the underlying factors contributing to that category's cause, commonly referred to as the root causes and effects of the pipeline system failures.

(Wang 2000; Xie, Tang & Goh 2002; Biyanto et al. 2016), present the failure rate is a model generally used in statistical analysis and reliability engineering to computing the likelihood of pipeline system failures or components of the system over time. The reliability and performance of a Sewer system or component is a critical parameter in understanding and predicting.

Mathematically the failure rate is the relation between the number of failures to the total time a system, usually expressed as failures per unit of time. The failure rate equation can be represented as:

Failure rate = number of failures / total time

In this research, the wastewater pipeline system failure rate will be determined for all causes of failures to calculate the overall failure rate. In addition, the failure rate for each type of the system for the wastewater pipeline system will be assessed. After that, a comparison with the system types will be found.

In this research, after studying the failure rate for the wastewater pipeline failure system, it will be clear to determine the failure mode for the causes in this study.

3.3.2 Pareto Chart

According to (Fadeyi et al. 2016) Pareto chart is a graphic tool that finds and lists the most significant causes of sewer pipeline system failures. It assists in focusing sources and efforts on focusing the most critical pipeline system failures, resulting in more effective and capable problematic solving.

The bar chart called the Pareto chart, shows information in descending order of frequency or magnitude. The Pareto chart contains two things: bars and a line graph. The bars on the bar chart or Pareto chart indicate the prevalence or frequency of each cause of sewer pipeline system failures. On the other hand, the line of the graph shows the cumulative percentage of the total incidences. In addition, speaking of the axis, it turns out that the vertical axis on the left side of the bar chart corresponds to the frequency or count of each sewer pipeline system failure. On the other hand, the vertical axis on the right side shows the cumulative percentage.

This study will be used a Pareto chart for sewer pipeline system failures. The first stage is to collect data on the sewer pipeline system failures. This step can be done through incident reports, inspection reports, or other related information sources. In addition, the causes of sewer pipeline system failures can contain several different failure modes. Furthermore, the Pareto chart can be useful to examine sewer pipeline system failures as the following steps:

Once the information on sewer pipeline system failures is collected, it can be prepared in a spreadsheet or a data analysis tool. The sewer pipeline system failures will be listed on the horizontal axis of the Pareto chart, and the corresponding frequency or count will be on the left vertical axis. The causes of sewer pipeline system failures are arranged in descending order of frequency and will be from the most frequent to the least frequent.

The bars in the Pareto chart represent the frequency of each cause of sewer pipeline system failures. Also, they are drawn in descending order. The tallest bar shows the most frequent cause of sewer pipeline system failures. Then, the second tallest bar for the second most frequent cause of sewer pipeline system failures, and so on. The line graph represents the cumulative percentage of the total incidences and is drew on the right side of the vertical axis. The cumulative

percentage is determined by adding the percentage of each cause of sewer pipeline system failures to the percentage of the previous cause of the system failures.

The Pareto chart identifies the "critical few" causes of sewer pipeline system failures contributing to the most critical pipeline failures. It helps spotlight the causes that need instant attention to moderate the overall failure rate. By concentrating on the causes of sewer pipeline system failures with the maximum frequency or cumulative percentage, resources, and efforts can be aimed toward addressing the most critical issues. It also results in more effective and efficient problem solving in this research.

In addition to detecting the significant causes of sewer pipeline system failures, the Pareto chart can also be applied to examine the development of improvement efforts over time. Renewing the chart regularly with new information makes it possible to track the effectiveness of involvements and measure the impact of mitigation measures.

The Pareto chart is beneficial for studying and listing the causes of sewer pipeline system failures. It optically represents the most critical sewer pipeline system failures and helps focus resources and efforts on adopting the root causes of sewer pipeline system failures. By finding and focusing on the critical few causes, organizations can develop the safety and reliability of their sewer pipeline system, eventually reducing the impact and regularity of failures.

According to the 80/20 rule in Pareto Chart used in maintenance management and reliability engineering, a significant proportion of sewer pipeline system failures are caused by a relatively minor number of root causes. The rule suggests that approximately 80% of sewer pipeline system failures are caused by 20% of the root causes. Also, it indicates that a small portion of problems is responsible for the majority of sewer pipeline system failures. There are many root causes that could be sewer pipeline system failures, like design deficiencies, material defects, Corrosion, external damage, operational errors, or other factors contributing to pipeline failures. By applying the 80/20 rule to sewer pipeline system failures, maintenance managers and reliability engineers be able to arrange their efforts and resources to address the critical few root causes responsible for most sewer pipeline system failures. In addition, to reducing the overall risk of sewer pipeline system failures and improving system reliability, this method allows for aimed and effective mitigation plans.

3.3.3 Fishbone Diagram

According to (Junga 2022), a fishbone diagram will be used to identify and examine the underlying causes or root causes of a failure or problem. According to sewer pipeline system failures, fishbone diagrams can effectively find the underlying causes and the factors that impact these failures.

First, identify the problem or failure. Then, state clearly at the head of the fishbone diagram. This step can be a specific case of a sewer pipelines system failure, such as a leak or Corrosion. The problem topic should be short and clear to serve as a reference work point for the following study.

Next, there are main branches, and it is resembling the backbone of a fish. These are drawn from the head of the fishbone diagram. These branches of the fishbone diagram represent the major types of reasons that could contribute to sewer pipeline system failures. In addition, these types can change depending on the detailed context of the pipeline system.

After the main branches are drawn, smaller branches resembling a fish's bones will be added to each main branch in the fishbone diagram. These smaller branches characterize the specific issues or causes that may have contributed to each group or category's sewer pipeline system failures. For instance, under the "Outside interference " category or group, smaller branches could include factors such as suppliers or earthquakes.

This method will continue until all possible causes or factors are found and entered into the fishbone diagram. This fishbone diagram will help to visually organize and study the potential causes of the sewer pipeline system failures. Also, it allows for efficient and comprehensive analysis.

Once the fishbone diagram is completed, the team can use it to guide advanced investigation and study. The team will evaluate each possible cause of failure and decide its likelihood and impact on the sewer pipeline system failures. This can require collecting information, reviewing data documentation, conducting interviews with experts, or performing tests and simulations to justify the potential causes.

The fishbone diagram can also assist list of the potential causes based on their importance and adopting corrective actions to address them. This can involve implementing change

techniques, organizing equipment inspections, improving training programs, or addressing environmental factors, among other actions.

Fishbone diagrams are an effective tool for studying sewer pipeline system failures. In addition, it provides a structured method for identifying and studying possible causes. Furthermore, fishbone diagrams help teams recognize the root causes and develop appropriate corrective measures to prevent future failures by visually organizing and analyzing the factors contributing to sewer pipeline system failures.

3.3.4 Failure Mode and Effect Analysis (FMEA):

(Hassan et al. 2022) The inability to identify, prevent, and minimize losses related to pipeline systems can be attributed to a flawed process of identifying hazards. The first risk analysis stage, hazard identification, entails proactively identifying all possible sources, situations, or actions that may pose a threat and lead to environmental harm. Insufficient hazard identification can occur due to the utilization of improper tools or the incorrect application of appropriate tools during the hazard identification process. Consequently, this could result in a wrong diagnosis or failure to recognize critical hazards.

The lack of dependable data pertaining to past failures, maintenance, and management of pipelines presents challenges in identifying hazards and conducting thorough risk analysis. In cases with inadequate data for conducting a data-driven assessment, an alternative approach, such as the suggested modified Failure Modes and Effects Analysis (FMEA), may be more appropriate (Shan, Liu & Sun 2017; Hassan et al. 2022).

According to (Carlson 2014; Hassan et al. 2022), the FMEA technique stands for Failure Modes and Effects Analysis. Also, it is a generally used risk analysis tool in the pipeline system. In addition, it includes analyzing possible failure types such as the poor performance of a function, failure to achieve a function within identified limits, or accidental or undesired functions.

The Failure Modes and Effects Analysis (FMEA) technique is a systematic and proactive approach. The Failure Modes and Effects Analysis approach is used in engineering and other industries to detect and assess possible failure modes in a technique or process, such as sewer pipeline system failures. The Failure Modes and Effects Analysis technique is a significant tool

that can help recognize possible failure modes, their causes, and their effects on sewer pipeline system failures. Also, it allows for prioritizing the risks and improving the mitigation plans. In addition, it can be applied to study sewer pipeline system failures in the following stages:

Discover the Sections and Functions of the Sewer Pipeline System: The first stage in executing a sewer pipeline system FMEA is to recognize all the components of the sewer pipeline system. This step can include the components of the sewer pipeline system, like pipes, valves, and other equipment, and their tasks. Also, it helps to create a complete list of all the possible failure modes of the system that can happen in the sewer pipeline system.

Recognize the Failure Modes of the Sewer Pipeline System: After finding the sections and functions of the pipeline system, the following stage involves finding all possible failure modes connected with each component or function. A failure mode relates to a particular mode in which an element or function can fail. For example, Corrosion of any components could be a failure mode, leakage for a valve or the joints, and motor failure for a pump could be a failure mode. These techniques can identify potential failure modes for brainstorming, past failure data analysis, and expert knowledge.

Determine the Causes and Effects of Failure Modes for Sewer Pipeline System: The following step is to determine the causes and effects of failure mode for each component in the Sewer Pipeline System. In addition, the Causes of sewer pipeline system failures are why the failure mode can occur. Also, the effects of the sewer pipeline system failures are the consequences of the failure mode on the sewer pipeline system. Furthermore, the causes of the failures can include manufacturing defects, design flaws, wear and tear, or environmental causes. Also, effects can include disruptions in the flow of fluids, leaks, system shutdowns, or spills.

Improve Mitigation Approaches: The most significant failure modes are selected for mitigation. In addition, mitigation approaches can include redesigning mechanisms, implementing monitoring techniques, or improving maintenance methods. The aim is to reduce failure modes' occurrence, severity, or detection.

Monitor and Review: After implementing mitigation strategies, it is important to continuously monitor and review the pipeline system to ensure the strategies' effectiveness and

any new failure modes that may arise. Lessons from previous failures can also be used to update and improve the FMEA process, continuously improving the pipeline system's reliability and safety.

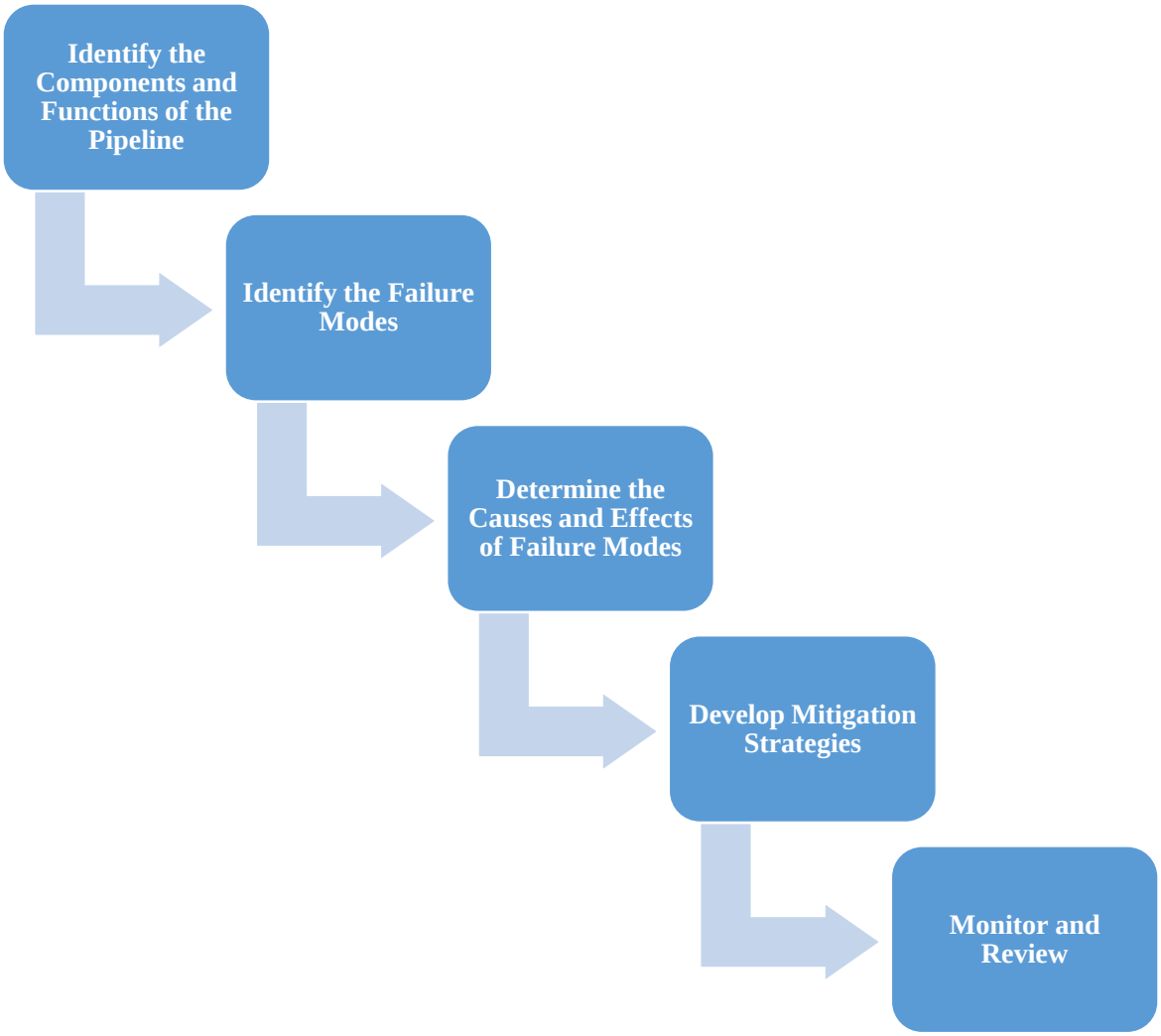

Figure 8: Failure Mode and Effect Analysis Steps

3.4 Failure Investigation Flow Chart

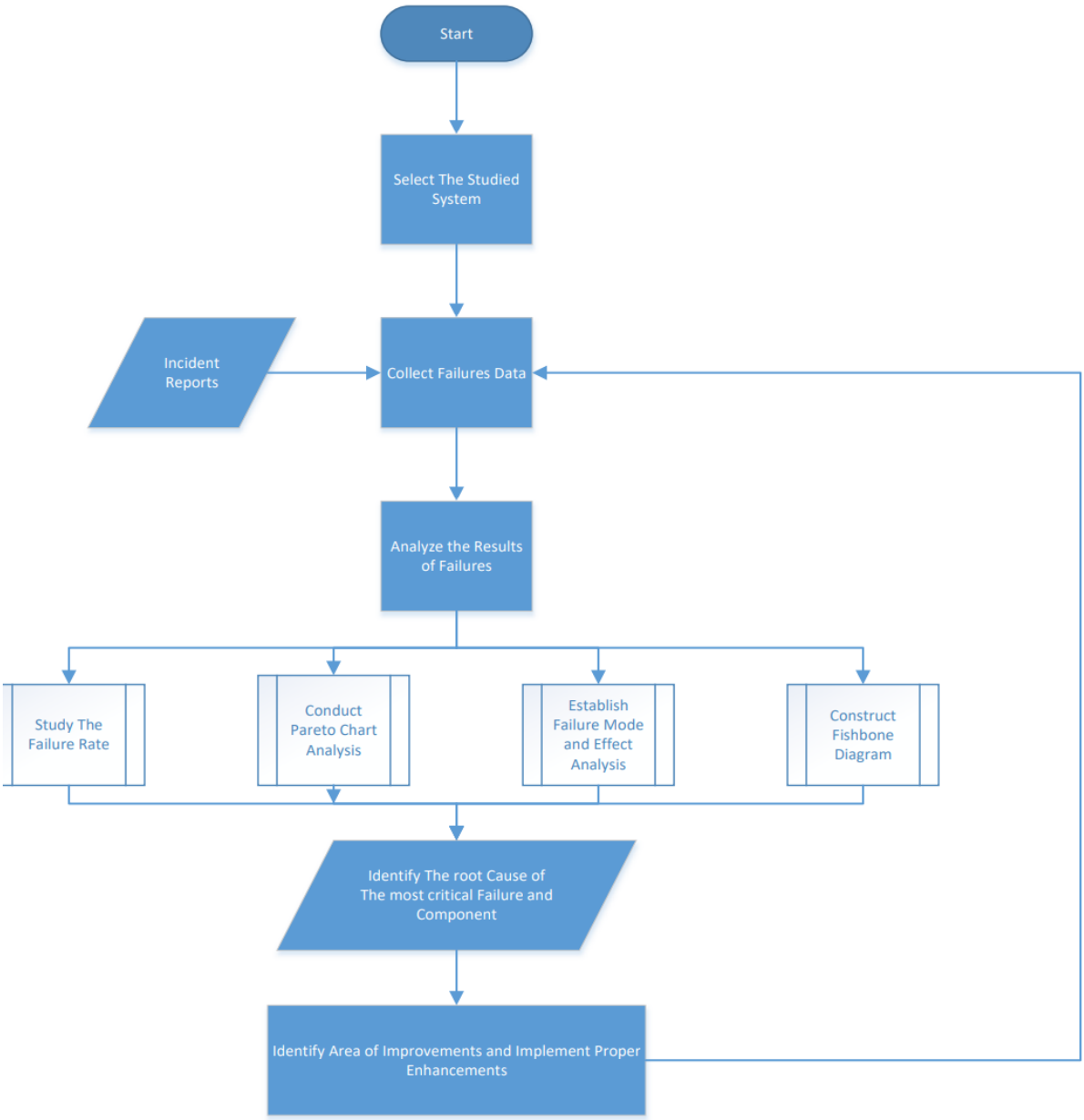

Figure 9: Failure Investigation Flow Chart

This Flow Chart, as shown in Figure 9, summarizes the root cause analysis approach that will investigate the failures of the systems using Failure Rate, Pareto Chart, Failure Mode and Effect Analysis (FMEA), and Fishbone Diagram. Moreover, this flow chart is a reference to follow and helps to study any other system.

Chapter 4 Research Result & Analysis

4.1 Introduction

This chapter presents the findings realized after analyzing the sewer pipe system failures. All collected data inputs come from the sewer pipe system in the Middle East region. Furthermore, there are two types of pipeline systems. The First is the Gravity pipeline system, and the Second is the Pressure pipeline system. The following section will represent the differences between each system. Also will realize and compare each system regarding the number of failures, failure rate, and Pareto chart. Then Failure Modes and Effects Analysis (FMEA) is used to evaluate the processes of the sewer pipe system. This was used to analyze the systems' possible failures and prevent them by modifying the processes. Finally, further analyses are conducted using the fishbone diagram to investigate the root causes of sewer pipe system failures.

4.2 System Differences

This section explores and analyzes the critical differences between gravity pipeline systems and pressure pipeline systems. Both systems are two distinct methods used for conveying Sewer through a network of pipes. This section will outline and explain the critical disparities between gravity pipeline systems and pressure pipeline systems. Examining these differences aims to understand better the variations, potential areas, implications, and types of failures for further investigation within the context of sewer pipeline system failures.

Table 4: Sewer Pipeline System Types Differences

No.	System application	Gravity	Pressure
1	Installation method	Directional / Slope	Non directional / Variable
2	Pipe thickness	Mainly thin	Mostly thick
3	Maintenance access	Manholes	Valves chambers
4	Maintenance difficulties	Easer	More difficult
5	Holes	Yes	No
6	Availabilities of control valves	Not applicable	Yes
7	Lift stations	Yes	No
8	Pump / Booster stations	No	yes
9	Failures troubleshooting	Difficult	Obvious
10	System application	Gravity	Pressure

Above Table 4 shows the difference between the Gravity and Pressure systems. The main difference is that the Gravity pipeline system works by gravity force, and the Pressure pipeline system works by electrical pumps. Also, the Pressure pipeline system is installed within very high specifications and after approvals from several parties, unlike the Gravity pipeline system, which is considered less harmful.

4.3 Analysis of Failures

This section analyzes the number of failures and the system's failure rate. Also, to represent the differences in the number of failures and the failure rate between each system. In addition, to calculate these differences between the components of each system.

Table 5: Failure Rate Statistics

	Type	Number of Failures	Time (# Months)	Failure rate Failure / Month
System	System failure rate	292	102	2.86
Gravity	Gravity failure rate	178	102	1.75
Pressure	Pressure failure rate	114	102	1.12
Gravity components	Joint	12	102	0.12
	Manhole	44	102	0.43
	Pipeline	122	102	1.20
Pressure components	Chamber puddle pipe	33	102	0.32
	Pipeline	68	102	0.67
	Valve chamber	13	102	0.13

Table 5 and below Figure 11 shows that the number of failures is 292 for the whole system. Also, the above Table 5 and the below Figure 12 shows that the Failure rate of the entire system is 2.86 Failure / Month. Also, the failure rate of each type of the system was calculated. The results were as follows, the failure rate of Gravity Pipeline system failures was 1.75 Failure / Month, and the failure rate of Pressure Pipeline system failures was 1.12 Failure / Month, as shown in Figures 13,14 and Table 5. It found that the Failure rate of the Gravity pipeline system is higher than the Pressure pipeline system, as shown in Figures 15,16 and Table 5. By searching more profound about the systems, it found that the Pipeline component has the highest Failure rate and the number of failures in the Gravity pipeline system. This significantly differs from the other Gravity pipeline system components, as shown in Figures 13,14. On the other hand, it found that the Pipeline component has the highest Failure rate in the Pressure pipeline system. But closely with the rest of the Pressure pipeline system's components, as shown in Figures 15,16.

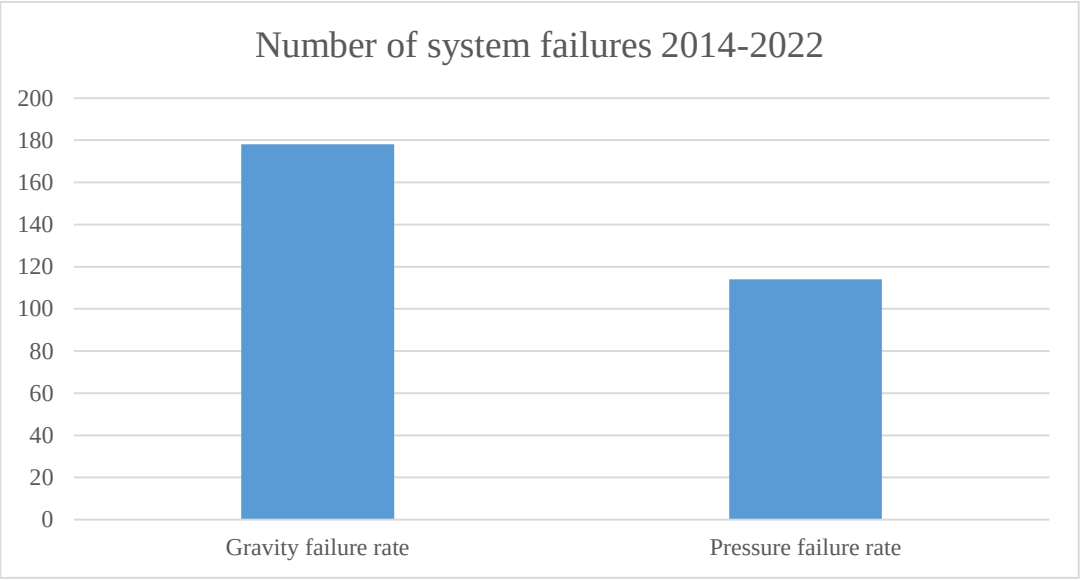

Figure 10: Number of System Failures 2014-2022

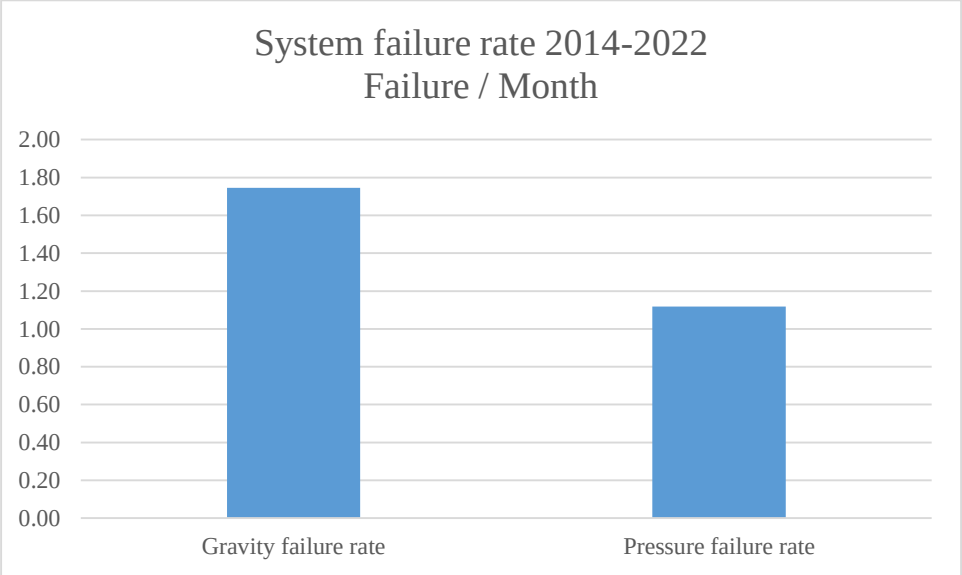

Figure 11: System Failure Rate 2014-2022

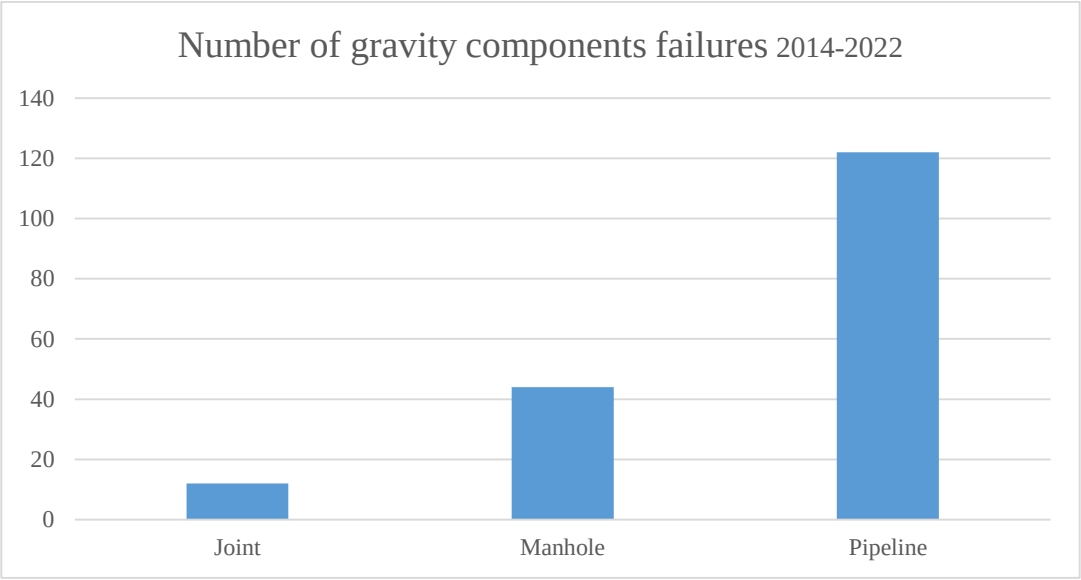

Figure 12: Number of Gravity Components Failures 2014-2022

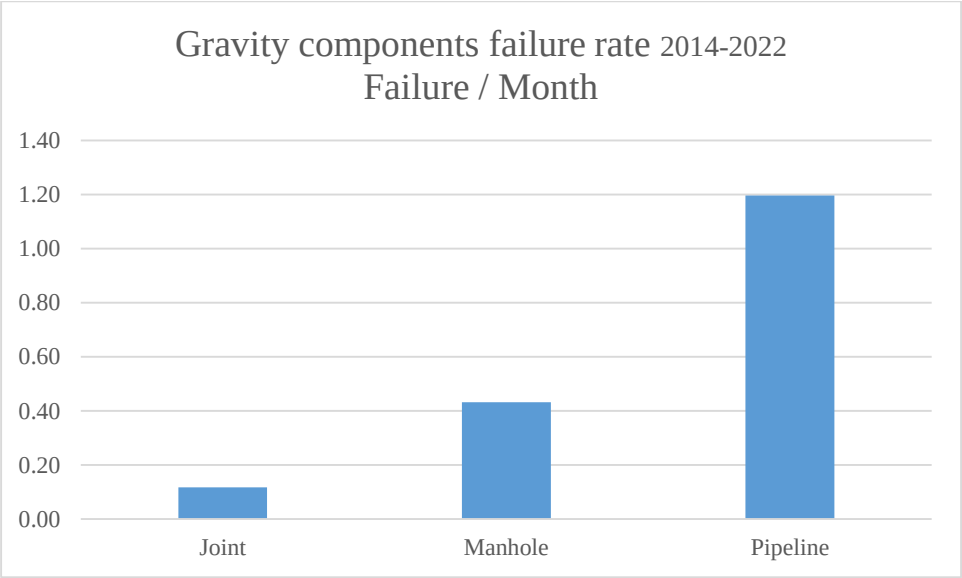

Figure 13: Gravity Components Failure Rate 2014-2022

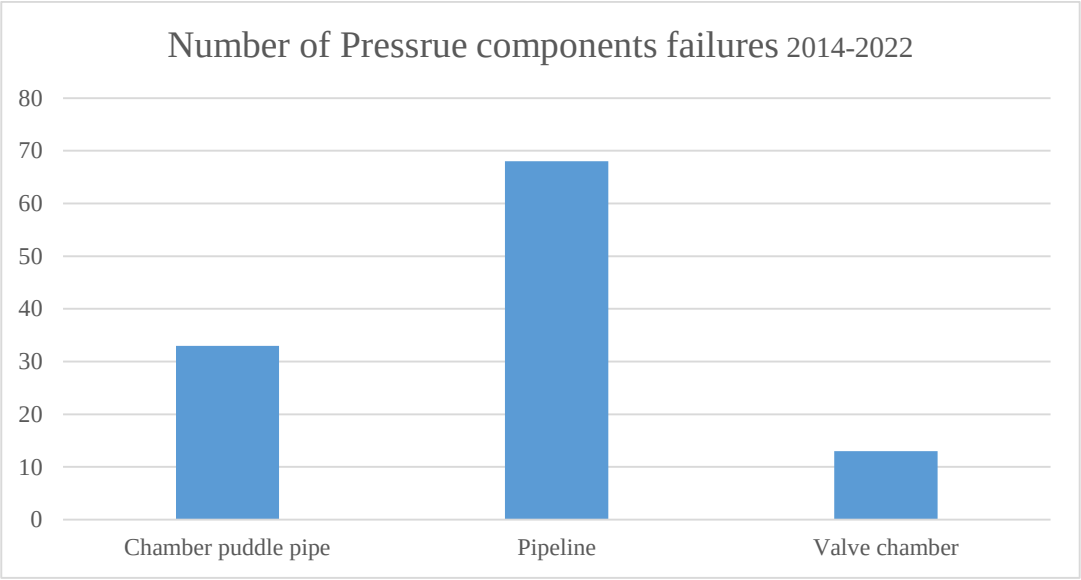

Figure 14: Number of Pressure Components Failures 2014-2022

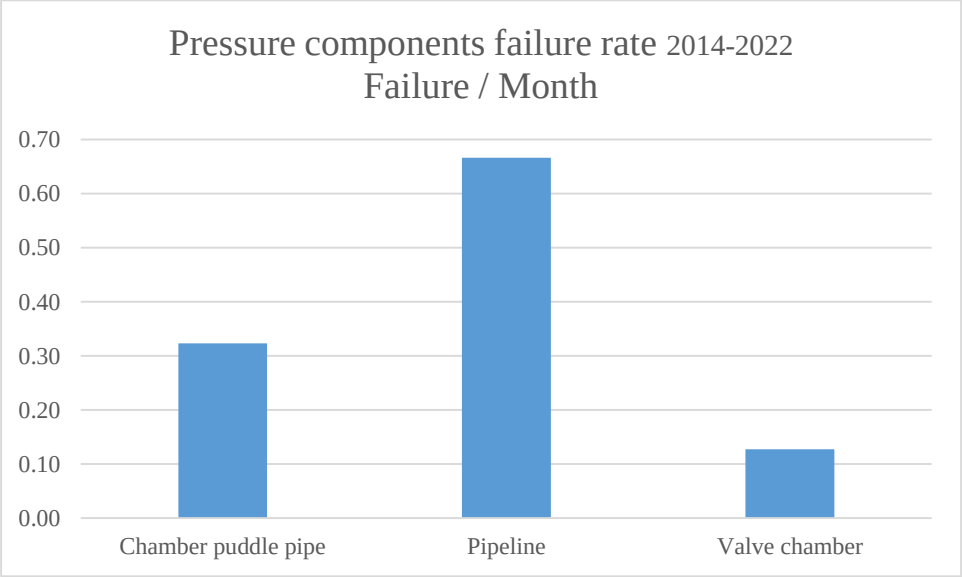

Figure 15: Pressure Components Failure Rate 2014-2022

4.4 Pareto Chart

This section uses a Pareto chart for visualizing and analyzing pipeline system failure data to identify the most significant failures contributing to a system. It presents the findings from both systems as one system. Also, it presents the findings from each system. This help to guide decision-making and problem-solving efforts. In addition, it addresses the most influential factors and improves overall outcomes.

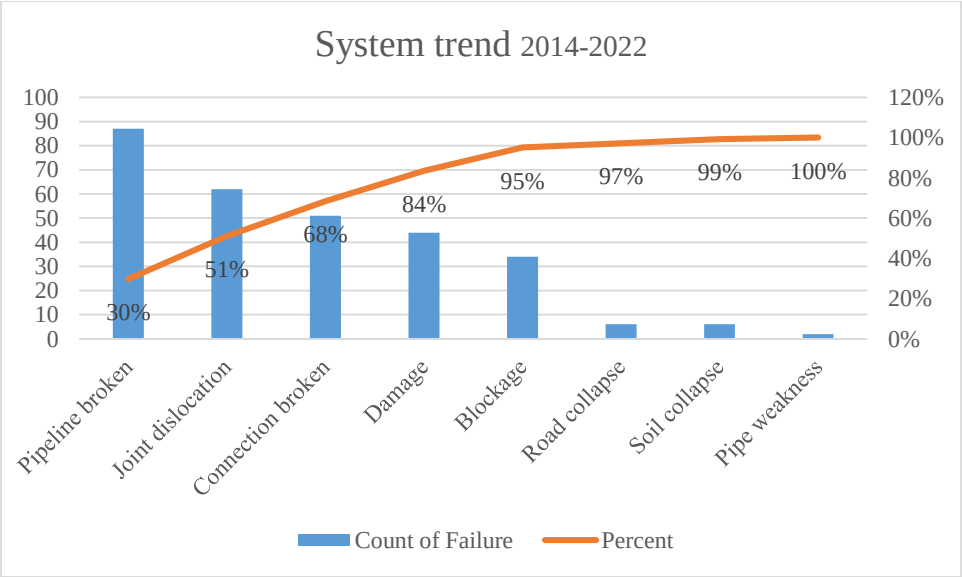

Figure 16: Pareto Chart of the System 2014-2022

The above Pareto chat Figure 17 was conducted using data from a Middle East company for Pipeline system failures from 2014-2022. The chart showed several significant findings. The data presented three major causes of pipeline system failures: Pipeline broken, Joint dislocation, connection broken, and damage. These causes are the main primary causes of system failure, accounting for 84% of the total failures. This included Gravity pipeline system failures and Pressure pipeline system failures.

Furthermore, these reasons are indicating the need to know the root causes of the failure. In addition, the root causes of the two additional causes mentioned above must be sought. It is recommended to arrange methods such as applying strong corrosion prevention strategies and

implementing stricter procedures for third-party activities near the pipelines to mitigate the risk of failures.

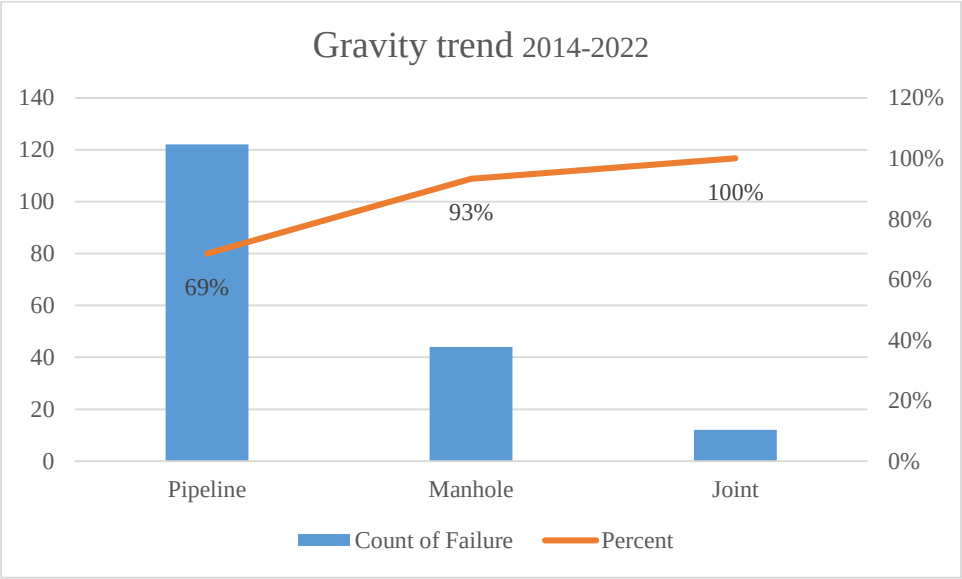

Figure 17: Pareto Chart of the Gravity System 2014-2022

The above Pareto chat Figure 18 was collected using Gravity pipeline system failure data. The data presented that pipeline system failures are the primary cause of the Gravity pipeline system, accounting for 68.5% of the total failures of the Gravity pipeline system.

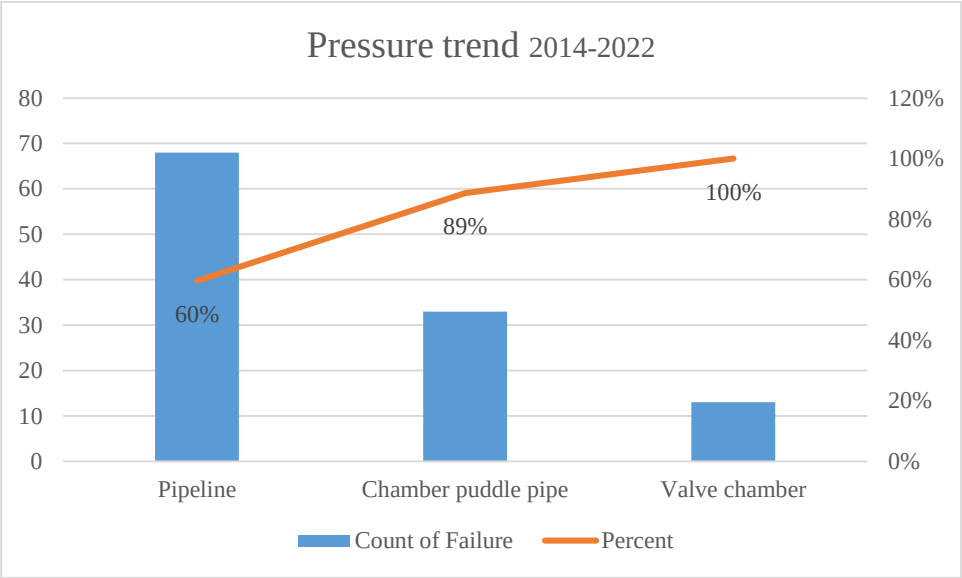

Figure 18: Pareto Chart of the Pressure System 2014-2022

The above Pareto chat Figure 19 was collected using Pressure pipeline system failure data. The data presented that pipeline system failures are the primary cause in the Pressure pipeline system, accounting for 60% of the total failures.

4.5 Failure Mode & Effects Analysis (FMEA)

This section is about Failure Mode and Effects Analysis for pipeline systems. It will identify and assess potential failure modes in a pipeline system. Also, it analyzes the possible ways components can determine their effects.

Table 6: Failure Mode & Effects Analysis

System type	Components	Failure mode	Causes of failures	Effect
Gravity	Joint	Joint dislocation	Collapse	Environmental consequence Health consequences Financial losses Infrastructure collapse
	Manhole	Crack	Damage	Environmental consequence Health consequences Financial losses
	Pipeline	Flooding	Blockage	Environmental consequence Health consequences Financial losses Infrastructure collapse collapse
		Joint dislocation	Blockage	
		Leakage	Joint dislocation	
			Pipeline broken	
Pressure	Chamber puddle pipe	Joint dislocation	Connection broken	Environmental consequence Health consequences Financial losses Sewage flooding
			Pipe weakness	
	Pipeline	Leakage	Pipeline broken	
		Joint dislocation	Connection broken	
	Valve chamber	Joint dislocation	Connection broken	

The above Table 6 shows the pipeline system's Failure Mode and Effects Analysis. FMEA crucial methodology employed in evaluating and mitigating risks to assess the components' criticality based on each failure mode's impact. The effect of pipeline system failures is very critical, especially because they affect the Environment and harm human health.

4.6 Fishbone Diagram

This section uses the visual tool to identify the potential causes of pipeline system failures. It is named the Fishbone diagram or Ishikawa diagram, and this diagram will help to explore the root causes of each pipeline system failure.

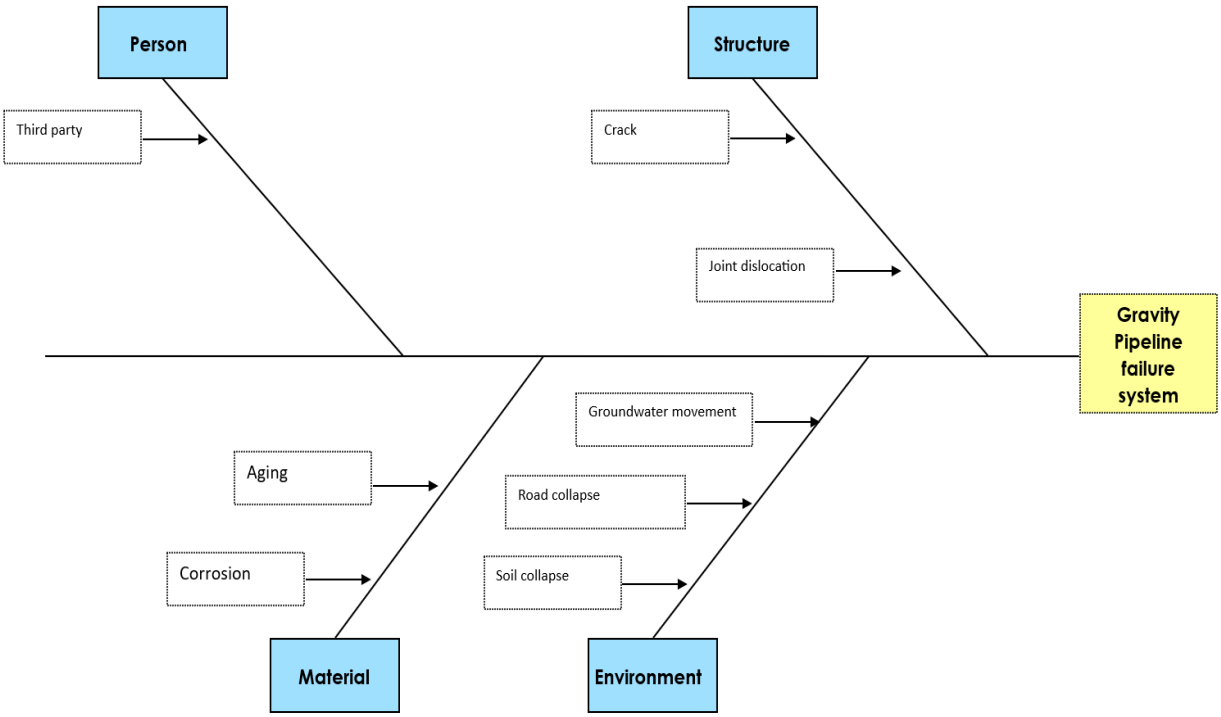

Figure 19: Fishbone Diagram for Gravity Pipeline Failure System

The above Fishbone Diagram Figure 20 shows several root causes of Gravity pipeline system failures. The major categories of the Gravity pipeline system failure causes are Structure, Person, Material, and Environment. The first category is structure, which includes the cracks in Pipelines, Joints, and Manholes. Also, sometimes when the joint becomes older Joint dislocation will happen. The second category is Person, which consists of all damages from Third party, including the contractors, government sector, or external authority or companies. This cause will not be immediately visible because these are pressure pipelines. The third category is material, which includes Corrosion in any system's materials. Also, Ageing is significant cause sometimes it can happen. The fourth category is Environment, which includes the collapse of either Road collapse or Soil collapse. Also, the most prevalent cause in this category is the

groundwater movement, as the Groundwater is affected by seawater tides, affecting the sewage pipelines. This system sometimes will not be visible to see the failure instantly because these are Gravity pipeline systems. A crack can be identified after the appearance of Sewer Water on the surface or the collapse happen.

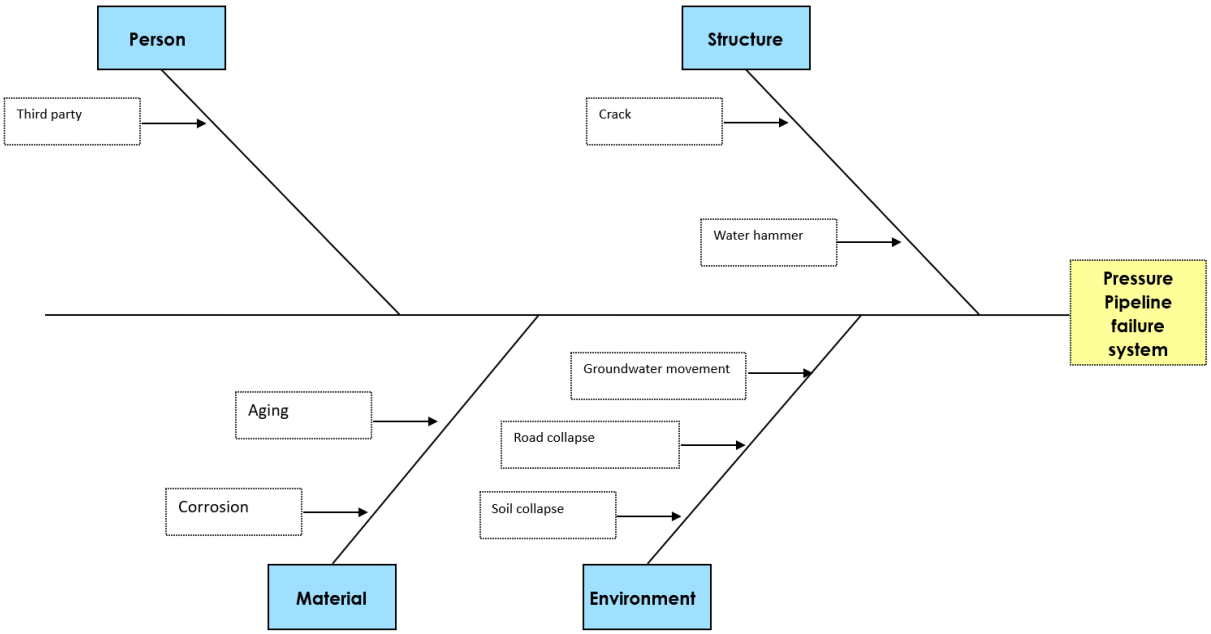

Figure 20: Fishbone Diagram for Pressure Pipeline Failure System

The above Fishbone Diagram Figure 21 shows several root causes of Pressure pipeline system failures. The major categories of the Gravity pipeline system failure causes are Structure, Person, Material, and Environment. The first category is structure, which includes the Cracks in Pipelines, Joints, and Chambers. Also, the Water Hammer is this category's most popular and very important cause. As it very much affects the sewage pipe system. The second category is Person, which consists of all damages from third party, including the contractors, any government sector, or any external authority or companies. The third category is material, which includes Corrosion in any system materials. Also, Ageing is significant cause sometimes it can happen. The fourth category is Environment, which includes either Road Collapse or Soil Collapse. Also, the most popular cause in this category is the groundwater movement, as the Groundwater is affected by seawater tides, affecting the sewage pipelines. The failure will be

instantly visible in this system because these are Pressure pipeline systems, as the pressure in the pipes will affect the sewage water and push it to the top of the surface.

4.7 Discussion

This section will address the total results obtained from the previous sections. Will also be analyzed the results and the data between each other. In addition, they will be linked to each other to achieve this research's aim and objectives.

The number of failures and the failure rate of the Gravity Pipeline system is higher than the Pressure Pipeline system. The reasons behind that are the material manufacturing of Pressure Pipeline systems are better than the Gravity Pipeline system material. Since the Pressure Pipeline system move the Wastewater with a very tremendous force, it needs to move in high-quality pipes that can withstand this high pressure. These Pipelines cannot be compared with the Wastewater in Gravity Pipeline system that move in the pipes by the force of gravity alone, so all of these lines are placed at an angle. Therefore, the Pressure Pipeline system installation must be accurately and cautiously handled and subject to approvals from several parties. Inspection and audit are carried out on the parts to ensure the installation is done correctly and safely. In addition, the movement of Groundwater affects the Gravity Pipelines system more than its impact on the Pressure Pipelines system due to what was previously mentioned of the difference between the manufacture of Pressure Pipelines system and Gravity Pipelines system.

The Pareto Chart was conducted to find out the most frequent system failures. Looking at Figure 16 for the whole system in general, found that the most frequent system failures are Pipeline broken, joint dislocation, connection broken, and damage. This means overcoming and solving these four system failures leads to overcoming 84% of the system's problems. In addition, Pareto Chart was conducted to determine the most frequent system failures for each type of system. This will help to improve each type of sewer pipeline system. Looking at Figure 17 for the Gravity System, found that the most frequent component in Gravity system failures was Pipeline. That was found to be a significant margin from the rest of the components in Gravity system. And on the other side as well, looking at Figure 18 for the Pressure System, found that the most frequent component in Pressure system failures was also the Pipeline but with Chamber. Furthermore, after using the fishbone diagram found that the most critical failure

mentioned above must work to improve the system by overcoming these failures, by analyzing and knowing the root causes.

Failure Mode and Effects Analysis (FMEA) was conducting and find out the failure mode, causes of failure, and effect of each component failure of each type of the system. For each component there is failure mode and cause of failure as shows in Table 6. Some of the components has same cause of failure. As for the effects, it is clearly turned out that the impact of the sewage pipeline system is somewhat similar. In addition, the most important consequences of the sewage pipeline system effects are the health and environmental effects. Furthermore, there is sometimes road collapse in some failure cases.

A fishbone diagram in Figures 20,21 was conducted to identify the root causes of each pipeline system. Depending on the previous methods and analysis, system failures were using Failure rate, Pareto chart, and Failure Mode and Effects Analysis. Accordingly, after using the fishbone diagram, the root causes of the Sewer Pipeline system were extracted. There are many root causes for Gravity Pipeline failures system like crack, joint dislocated, third party, groundwater movement, road collapse, soil collapse, aging and corrosion. On the other hand, the root causes for Pressure Pipeline failures system like crack, water hammer, third party, groundwater movement, road collapse, soil collapse, aging and corrosion. As showed mostly the root causes are similar. The most critical root cause based on the previous information, Third Party, Water Hammer, and Groundwater movement. Some of root causes are easily known like Water Hammer and this is happening in Pressure Pipeline systems only. And some of root causes are very difficult to known like Third Party failures in Gravity Pipeline systems. Because could bury the pipes and flee the site. These root causes must be overcome to develop and improve the sewer pipeline system.

Chapter 5 Conclusion

5.1 Conclusion

The wastewater system is one of the most critical infrastructure systems in any country in the world. It contains several systems from the beginning of the exit of water from homes to desalination and conversion of water for other uses. Therefore, it is significant to improve the system's reliability to avoid the implications of system failures.

This research focuses on Sewer wastewater, especially the pipeline system. In addition, the study aims to analysis pipeline system failures. This is for the Gravity or Pressure Pipeline systems, as the two systems work differently. Furthermore, each system has its materials and causes of failures. Accordingly, work was done to extract the statistics for the system in general, and the statistics were extracted for each system separately. There are multiple findings were found from the identified objectives in Section 1.3.2 as the following:

1. In this study, work has been done gradually to determine the causes and root causes of sewer pipeline system failures. It starts with the differences between each system to have a big knowledge of both systems and to facilitate extracting the causes. Then it begins with the calculations to extract the number of failures and the Failure Rate for the whole system and each system separately. Accordingly, it was found that the Gravity pipeline system has the highest number of failures and the highest Failure Rate. Consequently, delving more into the Gravity pipeline system, it turns out that the Pipeline is the highest number of failures and the highest Failure Rate in Gravity pipeline system components. Also, the Pressure pipeline system found that the Pipeline has the highest number of failures and the highest Failure Rate components.
2. Complementing the calculations and statistics, work has been done to do Pareto Chart. It shows that the most significant failures contribute to a system. And so, it has been shown that Pipeline broken, Joint dislocation, and connection broken are the most critical failures contributing to a system. Thus, it should be working to overcome these causes.

3. After that, Failure Mode and Effects Analysis (FMEA) was used to assess potential failure modes, Causes of failures, and effects in a pipeline system. There are various causes and different effects for each component of each system. The most common and critical system was found the Pressure pipeline system. The impact of the pressure pipeline system is more critical because of the enormous pressure from the pipes.
4. Finally, it used a fishbone diagram to identify the potential causes of pipeline system failures. It found that there are several root causes for each system's failures. First, for the Gravity pipeline system: the collapse could sometimes happen with the effect of damage to any components of the system. This could be known after a while for several reasons, whether because they did not appear on the surface or those damages were hidden if they were from a Third-party to escape responsibility. And this only happens when those failures in Gravity Pipeline. Second, for the Pressure pipeline system: The Water Hammer and Third-party reasons are the most critical root causes in this type of Pipeline.

After revising the data collected, it was found to get a very repetitive Water Hammer in the Pressure pipeline system. Also, the Third Party response is repeated in Pressure pipeline system failures. It remains that the impact of the Pressure Pipeline system is dangerous and harmful to the Environment, health, and human life. But knowing the failure is done easily, unlike the Gravity Pipeline system that was previously discussed.

5.2 Recommendations

Ultimately, the study represents the most critical and popular causes and root causes for the whole system and each separately. The study recommends that overcome of the most critical and popular causes and root causes were previously discussed. This will help to improve the system's reliability to avoid the implications of system failures.

The results of this research are reflected as an essential basis for future study, which leads to improving the system's reliability. In addition, the part of the improvement of future research are:

- How to overcome with Water Hammer arrestor in pressure pipelines system.
- Develop plans and methods for the work of the authorities and Third Party.
- Radical solutions to overcome the movement of Groundwater in Gravity pipelines system.
- Make standard comparisons and see the best practices used globally for using sewage pipelines that are suitable for the region and can overcome those causes mentioned previously.
- See best practices that may fit the sewage pipeline materials suitable for the region.

References

Antwi, S. K., Hamza, K., Polytechnic, T. & Polytechnic, T. (2015). Qualitative and Quantitative Research Paradigms in Business Research : A Philosophical Reflection, vol. 7(3), pp. 217–226.

Anwar, A., Liu, X. & Zhang, L. (2022). Biogenic corrosion of cementitious composite in wastewater sewerage system – A review. *Process Safety and Environmental Protection*. Elsevier Ltd, vol. 165(March), pp. 545–585.

Biyanto, T. R., Kusuma, F., Musyafa, A., Dwi, R., Bayuaji, R. & Irawan, S. (2016). Correction factor determination on failure rate equation of MacLaurin series for low and high mode application. *Ain Shams Engineering Journal*. Faculty of Engineering, Ain Shams University, vol. 7(2), pp. 827–834.

Boretti, A. & Rosa, L. (2019). Reassessing the projections of the World Water Development Report. *npj Clean Water*. Springer US, (June).

Carlson, C. S. (2014). Understanding and Applying the Fundamentals of FMEAs.

Colella, M., Ripa, M., Cocozza, A., Panfilo, C. & Ulgiati, S. (2021). Challenges and opportunities for more efficient water use and circular wastewater management . The case of Campania Region , Italy. *Journal of Environmental Management*. Elsevier Ltd, vol. 297(June), p. 113171.

Elizabeth, P. (2016). Developing a Qualitative Single Case Study in the Strategic Management Realm : An Appropriate Research Design ?, vol. 7(2), pp. 529–538.

Fadeyi, J. A., Okwu, M. O., Mgbemena, C. O. & Ezekiel, C. (2016). The Pareto principle and a hazard model as tools for appropriate scheduled maintenance in a manufacturing firm, vol. 1338.

Falakh, F. & Setiani, O. (2018). Hazard Identification and Risk Assessment in Water Treatment Plant considering Environmental Health and Safety Practice, vol. 06011, pp. 1–6.

Gyenes, Z. & Wood, M. H. (2016). Lessons Learned from Major Accidents Relating to Ageing of Chemical Plants, vol. 48, pp. 733–738.

Hassan, S., Wang, J., Kontovas, C. & Bashir, M. (2022). Journal of Loss Prevention in the Process Industries Modified FMEA hazard identification for cross-country petroleum pipeline using Fuzzy Rule Base and approximate reasoning. *Journal of Loss Prevention in the Process Industries*. Elsevier Ltd, vol. 74(June 2020), p. 104616.

Junga, P. (2022). Journal of Loss Prevention in the Process Industries Analysis of accidents at municipal wastewater treatment plants in Europe Petr Tr a, vol. 74(April 2021).

Khadom, A. A., Hassan, A. F. & Abod, B. M. (2015). Evaluation of environmentally friendly inhibitor for galvanic corrosion of steel – copper couple in petroleum waste water. *Process Safety and Environmental Protection*. Institution of Chemical Engineers, vol. 98, pp. 93–101.

Koning, J. De, Joksimovic, D., Savic, D. & Melin, T. (2006). Wastewater reuse in Europe Wastewater reuse in Europe, (February).

Lam, C., Engineer, A. & Zhou, W. (2016). International Journal of Pressure Vessels and Piping Statistical analyses of incidents on onshore gas transmission pipelines based on PHMSA database. *International Journal of Pressure Vessels and Piping*. Elsevier Ltd, vol. 145, pp. 29–40.

Li, J., Liang, B., Li, C., Yan, M. & Yu, J. (2019). Journal of Petroleum Science and Engineering Calculation methods for the gas pipeline failure rate. *Journal of Petroleum Science and Engineering*. Elsevier B.V., vol. 174(November 2018), pp. 229–234.

Magdalena, Ł. & Zakrzewska, A. (2020). Analysis of Risk Assessment in a Municipal Wastewater Treatment Plant Located in Upper Silesia.

Masi, F., Rizzo, A. & Regelsberger, M. (2018). The role of constructed wetlands in a new circular economy , resource oriented , and ecosystem services paradigm. *Journal of Environmental Management*. Elsevier Ltd, vol. 216, pp. 275–284.

Moskvicheva, E. V, Sidyakin, P. A. & Shitov, D. V. (2016). Method of Corrosion Prevention in Steel Pressure Pipelines in Sewerage Systems. *Procedia Engineering*. The Author(s), vol. 150(442), pp. 2381–2386.

Ricci, F., Moreno, V. C. & Cozzani, V. (2021). A comprehensive analysis of the occurrence of

Natech events in the process industry. *Process Safety and Environmental Protection*. Institution of Chemical Engineers, vol. 147, pp. 703–713.

Shan, X., Liu, K. & Sun, P. (2017). Risk Analysis on Leakage Failure of Natural Gas Pipelines by Fuzzy Bayesian Network with a Bow-Tie Model, vol. 2017(2).

Smol, M., Adam, C. & Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. *Journal of Material Cycles and Waste Management*. Springer Japan, vol. 22(3), pp. 682–697.

Srivastava, P., Abbassi, R., Kumar, A. & Garaniya, V. (2020). Chemosphere A review on the contribution of electron fl ow in electroactive wetlands : Electricity generation and enhanced wastewater treatment. *Chemosphere*. Elsevier Ltd, vol. 254, p. 126926.

Stanaszek-tomal, E. & Fiertak, M. (2016). Biological Corrosion in The Sewage System and The Sewage Treatment Plant. *Procedia Engineering*. The Author(s), vol. 161, pp. 116–120.

Tušer, I. & Oulehlov, A. (2021). Risk Assessment and Sustainability of Wastewater Treatment Plant Operation, pp. 1–17.

Voulvoulis, N. (2018). ScienceDirect Water reuse from a circular economy perspective and potential risks from an unregulated approach. *Current Opinion in Environmental Science & Health*. Elsevier Ltd, vol. 2, pp. 32–45.

Wang, F. K. (2000). A new model with bathtub-shaped failure rate using an additive Burr XII distribution, vol. 70.

Xie, M., Tang, Y. & Goh, T. N. (2002). A modi ® ed Weibull extension with bathtub-shaped failure rate function, vol. 76.

Yin, X., Chen, Y., Bouferguene, A., Zaman, H., Al-hussein, M. & Kurach, L. (2020a). Automation in Construction A deep learning-based framework for an automated defect detection system for sewer pipes. *Automation in Construction*. Elsevier, vol. 109(June 2019), p. 102967.

Yin, X., Chen, Y., Bouferguene, A., Zaman, H., Al-hussein, M. & Kurach, L. (2020b). Automation in Construction A deep learning-based framework for an automated defect

detection system for sewer pipes. *Automation in Construction*. Elsevier, vol. 109(August 2019), p. 102967.