

Critical Path Method and Economic Analysis of a Smart Leak Detection System for Desalination Water Networks in Saudi Arabia

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Abstract

Water scarcity is a growing global challenge, and leaks in distribution networks continue to contribute significantly to this problem. This paper presents an intelligent leak detection system for desalination networks. This system relies on integrating Internet of Things (IoT) sensors with automatic shut-off valves and ESP32 microcontrollers to accurately locate leaks and send notifications directly to the operator via the Blynk app. The Critical Path Method (CPM) was used to improve project scheduling and resource management while ensuring efficient execution. Simulation tools such as SolidWorks and Proteus were used to verify the electronic control logic and the correctness of the system design. The project management analysis determined the total project duration to be 15 weeks. The system demonstrated high feasibility with an initial cost of 916 Saudi Riyals and a payback period of approximately 1.22 years, which proves the system's cost-effectiveness in reducing water and operational losses. The results clearly demonstrate the potential for development and expansion to include several regions in the Kingdom, which will enhance sustainability and efficiency in water resource management in Saudi Arabia.

Keywords

Detecting Leaks, Critical Path Method (CPM), Risk Management, Water distribution networks, Economic study.

1. Introduction

Drinking water scarcity is a pressing problem facing all continents. Water resources are dwindling, and population growth is putting pressure on all economies. Inefficient water uses and reliance on traditional and ineffective methods exacerbate this problem. In 2020, approximately 2.4 billion people lived in countries experiencing water stress

(Jayakumar et al., 2024). The UN-Water 2025 report also indicated that approximately 4 billion people suffer from seasonal water scarcity, and that approximately 2.2 billion people do not have access to safe drinking water, highlighting the importance of water network management. Water distribution pipes are located underground, making water leakage a silent problem that causes financial losses worldwide. The challenge lies in detecting leaks in a timely manner, which is difficult (Awwad et al., 2020). These undetected leaks lead to many negative effects, including significant water waste, increased operating and maintenance costs, and higher energy consumption. The continuation of these deposits reduces the ability of operators to manage networks efficiently and make effective decisions (Rodriguez et al., 2025). In our current era and with continuous progress, intelligent management of distribution networks has become important to raise service efficiency and improve resource utilization (Gonçalves et al., 2020).

Water loss can reach up to 50%, and this can have a significant economic impact (Elshazly et al., 2024). Many current experiments face numerous challenges in innovation and rapid leak detection, especially if the water network and operating program are not properly planned (Shin et al., 2024). Furthermore, emerging economic consequences can shift water consumption from leaks to areas with limited water availability. When necessary, additional energy is required for water treatment, pumping, and distribution to compensate for the lost water (Reissue et al., 2023). Moreover, moisture erosion and marine fiber degradation are commonly observed as secondary effects of continuous water leakage. Some consequences of water leakage include increased humidity levels, which can affect foundation stability, deteriorate roads and materials, and lead to land subsidence (Dastpak et al., 2023). Consequently, a fast and effective water tapping device is crucial for controlling this issue. Costs began to improve, communication reliability improved, and the water-dependent environment improved (Moubayed et al. 2021).

A group of global water experts has pointed out that partnerships in the water sector are no longer limited to a single aspect; rather, they have expanded to include research and technical activities, in addition to developing specialized programs and projects that contribute to supporting the sustainability of water resources. In this context, the World Water Council has indicated its move toward a new phase of intensive cooperation with the Kingdom of Saudi Arabia, expecting that the Kingdom will attain a leading global position in the water sector over the next two years-and perhaps longer (Ministry of Environment, Water & Agriculture, 2025). The primary benefits of utilizing smart operating systems in water facilities lie in achieving the sustainability of water resources through the use of precise monitoring devices that provide real-time information, which facilitates the early detection of leaks and immediate handling of issues (Bhardwaj et al., 2022). Leak detection methods include both continuous electronic monitoring and periodic maintenance and inspection (Awwad et al., 2020). Examples of smart systems employed in urban water distribution include Machine Learning, the Internet of Things (IoT), and Artificial Intelligence technologies, which enable effective monitoring and precise management of water distribution networks (Naqash et al., 2023). Advanced network management is shifting from corrective maintenance (which intervenes after failures occur) to intelligent maintenance based on machine learning. These models are distinguished by their ability to identify complex and interrelated patterns among influencing factors and failure trends, thereby enhancing the accuracy of pipe burst prediction and the identification of high-risk areas (Chen et al. 2025). In this study, we will focus on addressing leaks in desalinated water distribution networks, as these leaks are a problem that causes financial, water, and environmental losses. There is a pressing need to solve this problem in areas where water is difficult to obtain and places high operational pressure. The city of Abha is one of these areas, being a mountainous region. This research utilized smart systems such as Internet of Things (IoT) sensors and an automatic shut-off valve that would be activated upon detecting a leak by calculating water loss and accurately determining the leak location. This principle was applied due to its proven effectiveness in providing accurate results according to previous studies. This will help reduce water loss and financial losses, as well as promote sustainability and increase the efficiency of water distribution networks management in Saudi Arabia.

1.1 Objectives

- 1- Planning and implementing an intelligent leak detection system in desalinated water distribution networks based on the analysis and application of the critical path method (CPM) to improve and manage time and resources.
- 2- Evaluating the economic feasibility of the system through an economic analysis to measure the impact of the smart system for leak detection based on the Internet of Things in reducing water loss and operating costs while ensuring high accuracy in leak detection.

2. Area of study

In this research, the city of Abha was chosen as the study site because it is considered one of the most challenging areas for pumping and distributing water in the Kingdom of Saudi Arabia. Abha is located in a mountainous region at a high altitude, which necessitates high pressure and significant energy to pump water from the Shuqaiq desalination plant. Therefore, every leak, no matter how small, is not only a waste of water but also a waste of effort and operational costs required to deliver water to the area, which may cause significant losses. More specifically, this research focuses on the Ahad Rafidah Governorate, which is part of the greater Abha region. The Ahad Rafidah Governorate is located southeast of central Abha and includes several neighborhoods such as Al Faisaliyah, Al Jarrah, Al Huda and Al Mazab. These neighborhoods are connected to a local water distribution network known to have problems due to the nature of the land and the age of the infrastructure.

Having an intelligent system capable of detecting leaks quickly and accurately is of great value, which is why Abha was chosen as the location for the study, as it is one of the most challenging areas in Saudi Arabia in terms of pumping and distributing water. If the system proves effective in Abha, it should serve as a model to be emulated in other regions with similar terrain and challenges, as the goal of this research is not limited to solving a local problem but lays the foundation for scalable solutions that benefit many regions in the Kingdom of Saudi Arabia (Figure 1).

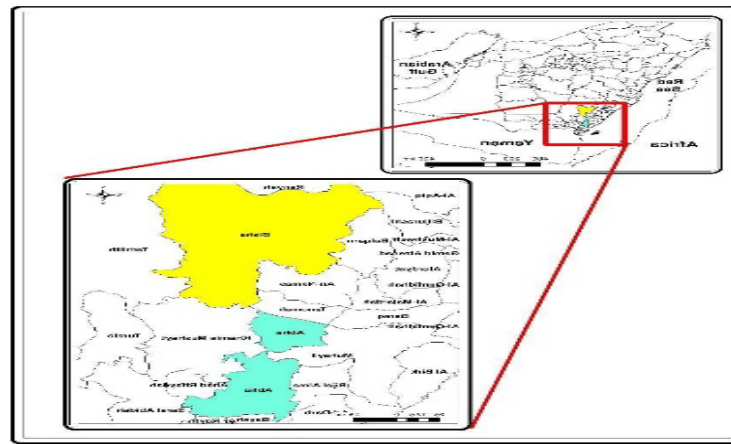


Figure 1. The location of Abha city

3. The hypotheses of the study

Hypothesis 1: Applying the critical path method (CPM) contributes to improving the planning and implementation of the smart system for leak detection to accelerate response, reduce financial and water losses, and improve project efficiency.

Hypothesis 2: The smart system for leak detection is economically viable with a favorable cost-benefit ratio; it is an effective solution for enhancing management efficiency in desalination networks in terms of cost.

4. Research Methodology

The Smart Water Leak Detection System adopts an integrated approach that combines Internet of Things (IoT) technologies with engineering management tools to improve water resource management. The development of the project was organized into several main phases. In the design and simulation phase, SolidWorks was used to design 3D models and achieve effective sensor distribution, while Proteus was utilized to test the electronic circuits and the control logic of the ESP32 unit. For project scheduling, the Critical Path Method (CPM) was applied to organize work stages and ensure adherence to the project timeline. The economic feasibility of the project was evaluated using Cost-Benefit Analysis (CBA) and Payback Period analysis to compare the initial costs with the economic returns resulting from reduced water leakage. In addition, risk and reliability management were structured using a Risk Breakdown Structure (RBS) and Failure Modes and Effects Analysis (FMEA) to identify potential sensor failures and establish preventive maintenance measures.

4. Data Collection

The data for this research was collected from multiple sources, including government organizations, academic studies, simulation tools, questionnaires, and scientific articles. All these sources contributed to the collection and analysis of the essential data needed to build an intelligent system.

- SolidWorks software was used to simulate a complete virtual water network model by adding sensors.
- MATLAB software was used to simulate the network and link it to SolidWorks to test its effectiveness and functionality.
- Proteus software was used to design a simulation of the electronic circuit, which includes a microcontroller, water flow sensors, a smart valve, and a display screen for data presentation.
- An Arduino board was used to write the code, operate the system, and send alerts in case of any leaks.

This combination of data sources and simulation tools provided an effective and reliable solution for ensuring the system's data collection reliability and its accuracy in detecting leaks in the desalination network.

6. Results and Discussion

6.1 Project Management

6.1.1 Project scheduling

Critical Path Method (CPM) is a technique used to evaluate manufacturing aspects, leading to reduced delays that cause prolonged migration. (Perrucci et al.,2025).

Table 1. Schedule of the Project

Activity cod	Activity Description	Predecessors	Estimated Duration (by Week)
A	Problem identification and project agreement	None	2
B	Task distribution among members	A	1
C	Building the simulation model using SolidWorks and Proteus	B	3
D	Ordering components to create prototype	C	1
E	Assembling and testing project components	C, D	4
F	Analysis and optimization	E	2
G	Filming and presenting the project	F	2
H	Writing the research paper	E	3
I	Reviewing the project	H	2

We use the Activity on Node (AON) method to calculate the critical path. This method links activities with arrows to show the sequence and what the activities depend on. Table 1 shows the project activities, what they depend on, and the time required to complete each activity.

- ES: Early Start. The first activity starts at zero.
- EF: Early Finish. Calculated by adding the activity duration to ES.
- EF: Minimum project completion time for the last activity.

As shown in Figure 2

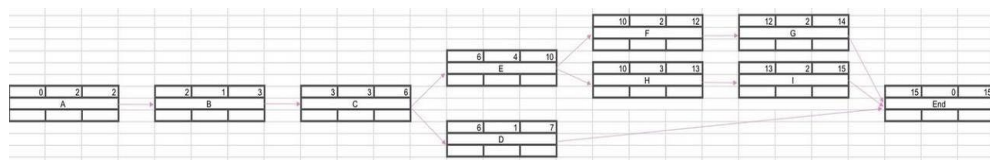


Figure 2. Network modeling and Forward pass

Reverse path: Calculating late and rest times

- LF: Late completion of the last activity equals EF.
- LS: Late Start. Subtracts the activity duration from LF.

- slack: $LF - EF$ or $LS - ES$

As shown in Figure 3

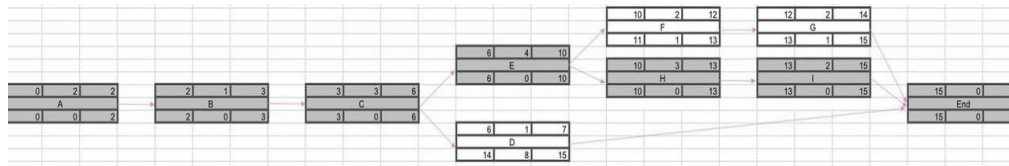


Figure 3. Backward pass and Critical Path

Results and Analysis

Total Project Duration: 15 Weeks

Critical Path with Total Slack of 0

$A \rightarrow B \rightarrow C \rightarrow E \rightarrow H \rightarrow I \rightarrow \text{End}$

Any activity with a Total Float of 0 (TF) is considered critical. Any delay, however small, will delay the project delivery. Therefore, it must be managed very carefully.

Other activities with a TF value can be delayed up to a certain point. These paths are not currently critical, but their low TF values make them very sensitive. Any delay in any of these activities could quickly turn it into a critical path, threatening the project's completion time.

6.1.2 Risk Management

It is a systematic process that identifies and analyzes potential risks, helps in making decisions to avoid and minimize damage, and may increase the chances of success and reduce threats that affect project objectives (Dogonyaro and Elnokaly, 2025).

6.1.2.1 Risk Breakdown Structure (RBS)

It is a tool used to categorize risks into levels and categories, organizing and assisting in their management and analysis. This structure helps in identifying all expected risks of various types and understanding their impact on the project. It is used to simplify and facilitate the risk assessment process and subsequently develop response plans (Figure 4).

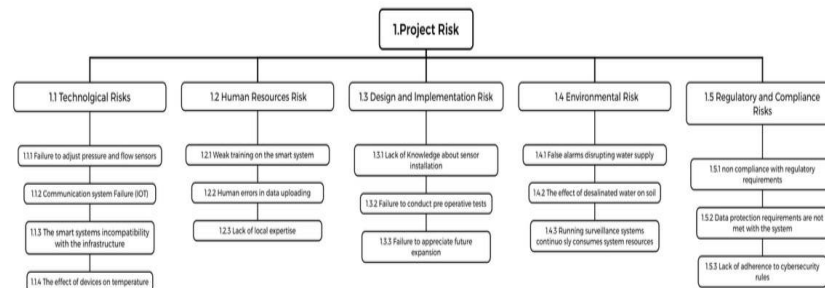


Figure 4. Risk Breakdown Structure (RBS)

6.1.2.2 Risk Management Plan

A plan is designed to prevent risks before they occur, improve decision-making, identify, analyze, and control potential problems, and help identify and mitigate risks that affect objectives (Abu Bakar et al., 2025). Table 2 assesses the risks associated with designing an intelligent leak detection system in Abha, Saudi Arabia, and outlines a mitigation strategy.

Table 2. Risk management plan

Risk Category	Identified Risk	Impact	Mitigation Strategy
Technological	Sensors not adjusted	Lower the quality of the leaks	Installing sensors designed for harsh desalination environments
Technological	Control system failure	Too many false warnings	Using eraser operating data to fine tune algorithms
Human Resource	Local talent scissors	Continued reliance on external support	Providing clear operating steps and established procedures
Human Resource	Human errors in data uploading	Not using the system correctly	Providing accredited training programs and courses
Design & Implementation	Lack of knowledge about sensor installation	Numerous modifications after implementation	Hydraulic simulation mode
Design & Implementation	Failure to conduct pre operation testing	Increase in operational malfunctions	Conduct comprehensive tests before commencing full operation
Environmental	High energy consumption	Operation devices continuously	Providing energy efficient devices
Environmental	The effect of water leakage on soil	Damage to the local environment	Accelerating response to leak detection
Regulatory	It violates data protection requirements	Stopping or delaying the project	Commitment to data protection
Regulatory	Disregard for rules	Financial penalties and punishments	Continuous review of required systems and standards

6.1.2.3 Risk Assessment Matrix

Risk assessment is a systematic methodology used to identify and evaluate potential risks by examining their probability of occurrence and magnitude of impact. Recent studies indicate the importance of using risk assessment matrices in engineering and infrastructure systems to systematically classify risks and support more accurate decision-making (Chaiklieng et al., 2025). The risk assessment matrix is also known as the probability and intensity matrix, and it provides a clear framework for prioritizing risks and enhancing system reliability, especially in critical infrastructure applications.

Risk Matrix		Severity				
		Insignificant	Minor	Moderate	Major	Severe
Likelihood	Almost Certain	Medium	High	Very High	Very High	Very High
	Likely	Medium	High	High	Very High	Very High
	Possible	Low	Medium	High	Very High	Very High
	Unlikely	Low	Low	Medium	High	Very High
	Rare	Low	Low	Medium	Medium	High

Figure 5. Risk Matrix

The qualitative levels of risk are determined by intersecting the probability of occurrence with the severity of impact, as illustrated in Figure 5. The specific criteria used to evaluate the severity of these risks are detailed in Table 3.

Table 3. Risk Assessment Matrix

Risk	Likelihood	Severity	Risk Level
Technological	Likely	Major	Very High
Human Resource	Unlikely	Minor	Low
Design & Implementation	Likely	Moderate	High
Environmental	Possible	Severe	Very High
Regulatory	Unlikely	Major	High

The risk assessment results indicate that technical and environmental factors pose the greatest threat to the smart water leak detection system. Accordingly, these risks have been addressed through preventative maintenance procedures, enhanced system reliability via redundancy, and a robust design that ensures continuous operation and reliable performance.

6.1.3 Preventive Maintenance Strategies

Preventive maintenance is a strategy aimed at minimizing unexpected breakdowns and maintaining the efficiency of equipment and systems. This strategy involves performing routine maintenance before any failure occurs. Regular inspection and maintenance procedures are implemented to help extend machine lifespan, improve safety levels, and significantly reduce repair costs. This, in turn, leads to increased productivity and efficiency. Preventive maintenance has evolved thanks to modern technologies such as the Internet of Things (IoT), artificial intelligence (AI), and the internet. These technologies monitor equipment and detect malfunctions before they occur. Preventive maintenance has become an essential aspect of industrial operations because it balances operational efficiency and cost, contributing to the success and sustainability of the production system (Berrahail et al., 2025).

6.1.3.1 Fault Tree Analysis (FTA)

A diagram used to identify potential causes of failure in complex systems and to analyze the relationship between causes and effects. It is one of the most important tools in industrial engineering and risk management, helping to reduce accidents and enhance safety (Göksu et al., 2025).

6.1.3.2 Failure Mode and Effects Analysis (FMEA)

It is a scientific methodology used to identify potential problems and weaknesses in a system, with the aim of preventing them and minimizing their negative impacts. This analysis is used to study the process and its steps, how it might fail, and what would happen if it did. Problems are classified according to their likelihood of occurring, their severity, and their ease of detection (Shao et al., 2024). This research was conducted on the safety and reliability of desalination plants in abha Saudi Arabia. We will use linear tree analysis (FTA) to minimize risks that may affect the system, and then we will use failure pattern analysis and its effects (FMEA) in an intelligent leak detection system to detect potential faults with the aim of improving and enhancing operational reliability and conserving water and the environment (Figure 6).

Section 1. Fault Tree Analysis (FTA) for Smart Leak Detection system



Figure 6. FTA for Smart Leak Detection Systems

Section 2: Failure Mode and Effects Analysis (FMEA) to Avoid Vehicle Malfunctions

Given that technical failures in water networks can lead to significant resource depletion and infrastructure damage, the FMEA methodology was used to identify potential failure points and implement appropriate preventative measures. This analysis aims to enhance the reliability of the proposed Internet of Things (IoT)-based leak detection system. Critical system processes—from sensor data acquisition to automated valve response—based on Severity (SEV), Occurrence (OCC), and Detection (DET). By determining the Risk Priority Number (RPN), high-priority risks can be identified and addressed to ensure 100% system continuity.

I. Determine the fundamental elements of the leak detection system for examination:

- 1- Flow Monitoring System
- 2- Leak Detection Logic
- 3- System Control Unit
- 4- Data Logging & Connectivity

II. FMEA Assessment Table (4) for Preventing System Failures:

Table 4. Failure Mode and Effects Analysis

Process	Failure Mode	Failure Causes	Failure Effects	SEV	OCO	DET	RPN	Preventive Measure
1-Flow Monitoring System	Hydraulic Noise	Pressure fluctuations	Potential false alarms	5	6	2	60	Two-stage verification logic
2-Leak Detection Logic	Verification Delay	Communication lag	Increased water loss	7	3	4	84	Optimized cloud synchronization intervals
3-System Control Unit	Valve Failure	Mechanical wear	Major water loss or flooding	9	2	5	90	Fail-safe manual override mechanism
4-Data Logging & Connectivity	Connection Loss	Wi-Fi instability	Loss of real-time monitoring	6	4	5	120	Auto-reconnect firmware scripts

Our system assesses the magnitude of risks, and we use what is called a Risk Priority Number (RPN) to determine this. The RPN is calculated by considering three factors: Severity (S), Frequency (O), and Detectionability (D). Based on the model discussed by (Tooranloo and Atabak, 2025), This method helps us manage risks effectively. A high RPN serves as a warning signal indicating weaknesses in the system, requiring immediate action to address them and ensure stability.

III. Analyzing Results and Prioritizing

The RNP is calculated by multiplying three factors: Severity (S), Frequency (O), and Detectionability (D). If the RNP is high, it means the risk is extremely serious, and urgent action must be taken to prevent it.

The highest RNP was recorded for data logging and connectivity (RPN = 120), primarily due to the potential for Wi-Fi signal instability. To mitigate this problem, we have integrated advanced software for automatic reconnection within the system, ensuring continuity of monitoring even during network fluctuations.

To maintain the operational safety of the system and ensure water conservation, a preventive maintenance plan was developed, as detailed in Table 5.

Table 5. Routine maintenance schedule

System Elements	Maintenance schedule
Flow Monitoring System	Periodic calibration and inspection of flow sensors every 3-6 months to ensure accurate flow measurements.
Leak Detection Logic	Routine verification of leak detection logic and cloud synchronization performance on a quarterly basis.
System Control Unit	Functional testing of the smart valve and control logic every 6 months to ensure reliable system response.
Data Logging & Connectivity	Continuous monitoring of network stability and verification of auto-reconnect functionality during monthly system checks.

6.2 Economic Study

This study aims to evaluate the economic feasibility of a water leak detection system in water distribution networks by comparing initial costs with expected savings (Table 6).

Table 6. Equipment and Software

Equipment and Software Description	Unit Price (SAR)	QTY	Total
ESP32 Development board	32	1	32
Roeling DC active	15	1	15
Water pump	34	1	34
MCU single channel 5v	16	1	16
LCD module with back light	50	1	50
Sensor controlling YF-S201	72	5	364
Aligo DuPont 120-MB	29	1	29
Interface board 102-MB	81	1	81
Solenoid valve	66	1	66
Power sockets	50	1	50
			Total = 733

Total Initial Costs

Equipment cost as per Table 3: 733 SAR and installation and training cost (25% of equipment cost): 183 SAR

$$\text{Total Initial Costs} = 733 + 183 = 916 \text{ SAR}$$

Annual Net Savings

Annual net savings are calculated according to the following equation:

$$\text{Annual Net Savings} = \text{Annual Gross Savings} - \text{Annual Operating Costs}$$

This value represents the gross savings (900 SAR), which is the financial value of the water and energy saved by reducing losses in the initial application. It includes annual operating costs (150 SAR), such as minor maintenance expenses and electricity consumption.

$$\text{Annual Net Savings} = 900 - 150 = 750 \text{ SAR}$$

Payback Period

$$\begin{aligned} \text{Payback Period} &= \text{Total Initial Costs} / \text{Net Savings Annual} \\ 916 \div 750 &= 1.22 \text{ years} \end{aligned}$$

Approximately one year and two months. Due to the short payback period compared to the system's expected lifespan, the project is economically efficient and contributes to reducing losses in desalination networks.

7. Conclusion

In this project, we focused on project management and risk management of desalination water networks in the Kingdom of Saudi Arabia. Through project planning and operational risk monitoring, we designed an integrated system for early leak detection in the network using ESP32 and flow sensors. This approach helped us identify potential risks before they occur, and we put in place rapid response mechanisms through instant alerts and automatic valve closure. This procedure reduces water loss and protects the infrastructure.

This project reflects the importance of project management and its integration with risk management to achieve the highest efficiency in system operation. The research shows that applying this methodology reduces economic and water losses and contributes to enhancing the environmental sustainability of the network.

We believe it is easy to expand the application of this system at the level of national networks that aim to enhance sustainability while promoting project management and risk management practices to ensure effective monitoring, thereby improving performance and operational efficiency in the long term.

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Biographies

Reem N. Alsaadi is undergraduate Industrial Engineer in final year at Bisha University with exceptional academic performance. She complete her coop-training with Saudi Mobily under Operational Excellence, focusing on Quality Assurance. Reem has been an active member of the Bisha Chapter of Industrial Engineering and Operations Management (IEOM) since its founding in 2022, serving as Programs and Activities Leader. She is also a member of the Society of Petroleum Engineers (SPE). A former member of the Engineering Club and the Renewable Energy Club. She always strives to contribute to innovative and sustainable projects that combine efficiency with societal impact.

Asrar A. Al-Shahrani is a senior industrial engineering student at Bisha University. She has a keen interest in project management, intelligent systems, and sustainability in industrial applications. During her studies, she developed her skills in analyzing and improving industrial systems, with a particular focus on enhancing efficiency and ensuring safe practices. She enrolled in numerous online courses to further develop her skills. Her academic career also reflects her commitment to integrating technical knowledge with practical applications to contribute to sustainable and well managed engineering projects.

Jawharah A. Al-Qasebah is a senior student in the College of Engineering, specializing in industrial engineering at Bisha University. She received a two-month internship at the Ministry of Environment, Water and Agriculture, which provided her with valuable information that provided significant support for this research. Jawharah has held several positions in extracurricular activities, including being the Programs and Activities Section Leader for the International Society for Industrial Engineering and Operations Management (IEOM), Bisha University Chapter. She is a strategic plan member of the Bisha University Engineering Club and a member of the Society of Petroleum Engineers (SPE), Bisha University Chapter. Her excellence is not limited to the Bisha University campus; she participated in innovating

a project that supports sustainability on campus at the Campusthon Hackathon held at King Abdulaziz University. Her idea won first place out of more than Fifteen hundred ideas. Her research interests include the environment, risk management, and continuous improvement.

Manar M. Al-Shahrani is a senior industrial engineering student at Bisha University, is an academically outstanding student. She completed a cooperative training at King Fahad Medical City - Project Management Department. She is a member of the Engineering Club and the International Society for Industrial Engineering and Operations Management (IEOM UB Student Chapter) at the university. She has practical experience in Arduino programming by building a remote-controlled car using sensors and basic electronics, as well as in Smart Product Prototyping by participating in an industrial hackathon and designing a smart base for gas cylinders. Her research interests focus on optimization, sustainability, environmental health, and risk analysis.

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