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- KPI Methodologies And definition

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SMART GRIDS EXCELLENCY – CYBERSECURITY IN EMPOWERING DIGITAL TRANSFORMATION

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Abstract

This paper is intended to elaborate on the 4th Industrial Revolution (Industry 4.0) that will alter and shift technologies and the utilities sector. Alongside advanced Cybersecurity technologies to be aligned with the need for more resilience and secured environments that empower digital transformation. Where we explore the drivers and applications of Cybersecurity considering 4thIR as an engine of digital transformation, that is governed and measured by complying with digital transformation rules, flowing from modern technology to the evolution where the quality of life is measured by its speed, energy, and security. As such, Industrial Control Systems (ICS) are a solid infrastructure for such a digital transformation. As the acceleration of cyberattacks are becoming more sophisticated, a well Cybersecurity strategies must be applied. Furthermore, we propose advanced Cybersecurity solutions for the smart grid that can be addressed by the efficiency of the Next Generation (SOC) and the utilization of Distributed Ledger Technology (DLT).

Keywords - Cybersecurity, Digital Transformation, Energy, Fourth Industrial Revolution

1. Introduction

As we live in the era of the 4th Industrial Revolution (IR), where a huge momentum and global trend of Energy and Digital Transformation in the utilities sector is represented in the Smart Grid and Smart Meter Projects; that are taking the headlines of mega projects worldwide as an application of Digital Transformation. With installing more than 600 million smart meters worldwide. Saudi Electricity Company, accomplished in record time the Smart Metering Project (SMP) as a model of Digital Transformation. Within a year's time, 10 million smart meters, of which 4 million meters, equivalent to 40% of them were built in Saudi Arabia from locally manufactured components, were installed all over the Kingdom to provide customers with a smart digital experience, complying with digital transformation demands to improve the efficiency, reliability, and quality of services in the utility sectors.

Digital transformation is utilizing all forms of technology to digitalize business and lifestyle. However, it is not as simple as it seems when it comes to digitalization in utility sectors (ex. Electricity, Energy). It has a much broader meaning than just business transformation. Smart grids and meters are a tangible sample of projecting 4IR and its challenges in utilities to comply with digital transformation demands. An Industrial Control System (ICS) is a concept that combines a range of industrial control systems as in Supervisory Control and Data Acquisition (SCADA), and Distributed Control System (DCS) technologies that encompass many components and controllers in the environment, such as Intelligent Electronic Devices (IED), programmable logic controllers (PLC) and many others that are managed and configured to achieve an industrial objective execution.

It is quite challenging to anticipate cyber-attacks in different interconnected systems and infrastructures between IT and OT environments as in ICS when it comes to the utilities sector. Although each area is seen and managed separately, it is proven that all systems are interconnected and must be secured, controlled, and visible from all aspects to ensure a steady digital transformation. Fourth Industrial Revolution Systems are known to be hybrid and connected towards performing industrial executions and operations, Distributed Ledger Technology is a decentralized technology that is considered an enabler of such operations while providing security features and opportunities across the network, as well as resolving network security complexity, gaps and concerns as it will be highlighted in this paper how Decentralization is a recommended Cybersecurity solution for complex and critical infrastructure.

2. Digital Transformation in Utilities

A concept that drives the 4th Industrial Revolution (IR) wheel to adjust and reshape all businesses and economics in utilities by underlying digitalized solutions to meet the 4IR vision and the world's demands and needs; by enhancing quality of life in different aspects. This can be seen in enhancing fuel efficiency, uninterrupted daily operations, ensuring quick resolution of defects, maintenance activities, and higher productivity across all sectors. Digitalization in utilities forces an advanced understanding and implementation of smart grid communication, controls, automation, and innovative technologies aligned to form the mean of 4th IR towards providing a more reliable, greener, and most importantly secured grid. Nowadays, there are opportunities and capabilities that have been handed to smart grids to ensure more sustainable, efficient, and smarter grids. Smart grid technologies when chosen and utilized as needed, it will ease the transition and the shift to a sustainable grid. A flexible and resilient strategy in implementing technologies that balances risk in utilities is a promising approach.

A. Utilities and Power Systems Evolution over the years

30 Years ago	Grid stability
5 Years ago	Renewable integration
3 Years ago	Demand response/DER(Distributed Energy Resources)
Today	Smart buildings and smart cities
Future	Next-Grid An open, flexible, interconnected model for energy Flow-based markets, DER integration New distribution grid management/microgrids Further expansion of grid digitalization

Table 1

SOURCE: Digital Utility Transformation Pwc Power & Utilities Roundtable Discussion Paper

B. Renewable Energy (RE) integration to Smart Grid

A stable source of energy is a global demand to power machines that run power generation, distribution, and other crucial functions of our life. The efforts continue toward increasing energy efficiency while reducing operational expenses. Accordingly, Vision 2030 programs have contributed to enhancing sustainability in RE and diversifying the government's sources of income in the energy sector by developing non-oil revenues while reducing operational expenses (OPEX). In the same context, Renewable Energy (RE) serves the purpose of having power stability and can be referred to as the ultimate resource of stability and greenness of human beings. With its great impact that will be brought to the world by diversifying energy sources while reducing the dependence on imported fuel, as well as in producing economic development opportunities. It is a shared responsibility and a common interest toward sustainable, cost-effective energy solutions to the world. Such a transition will require upgrades of old grid systems and new innovative solutions to accommodate the different nature of renewable energy solutions. The smart grid enables newer technologies to be integrated such as wind and solar energy production, further advances can be anticipated that will make the entire power grid smarter, as smart grids are able to incorporate such a transition. The simulation shown in Figure 1, simulates the role of Renewable Energy (RE) when integrated with smart grids.

C. Statistics and Numbers

Research stated that between the years (2018-2023) the utility industry will spend a total of $84 billion on building and implementing smart and digital infrastructure. The infrastructure of the utilities sector is being streamlined and renovated with a high investment, and more digital technology and connection between IT and OT environments, as in smart grids. This transition to "Smart Infrastructure" signifies a rapid shift in the utility sector. Case studies show that a transformation towards renewables is already happening, and several studies suggest that even higher shares of renewable energy power generation are foreseen.

The International Energy Agency's (IEA) "sustainable future" scenario shows renewables providing 57% of world electricity by 2050.

Based on data record and Statistical Review of World Energy 2022, the below was found:

[1] The share of Renewable Energy in global power generation continued its rise, driven by strong expansion.

[2] Renewable Energy share has increased to almost 13% in 2021, higher than the increment share of Gas and Coal.

[3] The share of Coal increased slightly from 35% to 36% in 2021 and remained below its 2019 level.

[4] The share of Gas generation in 2021 remained close to its 10-year average level.

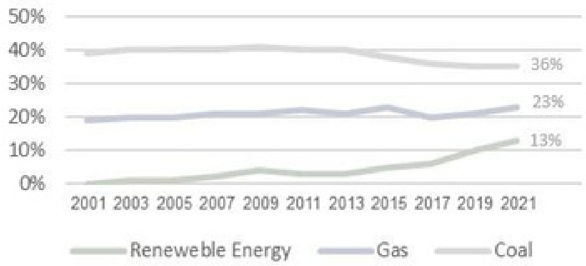

Fig. 1. Renewables in Global Power Generation
SOURCE: bp Statistical Review of World Energy

D. Smart Grid and Smart Meters

The concept of smart grid has been introduced as a new vision to shake off the traditional power grid to an efficient way of integrating advanced technologies and strategies. "*We need to pool resources, connect assets, automate optimization, trade energy and empower consumers to adapt their behavior in line with the needs of the grid – ultimately, we must use digital solutions to ensure that each component and system works smarter, not harder*.", with these words gridX CoFounder, Andreas Booke summarized the perfect strategy to utilize smart grids. The demand for reliable and efficient power generation, transmission, and distribution systems is an essential and vital demand. As traditional power grids are known to be centralized, The SCADA module in modern power systems collects data at remote terminals, transmits, and stores it in the main control center. This centralized data collection and storage is highly vulnerable to cyberattacks. With one-way limited communication, dialog makes it difficult for the grid to respond and interact with the instability and changes of energy. Smart grids have developed a different meaning of how power can be delivered and communicated in an efficient way that improves the reliability, security, and stability of the grid. As they are advancing towards the next-generation grid, with a two-way communication dialog that takes power systems to a higher level with decentralized networks and advanced control systems, that ensure resilience of power utility and enable flexibility. While decentralizing the operations and management of the smart grid has many benefits, it also brings security concerns; the more systems and environments are connected, the more Cybersecurity importance will rise.

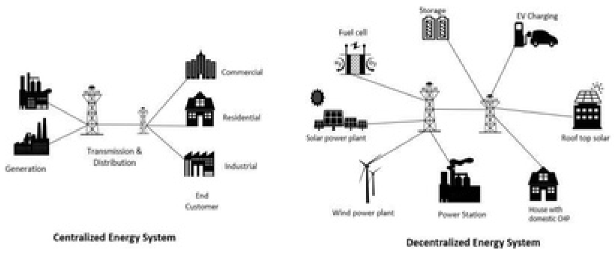

Fig. 2. Centralized vs. Decentralized Power Grid

3. Cybersecurity Consideration – Next Generation SOC Using SIEM and SOAR

Both SIEM and SOAR collect log and event data from applications and network devices, but each solution operates differently when it comes to alerts or threats. Security Information and Event Management (SIEM) and Security Orchestration, Automation, and Response (SOAR) contain similar components and tools that empower the SOC environment, it might be hard to differentiate between them due to the similarities of the components. however, the distinction between them can be addressed in the core functionalities and capabilities, human intervention, and source of data. As illustrated in Figure 5, shows how SIEM orients events and will only provide the alert. For more investigation, SOAR will be used to automate the investigation path workflows which can significantly cut down the amount of time required to handle alerts.

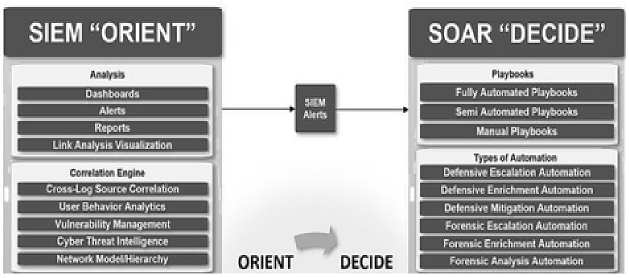

Fig. 3. SIEM "Orient" and SOAR "Decide"

A. SIEM

SIEM is involved in the collection and correlation of security logs and data from the different log sources within the SIEM environment. The log sources in SIEM can be derived from servers, network devices, firewalls, IDS, and IPS. This correlation is achieved, and analysis is carried out of the logs either by the analyst monitoring the SIEM solution or automation is involved, and alerts will be raised from SIEM solution.

Firewalls, network appliances, and IDS systems generate a huge amount of data, which may exceed the capability of Cyber Security teams to handle or to be responsible for such an event. A SIEM makes sense of all the derived data by collecting, and aggregating, thus identifying, and analyzing incidents and events. This can be achieved using analytics software, and dedicated sensors.

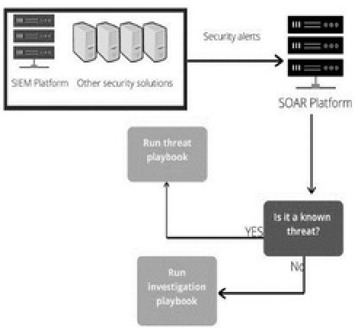

Fig. 4. How SIEM Works

B. SOAR

SOAR is designed to help Cybersecurity teams to manage and have better visibility while responding to endless alarms. It's known as a platform that takes SOC a step further by combining comprehensive data gathering, and analytics to provide the high management the needed visibility and ability that allow them to predict to implement sophisticated defense-in-depth capabilities based on what has been presented. SOAR combines advanced cyber technologies, as in:

- Security Orchestration and Automation (SOA)
- Security Incident Response Platforms (SIRPs)
- Threat Intelligence Platforms (TIPs)

These technologies are gathered into a product that allows IT and OT people to streamline security processes in three domains: threat and vulnerability management, incident response, and security operations automation that automate the handling of security operations tasks. As in executing these scanning for vulnerabilities or searching for logs without human intervention. Moreover, SOAR will pull information from external emerging threat intelligence feeds, endpoint security software, and other sources to get a better overall visibility of the security landscape inside the network.

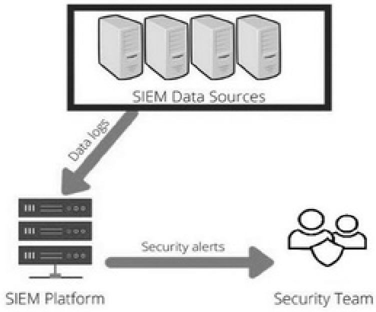

Fig. 5. How SOAR Works

4.Distributed Ledger Technologies (DLTs) Impose Many Cybersecurity Opportunities

Distributed Ledger Technologies (DLTs) are technologies enabling parties with no trust in each other to exchange any type of digital data on a peer-to-peer basis with fewer intermediaries. It's used to verify transactions, control deliveries, monitor workplace operations, and more. Blockchain is the most powerful and highlighted technology when it comes to the DLTs. It is known as a database (ledger) operating in a distributed manner in a network of multiple nodes or computers that keeps track of data transactions. A blockchain is run through a distributed network of participants who do not necessarily trust each other but follow the same rules (consensus).

A blockchain consists of blocks, ordered in a time-sequential manner, secured, using a hash function, as illustrated in Figure 8. The block is timely stamped and consists of transactions so it cannot be backdated, and it is immutable. A collection of data transmitted by each device node within the blockchain, and relevant details of the data are included, to ensure the traceability of the blockchain, each block will have its own timestamp (unique tag). The block is designed of two main parts:

[1] Block headers, where it link to the front blocks while providing integrity for the blockchain.

[2] The block body records the updated data information in each node.

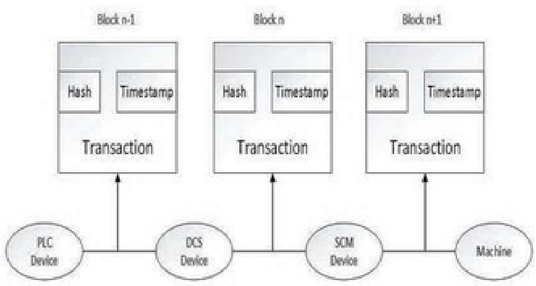

Fig. 6. Blockchain Transaction Modal in ICS

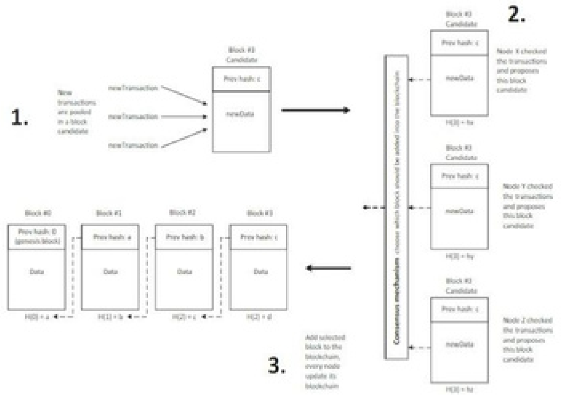

Fig. 7. Blockchain Transaction Scenario

A. Blockchain Transaction

When a transaction is initiated as illustrated in Figure 9, it is pooled in a block candidate (process no. 1), and nodes in the network validate the transaction (process no. 2). There will be many versions of block candidates since every node adds its address into the block candidate, but there must be only one block candidate added to the blockchain at a time. A consensus mechanism is then used, it is an automated process that ensures all participants accept or validate a block of identical copies of the distributed database files, and choose which block to be added (process no. 3). The cycle is then repeated and once the data entered the blockchain, the data cannot be altered or modified. In this manner, a blockchain maintains the traceability of an asset and it is preferable for auditing.

B. Blockchain Applications in Smart Grid

Many researchers believe that Blockchain is the vital strategy and technology trend that will move the smart grids to the next higher level. Security, trust, and privacy of the system in an environment are mandatory considerations to have for any transaction of information in such environments. The development of blockchain technology with its promising features will smooth the shift toward a decentralized and trusted approach that also provides a basis for smart grid evolution. Blockchain technology provides a desirable solution to smart grids which captured the interest of its adaptation. It can be implemented in different parts of the grid such as power generation, power transmission, and distribution.

C. Cybersecurity in Blockchain Technology

Blockchain is a decentralized approach, and this makes it a proper technology for Cybersecurity with its components and features as illustrated below.

Network users	A user with a digital signature and two keys (public and private).
Nodes	Refer to devices on the peer-to-peer network that form a Blockchain infrastructure.
Transaction	Includes Public key of the receiver, data, and sender key.
Authentication	Nodes to authenticate transactions.
Blocks	Blocks that are created by validator nodes that select pending transactions to be added to the chain.
Blockchain	Validated blocks are linked to each other with a unique hash.

Table 2

Main Components of a Blockchain In Cybersecurity

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Smart Contract - Smart contracts are programs and digital contracts stored on a blockchain that are automatically executed when predetermined terms and conditions are met.
Transaction endorsement via consensus algorithms - the consensus algorithms enable to collectively report and block malicious users, nodes, and apps while ensuring reliability in a network involving multiple users or nodes.
Data integrity - Data in BC are designed as ledgers, every block is linked using cryptographic hash functions. Once a transaction is recorded on the blockchain, it can't be changed, thus, any changes to the recorded data are processed as new transactions.
Availability - As each node in the network has a copy of the distributed ledger (shared database), the correct blockchain remains accessible to other nodes even in the case of a corrupted node.

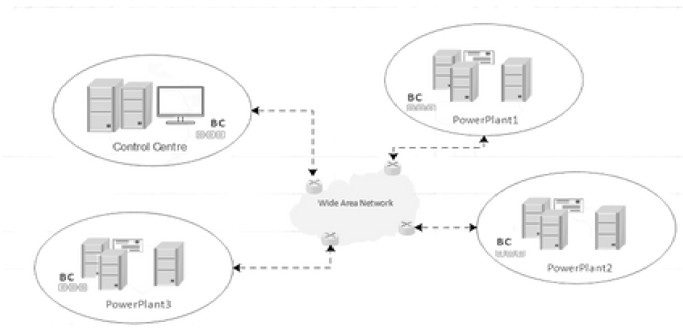

Fig. 8. Blockchain (BC) in PP

D. Blockchain Application – BC Microgrid Accenture SAP Intelligent Solution

In today's environment, decreasing investment costs of sustainable solutions and the acceptance of energy evolution are further pushing the transition from fossil fuels to renewables. This shift, however, makes it difficult for energy operators to balance supply and demand for home and business consumers. But with technological advancements and developments in the energy industry, new opportunities are present for consumers and operators to gain better insight on energy flows and more efficient energy usage. One such opportunity is a distributed landscape in which decentralized energy production is being consumed locally and surplus is delivered back to the grid and dozens of locations. This new model also allows consumers to become prosumers, allowing households and businesses to share and sell their excess energy. One step further and communities transform into connected microgrids, exchanging energy. Blockchain and DLT offers a practical view on optimizing a microgrid in an integrated scenario. Advanced EMS offers an enabling platform to facilitate local trading, enforces matches between demand and supply by smart contract on the blockchain, and integrates with SAP ERP application for invoicing and billing purposes. The blockchain solution framework allows immutability and transparency of the energy market and enforces the settlement of supply and demand orders through smart contracts.
The integration with SAP ERP demonstrates the connectivity potential for these new technologies. If fully implemented, here is how the solution will look in a microgrid:

[1] A prosumer produces energy locally; their household then consumes this energy while the surplus is automatically pushed as a sales order onto the marketplace.
[2] A community member with an energy shortage will push demand orders to the marketplace.
[3] The EMS forecasts demand and supply and the blockchain takes care of the matching and enforcing the contracts. SAP ERP then provides the invoice and billing process, showing the microgrid balance and grid consumption and production. Consumers will benefit from the lower prices of the locally produced energy, while prosumers can generate cash on their sold surplus. Grid operators benefit from savings in both operational and capital

spending. The result of combining the right technologies in the best right way will create in its turn a grid that is sustainable, efficient, and secure.

5.Recommendation

Old principles do not convey with the new generation of intelligent Industry Revolution (IR 4.0) that relies heavily on automation and hyper-connectivity. The centralization and connectivity of power systems and grids represent weaknesses and concerns for the industry as they are becoming more complex. Moreover, the changing nature of the power grid and utility sectors, and the growing connectivity of the electricity ecosystem are bridging OT network in the Industrial Control Systems (ICS) with IT network introduces challenges to Cybersecurity teams. These challenges force a decentralized approach to be followed when it comes to ensuring a Cybersecurity approach and solution that empowers such a complex environment.

- *Resources Allocation*

A decentralized Cybersecurity approach consists of distributed resources and workforce for each location and site. The process of assigning and managing resources and assets in a way that assists Cybersecurity strategic planning goals while increasing the level of visibility. Moreover, Policies will be forced and aligned with each location's specific model and needs and each site is managed and empowered by what it needs. Alongside the needed awareness and training for CS teams that each site might require. Where in a centralized approach, it requires all sites to agree on roles and policies that are to be used throughout a particular Cybersecurity scenario.

- *Distributed Ledger*

Distributed ledgers use independent device nodes to record, share, and synchronize transactions in their respective electronic ledgers. Instead of keeping data centralized as in a traditional ledger.

- *Security, Trust, Performance, and Transparency*

Decentralizing the processes of collecting and verifying data will add resilience to the grid and reduce the challenges of performance in a centralized grid. The approach to create security and trust with technologies is to assume that all participants are mutually untrusted, and trust is created by the consensus mechanism of the Blockchain. Transactions in a decentralized manner are encrypted, which makes them extremely secure. Each record is connected to the previous and subsequent records on a distributed ledger, all blocks will be chained via cryptography. This would strengthen the sense of security, and trust of the data as they are immutable while ensuring quite tight security. Moreover, A decentralized approach enables trust that improves communication between various nodes in a network, due to a shared view of transactions. Moving at the speed of trust is what can define a decentralized solution.

6. Conclusion

The concept of the fourth Industrial Revolution promises prosperity and smart solutions for t sector. Challenges to smart infrastructure and smart grids will increase, and they can be overcome by utilizing leading technologies in a decentralized manner to optimize and automate the technologies in a scalable, efficient, and cyber-secure manner. Industrial infrastructures are known to be challenging in many perspectives. Therefore, it's important to ensure the right technologies approach that drives and controls power generation, transmission, and distribution grounded by a steady Cybersecurity strategy as they are becoming more interconnected in IT and OT environments. Further, Confidence and trust in data and technologies that are used is a key advantage for society to gain from the potential opportunities that the Digital Transformation in line with the 4th Industrial Revolution can bring.

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ADAPTING MAINTENANCE EDUCATION FOR AN EVOLVING INDUSTRIAL LANDSCAPE: THE ROLE OF PROFESSIONAL INSTITUTIONS, CHALLENGES, AND FUTURE DIRECTIONS

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Abstract

In the face of a rapidly evolving industrial landscape, this paper explores the pivotal role of professional institutions in reshaping maintenance education to meet dynamic industry demands. The maintenance sector is undergoing significant transformation due to technological advances, sustainability priorities, and globalization. Maintenance professionals must adapt to Industry 4.0, sustainability practices, and global standards. The paper traces the evolution of maintenance from reactive to data-driven practices[1], outlining the multifaceted skills required, including technical proficiency, data literacy, problem-solving, interdisciplinary collaboration, and heightened safety and environmental awareness. Professional institutions, such as technical schools and vocational colleges, are vital in crafting industry-aligned curricula, offering hands- on training, providing certifications, and fostering industry connections. Innovative educational approaches, like online courses and simulations, cater to diverse learning styles, integrating practical experience with theoretical knowledge. While acknowledging challenges like curriculum updates and resource constraints, the paper emphasizes curriculum flexibility, technological investment, and industry collaboration. It anticipates future developments such as predictive analytics, augmented reality, sustainability practices, and cybersecurity integration, underscoring the importance of continuous learning, interdisciplinary skills, and adaptable curricula. This paper depicts that professional institutions play an indispensable role in preparing maintenance professionals for the future. Collaboration between industry and academia is key to ensuring a workforce adept at navigating evolving technology, sustainability, and global demands, securing the prosperity of the maintenance industry.

Key Words:

Maintenance industry, Education and training, Curriculum development, Predictive maintenance Industry collaboration, Continuous learning, Curriculum flexibility, Future developments, Industrial landscape.

I. Introduction

In the modern industrial landscape, where complex machinery and infrastructure are at the heart of productivity and progress, the maintenance industry plays an indispensable role. Whether in manufacturing, transportation, energy production, or facility management, the effective and efficient upkeep of equipment and systems is paramount. It ensures not only the continued functioning of vital assets but also the safety of personnel and the sustainability of operations[2] Education and training in the maintenance industry are pivotal factors that underpin its success. Maintenance professionals, often referred to as the unsung heroes of industry, are tasked with the responsibility of keeping machinery operational, minimizing downtime, optimizing efficiency, and adhering to ever-evolving safety and environmental standards. To excel in this multifaceted field, individuals require not only technical expertise but also adaptability, problem-solving skills, and a deep understanding of emerging technologies. This paper explores the dynamic interplay between education and the evolving maintenance landscape, emphasizing the role of professional institutions in preparing maintenance professionals for the challenges of the future. It covers the evolution of the maintenance industry, essential skills and knowledge for maintenance professionals, the need for education to adapt, the role of professional institutions, innovative educational approaches, challenges, future developments, recommendations, and

the importance of lifelong learning in maintenance education.

II. Evolution of the Maintenance Industry and the Changing Landscape

This section discusses how the maintenance industry has evolved over time, the skills and knowledge essential for maintenance professionals today, and the need for education to adapt to these changes.

2.1 Evolution of the Maintenance Industry

The maintenance industry has undergone a remarkable transformation over the years, driven by technological advancements, evolving requirements, and changing paradigms. Some key points of evolution include[2] Historical Roots: Maintenance, as a discipline, has its historical roots in reactive practices—fixing equipment when it breaks down. Preventive maintenance emerged as an improvement, focusing on scheduled inspections and maintenance to reduce unplanned downtime. Technological Revolution: The advent of computers and automation marked a turning point. Computerized Maintenance Management Systems (CMMS) enabled organizations to manage maintenance proactively, schedule tasks efficiently, and track equipment health. Predictive Maintenance: With the proliferation of sensors and data analytics, predictive maintenance gained prominence. Maintenance professionals now harness data to predict when equipment failures are likely to occur, enabling preemptive action. Industry 4.0 Integration: The fourth industrial revolution, often referred to as Industry 4.0, has reshaped maintenance. Smart factories, IoT-connected devices, AI-powered analytics, and autonomous robotics have become integral components, ushering in an era of data-driven maintenance.

2.2 Changing landscape.

The landscape of maintenance is undergoing a profound transformation. Advances in automation, robotics, artificial intelligence, predictive maintenance, and data analytics are redefining how maintenance activities are conducted. The shift towards Industry 4.0, characterized by smart factories and connected systems, demands maintenance professionals who can harness the power of technology to make data-driven decisions and anticipate equipment failures. Furthermore, the imperative for sustainability is reshaping maintenance practices. Environmental considerations are increasingly integrated into maintenance routines, prompting professionals to explore eco-friendly materials, energy-efficient processes, and environmentally responsible disposal methods. The changing landscape also encompasses a globalized marketplace. Maintenance professionals must be prepared to work on an international scale, adhering to global standards and collaborating with colleagues from diverse cultural backgrounds.

III. Essential Skills, Knowledge, and Education for Maintenance Professionals to Adapt.

The evolution of the maintenance industry necessitates a shift in education to meet the demands of a technology-driven, data-centric, and sustainability-focused future. It is through proactive adaptation and equipping maintenance professionals with contemporary skills and knowledge that the industry can thrive amidst these transformative changes.

3.1 Essential Skills and Knowledge for Maintenance Professionals [3]

The evolving maintenance landscape has elevated the skills and knowledge expected from maintenance professionals: Technical Proficiency: While traditional mechanical skills remain essential, maintenance professionals must also be proficient in digital technologies, including IoT devices, data analysis, and automation systems. Data Literacy: The ability to collect, interpret, and act upon data is paramount. Maintenance professionals need to understand how to use data analytics tools to make informed decisions. Problem-Solving and Critical Thinking: Maintenance is increasingly about troubleshooting complex systems. Professionals must possess problem-solving and critical thinking skills to diagnose issues and develop innovative solutions. Interdisciplinary Collaboration: Maintenance often requires collaboration with experts from various fields, such as engineers, data scientists, and cybersecurity specialists. Effective communication and interdisciplinary collaboration skills are crucial. Safety and Environmental Awareness: With sustainability concerns growing, maintenance professionals must consider the environmental impact of their actions and adhere to safety protocols rigorously.

3.2 The Need for Education to Adapt

To equip maintenance professionals with the skills needed in this evolving landscape, education must adapt:

Relevance of Curriculum: Educational institutions should revise their curricula to reflect the integration of digital technologies, data analytics, and sustainability considerations.

Practical Experience: Hands-on training and practical experience should be prioritized. Simulation-based learning and real-world scenarios can prepare students for the challenges they will encounter in the field.

Continuous Learning: Maintenance professionals should be encouraged to engage in continuous learning throughout their careers. This involves staying updated on emerging technologies and industry best practices. Soft Skills Development: In addition to technical skills, the development of soft skills such as communication, adaptability, and leadership should be emphasized to foster well-rounded professionals.

Industry Collaboration: Educational institutions should foster close collaboration with industry partners to ensure that their programs align with industry needs. Advisory boards composed of industry experts can provide valuable guidance.

IV. The Role of Professional Institutions in Education and Training

This section discusses the role of professional institutions in maintenance education and training, how they bridge the gap between traditional education and industry demands and provides examples of successful programs and initiatives.

4.1 Professional Institutions in Maintenance Education [4]

Professional institutions, including technical schools, vocational colleges, and industry associations, serve as vital pillars in the realm of maintenance education and training. Their role encompasses several key aspects:

Curriculum Development: Professional institutions often take the lead in developing curricula that align with industry requirements. They work closely with industry experts to ensure that educational programs are relevant, up-to-date, and meet the evolving demands of the maintenance field.

Hands-On Training: These institutions provide students with hands-on training, allowing them to gain practical experience in maintenance tasks. This practical component complements theoretical learning and prepares students for real-world challenges.

Certifications and Credentials: Many professional institutions offer industry-recognized certifications and credentials. These certifications validate the skills and knowledge of maintenance professionals, enhancing their employability and career prospects.

Industry Networking: Professional institutions often serve as hubs for networking and collaboration within the maintenance industry. They facilitate connections between students, educators, and industry professionals, fostering a sense of community and providing opportunities for mentorship and career advancement.

4.2 Bridging the Gap Between Education and Industry Demands [5]

Professional institutions play a crucial role in bridging the gap between traditional education and the dynamic demands of the maintenance industry:

Industry-Driven Curriculum: These institutions prioritize curricula that are shaped by industry input. They collaborate with local businesses, industries, and associations to ensure that educational programs directly address the skills and knowledge needed in the workforce.

Real-World Exposure: By offering hands-on training, professional institutions provide students with practical exposure to maintenance tasks and challenges. This experience prepares students for the complexities of the job, bridging the gap between theoretical knowledge and practical application.

Certifications and Credentials: Many professional institutions offer industry-recognized certifications that validate a graduate's readiness for the workforce. These certifications are often developed in close collaboration with industry partners, ensuring they align with industry standards.

Industry Advisory Boards: Some institutions establish industry advisory boards composed of experts and professionals. These boards provide guidance on curriculum development, industry trends, and emerging technologies, ensuring that educational programs remain relevant.

4.3 Examples of Successful Programs and Initiatives

Several professional institutions have implemented successful programs and initiatives to address evolving maintenance needs:

SMRP - Society of Maintenance and Reliability Professionals: The Society for Maintenance & Reliability Professionals (SMRP) is a nonprofit professional society established by practitioners with the aim of advancing excellence in maintenance, reliability, and physical asset management, while fostering leadership within the profession. Central to their efforts is the Certified Maintenance & Reliability Professional (CMRP) program, recognized as the premier credential for certifying the knowledge, skills, and capabilities of professionals in maintenance, reliability, and physical asset management. The CMRP program stands as a singular certification initiative accredited by the American National Standards Institute (ANSI), aligning with globally acknowledged ISO standards for accreditation.[6]

OMIANTEC: The International Operations & Maintenance Conference in the Arab Countries (OMAINTEC) commenced its inaugural edition in 2002 in Beirut and has since grown to become a paramount professional platform within the Arab region. This conference serves as a hub where experts, speakers, industry leaders, decision-makers, academics, and specialists in operations and maintenance, facilities management, and asset management converge to exchange experiences, enhance knowledge, and present the latest advancements and technologies in the realm of operations and maintenance engineering on a global scale [7].

MEFMA The Middle East Facility Management Association: MEFMA is dedicated to advancing and advocating for best practices and professional standards in facility management within the region. This is achieved through tailored membership packages that offer exclusive benefits, educational opportunities through specialized training programs and certifications, insightful reports and research studies on the latest industry trends, and a series of regional events that serve as a knowledge- sharing platform. By providing such resources and opportunities, MEFMA aims to add significant value to its members and contribute to the continuous growth and development of facility management professionals and the industry at large. [8]

The International Facility Management Association (IFMA): IFMA, an industry association, offers certification programs for facility managers. These programs provide professionals with the knowledge and skills needed to maintain and optimize building systems, aligning with sustainability and energy efficiency goals.[9]

The National Institute for Automotive Service Excellence (ASE): ASE, an industry association, provides certifications for automotive technicians. These certifications are recognized nationwide and ensure that automotive professionals meet industry standards for skill and knowledge.[10]

These examples illustrate how professional institutions create successful programs and initiatives that cater to industry needs, offer hands-on training, and provide industry-recognized certifications. They are instrumental in preparing maintenance professionals for the challenges of the ever-evolving maintenance landscape.

V. Innovative Educational Approaches in Maintenance Education

This section discusses innovative educational approaches, the integration of practical experience and theoretical knowledge, and provides case studies of educational institutions effectively incorporating these approaches.

5.1 Catering to Diverse Learning Styles

In the ever-evolving field of maintenance, education must adapt to cater to diverse learning styles. Innovative approaches have emerged to engage students effectively:

Online Courses: The proliferation of online education platforms has made it possible for students to access maintenance courses from anywhere. These platforms offer flexibility in learning, allowing students to pace their studies and access a wealth of digital resources, including videos, simulations, and interactive modules.

Simulations: Simulation-based learning provides a dynamic, risk-free environment for students to practice maintenance tasks. Virtual simulations replicate real-world scenarios, enabling students to troubleshoot issues, perform repairs, and gain practical experience.

Hands-On Training: Practical, hands-on training remains invaluable in maintenance education. Technical schools and vocational colleges often maintain workshops and laboratories equipped with actual machinery and equipment for students to work on, ensuring they develop essential skills through tactile experience.

5.2 Integration of Practical Experience and Theoretical Knowledge

The integration of practical experience and theoretical knowledge is fundamental in maintenance education:

Real-World Scenarios: Maintenance programs often incorporate real-world scenarios into their curriculum. Students are presented with actual maintenance challenges, requiring them to apply theoretical knowledge to solve problems encountered in the field.

Apprenticeships: Many educational institutions facilitate apprenticeships or cooperative education experiences. These programs enable students to work in real maintenance environments under the guidance of experienced professionals, merging theoretical understanding with practical application.

Laboratories and Workshops: Technical schools and vocational colleges maintain laboratories and workshops where students engage in hands-on training. This practical experience reinforces theoretical concepts and prepares students for the demands of maintenance careers.

5.3 Case Studies of Educational Institutions

Case Study 1: TAFE Queensland - Automotive and Engineering Training [11]

TAFE Queensland offers a comprehensive Automotive and Engineering training program that effectively integrates practical experience and theoretical knowledge. Students have access to fully equipped workshops where they work on real vehicles and machinery, allowing them to apply classroom learning to practical scenarios. This hands-on approach has resulted in a high employability rate for graduates in the automotive and engineering maintenance sectors.

Case Study 2: Virtual Aviation Maintenance Training at Embry-Riddle Aeronautical University [12]

Embry-Riddle Aeronautical University employs virtual aviation maintenance training as a supplement to traditional instruction. This includes interactive 3D simulations of aircraft systems and maintenance tasks. Students can practice procedures, troubleshoot issues, and gain practical experience in a controlled virtual environment before transitioning to real aircraft. This approach enhances safety and efficiency in maintenance training.

Case Study 3: Apprenticeship Programs at Siemens Technical Academy [13]

Siemens Technical Academy (STA) offers apprenticeship programs that combine classroom learning with on-the-job training. Students are employed by Siemens while completing their education. This immersive experience ensures that apprentices acquire practical skills while mastering theoretical knowledge. STA's approach has led to a skilled workforce that seamlessly transitions into Siemens' maintenance teams.

Case Study 4: Master of Maintenance and Reliability King Fahd University of Petroleum and Minerals [14]

This interdisciplinary program offers a mastery level knowledge and modern skills that are critical for keeping engineered systems and equipment up, safe, and well configured to achieve maximum performance, reliability, and utilization while minimizing failure, downtime, and cost. As plants and industrial systems are tuned for maximum performance, and many are mission-critical, the need for professionals well versed in the latest IR4.0 and digitalization technologies and who are knowledgeable in keeping these systems reliable is increasing rapidly. The program will prepare professionals from various engineering backgrounds to develop proactive maintenance and reliability strategies that keep systems safe to operate with high availability and reliability.

These case studies highlight how educational institutions effectively incorporate innovative approaches, such as online courses, simulations, and hands-on training, to cater to diverse learning styles and integrate practical experience with theoretical knowledge in maintenance education. These institutions have successfully prepared students for careers in the ever-evolving maintenance industry.

VI. Challenges and Considerations

This section addresses the challenges faced by professional institutions in adapting to industry changes, the need for curriculum flexibility and alignment with global standards, and the importance of collaboration between industry and academia.

6.1 Challenges Faced by Professional Institutions in Adapting to Rapid Industry Changes [15]

Professional institutions that strive to adapt to the fast-paced changes in the maintenance industry encounter several challenges:

Curriculum Adaptation[16}**:** Updating curricula to meet the demands of evolving technologies and industry practices can be a significant challenge. Institutions must strike a balance between teaching foundational skills and incorporating cutting- edge knowledge.

Resource Constraints[17]: Staying at the forefront of technology often requires substantial investments in equipment, software, and faculty development. Many institutions, particularly smaller ones, face resource limitations that can hinder their ability to keep up with industry advancements.

Faculty Training: Equipping educators with the necessary knowledge and skills to teach emerging technologies is essential. Providing ongoing training for faculty to ensure they remain current can be logistically challenging.

Dynamic Regulatory Environment: Maintenance industries often operate within highly regulated environments. Keeping curricula aligned with changing safety, environmental, and industry-specific regulations require vigilance.

6.2 The Need [18] for Curriculum Flexibility, Technological Advancements, and Global Standards Alignment

Curriculum Flexibility: To address rapidly changing industry needs, professional institutions must embrace curriculum flexibility. This flexibility allows them to swiftly introduce new courses, modules, and training programs as technology evolves. Modular and competency-based approaches enable students to select learning pathways that align with their interests and career goals.

Keeping Pace with Technological Advancements: Maintenance professionals are expected to work with cutting-edge technologies. Institutions must invest in modern equipment, software, and infrastructure to provide hands-on experience with these technologies. Additionally, partnerships with industry leaders can help institutions access the latest equipment and stay informed about emerging trends.

Alignment with Global Standards: Given the global nature of many industries, professional institutions must align their curricula with international standards and best practices. Collaborating with industry associations and regulatory bodies can facilitate this alignment, ensuring that graduates are prepared for careers on a global scale.

6.3 Importance of Collaboration Between Industry and Academia

Professional institutions face challenges in adapting to rapid industry changes, including curriculum adaptation and resource constraints. However, through curriculum flexibility, technological advancements, and alignment with global standards, they can prepare students to meet the evolving needs of the maintenance industry. Collaboration between industry and academia is pivotal in addressing these challenges and ensuring that maintenance education remains relevant and effective.

Knowledge Transfer: Collaboration between industry and academia is pivotal for effective knowledge transfer. Industry experts can share practical insights and experiences with educators, enriching the educational experience for students.

Workplace Relevance: Industry input helps ensure that education remains relevant to the workplace. Industry advisory boards can guide curriculum development, ensuring that graduates possess the skills and knowledge needed to excel in their roles.

Research and Innovation: Collaborative efforts between industry and academia can drive research and innovation in maintenance practices. Research projects that address industry challenges can lead to advancements and breakthroughs that benefit both students and industries.

Job Placement and Internships: Industry partnerships often lead to internship opportunities and job placements for students. These experiences provide students with practical exposure and establish pathways for their transition into the workforce.

VII. Future Developments in Maintenance and Implications for Education [19]

This section speculates on future developments in maintenance, presents recommendations for enhancing maintenance education with an emphasis on continuous learning and interdisciplinary skills, and underscores the importance of preparing maintenance professionals for lifelong education.

7.1 Speculation on Potential Future Developments

The maintenance industry is poised for further evolution, driven by emerging technologies and changing industry dynamics. Some potential future developments include:

Advanced Predictive Analytics: Maintenance will rely even more on predictive analytics and AI-driven algorithms. Machines will autonomously assess their own health, schedule maintenance, and order replacement parts, reducing the need for manual intervention.

Augmented Reality (AR) and Virtual Reality (VR): AR and VR technologies will become integral in maintenance training. Maintenance professionals will use AR glasses to access real-time equipment information, while VR simulations will offer immersive training experiences.

Sustainability and Green Maintenance: The industry will place greater emphasis on sustainable practices. Maintenance professionals will need to consider the environmental impact of their activities, leading to eco-friendly maintenance techniques and green materials.

Robotics and Drones: Robots and drones will be deployed for inspections, repairs, and data collection. Maintenance professionals will need to be skilled in operating and maintaining these technologies safely.

Cybersecurity Integration: Connected systems will require robust cybersecurity measures. Maintenance professionals will need knowledge of cybersecurity best practices to protect critical infrastructure from cyber threats.

7.2 Implications for Education

These potential developments will have significant implications for maintenance education:

Curriculum Evolution: Maintenance education must adapt to include training in emerging technologies, cybersecurity, and sustainability practices. Curricula should incorporate modules on AR, VR, and robotics to prepare students for the future.

Interdisciplinary Focus: Maintenance education should emphasize interdisciplinary skills. Collaborative projects involving data scientists, engineers, and cybersecurity experts will be crucial in addressing complex maintenance challenges.

Lifelong Learning Culture: Education should promote a culture of continuous learning. Maintenance professionals should be motivated to update their skills and knowledge throughout their careers, facilitated by institutions offering short courses and micro-credentials.

7.3 The Importance of Proactive Education and Training

In conclusion, proactive education and training are paramount in maintaining a skilled workforce for the evolving maintenance landscape. The maintenance industry is evolving at an unprecedented pace, driven by technology, sustainability concerns, and global interconnectedness. To thrive in this landscape, professionals must be lifelong learners, adaptable problem solvers, and collaborative leaders. Professional institutions serve as the linchpin in achieving this vision. They provide the means for individuals to acquire the skills and knowledge that empower them to address industry challenges head-on. Through collaborative efforts, innovative approaches, and a commitment to continuous learning, these institutions prepare maintenance professionals not only to meet current industry demands but also to anticipate and shape the maintenance landscape of the future. As we reflect on the importance of proactive education and training, we recognize that they are not only about staying competitive but also about contributing to the sustainability, safety, and efficiency of industries worldwide. It is through the collective efforts of maintenance professionals, educational institutions, and industry partners that we can ensure a skilled and adaptable workforce ready to meet the maintenance challenges of tomorrow.

7.4 Recommendations for Enhancing Maintenance Education

7.4.1 Emphasis on Continuous Learning

Recommendation 1: Professional institutions should establish lifelong learning programs that encourage maintenance professionals to continuously update their skills and stay informed about industry advancements.

7.4.2 Development of Interdisciplinary Skills

Recommendation 2: Curriculum design should incorporate interdisciplinary projects, encouraging collaboration between maintenance professionals and experts in related fields such as data science, engineering, and cybersecurity.

7.4.3 Curriculum Flexibility and Adaptation

Recommendation 3: Institutions should ensure that their curricula remain flexible and adaptable to rapid industry changes. Regularly consult with industry partners and update curricula to align with emerging technologies and practices.

7.4.4 Industry Collaboration

Recommendation 4: Strengthen collaboration with industry partners by establishing advisory boards composed of industry experts. These boards can provide valuable guidance on curriculum development, industry trends, and emerging technologies.

7.4.5 Soft Skills Development

Recommendation 5: Emphasize the development of soft skills such as communication, problem-solving, adaptability, and leadership. These skills are crucial for success in a rapidly changing and collaborative industry. By embracing these recommendations and fostering a culture of education that extends beyond initial training, professional institutions can ensure that maintenance professionals remain at the forefront of the industry, ready to meet the evolving demands of a dynamic and interconnected world.

VIII. Summary of Key Findings and Arguments

Throughout this research paper, several key findings and arguments have been presented:

Maintenance education and training are pivotal in preparing professionals to address the challenges of a rapidly changing maintenance landscape.

Professional institutions, such as technical schools, vocational colleges, and industry associations, serve as catalysts for change by offering dynamic, industry-relevant programs, hands-on training, certifications, and valuable partnerships.

These institutions bridge the gap between traditional education and industry demands by maintaining updated curricula, offering practical training, fostering industry collaborations, providing industry-recognized certifications, emphasizing soft skills, and promoting lifelong learning.

Innovative educational approaches, including online courses, simulations, hands-on training, and blended learning, cater to diverse learning styles and enhance the educational experience.

The integration of practical experience and theoretical knowledge in maintenance education is essential for producing well-rounded professionals who can excel in real-world scenarios.

Challenges faced by professional institutions include curriculum adaptation, resource constraints, faculty training, and keeping pace with a dynamic regulatory environment.

To stay relevant and effective, maintenance education must embrace curriculum flexibility, keep pace with technological advancements, and align with global standards.

Collaboration between industry and academia is pivotal for effective knowledge transfer, workplace relevance, research and innovation, and job placement.

Future developments in maintenance, including Industry 4.0 integration, augmented reality, sustainability, robotics, drones, and cybersecurity, will shape industry and education.

IX. Conclusion:

In conclusion, this research paper has examined the dynamic interplay between education and the evolving maintenance landscape, highlighting the pivotal role of professional institutions in preparing maintenance professionals for the challenges of the future. The paper has discussed the evolution of the maintenance industry, the essential skills and knowledge required for maintenance professionals, the need for education to adapt, the role of professional institutions, innovative educational approaches, challenges faced by these institutions, and potential future developments in maintenance. This paper asserts that professional institutions play a crucial role in reshaping maintenance education to meet the evolving needs of the industry. This role is significant because the maintenance industry relies on a skilled workforce that can adapt to technological advancements, navigate regulatory complexities, and address sustainability challenges. Professional institutions are at the forefront of ensuring that maintenance professionals are equipped with the skills, knowledge, and practical experience needed to excel in a rapidly changing field. As the maintenance industry continues to transform, with advances in technology and sustainability becoming increasingly prominent, the collaboration between industry and academia will remain vital. Maintenance professionals of the future will need to be adaptable, tech-savvy, environmentally conscious, and well-versed in cybersecurity. The recommendations provided underscore the importance of emphasizing continuous learning, developing interdisciplinary skills, maintaining flexible curricula, strengthening industry partnerships, and nurturing soft skills. Key findings emphasize that maintenance education and training are essential for equipping professionals with the skills needed to thrive in a technology-driven, data-centric, and sustainability-focused industry. Professional institutions act as key agents in addressing these evolving needs by offering relevant curricula, practical training, industry collaborations, and fostering a culture of continuous learning. This paper highlights the critical role that proactive education and training play in sustaining a skilled and adaptable maintenance workforce capable of meeting the challenges of a dynamic and interconnected world. It is through the concerted efforts of maintenance professionals, educational institutions, and industry partners that we can ensure a prosperous and sustainable future for the maintenance industry.

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[5] An Effective Framework for Bridging the Gap between Industry and Academia S. Zeidan1 and M.M. Bishnoi2 1Associate Professor, Department of Management and Commerce, Amity University Dubai, Dubai, UAE. 2Assistant Professor, Department of Humanities, Arts & Applied Sciences,Amity University Dubai, Dubai, UAE. (Corresponding author: S. Zeidan) (Received 24 February 2020, Revised 21 April 2020, Accepted 23 April 2020) (Published by Research Trend, https://www.researchgate.net/publication/341830407_An_Effective_Framework_for_Bridging_the_Gap_between_Industry_and_Academia

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Reshaping maintenance and asset management skills towards digital transformation in Portugal

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Abstract
The reshaping of civil engineering education and training has been found to enhance student performance and improve their skills when facing the challenges of the real world. The industry is asking for engineers with better communication and teamwork skills, and most importantly, a broader understanding of how to solve real working market problems and create value in the marketplace. Moreover, the professional research institutions throughout the world and particularly in Portugal, such as engineering schools, are beginning to integrate entrepreneurship and business concepts into their training options. The present paper intends to present an overview about the challenges for maintenance and asset management, education and training of future generations and reshaping of research institutions. Moreover, a proposal is presented for the reshaping of maintenance and asset management education and training considering Portugal´s needs. Additionally, the development of new approaches is presented, as well as a proposal for reshaping maintenance and asset management education and training: roadmap for Portugal needs. The main conclusions of the paper are also stated.

Keywords: Maintenance; Asset Management; Reshaping education and training

1. Introduction

Current trends in civil engineering raise questions about the future of the profession, namely the role played in society, in the integrity of infrastructure, as well as in the health of the natural environment. Technology and increasing market demand place additional pressure on how civil engineers perform their roles. The identified challenges raise concerns about future directions, it is necessary for civil engineers to start investing more in research and education and in the application of new technologies [3,19]. Industry and universities should be the organizations responsible for implementing measures to overcome the skills deficit identified in the field of civil engineering, namely regarding infrastructure maintenance. Although universities prepare their graduates well enough to work in industry, they are often only able to provide the theoretical knowledge necessary for an engineer. To improve the skills of recent graduates, it would be important that universities identify industry needs and teach them in the course, providing a close link between industry and university. Universities should also employ professors from the industry, bringing in experts with real-world experience [15]. The researchers of LNEC - National Laboratory for Civil Engineering, in Lisbon, Portugal, cooperate with different stakeholders of maintenance and asset management by bridging knowledge on innovative processing technologies to improve their competitiveness. On this subject, LNEC has/is hosting international conferences and several seminars in the areas of maintenance, asset management, and related fields, as a form of interaction between scientists, students, and other citizens [16].

2. Conceptual Overview

2.1 Challenges for maintenance and asset managers future generations

Current trends in civil engineering raise questions about the future of the profession, namely the role played in society, in the integrity of infrastructure, as well as in the health of the natural environment. For decades, civil engineering leaders have warned about the need to invest in the maintenance of existing infrastructure, since the lack of proper maintenance can have drastic consequences for public health, safety, and well-being of users [19]. On the other hand, technology and increasing market demands place additional pressures on how civil engineers perform their roles. The growing use of artificial intelligence leads routine engineering tasks (which should be human domain) to the technologist and technician domain. Likewise, end-users and owners, when looking for low-cost acquisitions, reduce the demand for innovation, instead of a selection based on qualifications and new opportunities that lead to the optimization of the life cycle of the infrastructures. Thus, a basic question arises related to how civil engineers will be able to achieve a necessary and continuous knowledge about the best international practices in the area [3,17,19].

These identified challenges raise concerns about future directions, it is necessary for civil engineers to start investing more in research and education and in the application of new technologies, to have a vision beyond the strategic issues of today and invest efforts on what the civil engineering profession must achieve in the next years [15]. Figure 1 shows the critical mindsets, skills, and experiences that students need.

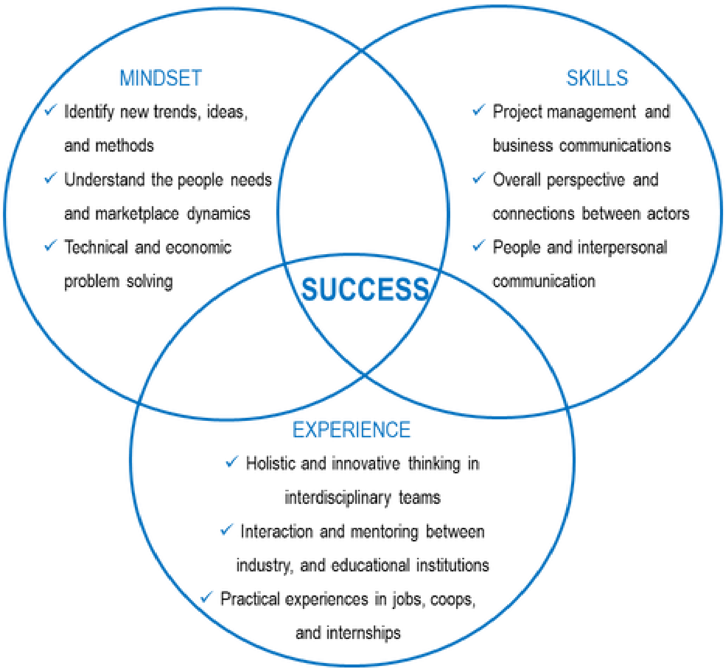

Figure 1 – Students need, adapted from [5]

2.2 Education and training of future generations and reshaping of research institutions

Industry and universities should be the organizations responsible for implementing measures to overcome the skills deficit identified in the field of civil engineering, namely regarding the infrastructure maintenance. In industry, specific postgraduate programs stand out, as the needs of each company are very different and the best place to develop your necessary skills is the company itself. However, the burden of responsibility in this matter must be in the hands of the universities, which must be the driving force behind the implementation of measures to overcome the existing challenges. Although universities prepare their graduates well enough to work in industry, they are often only able to provide the theoretical knowledge necessary for an engineer [6,15]. To improve the skills of recent graduates, it would be important that: i) universities identify industry needs and teach them in the course, providing a close link between industry and university; ii) engineering and technology programs and software that are used in industry must be addressed at universities (in lectures for the general public and in classes for students); and iii) universities should employ professors from industry, bringing in experts with real-world experience to provide a different perspective and outline for students the skills and abilities they would like to see in graduate engineers. It is also verified that many students are not mentally prepared for the expected work when they get a job as an engineer. The skills that are taught at university do not always reflect the roles and responsibilities assigned to them in the industry and it is unquestionable that the industry considers digital skills to be indispensable for working in the industry. [4,19].

2.3 LNEC as a research/professional and training institution

The National Laboratory for Civil Engineering (LNEC), is a public research institute, dedicated to science and technology, which carries out its activity in the large field of engineering, habitat, and environment sciences, comprising construction materials, public works, housing and urban planning, and hydraulics and transportation networks. Over the past decades, LNEC conducted studies and high-level consultancy in more than 40 countries, on all continents, and currently maintains nearly 300 agreements and consortia for Teaching and Research purposes with various entities around the world. At present, LNEC employs about 560 people, plus 140 science research fellows. Researchers have PhD degree or equivalent and represent 30% of the staff. LNEC´s model of organization enables expertise´s complementarity of different knowledge domains resulting in a benefit regarding support to industry. In developing its activity, LNEC aims to contribute to safety and quality of the works, protection, and rehabilitation of the natural and built patrimony, technological innovation in the construction sector and in the fields of water and environment. The activities related to regulation, standardization and quality of construction are equally relevant.

The Strategy for Research and Innovation at LNEC for 2021-2027 is directed to progressively increasing the R&D&I in the overall activity and frames projects that meet the needs of society in the fields of built heritage, cities and territories, natural resources, risk and safety and development of instruments for innovation. The definition of priority themes was focused on the relationship with priorities of Horizon Europe and Cohesion Policy. LNEC is an active actor of the Portuguese Construction Technology Platform (PTPC), an industrial driven platform, which assumes, at national level, the mission of the European Construction Technology Platform (ECTP), i.e., promotes innovation and competitiveness of the construction industry. Since the year 2000 until present, LNEC has developed activity in characterization of recycled aggregates processed from construction and demolition waste (CDW). In this field, seven technical specifications for the application of recycled materials in different construction works have been elaborated. LNEC is an active player on RILEM Technical Committees concerning the valorization of waste, namely TC 198-Use of Recycled Materials and TC 217-Progress of Recycling in the Built Environment.
The researchers of LNEC cooperate with different stakeholders of maintenance and asset management by bridging knowledge on innovative processing technologies to improve their competitiveness. On this subject, LNEC has/is hosting international conferences and several seminars in the areas of maintenance, asset management, and related fields, as a form of interaction between scientists, students, and other citizens [16].

3.Development of new approaches for maintenance and asset management education and training

Universities have a significant responsibility in providing the knowledge skills necessary for engineers to succeed in industry. However, the following recommendations for improvement by the industry are highlighted: i) greater involvement with the industry in order to identify programs, software and expected skills, in the area of maintenance and asset management, for implementation in daily practice; ii) use of relevant software in the field to develop familiarity and basic understanding on the part of students and extend skills and transfer this knowledge to other similar programs; and iii) invite industry speakers to discuss the software and technologies used in the sector and introduce students to the desired skills and abilities [3,17,19]. While universities are responsible for providing the necessary academic and theoretical foundations for graduate engineers, the industry is responsible for providing the necessary practical experience for graduates, as well as facilitating the transition from university to an engineer dealing with real-world problems. Recommendations are that industry should [19]: i) allow greater communication with universities, suggest ways on how the curriculum can be improved and provide information to universities to enable more relevant education for students ; ii) encourage more industry professionals to volunteer for speaking engagements, either as a guest speaker primarily to discuss the programs they use and skills they would like to see or to deliver learning modules; iii) participate in facilitating more job opportunities and/or internship placements, as per their responsibility to graduate students, and have greater contact with the industry, such as on-site visits; and iv) provide graduate or cadet programs to students to better assist with their university transition and develop the relevant digital skills they will need to fulfil their role. Lastly, the government has significant influence when it comes to implementing new digital technologies in the industry through the implementation of appropriate policies and legislation, as well as helping with funds and capital to drive specific new initiatives. The following is highlighted [15,19]: i) implement strategies that require the entire maintenance and asset management industry to implement digital technologies in accordance with the applicable standardization (e.g. ISO 550000); ii) providing grants and subsidies to universities and industrial organizations that are willing to implement new technologies; and iii) establish working groups that assist the public and private sectors, as well as universities in innovating their work practices. On the other hand, LNEC, as a governmental research and training institute, has an important role in the interconnection between the academic and theoretical part, taught by universities, and the practical part needed by the industry. LNEC can bring these two parts together, to prepare national and international conferences, workshops, post-graduations, and training courses that combine the two purposes and include the necessary innovation related to maintenance and asset management applied to civil engineering.

4. Proposal for Reshaping maintenance and asset management education and training: Roadmap for Portugal needs.

4.1 Challenges and strategies for implementing a national action plan

Given the current state, in the field of maintenance and asset management, it is considered that the Portuguese reality could materialize in the not too distant future [3]: i) Better visualization / better impact; ii) Increased productivity thanks to greater and better ease in structuring information; (iii) greater and better organization of documentation; iv) Integrate and link vital information such as specific material suppliers, location details and quantities required; (v) Acceleration of response to situations; vi) Reduction of costs and delays; (vii) creating/improving/increasing the development potential of the construction industry and related fields [1,7,9].

However, there are challenges that need to be overcome, such as [1,8]: i) There is still some lack of demand; ii) Some current entrenched practices; iii) Need for more qualified resources than the existing ones. Despite the challenges to be overcome, strategies can be identified (Figure 2) to encourage the dissemination and generalization of maintenance and asset management procedures in the construction sector in Portugal in the coming years, such as: i) Imposition by the public sector ; ii) Publicize and promote successful cases; iii) Minimize impediments and encourage maintenance actions as well as proper asset management of any type of asset; iv) Develop skills in the areas of maintenance and asset management, particularly those related to digital transformation and Construction 4.0.

4.2. National action plan proposal

Considering what was presented in a schematic way in the previous point, a proposal for the modernization of maintenance and asset management in Portugal in the coming years may generally comprise the strategies previously presented for each of the challenges, as well as the actions that take place to sum up (Figure 2). For the challenge, lack of demand, the imposition by the public sector and the dissemination of success stories were identified as challenges. In the first case, the following strategies are envisaged: i) Creation of an "*IT Centre*"; ii) "*collaborative work*"; iii) "*make mandatory implementation*". With regard to the action Creation of an IT Center, the following are considered as the most relevant line of action: i) Proposal for the development of a national strategic plan; v) interconnection between maintenance and asset management in a digital transition environment, for example through BIM and other national construction information systems; vi) adaptation of standards applicable to maintenance and asset management and their dissemination throughout the national technical environment (owners, consultants, designers, builders, public works owners, operation and maintenance managers). About the Collaborative work action, it is recommended that this should be developed by different bodies and within the scope of pilot projects that consider all actors in the AECO (Architectural, Engineering, Construction and Operation) sector to consolidate the dissemination of maintenance plans and asset management actions. The mandatory presentation of maintenance and asset management plans will bring benefits related to transparency in the exchange of information and minimization of possible errors inherent to the activities involved. In the second case, dissemination of success stories, within the scope of the action "*Disclosure of strategies and results obtained in Portugal and other countries*", the aim is to disseminate success stories in the areas of maintenance and asset management to raise awareness among AECO sector stakeholders of the benefits of its implementation, as well as encourage the generalization of its good practices in Portugal in the short/medium term. Regarding "*Competitions*" Maintenance and Asset Management, the aim is to promote the participation of entities involved in the implementation of maintenance and asset management strategies, in the AECO sector, in international initiatives sponsored by organizations of recognized merit and already identified, as well as promoting new initiatives at national level [7,20]. For the challenges of some currently entrenched practices and need for more qualified resources than the existing ones, strategies were identified that dynamically interrelate with each other, namely, to minimize impediments. With regard to the "*Community Growth actions*", it is recommended to promote: i) contact with local authorities with a view of establishing a closer relationship for synergies and support for the growth of the maintenance and asset management community, for subsequent dissemination of knowledge to designers, builders and participants in local architecture, construction and engineering activities; ii) direct contact with large companies to support the implementation of innovative and efficient maintenance and asset management strategies; iii) synergies with software companies to create products that are simpler and cheaper to use; iv) the development of free use modules for different situations. To "*Promote Leadership*" at national level, it is intended to enhance the use of maintenance and asset management standards, as well as to promote advice aimed at effective implementation, achieved through the development of guidelines for collaborative work about maintenance and asset management; ii) working groups dedicated to legal and contractual issues; iii) AECO, exploration and maintenance multidisciplinary working groups. Finally, with the aim of "*Creating a Training & Productivity Fund*" for maintenance and asset management (MAM Fund – Maintenance and Asset Management Fund), the following are envisaged: i) application to national or international structural funds to support their widespread implementation in Portugal; ii) the definition of business-level schemes and a collaboration regime for maintenance and asset management projects. With regard to the action "*Equipping future generations*", the following are considered as structuring lines of action: i) awareness-raising actions; ii) contact with universities to support the definition of disciplines in the area of Maintenance and Asset Management; iii) agreements with universities and other institutions of the scientific and technological system, in order to develop master's and doctoral theses and disseminate knowledge; iv) promotion of seminars, sessions, workshops, dissemination (for technicians and national students); v) development of specific programs and internships (national and international); vi) establishment of protocols with professional entities (engineers, architects, etc.) to encourage and promote maintenance and asset management in the national technical environment; vii) Center of Excellence in Maintenance and Asset Management; viii) development of applied research in the area [8,9,20].

Figure 2 – Challenges, strategies and actions for reshaping maintenance education and training

4.3. National action plan integrated actions

To respond to the challenges identified in the previous point, several actions have been developed to integrate a national plan of organized and directed implementation about Maintenance and Asset Management. Regarding collaborative work, emphasis should be placed on the creation of working groups in maintenance and asset management within the scope of activities carried out by the Portuguese Construction Technological Platform (PTPC), belonging to the European Construction Technologic Platform (ECTP). Within the developments verified, not only at CEN level but also in the countries that are part of the CEN/BT WG 215 group, it was understood as pertinent the creation of national commissions capable of collaborating in the developments of the CEN and of boosting the dissemination and the implementation of regulatory developments related to maintenance and asset management. In this way, the Technical Commission CT94 - Maintenance and the Technical Commission CT204 - Asset Management whose work has been monitored by various entities of the highest relevance in the national AEC sector. In addition to these two commissions, the Technical Commission CT192 – Facility Management also refers to work that is often interconnected [18]. About the Dissemination of Strategies and Results, reference is made to the organization of international conferences in the area (e.g., WCEAM, ConGrega) with the participation of renowned experts and national and international users. Within the scope of PTPC activities, a forum of great impact in the AECO sector was organized in 2014, under the theme “Until today I was always future” in which, in addition to BIM, gave emphasis to the importance of maintenance and asset management in the future of the industry construction in Portugal. IST and LNEC have been organizing courses and collaborative and dissemination sessions to present the themes in question, as well as ongoing research projects, subordinated to the referred themes. In general, national, and international conferences in recent years, in the field of construction, have increasingly included thematic sessions related to maintenance and asset management. Regarding “Competitions”, it should be noted that, although initiatives of this type have not yet been structured at national level, it has been verified that the Portuguese who implement maintenance plans and asset management actions in their activities, have have been winners of this type of initiative at an international level in recent years [7,9]. About the growth of the community in the thematic areas of maintenance and asset management, it has been verified that the number of scientific articles and publications of a technical nature has been increasing significantly in recent years. Companies in the AECO sector, due to the need to operate in international markets where innovative maintenance and asset management approaches already appeared to be an effective reality, have also been investing in the digital transition with a focus on BIM for support. In this way, in Portugal, more and more companies are using innovative maintenance plans and integrated approaches to asset management to respond to international requests, also contributing to the growth of the community. Regarding equipping future generations, the number of specific courses, face-to-face or via the web, in the broad areas of maintenance and asset management has been increasing, as well as initiatives of a more restricted nature, such as some specific training courses taught by public and private universities. In addition to this, various public and private universities have been including content related to maintenance and asset management in their programs of disciplines in the field of construction, as well as their importance and need for implementation in the AECO sector.

There is also a very significant increase in the number of master's dissertations and doctoral theses both presented and in progress in the referred areas. It is expected that this increase will also intensify in the coming years [7,8].

5.Conclusions

This paper intends to present an overview of the current and future trends in construction management and construction engineering and to identify the required skill sets of future civil engineers, namely for maintenance and asset management areas. The importance of digital skills to the graduate and post graduated engineers working in construction is also very important, not only from the perspective of the industry but also from the perspective of the students, that will be the future professionals. It is important to clarify the digital technologies that the construction industry is using nowadays and the digital skills still necessary to facilitate the digital transition in all areas of civil engineering in general, and in maintenance and asset management in particular. The review findings point to: i) digital skills being very important for graduate and post graduated engineers; ii) there are still significant digital skills gap, with most of graduates and post graduates having insufficient skills in planning and programming for maintenance tasks and asset management skills; iii) necessity of overcoming the skills gap by improving the current engineering curriculum. Some skill sets, identified as very important in succeeding as a future engineer in maintenance and asset management areas, still need improvement, namely in what concerns management documents, works simulation and project planning. A proposal for reshaping maintenance and asset management education and training including a preliminary Roadmap for Portugal´s needs was presented based on the review, including the challenges and strategies for implementing an action plan based on digital skills transition strategy that outlines some methods for overcoming the digital skills gap. The roles of universities, construction industry and its professional associations and government should be emphasized to give the necessary support for a necessary transition strategy to reshaping maintenance and asset management skills towards digital transformation. The proposal presented for Portugal aims to realize a vision of a modern, highly integrated, and technologically advanced construction sector during the 2020s and for the following decades, which will be led by companies with a high degree of progress and innovation and supported by a workforce with a high degree of qualification and competence, particularly in the areas of maintenance and asset management.

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Artificial intelligence diagnosis and analysis in roto-dynamic machinery faults recognition using AI techniques

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Abstract
In the domain of industrial machinery, predictive maintenance plays a pivotal role in minimizing downtime and optimizing operations. This comprehensive research explores an innovative approach to predictive maintenance by harnessing the vibration sensor signals analysis. The primary goal is to autonomously predict the timing and root causes of faults in roto-dynamic machinery, revolutionizing maintenance practices.

The methodology involves advanced artificial intelligence techniques, with a focus on deep learning, to analyse real-time vibration sensor data. Cutting-edge equipment with high-resolution data acquisition capabilities is employed, enhancing signal investigation and discrimination. Machine learning models like Convolutional Neural Networks (CNNs) [19] and Transfer Learning are integrated for accurate fault prediction.

The research demonstrates the effectiveness of deep learning algorithms in predictive maintenance. These algorithms can autonomously identify fault timing and causes, reducing reliance on human expertise and enhancing accuracy. A practical case study involving a centrifugal pump within a Reverse Osmosis process validates the system's capabilities[26].

The benefits of predictive maintenance using vibration sensor signals are substantial, including cost savings, reduced unplanned downtime, and improved operational safety. The study emphasizes the importance of proactive maintenance in optimizing industrial efficiency and ensuring the longevity of critical equipment.

The device underwent rigorous testing at the Jubail pilot plant in WTIIRA premises, where it was installed in the pump of the nano unit for an extensive one-month trial period. During this testing phase, the device demonstrated its capabilities by promptly detecting an alarm signal related to the bearing of the pump. This early warning provided crucial insights into the machinery's health and potential issues, identifying breakdowns and facilitating timely maintenance interventions. The successful trial at the Jubail pilot plant underscored the device's practical applicability and its potential to revolutionize predictive maintenance practices in the industrial sector.

This research showcases the transformative potential of artificial intelligence and deep learning in predictive maintenance. Proactive maintenance practices are highlighted as essential for operational efficiency and the preservation of vital industrial equipment.

Introduction

Pumps are crucial devices within the desalination industry, serving as the lifeblood of various processes critical to freshwater production. Desalination mainly has two operation techniques membrane (reverse osmosis) and thermal (Multi stage flash and Multi effect desalination) [1]. In the realm of Reverse Osmosis (RO), pumps play a pivotal role as the main driving force behind the pressurization of seawater, facilitating its passage through semi-permeable membranes to separate salt and impurities [2]. This process underpins the efficiency and productivity of RO systems, making pumps an essential component in the quest for freshwater generation. Moreover, pumps find their significance in Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED) systems by circulating water in the heat exchanger area. They maintain the circulation required for the evaporation and condensation stages, ensuring that thermal desalination processes operate optimally [3]. Thus, pumps are not only the heartbeat of the desalination industry but also a testament to the critical

synergy of mechanical and thermal processes in meeting the world's growing freshwater needs.
This was the driver for this research, to mainly predict the fault and its timing to avoid any forced shutdown and increase plant reliability, which will lead to reduce the water unit cost.
In the industrial machinery, the pursuit of seamless and uninterrupted operations has long relied on the discerning eye and expertise of human vibration analysts. These professionals have played a pivotal role in detecting faults within roto-dynamic machinery, offering invaluable insights into the reliabilty of critical equipment. However, as technology advances and operational demands grow more complex, the need for autonomous and real-time fault detection becomes increasingly pronounced [4].

The core objective of this research is to pioneer an intelligent system capable of autonomously detecting faults in roto-dynamic machinery, minimize the necessity for human interaction, and thereby elevating the accuracy and speed of condition monitoring. The cornerstone of this research lies in the utilization of microprocessor-based intelligence.

In this research, bound the power of artificial intelligence, leveraging a sophisticated AI software built on the Python programming language. Coupled with a cutting-edge data acquisition card, we interface vibration accelerometers to capture real-time raw signals in the amplitude-time domain. This synergy of advanced technology boasts a high-resolution 24-bit analog-to-digital converter (ADC) and a remarkable sampling rate of 48,000 samples per second (S/s), affording us the highest degree of signal investigation and discrimination across all types of signals.

on the test was conducted on a 75 kW centrifugal pump. Operating at various load through variable frequency driver for the Reverse Osmosis process

Figure 1. sensor installation on the pump and system installation

Methodology

Fault diagnosis is the process of extracting and analysing the characteristic data of the equipment[5] to obtain the state of the equipment and judge whether the equipment is abnormal. Generally, fault diagnosis technology includes three tasks:

fault detection, which is used to detect equipment faults;
fault isolation, which is used to locate and classify faults;
fault estimation, which is used to determine the nature and level of faults.

There are three kinds of fault diagnosis methods: experience-based method, model driven method and data driven method

The experience-based method is used in systems that lack information and are not easy to model[10], and requires a lot of expert experience; the model driven method relies on accurate mathematical model and requires a lot of expert experience too. The data driven method mainly adopts various data mining technologies to obtain the key information hidden in the data, analyses the state of the equipment, and achieves the goal of fault detection, diagnosis and isolation. Compared with the experience based and model driven methods, the data driven method solves the problem of relying too much on expert experience and mathematical model. With the rapid development of information technology, data-driven fault diagnosis technology [12] has been developing

rapidly and been widely used. Fault diagnosis based on deep learning is an important data-driven fault diagnosis method as in figure 2.
Fault diagnosis based on deep learning Deep learning is new research in the field of machine learning. It makes machine learning closer to the original goal -- artificial intelligence (AI) [7]. With the help of strong learning ability, deep learning transforms the low-level features of the input data into high-level features, simulates very complex functions, and obtains the inherent laws of sample data. Fault diagnosis technology based on deep learning takes feature learning as the main purpose. With the development and application of Convolutional Neural Network (CNN) figure 3, Deep Belief Network (DBN), Generative Adversarial Network (GAN), Transfer Learning and other algorithms, the application of fault diagnosis based on deep learning is more and more common.

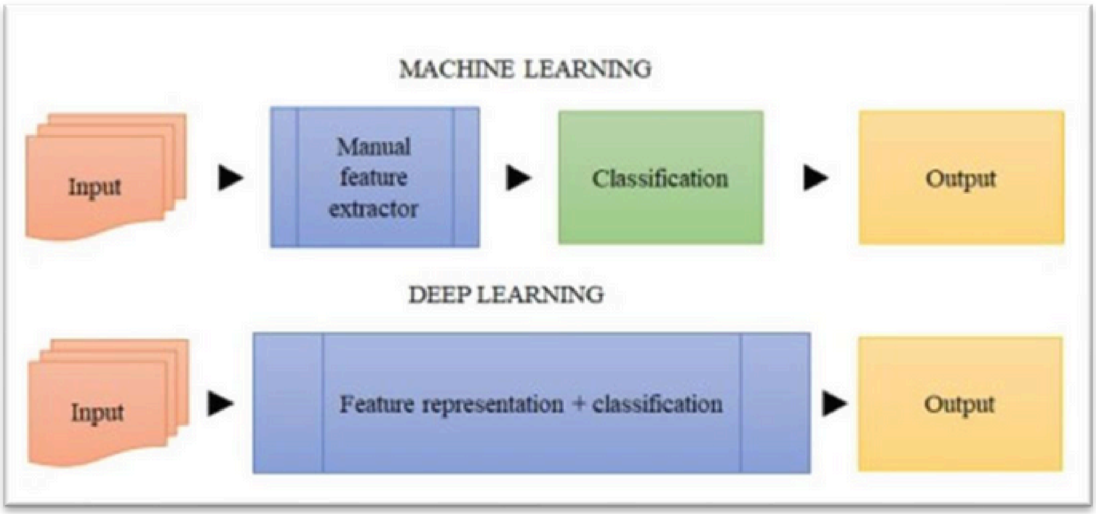

Figure.2 machine learning (ML) vs deep learning (DL)

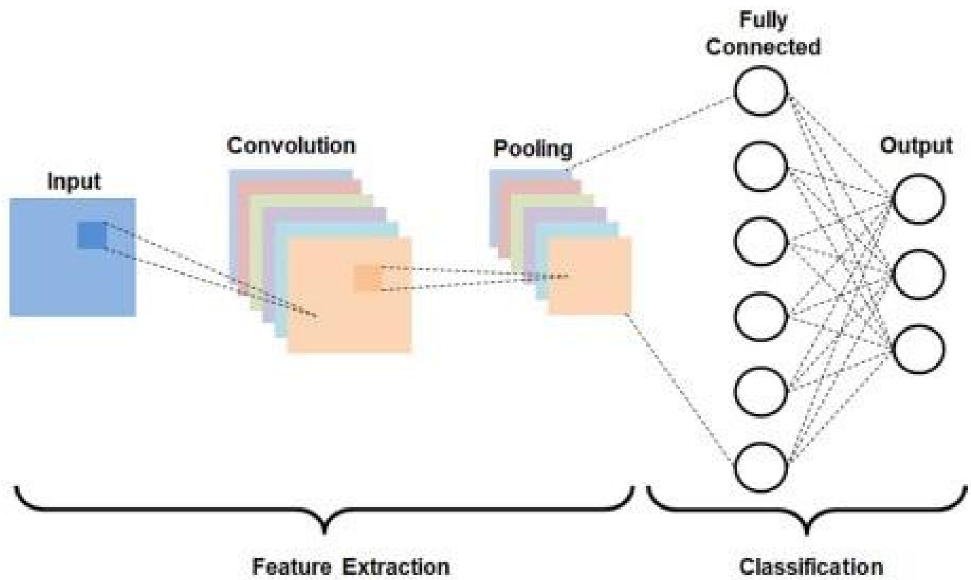

Figure3: CNN architecture

SO, fault diagnosis using AI plays a significantly important role [11] in reducing both operation and maintenance costs and ensuring safe operations and it generally has three diagnosis steps:

1. Sensor data that can show the health status of equipment is collected.
2. The features are extracted from the collected data by various algorithms.
3. According to the extracted fault-sensitive features, various ML algorithms are used to identify and classify the faulty states of equipment. With the rapid development of DL.

In this case a regular trend analysis for the parts (break down) estimated for avoid the failure of machine parts and this is a highest priority aspect for the possessor of right to maintain the machines in good working condition without facing the unplanned or off schedule shutting down
The figure 4 represent an example of trend analysis

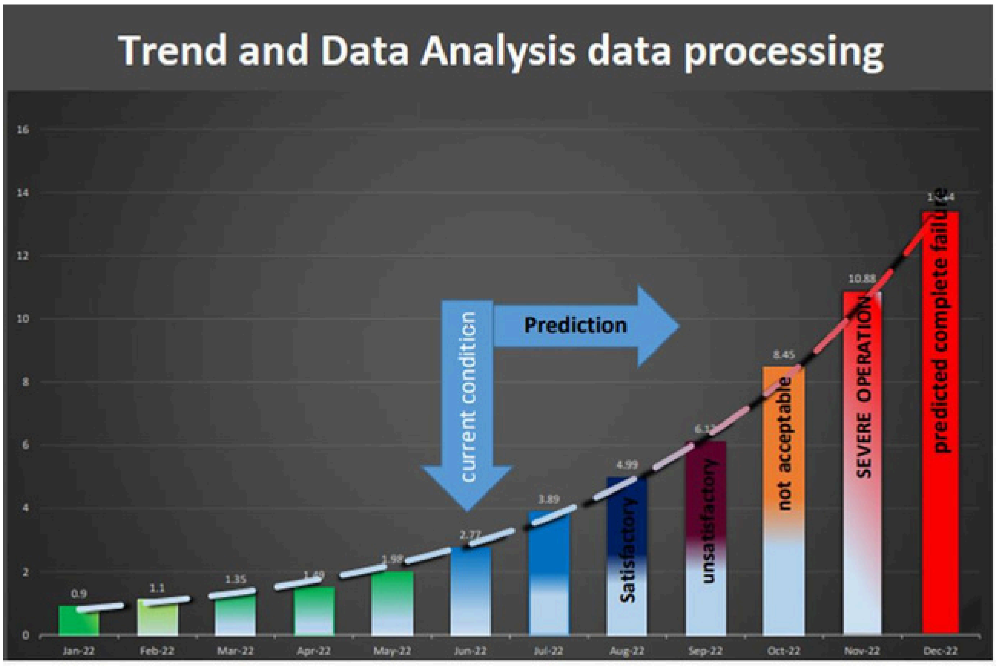

Figure 4: represent an example for trend analysis

Evaluation test

The advanced system of artificial intelligence was tested on the pump shown in figure 1 as discussed which has the following characteristics:

- Centrifugal type
- rotating speed (59 revolutions per second)
- The power is 75 kW

that the system is placed on a pump that is likely to have a specific defect
In the following report, some points are reviewed that indicate the presence of an accuracy or defect in the artificial intelligence program

In the event of running the program, the program, after a measurement period of about 3-4 seconds, determined a degree of severity of the above-average type, which is close to a very dangerous condition, and therefore the occurrence of an imminent defect and the possibility of a breakdown in the pump, but the program cannot determine the time of the breakdown except after a period of time Specific to complete the rest of the inputs and determine the most accurate times for the collapse

However, the extrapolated signals, as in Figure 4, show that a maximum value of mechanical vibration occurred at a frequency of 1.3 kHz, with a warning that this potential defect is a defect of the bearings.

Figure 4 shows another application used, but less than developed, for measuring signals

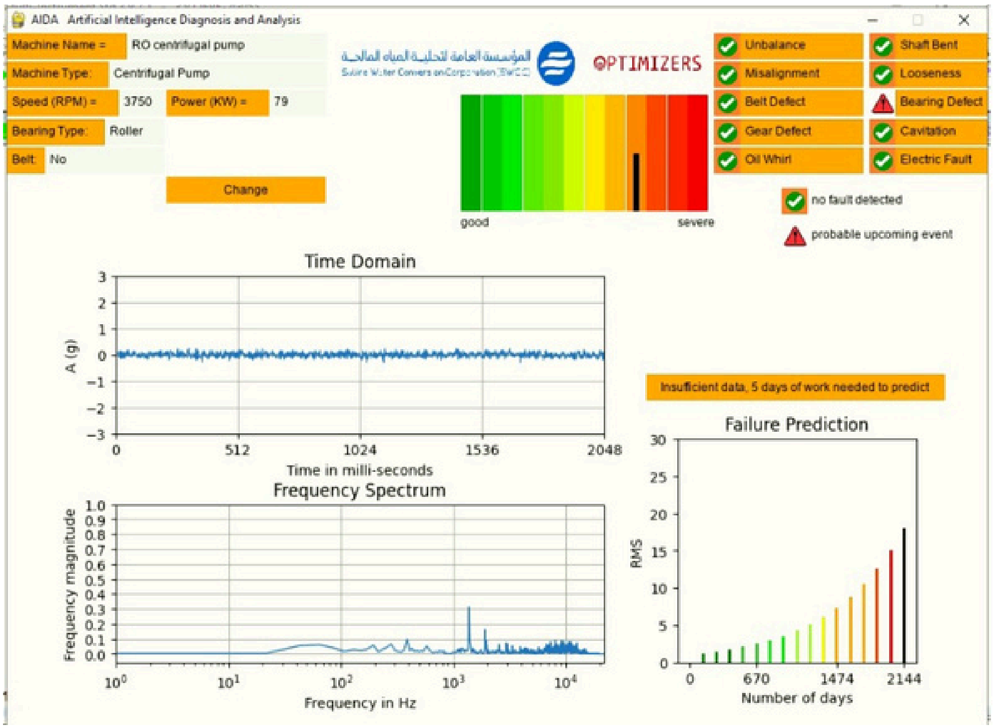

Figure 5: represent the image of operating AIDA program referring to fault

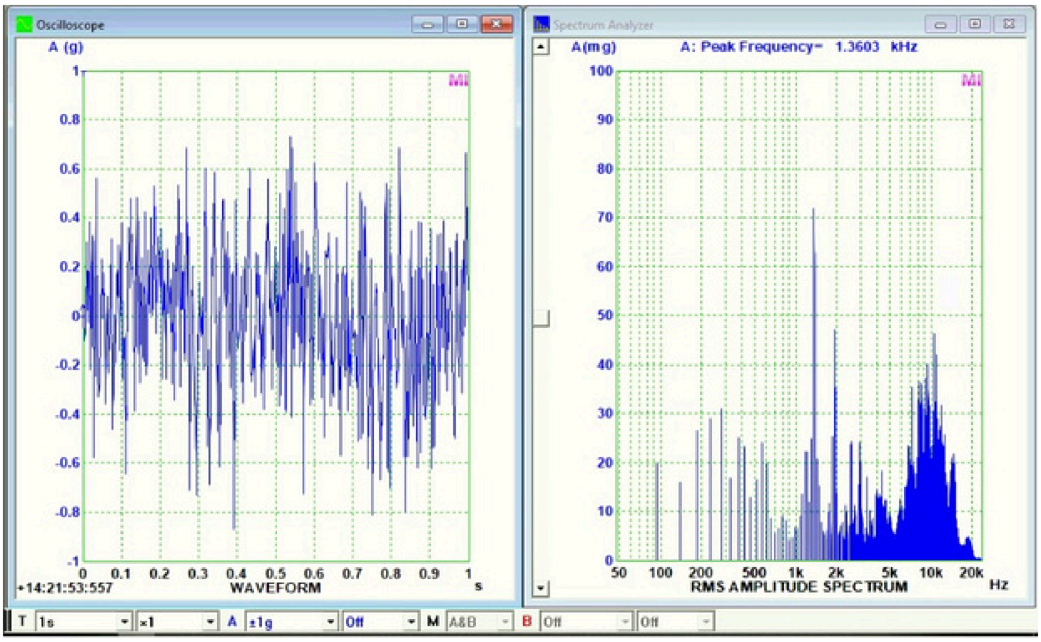

Figure 6: represent time wave form and FFT wave form

Whereas, if compared to any traditional system, it is found that the defects related to the bearings indicate the presence of mechanical vibration resulting from the defects of the dynamic bearings in the figure 6 , and this is according to the tables and scientific references listed by the American Vibration Institute, which is subject to the American Petroleum Institute .
From the figure, it is clear that the current range of the possibility of a malfunction is a defect in the bearings of the machine, and the defect is from the second stage, as the frequency is between 600 Hz and less than 3 kHz, which indicates that the remaining life of the bearings is from 10-20% of its life default

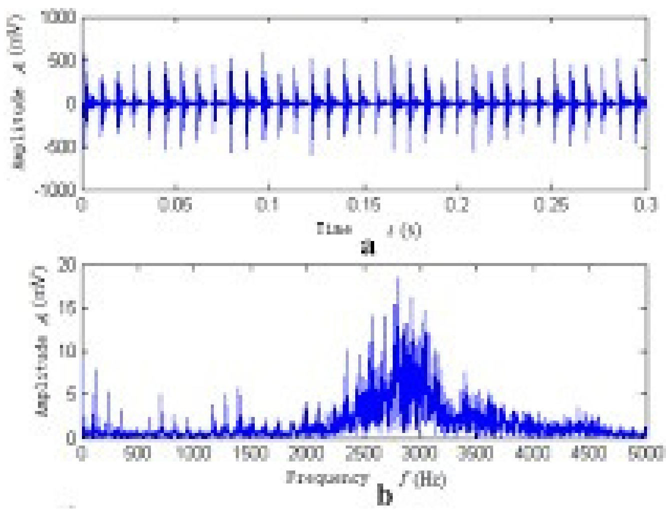

Figure 7: represent the bearing fault standard wave form

Determining the malfunction and making the claim that it is a bearing issue[21],is not an exact engineering act, but the artificial intelligence must determine what the malfunction is exactly, and therefore the computer does coordination and scrutiny with the highest accuracy and knows where the problem is located inside the bearing, so is it the rotating elements or External or internal framework, and this is what the program is developed for

The system must collect data n for a certain period of time to obtain the best accuracy in reading, which would store the data and create a time visualization with very high accuracy through artificial intelligence and make a graphic curve for the user to show the earliest time period in which the machine may be destroyed as a result of the accumulation of mechanical vibration data as shown in the figure 4.

After disintegration of the machine it was obvious that the bearing has been subjected to a severe operating condition due to lack of greasing as in image

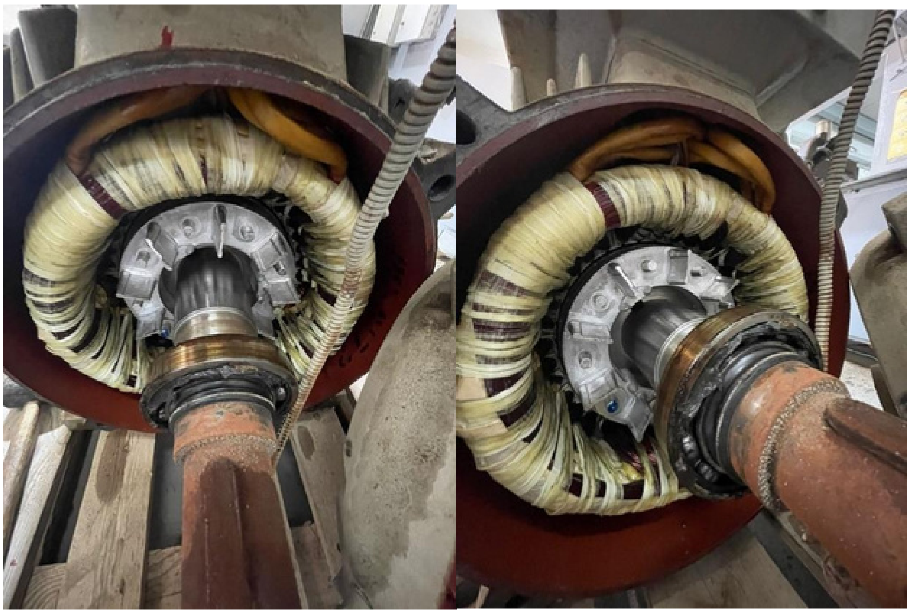

Figure 8: represent identical fault detected by the AIDA

In design consideration and after the system delivery the designer / possessor of rights shall run a vibration analysis testing which will indicate the severity and or the normal operation of items according to the ISO Standards 10816-3 as represented in fig 8

VIBRATION SEVERITY PER ISO 10816

Vibration Velocity Vrms in/s	mm/s	Class I small machines	Class II medium machines	Class III large rigid foundation	Class IV large soft foundation
0.01	0.28	good	good	good	good
0.02	0.45	good	good	good	good
0.03	0.71	good	good	good	good
0.04	1.12	satisfactory	good	good	good
0.07	1.80	satisfactory	satisfactory	good	good
0.11	2.80	unsatisfactory	satisfactory	satisfactory	good
0.18	4.50	unsatisfactory	unsatisfactory	satisfactory	satisfactory
0.28	7.10	unacceptable	unsatisfactory	unsatisfactory	satisfactory
0.44	11.2	unacceptable	unacceptable	unsatisfactory	unsatisfactory
0.70	18.0	unacceptable	unacceptable	unacceptable	unsatisfactory
0.71	28.0	unacceptable	unacceptable	unacceptable	unacceptable
1.10	45.0	unacceptable	unacceptable	unacceptable	unacceptable

Fig 8: represent the severity chart of machine classification in ISO standard

The computer, based on a pre-set database, matches the standard table used ISO 10816, which is responsible for determining the best operating conditions according to the value of mechanical vibration, as in Figure 8

Conclusion

With the development of science and technology, the continuous improvement of data acquisition, the continuous maturity of data mining, the continuous improvement of computing power and the continuous optimization of algorithms, it is possible to apply artificial intelligence analysis for fault diagnosis. Fault diagnosis technology based on deep learning has become popular research and continues to mature. It will solve the difficulty of modelling, identification, and positioning of traditional fault diagnosis, and ensure the safety of production and life.

The successful evaluation test of utilizing artificial intelligence (AI) and machine learning for pump fault diagnosis marks a significant milestone in the field of predictive maintenance. The test, conducted on a pump within the Jubail pilot plant, demonstrated the potential of AI in autonomously detecting faults and pinpointing their nature, particularly identifying bearing defects. This achievement underscores the transformative power of advanced technology, including deep learning, improved data acquisition, and refined algorithms. By harnessing AI's capabilities, industries can revolutionize their approach to equipment health monitoring, ensuring reliable operations while minimizing downtime and maintenance costs. The proven effectiveness of this approach would play a central role in optimizing industrial processes, enhancing efficiency, and prolonging the lifespan of critical machinery.

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[5] applications of artificial intelligence in fault detection and prediction in technical systems
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The Suez Canal Incident: Learning from Failure by Using Reliability and Maintenance Techniques

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Abstract
The purpose of this paper is to investigate the Suez Canal incident by formulating a hybrid model, inspired by maintenance and reliability techniques, that can enable the process of learning from failures. The hybrid model uses a fault tree analysis (FTA), reliability block diagram (RBD), cut set analysis (CSA), and the bowtie method (BTM). The formulated techniques show the synergy between the techniques and how they can be incorporated in order to provide a better understanding of the incident and extract the lessons learned that can prevent a reoccurrence of such an incident. The need for a such hybrid model is essential nowadays since incidents and disasters are becoming more complex, hence a deep analytic technique is required to cover all reliability factors. It can be argued that there is no perfection in using only one technique to address all the reliability aspects, and it is vital to integrate more than one technique, with its particular advantage, in order to have a clear, focused and comprehensive understanding of the area of concern. In addition, it is essential to derive from that level of analysis lessons that can help to improve the overall system reliability and prevent future undesired events.

INTRODUCTION

Is the sky yellow? This question is frequently asked in the Gulf and African regions before planning any trip out. Due to the mother of nature in this kind of region, the word yellow has only one vital meaning (Dusty). The Gulf and African regions have a wide range of desert land. Sandstorm frequently occurs during the period of the year and subsequently affects most planned trip decisions, and the practical decision is to stay grounded until the sandstorm finishes or passes the affected area. This is because the sandstorm is usually riskier than fog, snow, and high wind; specifically, because the sandstorm blocks the complete visibility and has a high air density that can maneuver any heavy objects because of the soil particles and dust contained in the air. Thus, on sandstorm occasions, the safest decision to be taken is to delay or reschedule any planned trip for safety purposes.

On March 23, 2021, a high wind sandstorm occurred in the north-eastern of Egypt, affecting the busiest seaport in the world, the Suez Canal. On that day, 12 ships have navigated successfully through the canal while a high wind sandstorm affecting the vision clarity and ship navigation control. However, one of the giant ship containers in the world (Ever Given) was lined up in the queue to be the 13th ship to navigate through the canal sailing on its way to Rotterdam, Netherlands. Unfortunately, a few miles after entering the canal, the captainship lost control of the Ever-Given ship, causing a diagonal wedge ship position that blocked the entire waterway of the Suez Canal, as illustrated in figure 1. Risk of grounding and collision is one of the major failure modes in navigation of vessels (Bakdi et al, 2019). Moreover, around 46% of collisions occurred in restricted waters; rivers or fairways (Fan et al, 2022). Hence the analysis in this paper provides a set of integrated tools that can help in analyzing the causes of many similar accidents for both prevention and mitigation of risk.

LITERATURE REVIEW

Based on European Maritime Safety Agency (EMSA), the total number of reported ship accidents from 2014 to 2019 is 3,174. The accident classifications and rates were identified as grounding (12.9%), contact (15.3%) and collisions (26.2%) of total reported accidents. Hence, navigation failure is rated to be related to more than half of the accidents. It is crucial to investigate and identify the causal factor of ship accidents to prevent such events since the severity occurring to the human, environment, and the economic impact is very serious, and it is essential to minimize the risk of the incident to reduce the finical losses and negative impacts (Sakar et al, 2021). With engineering reliability and technology development, the understanding of accidents becomes more crucial for both industrial and academia especially when risk and hazard are of a cascading nature (Suppasri et al, 2021).

Major disasters are characterized as of having low probability of occurrence and high severity of consequences. This makes the associated risk assessment characterized by a high degree of uncertainty. Therefore when modelling sources of uncertainty in risk, one can classify such sources into either aleatory (the intrinsic randomness nature of a phenomenon) or as epistemic (due to lack of knowledge) (Taarup-Esbensen 2020). As will be shown later on, we develop our classification of the causal factors of the chosen incident based on such categorization.

Fault Tree Analysis (FTA) has drawn attention for both sectors by systematically structuring trees investigating the casual factors and their associated relationships. Another distinguished reliability technique is the reliability block diagram (RBD) which expresses the graphical analysis technique to demonstrate the area of concerns of system connection components with their associated reliability of logical relation. Hence, the RBD signifies the system performance based on the effect of component failures. Each of the components is categorized into two boxes which can be described as operating or failing. The RBD have two main classifications parallel RBDs and series RBDs. (Kim, 2011). Additionally, employing a number of techniques to strengthen the investigation analysis has been proposed by using FTA to identify direct causes and their associated contributing factors to simulate the interaction with each other and use it as input to the reliability block diagram (RBD) analysis to measure the effectiveness and the improvement of the overall system reliability (Labib, 2021).

Moreover, A bowtie framework is a broad analysis technique that tends to demonstrate FTA to an integrated analytical model to analyse the causing of the event from one side, and the event consequence from the second side with a traditional FTA top event in the centre of the bowtie model. The bowtie framework has proven its capability for analyzing both retrospective and prospective incidents. Such an integrated structure of analysis will be able to signify system reliability improvement and prevent further reoccurrence of undesired incidents. (Mokhtari et al, 2011).

Based on the literature review above, it is crucial to incorporate more than one reliability technique to investigate and analyse a recent or previous incident to structure a comprehensive model analysis. Therefore, a hybrid technique will be structured to investigate the recent incident (Suez Canal Incident) that occurred on March 23,

3. PROBLEM CONTEXT:

3.1 Egyptian Seaport Suez Canal Overview

The Egyptian Suez Canal operation started in 1869. The Suez Canal's dimensions are 120 miles (193 km) long, 205 meters wide and 28 meters in depth. In addition, Suez Canal connected the Mediterranean Sea to the Red Sea with a crucial trading waterway between Asia, Africa and Europe, as illustrated in figure 1. In 2020, the canal usage estimated capacity was averaged around 19,000 ships per year with a total tonnage of 1.7 billion tons, the canal controls up to 13 percent of the world's maritime trade, with approximate 10 percent of oil trade that passes the channel. (Yizhen, et al, 2021).

In 2014, the Egyptian authority launched a new $ 5 billion project to expand the Suez Canal to create a parallel channel, and the expansion was fully completed in 2015. The canal's estimated traffic was averaged around 49 ships per day before the expansion project. The Suez Canal was expected to accommodate 97 ships per day following the completion of the expansion project. In addition, the vessel transit time and waiting time have been reduced. For instance, the southbound transit time has been reduced from 18 to 11 hours. On the other hand, the vessel waiting time has also been reduced from 11 to 3 hours (Rusinov et al, 2021).

3.2 The Ever Given Ship And The Suez Canal Incident

The named cargo ship (Ever Given) was built by a Japanese shipbuilder Imabari Shipbuilding in 2018. Currently, the vessel is sailing under the flag of Panama, and the vessel is considered one of the 10th largest ships globally. The ship's container specifications are 400 meters long, 60 meters wide, speed 22.8 knots and carry 18,000 containers. (Yizhen, et al, 2021). The ship accommodates up to 25 sailing crew, the majority from India.

At the time of writing this work in August 2022, the Egyptian Suez Canal incident is still under investigation by the International Maritime Organization (IMO). In addition, an independent investigation is also ongoing by Suez Canal Authority (SCA) since the incident occurred in late March 2021. Unfortunately, various information is still faded until this moment. Therefore, a secondary source of information collection will be used through a widely proven research method to structure the incident.

On March 23, 2021, at 5:40 UTC, Ever-Given was sailing northbound through Suez Canal, heading on its way to Rotterdam. The weather condition at the sailing time was not ideal due to the severe sandstorm with high-speed wind estimated at around 40 knots. (Forti et al, 2021). According to the Suez Canal Authority (SCA), In this kind of weather condition, (SCA) usually leaves the final decision to the captainship to decide to navigate the ship or wait until the weather condition becomes ideal. Ever given was queued at number 13th at that date, where 12 vessels were ahead to be sailed before Ever Given, and the 12 ships have decided to float and made it through the canal and headed its way to the Mediterranean Sea.

Initially, the Ever given decided to sail through the Suez Canal despite the severe weather condition. The (SCA) usually assign an experienced Egyptian pilot to support any ship entering the canal and provide instruction and advice to the captainship during the sailing through the canal. However, the pilot will not have complete control to steer the ship. Therefore, the ship will always be fully steered and managed by the captainship.

Furthermore, once the ship entered the narrow one side canal, the sandstorm with a high wind speed reached 40 knots (74 Km per hour) caused the vessel to swing back and forth in the canal and the control of steering the ship was hardly unmanaged by the captainship. This is due to the fact that the Ever Green containers acted like a sail that generated a significant force that led to the erratic steering and uncontrolled sideway navigation (Khan and Rahman, 2021). However, a few minutes later, the captainship started to increase the ship's speed to 13 knots, whereas the canal's recommended speed is 8 knots. Subsequently, the captainship lost control of the ship due to the high wind sandstorm that caused the ship to navigate and aground diagonally in the canal with its bow to one of the banks and the back of the ship grounded to the second bank.

Consequently, a diagonally 40 Degree ship position in the middle of the canal caused a total closure of the southern waterway of the Suez Canal. Subsequently, the blockage caused a traffic jam for more than 360 ships and held more than $ 9.6 billion maritime global trade for seven days (Forti, et al, 2021).

On March 24, the Egyptian (SCA) announced a deceleration of emergency due to Suez Canal blockage and suspension of navigation through the canal. Moreover, all the ships have been diverted to the old canal channel.

On March 25, an operation center was framed by (SCA) to perform an immediate risk assessment in order to re-float the Ever given ship and clear the water pathway of the Suez Canal. The (SCA) operational rescue plan was consistent with three main options:

Firs t, dredging and digging at the bow of the ship.
Sec ond, Tugboats pull and push the ship.
Third, Offload the ship containers to lighten the vessel.

According to (SCA), the ship owners hired a Dutch firm called Smit who is considered one of the preeminent rescue ships firms in the world. Nevertheless, the rescue operation was managed by the (SCA), and there was not much involvement of Smit firm in the ship rescue operation.

The (SCA) tended to avoid as much as they can the third option since it is a highly risky and extremely expensive approach, and all the cranes and equipment are not available at the site. In addition, such an approach might take weeks or months in order to complete the offload of the ship containers Therefore, the (SCA) focused on the first and the second options.

On March 25-26, (SCA) worked simultaneously on the first and the second options and continued dredging, digging, tugboats pull and push activities, which resulted in freeing the ship's back by 4 meters from the bank. Moreover, on March 27-28 significant progress was accomplished by SCA where the gap between the bank and the ship's back was increased by 102 meters. However, the bow of the ship was still wedged.

On March 29, (SCA) decided to use 15 tugboats to pull and push the ship with the association of the high tidal peaks that occurred due to the supermoon on that day, which contributed to increasing the water level in the canal. Furthermore, at 13:30 UTC, Ever Given has completely freed from both sides and the Suez Canal resumed its normal operation.

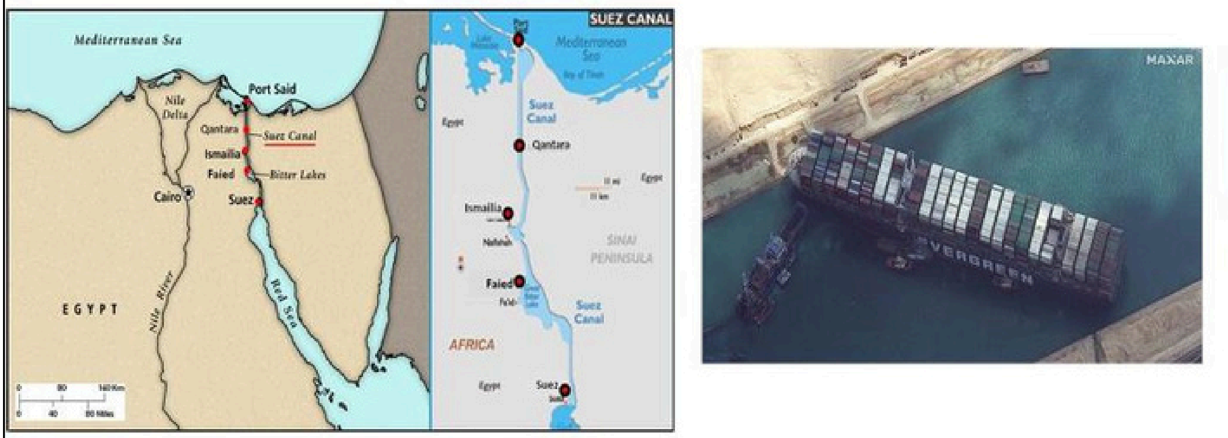

Figure 1. Egyptian Suez Canal on the left, and Ever Given container ship grounded in the Suez Canal on the right [Forti, et al, 2021]

3.3 Consequences Of Suez Canal Incident

Suez Canal blockage: seven days of blockage and ten days of canal maintenance restoration claimed to cost more than $ 100 million.
Vessel Disruption: More than 360 vessels are grounded in or out of the canal due to the blockage, which has held more than $ 15-17 billion for seven days of global maritime trade.
Vessel renavigation: Due to the canal blockage, several vessels have been diverted to use another longer channel through the Cape of Good Hope, which is estimated at around fifteen days delay.
Salvage Reward: Egyptian (SCA) claimed a settlement of $ 1 Billion of a salvage reward. However, the compensation was later reduced to $ 550 million.
Death: In June 2021, the SCA stated that one person died during the six-day salvage operation (Ankel, 2021).

4. HYBRID MODELLING APPROACH

Incidents and disasters become more complicated each day, and this might be due to the system integration with various advanced designs and technologies. Therefore, a standalone technique might not achieve all the requirements to identify the primary issue of the incident or the disaster since each technique has its capabilities and limitations to reach a particular investigation analysis.

A hybrid modelling approach provides a wide range of terminology to support the investigation team in analyzing and reviewing the event from different angles. For instance, many things can happen in the incident due to a specific factor that can be identified through a particular technique of analysis, which makes this factor the main route cause for the incident to occur. However, in terms of causality analysis, in a hybrid modelling approach, the primary factor might not be necessarily be the main factor that led to the incident, as it can reveal through further analysis of two or three sub-factors to the primary factor, and this can then be identified as the real root cause of the incident.

5. FTA AND RBD FOR SUEZ CANAL INCIDENT

A comprehensive analysis has been conducted utilizing the FTA technique to analyze, review, and identify the main causal factor for the Suez Canal blockage caused by a wedge grounded Ever-Given ship. In figure 4, FTA of Suez Canal blockage shows two primary causal factors, which are (banks collusion) and (failure associated with perception). Both casual factors have been contributed simultaneously to the canal blockage. Hence an AND gate has been linked to the FTA.

Notice that these two broad factors share similarity with the categorization of causal factors of risk, as proposed by Taarup-Esbensen (2020) as either based on the intrinsic randomness nature of the phenomenon (aleatory), or due to lack of knowledge (epistemic). In our case banks collusion was mainly due to randomness of weather conditions and lack of effective responsive procedures, and failure associated with perception due to lack of situation awareness or navigation failure.

There are two intermediate events identified that the ship banks collusion was contributed by the insufficient weather condition and procedure failure. Hence an AND gate have been linked to these two factors. Moreover, the insufficient weather condition was caused by poor visibility and high wind sandstorm that was estimated at around 40 knots. Thus, an AND gate have been linked to these two factors.

In addition, failure to follow the canal recommended procedure by violating the speed limit inside the narrow canal, which was 13 knots or lack of communication between the ship and tugboat pilot to follow the right and adequate procedure through navigating the ship inside the canal, which have heavily contributed to losing the ship navigation control. Hence, an OR gate is linked to these two factors. Furthermore, the failure associated with perception was caused by a lack of situational or navigation failure. Hence, an OR gate has been linked to the two factors. Also, the lack of perception was caused either by insufficient captainship reaction time or captainship over-reliance on tug pilots. Thus, an OR gate has been assigned to both events.

Finally, adequate navigation could contribute to preventing the incident from occurring. However, the failure of navigation was caused by either lack of communication between the ship and tugboat pilot or poor coordination to enter the canal in such insufficient weather conditions. Hence, an OR gate is linked for both factors. After carrying out the Suez Canal incident FTA, the Reliability Block Diagram (RBD) is a crucial technique to be used to assess the reliability of the system. The RBD technique uses the basic event generated from the FTA. Each AND gate indicate a parallel structure, and each OR gate indicates a series structure.

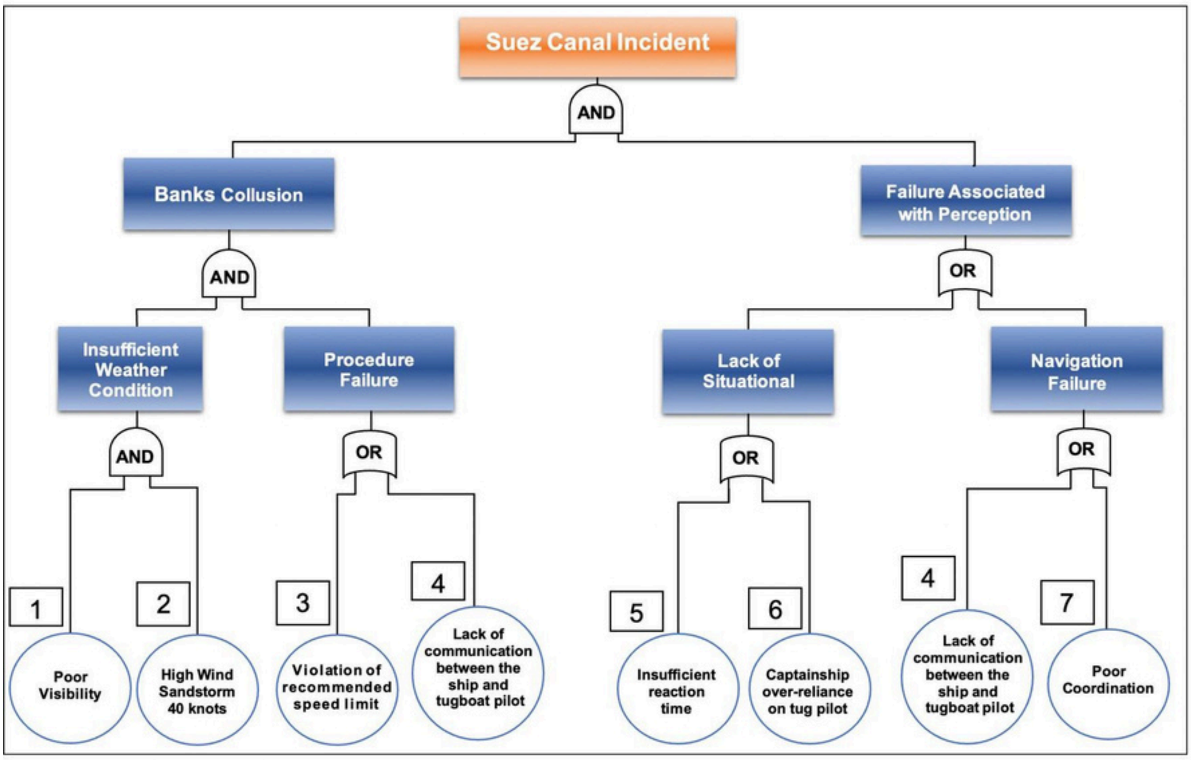

Figure 2. FTA Analysis of Suez Canal Incident

The RBD structured for the FTA Suez Canal incident in figure 3 shows a system vulnerability in the procedure failure items (3 and 4), lack of situational item (5 and 6) and the navigation failure items (4 and 7). In contrast, all the model structures are in a series configuration. Hence, to increase the system reliability, the series structure shall be minimized in order to reduce the failure of the system.

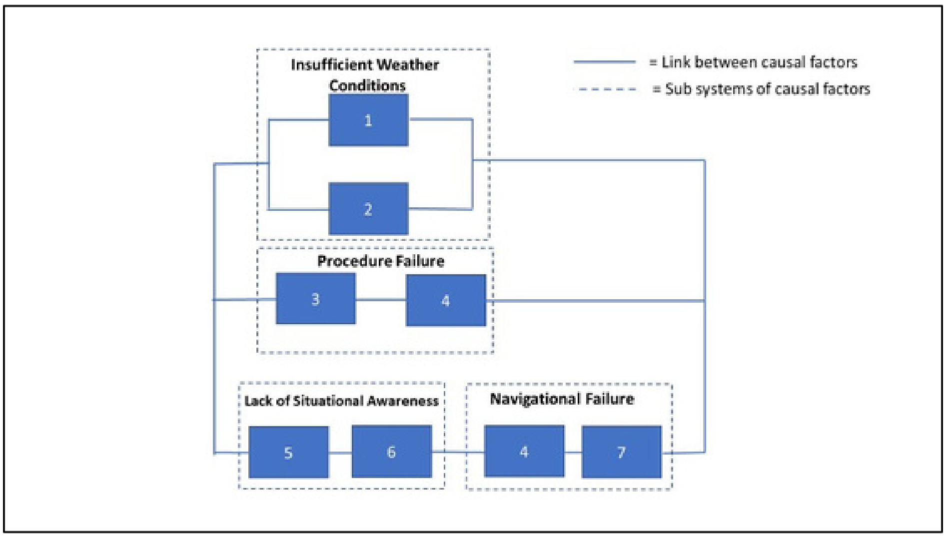

Figure 3. RBD Analysis of Suez Canal Incident

Furthermore, in table 1 and 2, a minimal cut set rules have been driven in this analysis in order to identify any FTA combination events that can be eliminated to avoid a reoccurrence of the Suez Canal blockage.

Note: in Boolean: Plus "+" represents "OR" gate Multiplication "." represents "AND" gate.

TABLE 1: Axiom of Boolean Algebra

[A1] a.b = b.a	Commutative Law
[A2] a + b = b + a	Commutative Law
[A3] (a + b) + c = a + (b + c) = a + b + c	Associative Law
[A4] (a.b) . c = a . (b.c) = a.b.c	Associative Law
[A5] a . (b+c) = ab + ac	Distributive Law

TABLE 2: Theorems of Boolean Algebra

[T1] a + 0 = a	
[T2] a + 1 = 1	
[T3] a . 0 = 0	
[T4] a . 1 = 1	
[T5] a . a = a	Idempotent Law
[T6] a + a = a	Idempotent Law
[T7] a + ab = a	Absorption Law
[T8] a (a + b) = a	Absorption Law

Both Idempotent and Absorptions Laws are described in Appendix.
Therefore, the logic expression has been derived for the Suez Canal Incident (SCI) as the cut set shown below.

SCI = (1.2) . (3+4) . (5+6+4+7)

SCI = (1.2) . (3.5 + 3.6 + 3.4 + 3.7 + 4.5 + 4.6 + 4.4 + 4.7)	[Applying [T5]: a.a = a]
SCI = (1.2) . (3.5 + 3.6 + 3.4 + 4 + 3.7 + 4.5 + 4.6 + 4.7)	[Applying [T7]: a + a.b = a]
SCI = (1.2) . (3.5 + 3.6 + 3.7 + 4 + 4.5 + 4.6 + 4.7)	[Applying [T7]: a + a.b = a]
SCI = (1.2) . (3.5 + 3.6 + 3.7 + 4 +4.6 + 4.7)	[Applying [T7]: a + a.b = a]
SCI = (1.2) . (3.5 + 3.6 + 3.7 + 4 + 4.7)	[Applying:[T7]: a +a.b = a]
SCI = (1.2) . (3.5 + 3.6 + 3.7 + 4)	[Applying [A5]: a (b + c) = ab + bc]
SCI = (1.2.3.5 + 1.2.3.6 + 1.2.3.7 + 1.2.4)	[Applying [A5]: a (b + c) = ab + bc]

Therefore, the minimum cut set are as the following four scenarios of combination of causal failures:
1.2.3.5; 1.2.3.6; 1.2.3.7; 1.2.4

Scenario 1: Poor visibility. High wind sandstorm. Violation of recommended speed limit. Insufficient reaction time.

Scenario 2: Poor visibility. High wind sandstorm. Violation of recommended speed limit. Captainship over-reliance on tug pilot.

Scenario 3: Poor visibility. High wind sandstorm. Violation of recommended speed limit. Poor coordination.

Scenario 4: Poor visibility. High wind sandstorm. Lack of communication between the ship and tugboat pilot.

Here each of the above four scenarios contain the least combination of factors that are necessary and sufficient to cause the top event (disaster) to occur. It is interesting to observe that the two factors of poor visibility and high wind sandstorm are common in all four scenarios, and that the violation of recommended speed limit comes as a second highest in terms of priority as it is common in three of the four scenarios.

5.1 Bowtie Model of Suez Canal Incident

The bowtie methodology is an analysis technique named after its shape, and this method identifies the factors that could lead to the high-risk event. (Labib, 2021). In this assessment, the Suez Canal incident will be placed in the centre of the bowtie diagram knot, which also presented the top event of the FTA. The structure model of the bow tie consists of two sides; the first left side of the model is to prevent the threat by constructing safety barriers. On the other hand, the second right side of the model is the proactive approach by controlling and mitigating the consequences of the high-risk events by creating new or additional safety barriers.

The technical logic of the bowtie model is to start with a fault tree analysis on the left side, concentrate on the causes that lead to the top event, and focus on how to prevent it. Then, the right side of the model is constructed around the event tree analysis (ETA) and deep focus on the consequences that occur due to the FTA top event in order to minimize any further escalation as a result of the top event (Labib, 2021)

For example, figure 4 shows the Suez Canal Incident in an integrated model of FTA incorporated in the left side of the bowtie, and figure 5 shows the full bowtie model. The left side of the bowtie model, as illustrated in figure 6, shows the blue boxes where the concentration is on the casual factor's prevention as a proactive approach, and this could be achieved through the grey safety barriers. In this case, the blue boxes of the Suez Canal indecent that led to the top event are insufficient weather conditions, procedure failure, lack of situational and navigation failure and the prevention safety barriers.

On the opposite right side are the red boxes, which represent the consequences that occur after the top event of the FTA: vessel disruption, canal blockage, reputation damage, and salvage. Hence barriers here are configured to act in a reactive approach to mitigate against the consequence of the hazard.

A question may arise about how the sequence of time is depicted in such modelling techniques? Although the FTA is a logical-based model, where the sequence of time is normally not captured in such analysis, one is able to capture time in terms of causality. Since causality based on the concept of cause and effect implies that a cause happens before an effect, then if A causes B, then A happens before B. Then one can say that if A AND B causes C, then both A and B happen before C. Therefore, the more we go down (vertically) in an FTA the more we go back in time. However, when it comes to Bowtie modelling, the FTA is represented side-ways as shown in figure 4. Hence time flows from left to right, and the same logic can apply on the consequence side of the bowtie model. Such conceptual modeling help to characterize 'resilience', which is about the ability to bounce-back after major disturbance. Such linking of bowtie and resilience modeling has been proposed by Labib (2021).

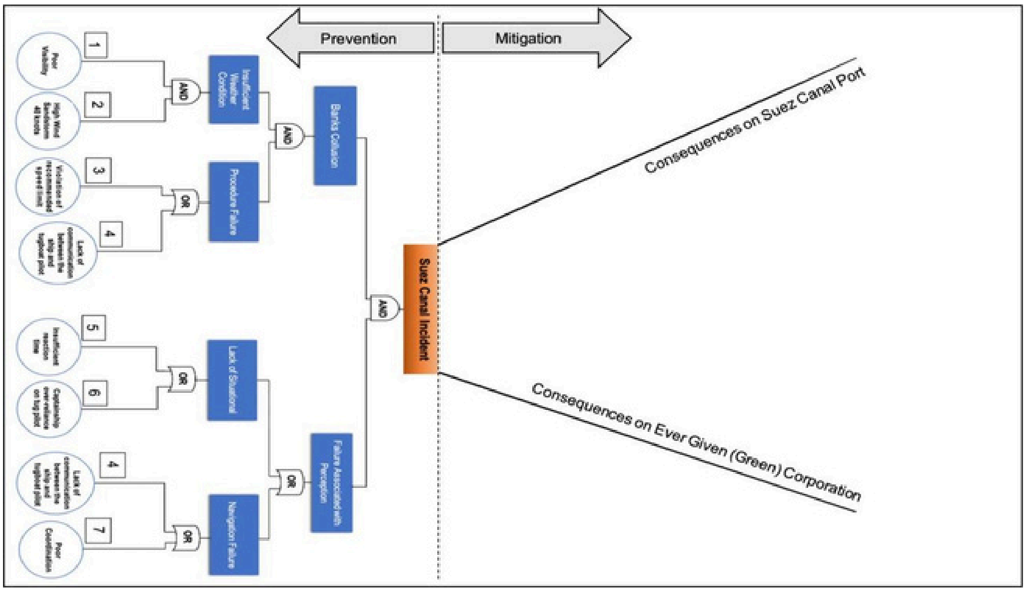

Figure 4. Suez Canal Incident in an Integral model of FTA Incorporated in the bowtie

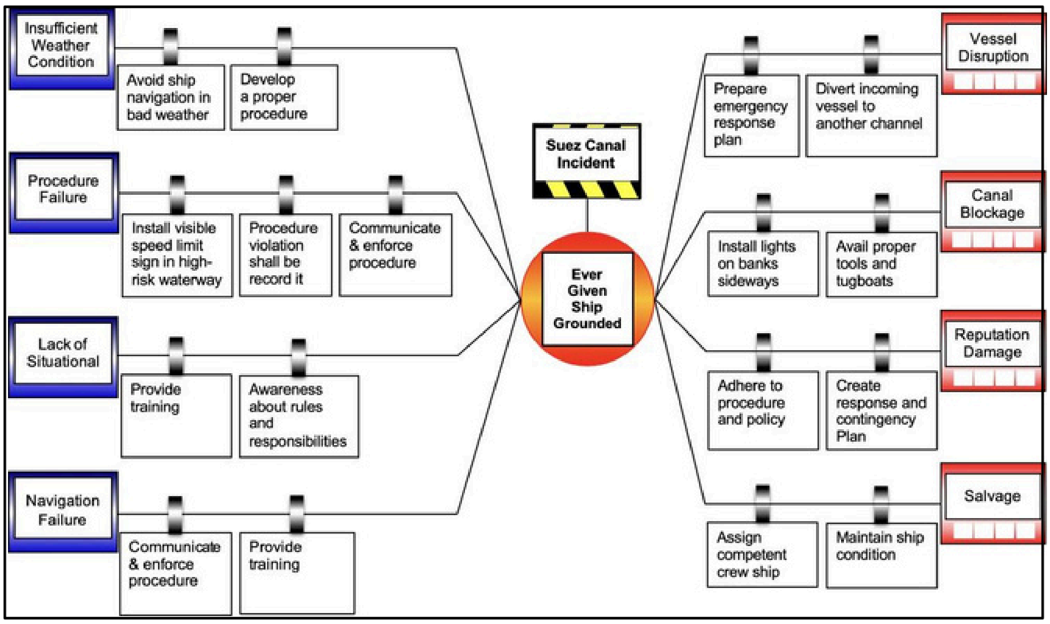

Figure 5. Bowtie model of Ever Given ship grounded of Suez Canal Incident

In order to prevent such an incident from reoccurring, sets of safety barriers have been created for each casual factor, as shown in table 3 and table 4.

Table 3: Classification of Safety Barriers (Preventative/ Proactive)

Threat		Barrier	Type	Escalation Factor
Insufficient Weather Condition		Avoid ship navigation in bad weather Develop a proper procedure	Preventative	Loss of ship navigation control
Procedure Failure		Install visible speed limit sign in a high-risk waterway. Procedure violation shall be recorded. Communicate & enforce procedure.	Preventative	A prohibition from using the Suez Canal waterway. Pay fine.
Lack of Situational Awareness.		Provide training. Awareness about rules and responsibilities.	Preventative	Human error
Navigation Failure		Provide training. Communicate & enforce procedure.	Preventative	Human error

Table 4: Classification of Safety Barriers (Corrective / Mitigation)

Consequence	Barrier	Type	Escalation Factor
Vessel Disruption	Prepare an emergency response plan b. Divert incoming vessel to another channel	Control Mitigate	Traffic jam Uses longer channel (Cape of Good Hope)
Canal Blockage	a. Install lights on banks sideways b. Avail proper tools and tugboats	a. Mitigate b. Control	a. Disturbed global maritime trade b. Affect global stock markets
Reputation Damage	Adhere to procedure and policy Create response and contingency plan.	Control	Customer uses another carrier
Salvage	Assign competent crew ship. Maintain ship condition.	Mitigate	Settlement/award Bankruptcy.

6. DISCUSSION AND LESSONS LEARNED

The Suez Canal incident investigation is still ongoing, and there is no official detailed information of what happened exactly on March 23. However, according to the recently published papers and (SAC) official conferences, the initial investigation revealed that the root cause of the Ever-Given Suez Canal incident is the high wind sandstorm that caused the ship to wedge and block the canal, and there is no other information revealed by any entities to provide a framed picture of the incident which was a big challenge to conduct this case study.

Nevertheless, the analysis conducted in this case study agrees and disagrees with the official revealed root cause. For instance, the high wind sandstorm is a contributing factor to the incident. However, it is obvious and easy to detect through the visual or the technologies embedded in the ship or the bridge. Moreover, for some reason, the captainship has finally decided to navigate the ship in such insufficient weather going through a very narrow channel. What is certain, is that the Suez can incident has a major disruption on the global supply chain (Lee and Wong, 2021).

According to BBC News (2021) during a press conference, Osama Rabie, SCA chairman, mentioned that weather conditions were "not the main reasons" for the ship's grounding, then added that "there may have been technical or human errors", and that all factors would be looked into in the investigation on the incident.

Also according to CNBC (2021) this incident has exposed the need for more research into cascading risk, supply chain disruption and resilience, and impact of pandemics such as COVID-19 on global trade. Our analysis complements a recent work conducted on the Suez Canal incident using Bayesian Network (BN) analysis, which was indented to extract lessons learned, and have identified them as being due to insufficient information, poor communication, a complacent issue, and in adequate safety culture for the Ever Given organization management (Fan *eta*l, 2022).

Furthermore, the analytical techniques used in this case study identified several safety barriers recommendations in table 3 and table 4 to prevent the reoccurrence of such an indecent. In addition, to the below lesson learned that can be summarized as the following:
Clear communication between the captainship and the tugboat pilot was extremely important during the canal navigation.
Captain of the ship shall always adhere to the Suez Canal navigation procedures.
Insufficient weather can cause unpredictable consequences.
Improve Suez Canalside banks design by:
Installing lights to provide better vision during night, fog or sandstorm.
Safety signs
Wind protection to minimize the wind speed.
Furthermore, during the analysis of the minimum cut sets, we identified four scenarios of the least combination of factors that are necessary and sufficient to cause such a major accident. Each of these scenarios can be embedded in the planning of future training simulation exercises and drills for different stakeholders.

7. STRENGTH AND LIMITATION OF PROPOSED TECHNIQUES

The integrated approach used in this case study, as illustrated in figure 6 has provided a reliable analytical companied tool to formulate the incident framework to analyse the factors that led to the Suez Canal incident. In addition, it provides the provision to either prevent or eliminate the possible causes to prevent the reoccurrence of such an incident. The FTA was a crucial technique used in this case study to identify the specific undesirable incident event and the causal factors through an AND and OR logic gates and feed the relationships among causal factors to the RBD model with input to demonstrate the overall system reliability. Moreover, the RBD model transforms the FTA gates to parallel or series structures to underline the system vulnerability. Additionally, a minimal cut set was applied to the FTA logic gates to perform an evaluation analysis in order to identify any FTA combination events that can be eliminated to avoid a reoccurrence of the incident.
Furthermore, the bowtie technique has been incorporated with FTA to build a new defense strategy of the system reliability by creating a new safety barrier to control, prevent and mitigate the overall system vulnerability.

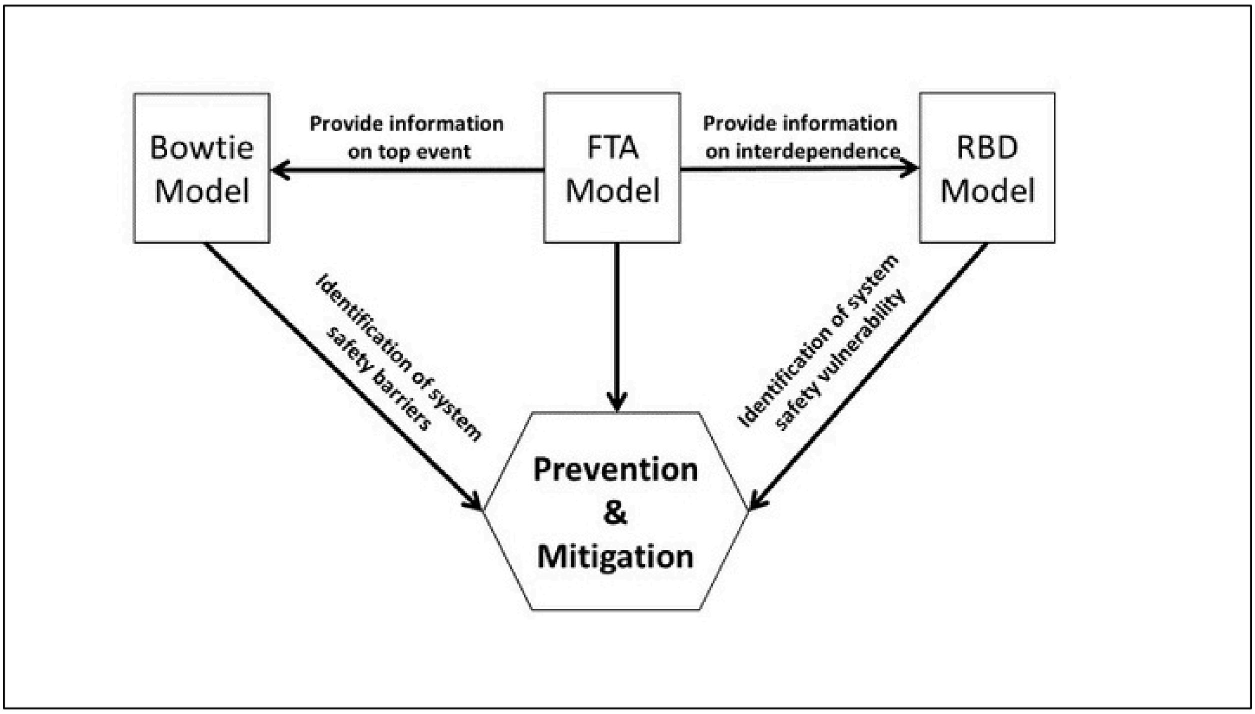

Figure 6. The relationships between the different techniques

Note that in such risk assessment framework there are many uncertainties in practice. This is in line with the literature related to the practical challenges in risk assessment (Taarup-Esbensen, 2020) that can be itemized as follows:

1.The root cause is not one simple cause but usually a combination of different events that happened simultaneously, or have been affected by each other.

2. Risk assessment relies on assigning a probability of a given event. This assignment requires confidence by having a good statistical sample size. However, a major incident is characterized by high severity and low frequency, which makes such assignment a pure speculative exercise based on evident either from expert assessment or near misses.

3. Risk assessment also relies on estimating the severity of an event, which can be either optimistic or pessimistic consequence based on a worst-scenario estimation.

4. In deciding to enact safety barriers for both prevention and mitigation based on the previous three challenges, it becomes a difficult decision for the organization to have confidence in the efficacy of such barriers.

In the aftermath of any major accident, one is often faced by a messy situation, where there are many uncertainties and complexities involving fragmented information and many stakeholders and with different types of biases. There are three lenses which influence accident analysis, as proposed by Filho et al (2019); Lens 1 is about 'data' in terms of its sources and collection methods, Lens 2 is about 'method' in terms of type of method for analysis, and Lens 3 is about 'analyst' in terms of background profile and biases.

Despite these challenges, it is believed that the proposed model analysis offers a comprehensive approach to carry out a systematic analysis. However, it was limited due to the lack of incident information since there are several factors that are not yet revealed by SCA or the IMO, which was a challengeable factor during the analysis of the case study. Nevertheless, more data would provide a better realistic analysis approach than subjectivity.

8. CONCLUSION AND FUTURE WORK:

This case study showed the influence of using a hybrid technique approach to address the prevention of the Suez Canal incident by selecting a reliability analysis technique in an integration model. Each reliability technique has a limitation analysis which will cause a gap in the fundamental function of reliability. The advantage of using the hybrid technique in this case study is that it tends to work in a way to determine the reliability analysis limitation by integrating three main techniques FTA, RBD and bowtie, to achieve the desired reliability outcome. For instance, FTA and RBD are structured to provide the incident's direct cause and contributing factors. In addition, FTA was incorporated in the bowtie to minimize and maximize the system reliability by building safety barriers. Although this case study has demonstrated the capability of the reliability analysis that enriched by the hybrid model approach. However, a Fuzzy bowtie analysis can be considered as future work to clear the uncertain information by calculating the factors' probability and determining the risk priority. In addition, the Formal Safety Assessment (FSA) method can be deployed to analyse risk and cost benefits to assist the decision-making.

Learning from failures in order to prevent and mitigate against future incidents relates to two key concepts in risk and safety management; resilience and high reliability organizations (HRO). Resilience is about the ability to bounce back and its link to bowtie modeling has been discussed in Section 5 and previously in the work of (Labib, 2021). The concept of HRO originated by (La Porte, 1996; Weick and Suttcliffe, 2001) where it relies on the concept of mindfulness and five features to characterize organizational culture and structure. The measuring of degree of maturity of HRO has then been proposed through a maturity grid in the work of (Agwu etal, 2019). Future work can extend this analysis and integrate it to HRO maturity assessment in order to assess whether lessons have been learnt and provide future directions for improvement

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Appendix

Idempotent and Absorption Laws:

Both laws are mathematical operations that are either 'addition-like' or 'multiplication-like', but they are not actually these operations; they are just representations of mathematical operators.

Cut set are sets of basic events that can cause the top event to occur. They can be considered as 'scenarios' of a combination of events that can cause the failure (top event) to occur. The idea of minimum cut sets is to reduce these cut sets by removing any redundancies so that one can focus on the core ones that can cause the top event failure to occur.

Idempotent Law:

Idempotence is a feature of a mathematical operation that implies its application of multiple times without altering the final result.

The formal definition is $x.x \Leftrightarrow x$

So in other words this means that when two basic events are similar (x) and they both need to occur (AND gate), then the if x fails the whole system will fail (top event)

Figure A1 describes how fault tree can represent the idempotent law for a minimum cut set.

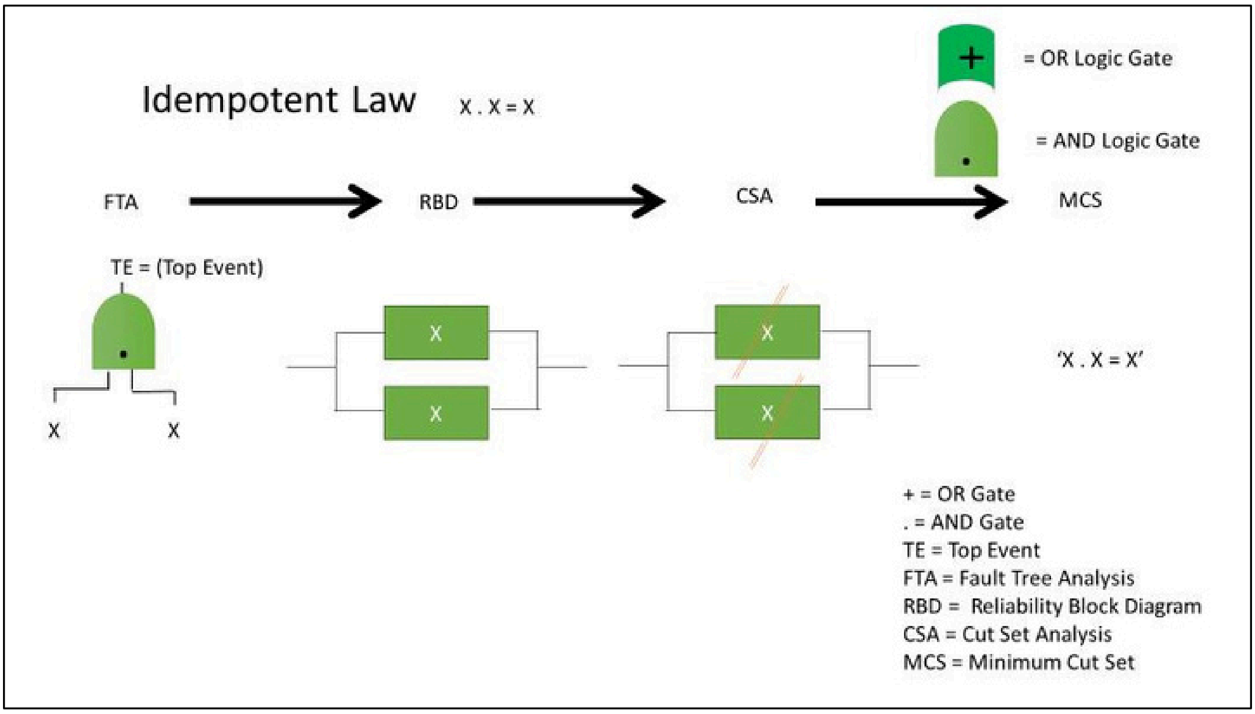

Figure A1: Idempotent Law in FTA and its equivalent RBD

Absorption Law:

Absorption law allows one cut set that contains all the events in another to be eliminated. The formal definition is:

$x + x.y \Leftrightarrow x$

$x\ (x + y) \Leftrightarrow x$

In other words, the expression 'absorption' implies being absorbed by the term in the consequent. Figure A2 describes how fault tree can represent the absorption law for a minimum cut set.

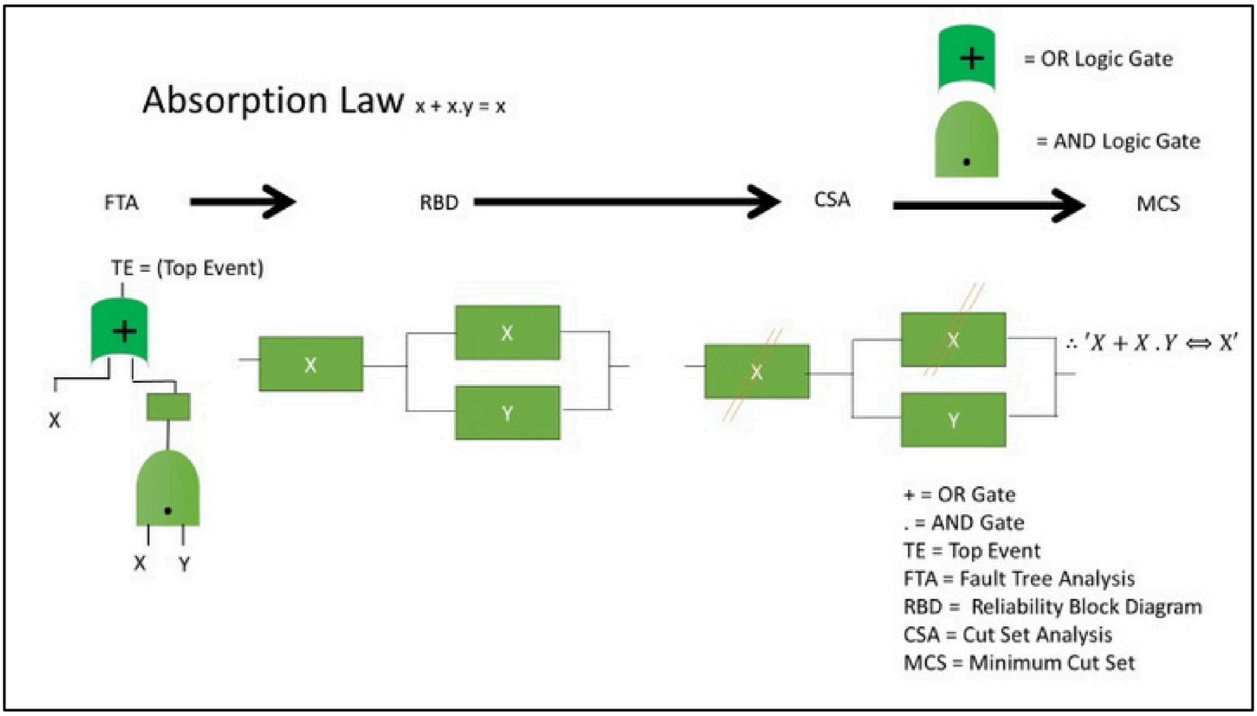

Figure A2: Absorption Law in FTA and its equivalent RBD

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Implementation and Experimental Analysis of Finding Partial Discharge Source between a Transformer and its Peripheral High Voltage Devices using Several Heterogeneous PD Sensors

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Abstract – Monitoring the transformer's condition and fault diagnosis are essential to maintain the reliable operation of the transformer and maximize its lifespan. Usually, detecting PD signal from UHF PD sensor installed in a transformer is a method for monitoring the transformer conditions. However, the PD The PD signals leaked from Transformer will be detected by PD sensors due to peripheral high voltage. And it could be mistaken for as PD signal occurred in the transformer. In this paper, through experimental analysis, we propose a technology that installs several heterogeneous PD sensors in a transformer and a peripheral high voltage device and processes PD signals simultaneously to distinguish between PD signals generated inside a transformer and PD signals generated in peripheral high voltage devices. Several heterogeneous PD sensors, such as UHF sensors, TEV sensors, and HFCT sensors, are installed in transformers and peripheral high voltage devices, and the normalized amplitude of PD signals received from each sensor are compared and analyzed on a synchronized time and phase axis. For example, if the PD signals detected by the transformer and the peripheral high voltage device are on the same time and phase axis, and the normalized amplitude of PD signal from transformer is larger than the normalized amplitude of PD signal from the peripheral high voltage device. At this time, this PD signal is determined to have occurred inside the transformer. Whereas, if the normalized amplitude of the PD signal introduced from peripheral high voltage devices is larger than the normalized amplitude of the PD signal introduced from the transformer, it is determined to be PD signal introduced from the peripheral high voltage devices. With the results of experimental analysis, this technology can be effectively used to determine whether the detected PD signal from transformer PD sensor is originated from inside of the transformer or from peripheral high voltage device.

Index Terms – Power Transformer, Heterogeneous PD Sensors, Partial Discharge, Pulse Gating

1. Introduction

As the demand for electric power continues to increase, the demand and capacity of a transformer of power are growing, but to prevent an accident in a substation in advance and supply stable electric power is greatly increased. The biggest causes of failure of high voltage power facilities are insulator defects and aging, which may be detected by measuring partial discharge using suitable techniques.

Currently, the most frequently used technology to check the health status of the transformer is the DGA (Dissolved Gas Analysis) method. However, it is not easy to identify the symptoms from the beginning of the occurrence of the partial discharge because the partial discharge is activated to some extent until the change in the gas component caused by the partial discharge is detected [1-2]. To overcome these problems, there are technologies capable of monitoring partial discharge occurring inside a transformer from an early stage. Among them, the most widely adopted method is a technology that detects and analyzes electromagnetic

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waves generated during partial discharge. The core of this technology for detecting and analyzing partial discharge signals is a technology for distinguishing noise signals and partial discharge signals generated from peripheral signals [3-5]. Numerous technologies are researched and applied to distinguish internal and external noise signals of high voltage equipment from partial discharge signals, and RF filter design technology, noise gating technology, time and frequency domain signal processing technology, etc. are most commonly used.

Despite these advances in technology, the development of technology that effectively eliminates noise signal still present in broadband to distinguish only partial discharge signals is still a challenge for experts in this field [6]. For partial discharge signals that occur in such environments, when the amplitude of noise signal is larger than the amplitude of partial discharge signal or when the noise signal has impulse or corona characteristics from its peripheral high voltage devices, expert precision analysis is absolutely required. This means the occurrence of time and cost. Moreover, since transformers are generally outdoors, they are exposed to peripheral noise signals (Electromagnetic noise such as peripheral mobile phones, peripheral impulse or corona noise) that are absolutely diverse and large in amplitude compared to the GIS installed indoors. Therefore, the biggest solution to achieve the goal of distinguishing only partial discharge signals generated inside the transformer is to obtain new technologies to distinguish between peripheral noise signal and partial discharge signals generated inside the transformer.

In this paper, through experimental analysis, we introduce a technology that installs several heterogeneous PD sensors in a transformer and a peripheral high voltage device and processes PD signals simultaneously to distinguish between PD signals generated inside a transformer and PD signals generated in its peripheral high voltage devices. For PD signals detected by several heterogeneous PD sensors installed in the transformer and its peripheral high voltage devices, only PD signals generated inside the transformer can be extracted by comparing and analyzing the amplitudes on the synchronized time axes in the PRPD graph. Also, a method of distinguishing PD signals generated by transformers and its peripheral high voltage devices is demonstrated through experiments. Based on the results of this experiment, a technique for distinguishing PD signals generated by transformers and its peripheral high voltage devices can be useful for analyzing PD signals generated inside transformers more effectively than other techniques.

2. A method of finding PD source of transformer and peripheral high voltage devices using several heterogeneous PD sensors

Figure 1 shows a method for solving the disadvantages of the conventional technology for detecting electromagnetic waves and analyzing PD signals as a block diagram. The signals detected from several heterogeneous sensors installed in transformers and peripheral high voltage devices remove the noise signal using a noise filter and then extract only the PD signal. The amplitude of the extracted PD signals is normalized and only PD signals generated inside the transformer are classified using pulse gating technology on the synchronized time axis.
Pulse gating technology is a technology that converts a signal detected by a sensor installed in a transformer and a signal detected by a sensor installed in a peripheral high voltage device into a normalized amplitude and logically removes the PD signal to extract only the PD signal generated inside the transformer.

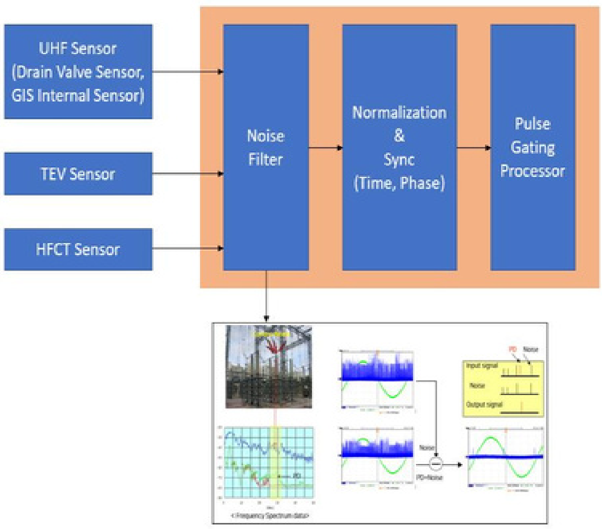

Fig. 1. Block Diagram of the proposed technology

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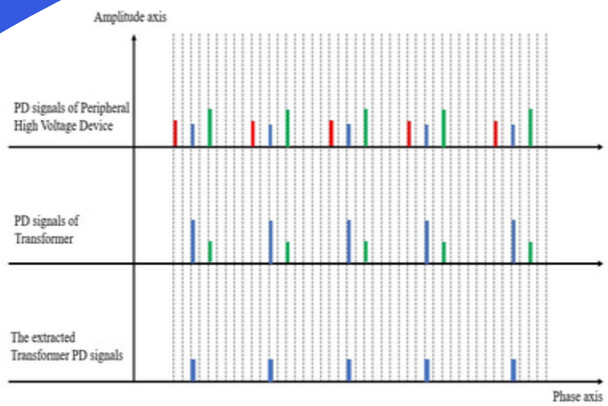


Fig. 2. PD signals of peripheral high voltage device, transformer and the extracted transformer PD signals

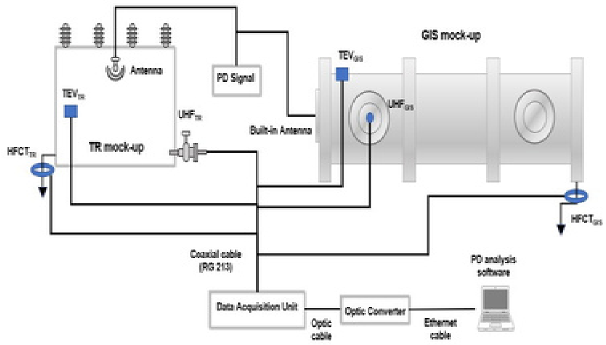
Figure 2 shows the principle of pulse gating. As shown in Figure 2, PD signals are detected from several heterogeneous sensors installed in transformers and peripheral high voltage devices. Among the PD signals, red and green are PD signals generated by the peripheral high voltage device, and blue is PD signals generated inside the transformer. It can be seen that the PD signal detected from the sensor installed in the transformer is blue and green. The blue PD signal shows that the signal amplitude detected by the transformer is larger than that detected by the peripheral high voltage devices, and the green PD signal shows that the signal amplitude detected by the transformer is smaller than that detected by the peripheral high voltage devices. The red PD signal did not flow into the transformer and was not detected by the transformer. If the amplitude of PD signals detected from several heterogeneous sensors installed in transformer and peripheral high voltage devices is normalized and compared on a synchronized time axis and logically removed using pulse gating technology, only PD signals generated inside the transformer can be extracted.

3. Experimental Environment & Results

3.1 Experimental Environment & Method

In this section, we represent an experimental analysis of finding partial discharge source between transformers and peripheral high voltage devices using through several heterogeneous PD sensors based on the technology described in section 2.

Figure 3(a) shows the experimental configuration diagram. Figure 3(b) shows an experimental environment in Lab. The experimental methods to verify the technology are as follows.



(a)

(b)

Fig. 3. (a) Experimental configuration diagram (b) Experimental Environment in Lab

As shown Figure 3, an experiment was conducted to distinguish PD signals source generated by the transformer or the peripheral high voltage devices using TR mock-up and GIS mock-up, respectively. In STEP 1, an experimental method for the case where a PD signal is generated inside a TR mock-up and in STEP 2, a PD signal is generated inside a GIS mock-up has been described, respectively.

<u>STEP 1: PD Source in TR Mock-up</u>

Install UHFTR, TEVTR, and HFCTTR in TR mock-up, and install UHFGIS, TEVGIS, and HFCTGIS in GIS mock-up. Install an antenna inside the TR mock-up and connect the PD generator to the antenna in order to generate a PD signal source inside the TR mock-up. At the same time, check whether the PD signal is detected by the UHFTR, TEVTR and HFCTTR, and after that, check whether the detected PD signal appears in the same phase or not. If PD signals are detected in both UHFTR, TEVTR and HFCTTR and occurred on the same time axis and phase,

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the detected PD signals can be interpreted as being generated inside TR Mock-up.

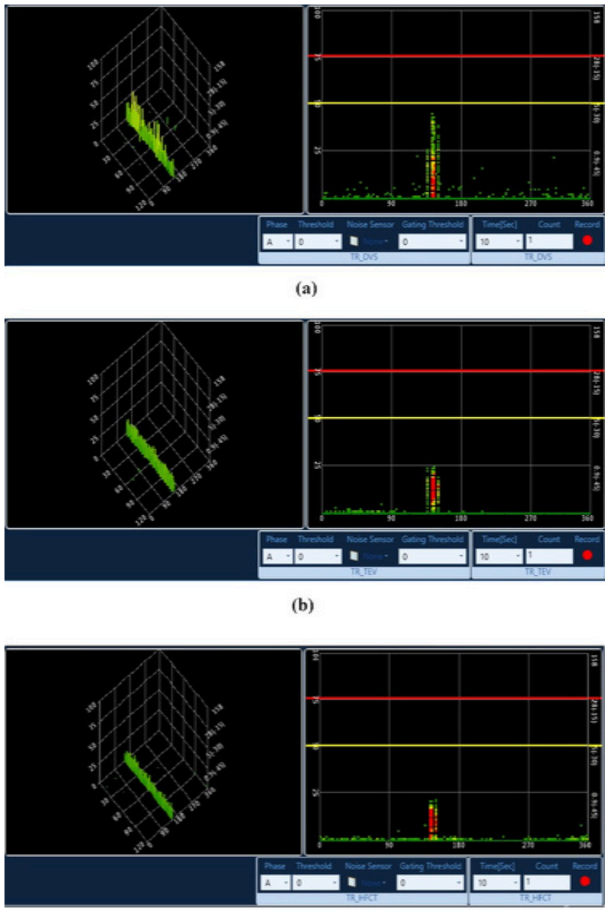
STEP 2: PD Source in GIS Mock-up

Install an antenna inside the GIS mock-up and connect the PD generator to the antenna in order to generate a PD signal source inside the GIS mock-up and check that the PD signal is detected by the UHFGIS, TEVGIS and HFCTGIS installed in the GIS mock-up. At the same time, check whether PD signals are detected from UHFTR, TEVTR, and HFCTTR installed in the TR mock-up to check that PD signals generated inside the GIS mock-up are detected from the heterogeneous sensors installed in TR mock-up. If a PD signal is detected from one or more of the UHFTR, TEVTR and HFCTTR, the PD signal amplitude is compared after confirming whether the PD signal is in the same phase as the PD signal generated in the GIS mock-up. For example, if a PD signal is detected in the UHFTR, compare it to the amplitude of the PD signal detected in the UHFGIS. In addition, when a PD signal is detected in TEVTR, it is compared with the amplitude of the PD signal detected in TEVGIS, and when a PD signal is detected in HFCTTR, it is compared with the amplitude of the PD signal detected in HFCTGIS. If the PD signal detected by the TEVTR or HFCTTR is in the same phase as the PD signal source generated in GIS mock-up and the amplitude is smaller than that of the TEVGIS or HFCTGIS, PD signal may be interpreted as generated from the outside rather than inside the TR mock-up.

The experimental method described above could distinguish a PD signal generated inside transformer from a PD signal generated in peripheral high voltage devices using several heterogeneous PD sensors, and in the next section, it shows the result through the experimental data.

3.2 Experimental Results

Figure 4 shows the analysis of PD signals detected by several heterogeneous sensors when PD signals source are generated using a PD generator in an antenna installed inside TR mock-up. Figure 4(a) shows the PD signal detected by the UHFTR in the PRPS graph, and Figure 4(b) shows the PD signal detected by the TEVTR in the PRPS graph. Figure 4(c) shows the PD signal detected by the HFCTTR in the PRPS graph. As shown in Figures 4(a), (b) and (c), when a PD signal source is generated inside TR mock-up, it can be seen that the PD signal detected by several heterogeneous sensors is in the same phase. As a result, it can be seen that the PD signal is detected by the UHFTR, TEVTR and HFCTTR, and the detected PD signal is the same phase, This confirms there



(a) (b) (c)

Fig. 4. (a) The PRPS Graph of PD Signal Detected by UHFTR (b) The PRPS Graph of PD Signal Detected by TEVTR (c) The PRPS Graph of PD Signal Detected by HFCTTR

is a PD signal generated inside the TR mock-up.
Figure 5 shows the analysis of PD signal detected by several heterogeneous sensors installed in GIS mock-up and TR mock-up when a PD signal source is generated using a PD generator in an antenna installed inside the GIS mock-up. Figure 5(a) shows the PD signal detected by the UHFGIS in the PRPS graph, and Figure 5(b) shows the PD signal detected by the TEVGIS in the PRPS graph. Figure 5(c) shows the PD signal detected by the HFCTGIS in the PRPS graph. At this time, Figure 5(d) shows the PD signal detected by the UHFTR in the PRPS graph, and Figure 5(e) shows the PD signal detected by the TEVTR in the PRPS graph. Figure 5(e) shows the PD signal detected by the HFCTTR in the PRPS graph. As shown in Figure 5(e), it can be verified that, when a PD signal source is generated using a PD generator inside a GIS mock-up, the PD signal is also detected by the TEVTR.

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When several heterogeneous sensors are installed only in TR mock-up, it is difficult to distinguish whether it is the PD signal generated from peripheral high voltage devices or the PD signal generated inside a transformer.

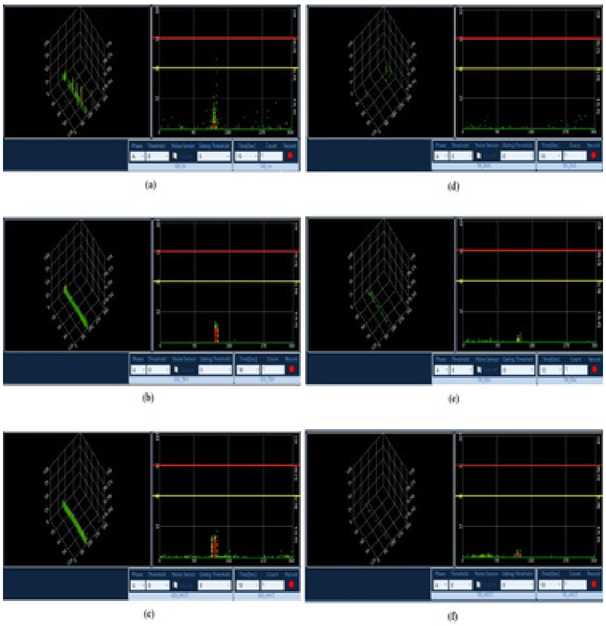

Fig. 5. (a) The PRPS Graph of PD Signal Detected by UHFGIS (b) The PRPS Graph of PD Signal Detected by TEVGIS (c) The PRPS Graph of PD Signal Detected by HFCTGIS (d) The PRPS Graph of PD Signal Detected by UHFTR (e) The PRPS Graph of PD Signal Detected by TEVTR (f) The PRPS Graph of PD Signal Detected by HFCTTR

Figure 6(a) shows the PD signal detected by the TEVGIS in the PRPS graph. Figure 6(b) shows the PD signal detected by the TEVTR in the PRPS graph. Figure 6(c) shows the PRPS graph that logically removes the PRPS graph shown in Figure 6(a) from the PRPS graph shown in Figure 6(b) using pulse gating technology. Since the phase of the PD signal detected in TEVGIS and the PD signal detected in TEVTR are the same, and the amplitude of the PD signal detected in TEVTR is smaller than the amplitude of the PD signal detected in TEVGIS, no signal remains when logically removed using pulse gating technology.

This can effectively distinguish whether the detected PD signal source is from inside of TR or from external periperals devices.

4. Conclusion

In this paper, we proposed a technique for installing several heterogeneous PD sensors in transformer and peripheral high voltage devices and comparing the normalized amplitude of PD signals received from each sensor in synchronized time and phase axes to distinguish PD signals from those generated inside the transformer. We have demonstrated the excellence of the proposed

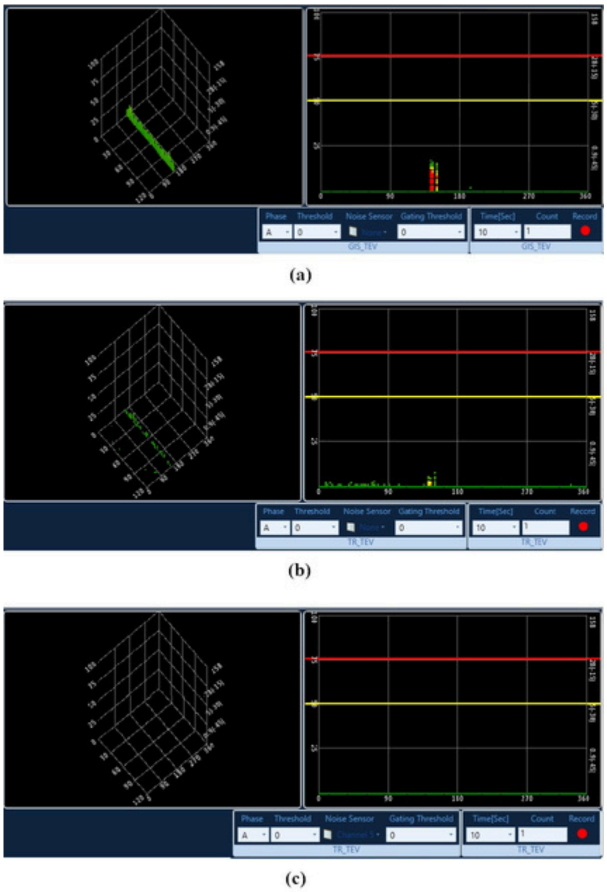

Fig. 6. (a) The PRPS Graph of PD Signal Detected by TEVGIS (b) The PRPS Graph of PD Signal Detected by TEVTR (c) The PRPS graph logically removed Figure 5(a) and Figure 5(b)

We have demonstrated the excellence of the proposed technology to overcome the difficulty of distinguishing PD signals generated inside transformer and PD signals generated in peripheral high voltage devices, which are disadvantages of the conventional technology for detecting and analyzing electromagnetic waves through experiments. The proposed technology is expected to be useful for the analysis of only PD signals from inside of transformers.

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DIGITAL TRANSFORMATION (DX) IN MAINTENANCE AND ASSET MANAGEMENT. LESSONS LEARNED IN PROJECT 25DX OF THE GLOBAL FORUM ON MAINTENANCE AND ASSET MANAGEMENT

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Abstract

The Global Forum on Maintenance and Asset Management (GFMAM) collaboratively shares knowledge and standards in maintenance and asset management. The digital transformation (DX) landscape in this field is rapidly evolving, presenting various challenges and opportunities. This paper provides an overview of key findings, implications, concerns, and guidelines to facilitate the transformative process.

This analysis reveals significant implications for asset management and maintenance, highlighting the vital role of data, analytics, compliance, optimization, human resources, and holistic lifecycle management in navigating challenges and leveraging opportunities brought by digital transformation. Organizations must embrace these changes, foster innovation, and adapt their strategies and processes to fully capitalize on digital transformation's benefits. To understand community concerns, a thorough survey was conducted among industry professionals from diverse sectors and roles. The survey aimed to identify current challenges, barriers, and readiness for digital transformation, enabling us to offer tailored guidance and recommendations for professionals and organizations at different levels of asset management maturity. In this paper we briefly review implications of digital transformations, we present some results of the survey to show some specific concerns of the respondents, and we introduce a list of guidelines elaborated, per role in the organization, to navigate this digital transformation. The This is and advance of the GFMAM document on DX in maintenance and asset management, that is expected to be published by the end of 2023.

Keywords

Maintenance, asset management, digital transformation, Guidelines

1.Introduction

Digital Transformation (DX) is defined by the United Nations [1] as the integration of digital technology into all organizational areas, fundamentally changing how the organization operates and delivers value to customers or stakeholders. It is also about prioritizing organizational culture change, which requires organizations to continually challenge the status quo, experiment and get comfortable with failure.

Digital transformation is a widely used term that, in practice, will look very different in each organization. In essence, it refers to the customer-driven strategic business transformation requiring organizational change and the implementation of digital technologies to reach digital capabilities [2]. In maintenance and asset management has seen rapid advancements in data analytics, artificial intelligence, and Fourth Industrial Revolution technologies. These tools offer insights into complex systems, revolutionizing asset management practices. Some important findings are:

- Advanced analytics make condition-based maintenance (CBM) attractive for increased efficiency. Transitioning to predictive maintenance may require further investments, but it yields significant gains by monitoring influential factors alongside component conditions.

- Data plays a pivotal role, requiring collaboration between experts and data scientists to develop robust models. Regulatory compliance and effective change management are critical considerations for evolving maintenance strategies.

- Digital transformation optimizes maintenance dynamically and automates tasks, reshaping roles in maintenance and asset management. Human expertise remains vital for decision-making in the data-driven landscape.

- Digitalization allows for servitization [3] of products and complete lifecycle management. Manufacturers will prioritize asset lifecycle aspects more attentively, leading to more sustainable practices.

By embracing data-driven approaches and human expertise, organizations can achieve efficiency, cost-effectiveness, and sustainability in maintenance practices.

2 Implications of Digital Transformation in Maintenance and Asset Management

2.1 Policy Implications

The policy implications of digital transformation offer a comprehensive approach to incorporating data and digital technologies in asset and infrastructure management. This policy approach seeks to promote an integrated view of data's economic characteristics, facilitating cost management, risk mitigation, and performance optimization.

State governments are proactively investing in and developing digital capabilities, platforms, and use cases, while local governments are actively formulating strategies to embrace digital transformation. The policy implications underscore the importance of coordinated efforts across different government levels. By aligning policies and fostering collaboration among stakeholders, governments can effectively navigate digital challenges and leverage digital tools to improve cost management, risk reduction, and operational performance.

2.2 Business Implications

Digital transformation is reshaping the landscape of business operations, customer engagement, and value creation, becoming a crucial aspect for organizations to thrive in the digital era. This transformational process streamlines operations through automation, artificial intelligence (AI), and robotics, resulting in enhanced efficiency and cost reduction. Organizations now have the capability to engage with customers in real-time, personalize experiences, and provide tailored solutions through digital channels and social media platforms. This level of interaction allows for deeper connections and improved customer satisfaction.

As a result of digital transformation, new revenue streams and business models emerge, enabling organizations to capitalize on data assets and participate in platform ecosystems. In order to remain competitive and drive growth, adapting to digital transformation becomes imperative. This process demands a holistic approach, incorporating cultural, process, and skill changes. Leaders must foster innovation and a learning culture, empowering the organization to seize digital opportunities and deliver superior customer experiences.

2.3 management Implications

The advent of digital transformation has profoundly impacted asset management, prompting organizations to reassess their approaches throughout the different stages of the asset lifecycle. To comprehensively address these implications, a strategic division of asset management into distinct lifecycle stages is advantageous. This enables organizations to examine the key aspects within each stage, gaining a deeper understanding of how digital transformation influences asset management. By studying the implications at each lifecycle stage, organizations can harness digital technologies effectively to optimize asset performance, enhance maintenance practices, improve decision-making, and achieve greater operational efficiency. This detailed exploration spans from asset acquisition and commissioning to operation, maintenance, and disposal.

As the digital landscape rapidly evolves, this approach empowers organizations to proactively adapt and thrive, ensuring they remain at the forefront of the digital revolution. By embracing the opportunities presented by digital transformation, organizations can elevate their asset management practices to new heights, driving success across the entire lifecycle.

2.4 Technical Implications

As organizations embrace digital technologies and undergo transformative changes, it becomes essential to explore how these advancements reshape maintenance practices, processes, and technologies. For instance, in terms of maintenance activities, they can be broadly classified into two categories: preventive and corrective maintenance. Preventive maintenance involves proactive actions to prevent equipment failures and mitigate potential issues, while corrective maintenance addresses equipment failures, malfunctions, or identified problems.

To comprehensively examine the implications of digital transformation in maintenance, Table 3 is utilized for categorization. It provides concise descriptions of maintenance activities, facilitating a direct comparison between pre- and post-digital transformation scenarios This allows to better understand the impact of digital transformation on different maintenance activities.

While embracing digital technologies in maintenance offers numerous advantages, it also comes with its share of challenges. These challenges encompass technical complexities, integration hurdles, data security concerns, and the demand for skilled personnel. Moreover, the initial investment costs and the need for infrastructure upgrades can pose obstacles for organizations contemplating digital transformation in their maintenance practices. To unlock the full potential of digital technologies in maintenance operations, it is imperative for companies to address these challenges effectively and devise strategies to overcome them.

Maintenance Type	Activities description	Before digital transformation	After digital transformation
Preventive maintenance	Maintenance tasks performed on a regular basis to prevent equipment failures	Manual inspections and services using checklists and maintenance schedules	Preventive maintenance Maintenance tasks performed on a regular basis to prevent equipment failures Manual inspections and services using checklists and maintenance schedules Automated inspections and services using digital monitoring systems. Maintenance schedules created using EAM systems. PM optimized using APM systems. Major interventions optimized using AIP systems.
Condition-based maintenance	Preventive maintenance tasks performed based on the actual condition of the equipment (includes condition assessment)	Manual inspections and subjective assessments to determine when maintenance is needed	Digital sensors and monitoring systems to continuously monitor equipment and trigger data-driven condition-based maintenance in real-time.
Predictive maintenance	CBM tasks performed based on predicted equipment failures (includes activities enabling prediction)	Expert inspections and analysis to identify potential failures	Digital sensors, data analytics, and machine learning algorithms to classify & predict (RUL) equipment failures and schedule maintenance before failures occur.
Corrective maintenance	Maintenance tasks performed after equipment failure	Reactive maintenance including failure diagnosis and repair.	Reactive maintenance performed after equipment failure, but with the use of digital tools such as remote monitoring and diagnostic systems to quickly identify the root cause of the problem

Table 1. Implications of digital transformation in different type of maintenance activities

2.5. Human Implications

The digital transformation journey in maintenance and asset management goes beyond technical aspects; it profoundly affects the people involved in these fields. As organizations adopt digital technologies, it becomes crucial to acknowledge and address the human implications of this transformation. The workforce engaged in maintenance and asset management experiences a paradigm shift in their roles, responsibilities, and required skill sets. We must focus on areas such as the new workforce environment, the emergence of new roles and responsibilities, job satisfaction, and the necessity for collaboration and effective change management. By understanding and responding to these human-centric aspects, organizations can ensure a successful and smooth integration of digital technologies in their maintenance and asset management practices, maximizing the benefits for both the workforce and the overall organization.

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3 Concerns

3.1. The Survey

The focus of project 25 DX is formulating practical guidelines to navigate digital transformation. To ensure the relevance and effectiveness of these guidelines, we have conducted a survey and some examples of the results are presented in this section. The survey, designed to capture insights from the maintenance and asset management community, seeks to shed light on their concerns and challenges in the context of digital transformation. To facilitate this, Google Forms® was employed as the survey software. By exchanging experiences and viewpoints of more than 500 respondents, we could shape the forthcoming guidelines outlined in the subsequent section of this paper

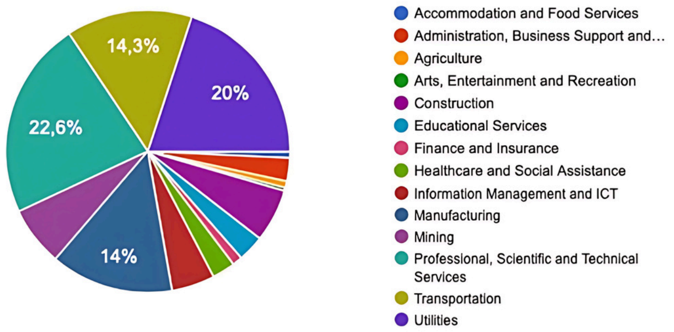

Figure 1. Survey respondents by Sector of activity.

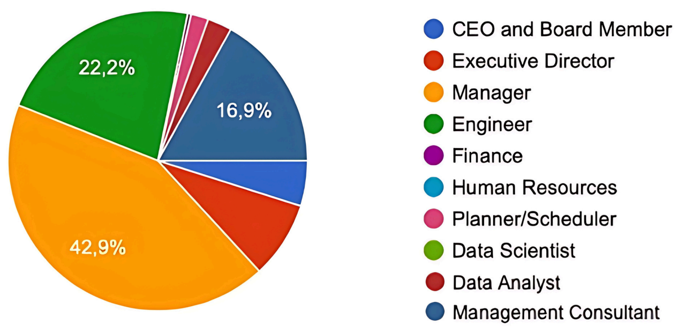

Figure 2. Survey respondents by role in the organization

By exchanging experiences and viewpoints of more than 500 respondents, we could shape the forthcoming guidelines outlined in the subsequent section of this paper. Through this collaborative effort, we contribute to enhancing their pertinence and applicability. The engagement of the community in this survey is highly valued by the Project 25 DX working group, as it enables the formulation of focused and tailored recommendations that directly address the unique needs and challenges faced by professionals in the field. Through this collective endeavor, we are poised to pave the way for a successful digital transformation in maintenance and asset management.

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3.1. Survey Sample Results

The analysis of some digital transformation concerns is done in this paper is general, considering all respondents, but in the GFMAM document, is also done by industry sector and respondent role. So the GFMAM Project 25 DX document provides valuable insights into the specific challenges and barriers faced by different sectors and roles within an organization, allowing for targeted strategies and solutions. This information helps us understand the unique obstacles and priorities that exist within each sector and role, enabling us to tailor our guidelines and recommendations accordingly.

3.1.1. The existence of tools & metrics available to justify DX

The responses to the question regarding the availability of tools or techniques to justify and measure the value of Digital Transformation for organizations in the bottom line reveal a mixed landscape (see Figure 3).

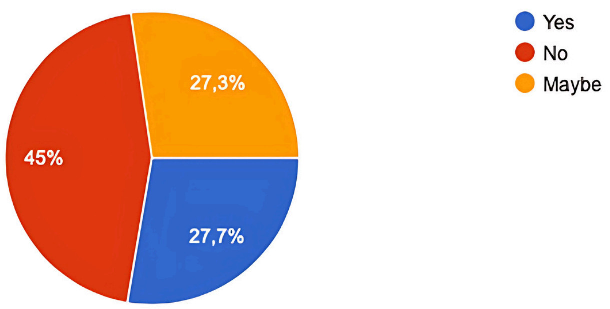

Figure 3. The answers concerning the existence of tools and metrics ti justify DX.

A significant percentage of respondents (45%) indicated that their organizations do not currently possess the necessary tools or techniques to justify and measure the value of digital transformation in terms of its impact on the bottom line. This suggests a potential gap in organizations' ability to effectively quantify the return on investment and demonstrate the financial benefits derived from digital transformation initiatives. On the other hand, a smaller percentage of respondents (27.7%) stated that their organizations do have the tools or techniques in place to justify and measure the value of digital transformation. This indicates a positive readiness to assess the financial impact of digital transformation efforts and align them with the organization's bottom-line goals. A similar proportion of respondents (27.3%) chose the "Maybe" option, reflecting uncertainty or a lack of clarity regarding the availability or effectiveness of tools and techniques for measuring the value of digital transformation. It is important to address this uncertainty and provide organizations with the necessary guidance and resources to develop robust measurement frameworks that align with their specific business objectives.

To ensure the success and sustainability of digital transformation initiatives, organizations should focus on developing or acquiring suitable tools and techniques that enable them to effectively evaluate the financial impact and value generation of their digital transformation efforts. This may involve adopting key performance indicators (KPIs), implementing data analytics capabilities, and leveraging relevant frameworks or methodologies for assessing the return on investment. By doing so, organizations can make informed decisions, optimize resource allocation, and communicate the tangible benefits of digital transformation in terms of the bottom line.

3.1.2 The problems expected to be solved by using DX

The responses to the question regarding the problems that organizations aim to solve using digital technologies provide valuable insights into their priorities (see Figure 4).

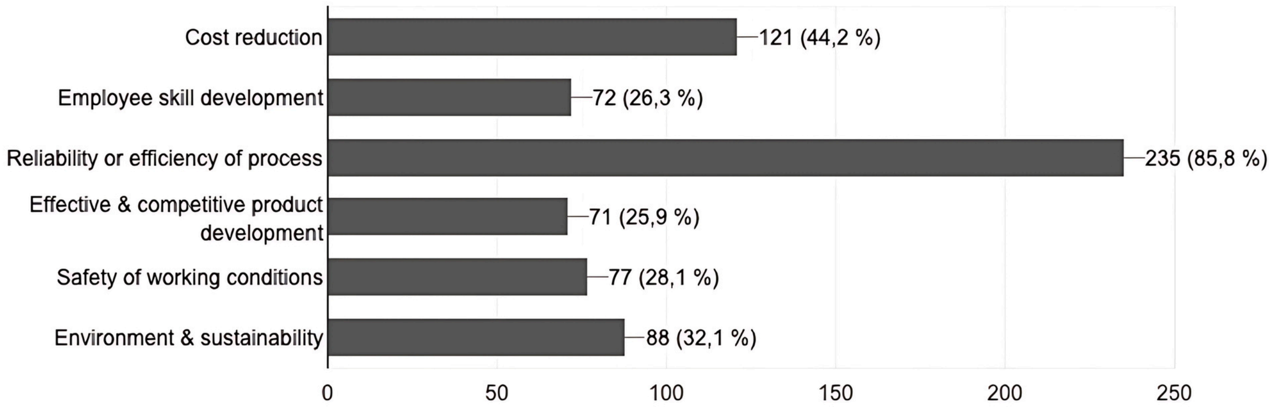

Figure 4. The problems that are expected to be solved thanks to DX

The highest percentage of respondents, 85.8%, identified the improvement of reliability or efficiency of processes as the problem they want to address through digital technologies. This aligns with the potential of digital solutions to optimize and streamline operations, automate manual tasks, and enhance overall process efficiency. By leveraging digital technologies such as IoT, AI, and data analytics, organizations can drive operational excellence, reduce downtime, and improve productivity. Cost reduction was selected by 44.2% of respondents, highlighting the financial aspect of digital transformation. Digital technologies offer opportunities to identify cost-saving measures, eliminate inefficiencies, and optimize resource utilization. By leveraging automation, predictive maintenance, and data-driven decision-making, organizations can achieve significant cost savings across various areas of their operations. Employee skill development, selected by 26.3% of respondents, signifies the importance of nurturing a skilled workforce in the era of digital transformation. Organizations recognize that equipping employees with the necessary digital skills and fostering a culture of continuous learning are crucial for successful digital transformation initiatives. Digital technologies can support employee training and development, enabling them to adapt to new technologies and take advantage of digital tools and platforms.

Other problem areas mentioned include safety of working conditions (28.1%), effective and competitive product development (25.9%), and environment and sustainability (32.1%). These responses highlight the broader impact of digital technologies beyond operational efficiency and cost reduction. Digital solutions can contribute to enhancing workplace safety with IoT sensors, real-time monitoring, and predictive analytics. They can also enable organizations to innovate and bring competitive products to market faster while considering sustainability and environmental factors.

4 Guidelines to Navigate DX in Maintenance and Asset Management.

In project 25 DX document we identify key guidelines that can be followed by specific roles within the organization to address the concerns discussed in the previous section. By understanding the responsibilities and challenges faced by these roles, we can provide actionable recommendations to guide them in navigating the digital transformation journey. The roles considered are the following:

- Managers and Business Leaders,
- Engineers and Technical Professionals,
- Area Responsible Professionals,
- Legal Professionals,
- Commercial Professionals,
- Procurement Professionals.

While in this article we present only the general guidelines per role, in Project 25 DX document these guidelines are customized by role and by maturity of the asset management organization. The guidelines will be relevant to the organization depending on its level of maturity in asset management. This approach allows for greater customization and adaptation of the guidelines to the specific needs of the organization at each maturity stage. By understanding the reasoning behind the choice of each guideline, stakeholders can make more informed and strategic decisions about which aspects to focus on based on their current maturity level.
Based on the survey findings, a total of 19 guidelines are proposed for specific roles within the organization, to navigate the digital transformation journey effectively. Each guideline is presented with suggested KPIs and with the rational for the focus to placed, per guideline, on specific organization maturity levels.

Role	Guidelines to follow
Managers and Business Leaders	1. Lead the vision and strategy for digital transformation initiatives. expand
	2. Foster strategic partnerships.
	3. Cultivate a culture of innovation.
	4. Provide adequate resources and budget for digital transformation initiatives. Expand cost-benefit analysis for budget
Engineers and Technical Professionals	5. Stay updated with the latest advancements in digital technologies, such as data analytics, predictive maintenance, augmented reality (AR), and cloud platforms.
	6. Collaborate across disciplines.
	7. Lead implementation and integration of digital tools and technologies.
	8. Ensure data integrity and quality for digital systems and databases.
Area Responsible Professionals	9. Establish data governance practices and standards to maintain accuracy, integrity, and reliability of data used in asset management and maintenance.
	10. Provide training and skill development opportunities.
	11. Promote user adoption and engagement with digital systems and tools.
Legal Professionals	12. Stay updated with evolving laws and regulations related to digital transformation in asset management and maintenance.
	13. Provide legal advice and support for digital transformation initiatives.
	14. Review and negotiate contracts with digital service providers.
Commercial Professionals	15. Conduct market research to identify digital service providers that align with the organization's objectives and requirements.
	16. Negotiate contracts and agreements with digital service providers.
	17. Monitor and evaluate the performance of digital service providers.
Procurement Professionals	18. Align procurement strategies with the organization's digital transformation goals and objectives.
	19. Identify and onboard digital service providers through streamlined procurement processes.

Table 2. List of guidelines per role in the organization.

5 Conclusions

The Global Forum on Maintenance and Asset Management (GFMAM) collaboratively shares knowledge and standards in maintenance and asset management. The Project 25 DX of the GFMAM is exploring how digital transformation (DX) landscape in this field is rapidly evolving, presenting various challenges and opportunities. This paper provides a brief overview of the project document content and results in terms of guidelines provided per role and per maturity of the organizations.

The survey findings shed light on the multifaceted nature of digital transformation in maintenance and asset management. By understanding the specific challenges, perspectives, and opportunities within sectors and roles, organizations can chart a strategic path forward.

The reader can appreciate how emphasizing data governance, information security, leadership, and culture will be key to sustained success in the digital era. By implementing the proposed guidelines, organizations can navigate the digital transformation journey effectively, drive innovation, and optimize their maintenance and asset management practices.

The GFMAM document is expected to be published at the end of 2023.

6 Acknowledgements

We would like to acknowledge the work of the rest of the Project 25 DX members, in alphabetical order: Alex Afshar, Adolfo Crespo Del Castillo, Raymond Hickey, David Smallbone and Ali Zuashkani.

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Autonomous Decision Support Based on Artificial Intelligence Techniques for Maintenance Processes

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Abstract

Through the recent digitalization of the industry and the use of technologies and ideas from Industry 4.0, maintenance tasks have altered. Companies are now able to develop knowledge about the production system's present and future health state by connecting to and talking with it, which enables more effective control over the machinery. Predictive maintenance is a technique whose objective is to minimize unscheduled downtimes and efficiently arrange maintenance tasks before faults and stoppages occur. Several Artificial Intelligence (AI) data analysis tools have been presented in recent decades to construct a prescriptive maintenance system that will aid with the autonomous choice in order to better assist this work. In order to comprehend how artificial intelligence algorithms are affecting maintenance policies and to analyze their implications in strategies, we investigate the state-of-the-art technologies in the prescriptive maintenance system in this study. The findings are compiled in a thorough database that offers illustrations of how to adopt maintenance policies based on descriptive, predictive, and prescriptive analytics using concepts and empirical evidence from the literature. The goal of this study, which is the first in-depth inquiry of these research subjects, is to provide a deeper understanding and awareness of current trends and major challenges while highlighting important aspects and barriers to the adoption of novel policies. *Keywords:* Intelligent maintenance system, artificial intelligence, prescriptive maintenance.

1. Introduction

Due to changes in the manufacturing production planning and control systems, the area of maintenance management has come under growing strain. Plant management has recently been faced with challenges to productivity and quality unprecedented in corporate history. The maintenance department is crucial to achieving higher levels of productivity and quality in order to continuously reduce costs and support a more dependable and long-lasting operation. New condition-monitoring technologies have since emerged, and they are anticipated to enhance maintenance procedures by lowering costs and enhancing the availability and dependability of the equipment. Since many of these technologies are still in their early stages of development, it is important to assess the projected benefit for the operation process at each stage of technical maturity and to create appropriate maintenance strategies that take these newly discovered insights into account. Although there are methods for aiding decision-making processes, most of them have the following drawbacks:

- Consider conventional preventive maintenance techniques.
- Use-case specific (unique difficulties) and not easily transferable to other problem categories.
- Currently used predictive maintenance techniques frequently overlook autonomous decision support. A key building block for creating intelligent cyber-physical maintenance systems that are capable of taking independent decision-supporting activities is artificial intelligence practice.

Future factories that integrate production planning and prescriptive maintenance will have maintenance plans that are more adaptable, customizable, and resilient.

2. Literature Review

Several studies on maintenance methods with a data analytics focus have been done in the last ten years. A substantial body of literature addresses issues, such as enhancing availability by forecasting the condition of equipment using historical and current data as well as expert knowledge. In their evaluation of a large body of research on prognostic-based decision support for condition-based monitoring, Bousdekis et al. [1] offered a useful way for efficiently identifying and choosing the best combinations of techniques, including data- driven approaches. A variety of Deep Learning-based techniques have been researched as alternatives to manual feature engineering. Convolutional Neural Networks, for instance, have been used to identify structural deterioration and detect defects in rotating machinery [2]. However, both approaches have been evaluated in simulated environments, which shows that Deep Learning is still in its infancy and requires further systematic research (e.g., standard datasets, insight into black box models, transferring models, imbalance in training data, etc.) before it can be applied in the field of prescriptive maintenance (PsM) [3]. Additionally, Wöstmann et al. [4] investigated how well-established predictive maintenance technologies may be applied to production systems while considering a number of requirements for a successful implementation. In the literature on maintenance, knowledge- based decision support strategies for PsM are a new trend. This area has not yet been thoroughly investigated. The process of finding, comprehending, and communicating maintenance data was covered by Karim et al. in their discussion of maintenance analytics [5]. A comprehensive strategy that incorporates modelling of data, knowledge, and context is required to design a maintenance analytic-based decision support solution [6]. PsM also refers to recent developments in enhancing self-organization and self-direction capabilities of cyber physical production systems (CPPS), which in theory aim at machine self-diagnosis and scheduled maintenance [7]. Condition-based maintenance or predictive maintenance

(CbM/PdM) enhances condition monitoring by employing statistics, stochastics, simulation-based, data-analytics, and even machine learning algorithms, which allow making failure predictions. Prescriptive maintenance may therefore mature to its full potential, involving sophisticated techniques to foster and strengthen capacities for adaptation and optimization [8]. Not only can PsM forecast the system's future health condition, but it may also suggest autonomously timed judgments for maintenance chores (inspection, repair, and replacement) or action plans. As a result, PsM mandates the incorporation of a decision support system that prescribes and approves specific maintenance action plans that can be carried out automatically or manually. In this regard, PsM exemplifies the self-organization and self-direction capabilities of CPPS [9] while also keeping the operators informed by asking them to monitor the status from AR-based monitoring tools, check the available windows for maintenance planning, and choose whether to immediately call for augmented reality (AR) remote maintenance or schedule maintenance tasks for a later time [10]. PsM systems will eventually develop into autonomous digital orchestrators that schedule maintenance jobs in line with production plans, whereas in this application a human operator mediates and serves as a decision agent in a CbM/PdM environment [8]. While there has been a lot of study on techniques to integrate planning areas (such as production, maintenance, and quality) [11,12], novel maintenance strategies like PdM or PsM are typically lacking a global smart factory perspective and are not yet fully developed from a PPC standpoint. This connection would have a big impact on material planning, reducing waste from unanticipated tool failure/degradation [14], increasing energy efficiency [15], and minimizing the impact of remanufacturing on schedules [16]. The majority of research focuses on allocating suitable time frames for maintenance tasks [17]. For example, production scheduling and preventive maintenance have been combined in decision models to account for demand unpredictability [18]. Only a few models, meanwhile, focus on either CbM for resolving various job-shop scheduling issues [20] or on periodic maintenance [19] to record and use feedback data from the shop floor. Few research has recently begun to examine the relationship between PPC and PdM, for example, for job-shop scheduling based on degradation rates and projecting failure moments [21], but the promising relationship with PsM has not yet been examined. As a result, the discussion below identifies two holes that provide inspiration for the current research:

• PPC cannot afford to disregard the most recent advancements in data-driven maintenance strategies, such as PsM, which must be incorporated in real-world case studies from an application- and technology-focused standpoint. To this purpose, additional research is still needed on data interoperability, evaluation of potential production maintenance scenarios, and knowledge discovery and preservation.

•A factory's planning complexity and technological readiness level greatly influence the design decisions for an integrated PsM-PPC decision support system (and its successful implementation in an actual production environment) (concerning, e.g., available ICT infrastructure, data accessibility, availability, and quality as well as staff qualifications). Application studies are therefore required to evaluate and talk about the difficulties and technological problems resulting from actual use cases.

3. Study Aims

This study's objective is to provide the state-of-the-art in intelligent maintenance systems based on approaches that can influence maintenance policies, including descriptive, predictive, and prescriptive approaches, and to examine how these approaches may be applied to innovations. To do this, a review of recent publications in the literature was first required. This allowed the authors to pinpoint knowledge gaps and provide solutions for our goal of determining how descriptive, predictive, and prescriptive approaches are strengthening traditional maintenance practices. To the best of the authors' knowledge, there are currently no studies in the literature that explore the cutting-edge descriptive, predictive, and prescriptive methodology used in maintenance policies. Finally, by highlighting important characteristics and drawbacks for the adoption of novel policies based on descriptive, predictive, and prescriptive approach, the study offered in this paper aims to produce a deeper understanding and knowledge of current trends and significant challenges.

4. Knowledge-Based Maintenance Strategies

The greatest level of knowledge-based maintenance (KBM) in terms of complexity and maturity is known as prescriptive maintenance [22]. KBM presupposes that holistic assessment of production processes, as opposed to atomistic inspection of (all) influential components, results in competitive advantages for stabilizing maintenance operations and lowering unexpected costs [22, 23]. As a result, KBM focuses on examining maintenance as a non-isolated sub-domain of production systems, which in turn affects the development of organizational value [23]. Recent studies have revealed that the sub-domains of production planning, maintenance, and quality management interact strongly and collectively impact the attainment of the intended production performance, equipment availability, and product quality [24, 25]. Through careful examination of maintenance repercussions, system circumstances, organizational structure, and processes, KBM's primary goal is to build a general concept for optimizing maintenance processes [23]. The following categories can be used to classify current methods for fulfilling KBM objectives (see Fig. 1) [22]:

- Descriptive maintenance provides details on earlier maintenance procedures in response to the question "What happened?"
- Diagnostic maintenance examines cause-and-effect relationships, provides further technical information regarding previous maintenance operations, and provides an answer to the query "Why did that happen?"
- Predictive maintenance forecasts future events using historical maintenance data, possibly in real-time, to answer the question "What will happen when?" The terms "Smart Maintenance," "Data Driven Maintenance," and most recently "Maintenance 4.0" are also used to describe this.

- Prescriptive maintenance provides actionable advice for decision-making and enhances and/or optimizes upcoming maintenance operations to address the question of "How can we make it happen?" or, alternatively, "How can we control the occurrence of a given event?" It also refers to recent improvements made to the CPPS's self-organization capabilities, which ideally aim to facilitate planned maintenance and machine self- diagnosis.

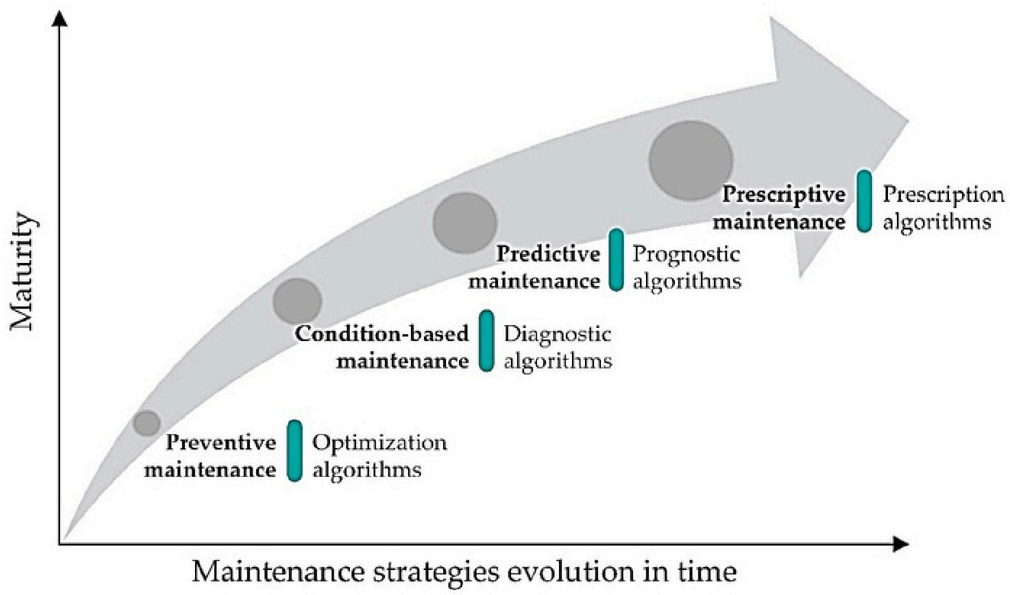

Fig. 1: Knowledge-Based Maintenance Strategies [22]

5. Artificial Intelligence in Maintenance

Because industrial maintenance tasks are inherently complicated, academics are increasingly turning away from more straightforward technological fixes in favor of more sophisticated strategies based on AI to address a variety of maintenance and evaluation difficulties. Artificial intelligence, often known as machine intelligence, refers to a machine's capacity for learning and problem-solving. It can serve as a catalyst for several advancements and cutting-edge technologies in the rail sector. Examples of areas where AI is used include pattern recognition, image processing, diagnostics, remote sensing, process planning and optimization, decision-making, and system control [26–28]. Machine learning (ML) offers powerful capabilities for adopting predictive maintenance and making significant financial savings. With AI-based predictive maintenance, availability can increase by up to 20% while inspection costs and yearly maintenance expenditures are reduced by up to 25% and 10%, respectively [29]. High uncertainty and numerous components that are frequently difficult for engineers to pinpoint directly are two characteristics that define maintenance challenges.

Additionally, due to developments in information technology (IT), the volume of digital data gathered from maintenance tasks has substantially expanded over the past few decades. These data can be mined for possible predictive and prescriptive knowledge utilizing AI techniques. It has been shown that AI can monitor systems, diagnosing faults, identifying acoustic emissions, and performing predictive maintenance [30–32]. Data accessibility and the application of machine learning algorithms to maintenance tasks have the potential to increase productivity and lower maintenance costs [33–35]. The machine learning approach can offer a way to gain the knowledge required to make predictions and judgments by learning from past or present data [36–39]. To diagnose the technical status of the systems and track them using the online mode (in real time), AI systems can be used. Furthermore, faulty system components can be found using an artificial intelligence system. Iterative training of the neural network's input data is possible in both supervised and unsupervised learning environments. Through supervised learning, predictions regarding the component's health status can be made in the future using previous or current data. On the other hand, in an unsupervised learning environment, the data collected is typically trained to confidently recognize and identify significant traits or trends related to component health and failure. The creation of intelligence systems for the early detection of flaws or mechanical issues prior to failure is the current area of research attention. This provides equipment remote diagnosis, real-time defect detection and diagnosis, and predictive maintenance. Additionally, artificial intelligence serves as the foundation for robotic systems that can help with assembly operations, maintenance, and repair works. In some system industries, AI can be used for predictive maintenance [40]. AI will also improve the reliability of the systems and reduce failure rates. Over time, data can be gathered from the measurements and used to train AI algorithms. Predictive models can be created using historical data trained to forecast system behavior in the future. Data mining and machine learning were used to apply predictive maintenance, according to Kalathas and Papoutsidakis [41]. The study's findings point to the suitability of using machine learning to achieve preventive maintenance. According to Famurewa et al. [42], maintenance analytics can improve e-maintenance and decision-making. Not many works have been reported on the development of predictive maintenance based on AI. As a result, this study's principal objective is to advance maintenance activities in the rail industry. The combination of AI and technology for predictive maintenance is shown in Figure (2). The image demonstrates how artificial intelligence can be used for proactive maintenance. Before a predictive model can be produced for making future predictions, an AI algorithm can be trained.

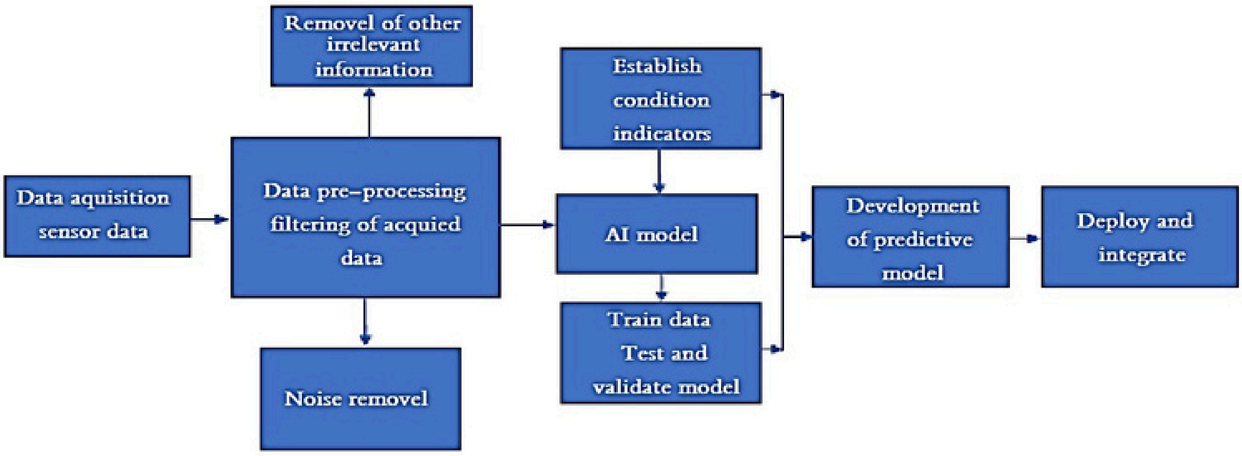

Fig. 2: Integration of AI and predictive maintenance technologies.

6. Predictive and Prescriptive ML Algorithms

Without making any presumptions, ML algorithms [43] can identify potential correlations between pieces of information [44]. Several supervised learning machine learning (ML) algorithms are now available that enable the creation of predictive models from historical data, each with specific benefits and drawbacks [45]. ML approaches are frequently used to diagnose faults in assets by spotting aberrant conditions. Most of the time, bad circumstances aren't immediately apparent; instead, they're shown by their symptoms, including increased vibration and rising temperature, which can be monitored by sensors. The performance of an ML model can be considerably impacted by the choice of an appropriate type of data that best represents the target fault. Mechanical, hydraulic, and electrical data are the three primary data kinds that are frequently utilized to identify system states, according to the literature. System mechanical data, including vibration, speed, and temperature, are important for fault diagnosis because they show the health of various system components. The most common mechanical data utilized for identifying a variety of issues is vibration [46]. In a digital twin, data analytics is essential (DT). Machine learning technology is described in this section as a potential key actor in the data analytics part of DT enabled PdM. A system or machine's health state can be understood and recognized through fault diagnostics (such as anomaly detection and faults categorization) based on historical and current condition monitoring data [47]. Manual diagnosis techniques took a long time and required a lot of expertise and experience. Artificial neural networks (ANN), support vector machines (SVM), and decision trees are examples of machine learning techniques that have opened the way for a higher level of automation in machine maintenance and a more precise problem diagnostic procedure [48]. Machine learning algorithms learn from labelled data with the goal of automatically identifying and categorizing faults. An algorithm would be used to identify problematic conditions and proactively predict future failures based on real-time condition monitoring data after being trained typically on past data. Deep learning, a branch of machine learning, differs from typical machine learning in that it doesn't rely on human input but instead uses a neural network to continuously study the data to increase prediction accuracy [49]. The pre-processing of raw data is necessary for traditional machine learning techniques like SVM and Random Forests before training and learning. Accordingly, data preprocessing and algorithm creation are the two processes involved in defect diagnosis utilizing conventional machine learning techniques. The number of data that has been collected has significantly risen because to developments in ICT and the Internet of Things (IoT), making it possible to use more precise problem diagnostic methods [50]. Traditional machine learning techniques, nevertheless, fall short when it comes to evaluating such large data sets with a diversity of data kinds (volume, velocity, variety, and veracity). Deep learning, a new advancement in machine learning, is built using hierarchical neural network topologies that can handle and process large amounts of data [51]. Through the elimination of pre-processing, feature extraction, and feature selection, this method streamlines and expedites the fault diagnostic prediction process. Importantly, this approach decreases human error in defect identification and does away with the necessity for signal processing knowledge [52].

7. Prescriptive Analytics for Maintenance

According to its definition, prescriptive analytics is a mathematical technique that uses computing to identify a collection of highly valuable activities or decisions. Decisions are made based on a wide range of goals, restrictions, and needs that help a certain sector work better [53]. Prescriptive analytics uses mathematical models to combine the usage of models, rules, and data with hybrid data and rules. It assists in resolving issues with Big Data, operational research, decision support systems, and optimization in the maintenance sector [54]. To make better decisions in prescriptive analytics, statistical and mathematical procedures are integrated with optimization techniques [55]. Prescriptive analytics explains, describes, and forecasts how to advise future courses of action. To accomplish the aim with better objectives, this improves the applications and company. The prediction result is connected to the decision alternative. Prescriptive analytics employs simulations and optimization to improve decision-making. The five main pillars of prescriptive analytics are represented in Fig. 3:

- Adaptive algorithms: As the volume, velocity, and diversity of data increase quickly, prescriptive analytics technology should be able to produce new protocols and automatically recalibrate all its built-in algorithms. To support the business process that is being handled continuously, this whole recalibration needs to be adaptive—dynamic and/or continuous.
- Integrated predictions and prescriptions: Predictive analytics' guaranteed promise is ensured by the prediction and prescription working together. The secret to wide adoption and retaining the benefits of prescriptive analytics is to integrate the two.

• **Hybrid data:** This type of data combines both structured and unstructured data. By using both structured and unstructured data, hybridized data enables the business to reach the optimal conclusion. The prescriptive analytics technology is transformational because it has the capacity to handle hybrid data. Nowadays, a lot of businesses work with structured data, which consists of numbers and categories.

• **Prescriptions and side effects:** Prescriptions suggest time-sensitive activities to improve the future using a variety of techniques.

• **Feedback mechanism:** Prescriptions are typically time-sensitive action plans that incorporate changes over a limited number of controllable influencers to foresee one or more anticipated issues (or to capitalize on one or more anticipated opportunities) [56].

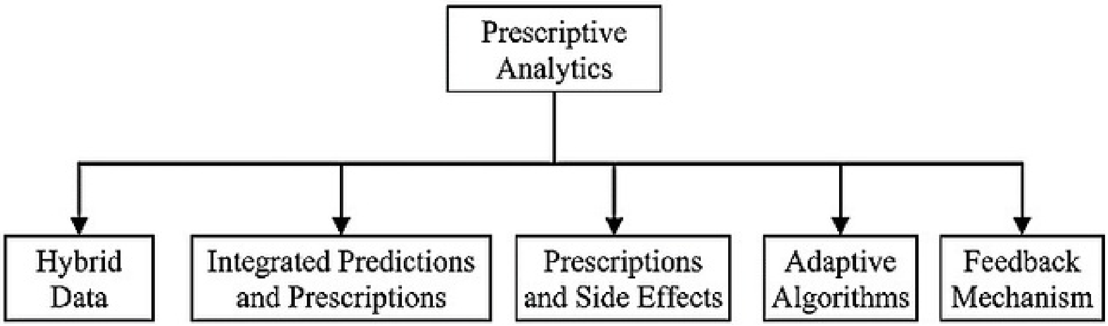

Fig. 3: Prescriptive analytics features.

In big data analytics, prescriptive analytics addresses what, when, and why of the forecast. Analytics are performed using operational research techniques that coordinate with the company and any applicable domain norms. As a result, the influence and its result can be recognized right away [57] compared to descriptive and predictive analytics.

8. Maintenance Decision Support Models

The most recent analysis of the literature suggests that most maintenance models in use are intended to help decision-making procedures. The intelligence of maintenance systems is increased by merging various data sources and knowledge assets and by using data-science techniques like exploratory data analysis or machine learning. This section presents several recently created maintenance decision support models (MDSM). A comprehensive and anticipatory approach was described by Glawar et al. [58] as being able to "identify maintenance critical conditions and predict failure moments and quality variations" for tooling machines. A degradation-based selective maintenance choice problem of a continuously monitored multicomponent system was addressed by Aghezzaf et al. [59]. A cost-effective collection of required maintenance procedures is discovered by modelling components as time-dependent stochastic processes. The study by Wang et al [60] also looked into "a cloud-based paradigm of predictive maintenance based on mobile agent to enable timely information acquisition, sharing and utilization for improved accuracy and reliability in fault diagnosis, remaining service life prediction, and maintenance scheduling." Arab et al [61] used real-time data from workstations, such as cycle times, buffer capacities, and mean time to repair of machines, to solve a dynamic maintenance scheduling problem for a multi-component production system. Additionally, Bärenfänger-Wojciechowski et al. [62] offered a reference integrated management method dubbed "smart maintenance" that incorporates essential maintenance knowledge assets, including people, sensors, data management, and help technologies. Abramovici et al. [63] developed the idea of "knowledge as a service," which facilitates knowledge allocation and the recommendation of potential fixes in line with failure reasons and the degree of similarity between prior failure descriptions recorded in a semantic knowledge base. Finally, Muchiri et al. [64] created a theoretical framework for assessing the effectiveness of maintenance interventions from a technical, management, and human standpoint. Mehairjan et al. [65] created a maintenance management maturity model based on five holistic dimensions, one of which was data quality, while Schumacher et al. [66] created an Industry 4.0 maturity model, which inferentially evaluated elements important for data-driven maintenance. These models produce useful results in prescriptive maintenance, but they have the following drawbacks:

- They consider the dynamics of maintenance processes (using time variables), but they do not entirely or partially consider learning and predicting how process-related parameters will behave over time.
- They are difficult to generalize to similar sets of problems since they are use-case-specific (a singular problem),
- They fail to appropriately use efficiency assessment methods and feedback loops to raise the caliber of maintenance planning.
- They employ well-established but dated process models for knowledge discovery and data analysis, which obviously call for improvement and extension for predictive analytics jobs.

9. Conclusion

This study reviews the state-of-the-art of intelligent maintenance systems using descriptive, predictive, and prescriptive approaches that might influence maintenance policies. It also discusses the implications of these approaches for innovations. AI will also improve the reliability of the systems and reduce failure rates. With AI-based predictive maintenance, availability can increase by up to 20% while inspection costs and yearly maintenance expenditures are reduced by up to 25% and 10%, respectively. The goal of machine learning algorithms is the automatic identification and classification of faults. To be more effective for autonomous decision support based on artificial intelligence techniques, maintenance decision support models need to put in more effort.

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Integrating Digital Twin and Asset Management System for Enhanced Pavement Infrastructure Maintenance

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Abstract

Aligned with the "Future of AI Technologies in Maintenance Training & Education," our paper illustrates the methodology needed to bridge the gap between technological advancements and effective training and education in pavement infrastructure maintenance, by developing a maintenance decision tool through the seamless integration of asset management systems (AMS) with digital twin technology (DT). This approach empowers decision-makers with accurate and efficient maintenance planning capabilities. In summary, our goals intricately intertwine with the future of Artificial Intelligence (AI) technologies in maintenance training and education, highlighting the need for upskilling and integrating technology-driven methodologies into the educational landscape.

The efficient management of pavement infrastructure is crucial for ensuring safe and sustainable transportation networks. In this context, the integration of cutting-edge technologies holds immense potential to redefine maintenance practices. This paper delves into the integration of Digital Twin technology with Asset Management Systems (AMS) as a pioneering approach to optimize pavement infrastructure maintenance.

Digital Twin technology, acting as a virtual replica of physical assets, has revolutionized the way infrastructure is monitored and managed [1]. Complementing this, Asset Management System (AMS) is a systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public's expectations providing a systematic framework for effective asset maintenance [2]. This paper outlines merging of these two systems, yielding a methodology for developing a maintenance decision tool through the seamless integration of pavement management systems with digital twin technology. This approach empowers decision-makers with accurate and efficient maintenance planning capabilities

Through a real case study conducted on a significant road segment in Jeddah Municipality, Saudi Arabia, the paper showcases the possible benefits of this integration. The case study explores data acquisition, manipulation, and modeling processes. The integration further facilitates advanced analytics, and maintenance decision planning. As the transportation industry seeks innovative solutions to enhance infrastructure sustainability, the integration of DT technology and AMS emerges as a promising avenue.

Keywords: Asset Management System AMS, Digital Twin DT, Maintenance Training and Education.

1. Introduction

In the realm of infrastructure maintenance, the integration of advanced technologies has become crucial to optimize efficiency, resource allocation, and decision-making processes. Among these technologies, digital twin technology has emerged as a transformative tool with immense potential to revolutionize pavement management systems.

Digital twin technology serves as a bridge between the virtual and real worlds. By leveraging real-time data collected from physical sites, we can create virtual replicas of our infrastructure and enhance our understanding of its current state. In today's digital era, we have the capability to digitize every component of our network, allowing us to develop a comprehensive Asset Management System (AMS). This integrated system ensures the safety, sustainability, and optimal performance of our road networks by enabling real-time monitoring, data analysis, and informed decision-making.

Traditional methods of pavement management are plagued by several weaknesses, including data gaps, escalating costs, and lengthy data collection and analysis processes. However, the integration of AMS and digital twin technology addresses these challenges and offers numerous advantages. By consolidating both systems into a single application or platform, stakeholders gain a deeper understanding of the infrastructure's current condition. Decision-makers and asset owners can visually assess the infrastructure, simulate various scenarios, and evaluate the potential impact of interventions. This fosters data-driven discussions, enabling them to make well-informed decisions and enhance the efficiency, effectiveness, and sustainability of infrastructure management.

Furthermore, the integration of digital twins with pavement management systems facilitates advanced analytics and predictive modeling. Machine learning algorithms have the ability to analyze vast amounts of data, detect patterns, and forecast deterioration trends. This empowers stakeholders to develop optimized maintenance strategies and allocate resources more effectively. By adopting proactive maintenance practices instead of reactive approaches, asset owners can minimize downtime, extend the lifespan of assets, and ultimately reduce overall lifecycle costs.

In conclusion, the integration of digital twin technology with pavement management systems represents a significant advancement in infrastructure maintenance. This integration empowers stakeholders to gain real-time insights, simulate scenarios, and make data-driven decisions. By harnessing the power of digital twins and advanced analytics, asset owners can optimize resource allocation, improve infrastructure performance, and achieve long-term sustainability. In the following sections, we will delve deeper into the technical considerations, benefits, challenges, and practical methodology model of integrating digital twins with pavement management systems.

2. Background and Related Work

The concept of Digital Twin (DT) has evolved significantly since its introduction in 2002 by Grieves. It has transformed from a basic virtual replica of real-world objects to a fundamental component of decision support systems. Recent research by Fuller et al. (2023) [3] highlights the integration of physical and virtual elements in various domains such as manufacturing, healthcare, and smart cities, offering opportunities for innovation and optimization. However, there are ongoing challenges and research gaps to explore, indicating the potential of Digital Twins to revolutionize decision support systems across industries.

In the context of pavement management systems, Mehran (2022) [4] emphasizes the combination of physics-based models and data-driven machine learning techniques for predicting road deterioration. This approach leverages physics-based models to simulate the physical processes associated with road degradation, while machine learning algorithms analyze historical data to uncover patterns and trends. The integration of these approaches enhances the accuracy and robustness of road deterioration prediction, leading to improved decision-making in pavement maintenance strategies.

Furthermore, Consilvio et al. (2023) [5] presents a methodology for creating a maintenance decision tool by integrating pavement management systems with digital twin technology. This integrated approach aims to empower decision-makers with a powerful tool for accurate maintenance decision-making processes. By leveraging the insights and data analytics provided by digital twins, real-time monitoring, asset condition analysis, and predictive modeling can optimize resource allocation, reduce costs, and prolong the lifespan of road infrastructure.

2.1. Real Case Study

Real-life case study in Australia demonstrates the benefits of integrating digital twin technology with pavement management systems. [6]. Using advanced modeling and machine learning from Unmanned Aerial Vehicle (UAV) data, the study developed a cognitive twin capable of detecting pavement distress. Compared to manual survey and laser detection, the digital twin approach showed improved efficiency, cost savings, and better infrastructure management.

2.1.1 Study area

Turner Street in Port Melbourne, Victoria, as shown in figure 1 [6] , was selected for the case study. The 1.2 km road is situated in a transited industrial area, experiencing continuous damage and requiring ongoing maintenance. A cognitive digital twin was developed for the pavement, accurately depicting its current condition and detecting distresses like cracking and rutting. The road's high traffic and maintenance challenges made it an ideal test bed for continuous UAV surveillance proof of concept.

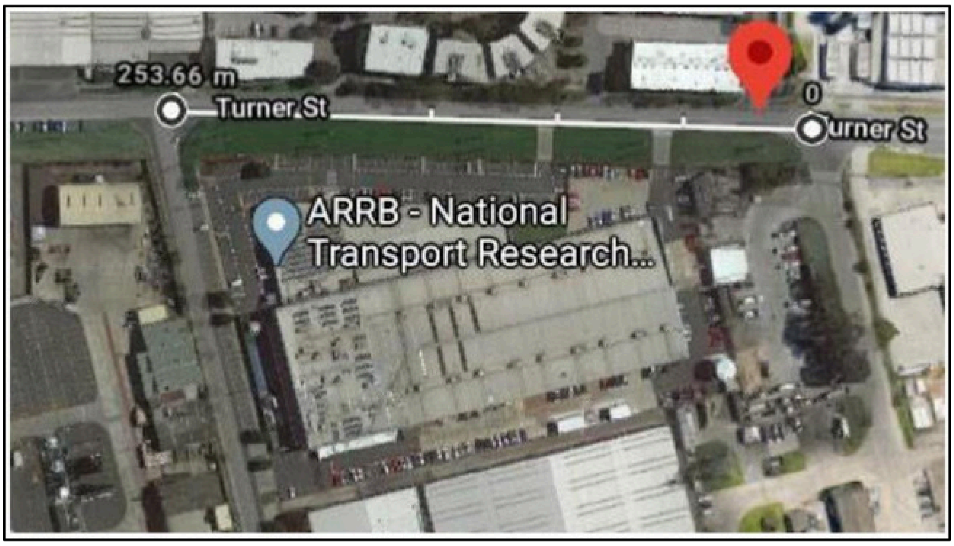

Figure 1: Turner Street drone capture area.

2.1.2 Methodology

The methodology used in the case study involved three key steps:
Data Acquisition: Two Phantom 4 RTK drones with a D-RTK 2 base station were used to collect photographic data of Turner Street. The drones employed an embedded RTK system for precise coordinates. Manual still image flight approach was selected as the optimal method for recreating the road, capturing 205 images over 250 meters in 10 minutes.
Twin Model Development: The acquired images were processed to create a complete reality model figure 2 [6] within 2 hours. The reality model accurately represented the road's current condition, including various distresses such as rutting, potholes, and crocodile cracking and this can be seen in figure 3 [6].

Figure 2: Turner Street reality model developed through photogrammetry.

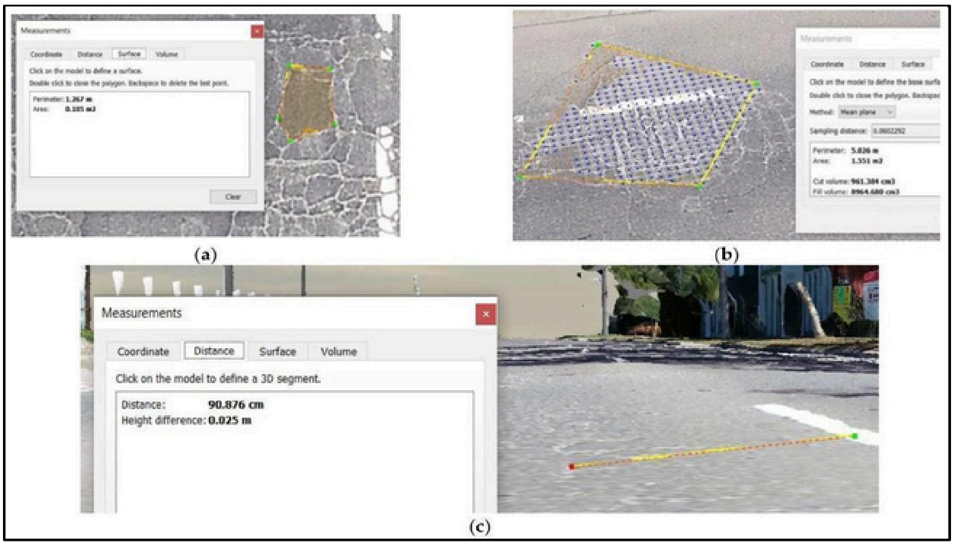

Figure 3: Distresses from the reality model: (a) crocodile cracking; (b) pothole; and (c) rutting.

2.1.3 Cognitive Twin Architecture

Transfer learning technology and VGG16 CNN models were utilized as feature extractors for the ML-based classifier. The network was trained on RGB crack images of pavement, achieving reliable distress detection with a failure rate of less than 20%. The trained model successfully detected cracks in test images. Figure 4 [6] represents a prediction of cracks from a test image.

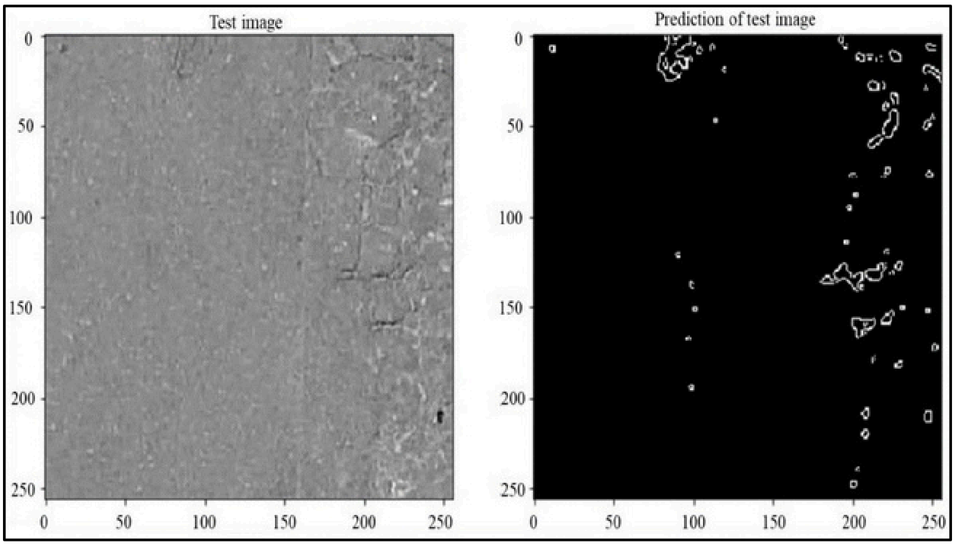

Figure 4: Predicting the cracks from the trained model using a new image.

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Overall, the methodology involved data acquisition through RTK-enabled drones, reality model development through photogrammetry, and cognitive twin architecture employing transfer learning for distress detection. The results showcased the effectiveness of integrating digital twin technology with pavement management systems for accurate monitoring and decision-making.

2.1.4 Cost and Time Analysis

The cost and time analysis compared three methods for pavement assessment: traditional manual survey, advanced vehicle data capture, and the proposed digital twin method, which is illustrated in table 1 and figure 5 [6].

Method	Cost (in units)	Labor Requirement	Output	Time (in hours)
Traditional Manual Survey	Moderate	Two individuals	Conventional Report	Similar to others
Advanced Vehicle Data	High	Two individuals	Detailed Data Capture	2.1 hours
Proposed Digital Twin	Cost-Effective	One individual	Digital Twin Model	Similar to others

Table 1: Comparison Between Three Pavement Assessment Methods.

Please note that the "Cost" column represents a qualitative comparison (e.g., High, Moderate, Cost-Effective) rather than specific numerical values. The time is indicated as "Similar to others" since the time taken by all three methods was comparable, with the advanced vehicle method being slightly faster

3. Smart Maintenance Decision Tool Methodology

The methodology for developing the smart maintenance decision tool involves four essential layers, culminating in the creation of a comprehensive model that integrates digital twin and AMS technologies. This model follows a systematic process, as depicted in Figure 6.

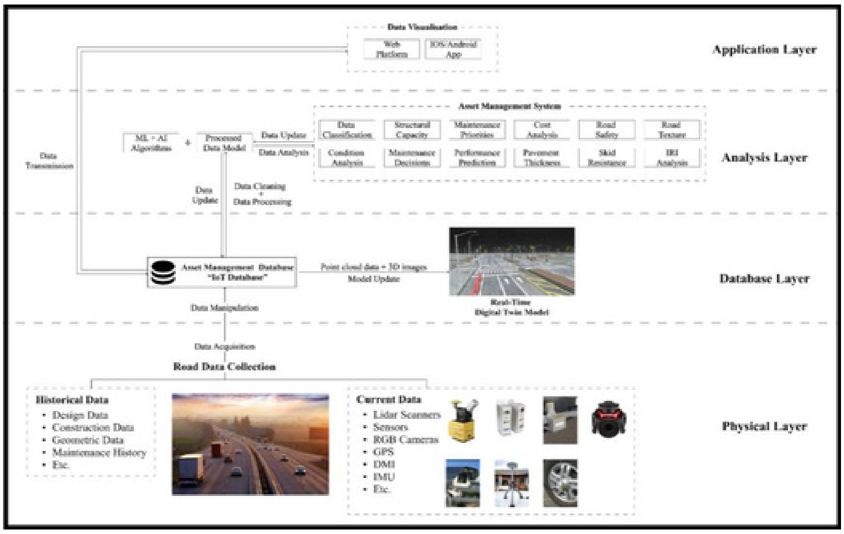

Figure 5: Cost and time comparison for 1 km of pavement.

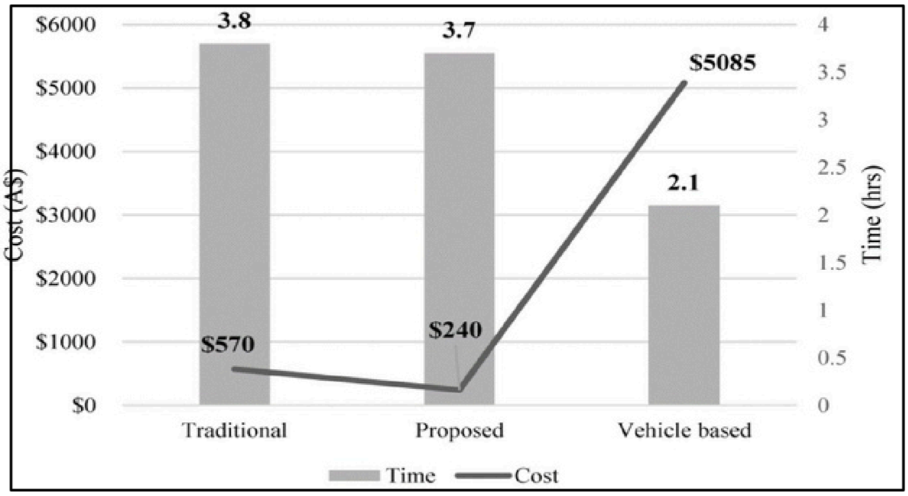

Figure 6: AMS and DT integration methodology layers.

The initial layer, known as the Physical layer, focuses on the data collection process. This layer aims to collect data "historical and current" throughout the lifecycle of the road, from design and construction to operation and maintenance. Handling a vast amount of data presents a significant challenge, which includes gathering information from various equipment and sensors. Incorporating the concept of the Internet of Things (IoT), each vehicle in the network is equipped with a data acquisition system that ensures real-time data collection from all its sensors. This allows for the retrieval of valuable and usable data in real-time from every vehicle in the network. Subsequently, data acquisition and manipulation are conducted to convert the raw data into usable format data for the subsequent layers of processing, analysis, visualization, and modeling.

The second layer, referred to as the Asset Management Database layer, is an IoT cloud database. This database stores all the data gathered during the initial layer in real-time. In this layer, point cloud data and 3D images are utilized to generate real-time digital twin models of the road being studied. This enables a dynamic representation of the road's characteristics. The reason for using an IoT database was mainly due to 2 reasons: real-time data collection, where IoT devices can gather and transmit data continuously, allowing for up-to-date information on various parameters. And remote monitoring and control, where IoT enables remote monitoring and control of devices and systems, providing convenience and efficiency in managing assets.

In the data analysis layer, data cleaning and processing take place. Advanced Artificial Intelligence (AI) and Machine Learning (ML) computer vision algorithms are deployed for automated classification and analysis of both current and historical data. For instance, the point cloud data allows for automatic classification of objects like light poles, traffic signs, or traffic poles, along with determining their condition. Additionally, using deep learning and convolutional neural networks (CNN), a model is created to accurately identify pavement distress and asset conditions, providing efficient and timely assessments of the network's assets. The analyzed data are updated in the Asset management Database, consequently updating the digital twin model. This step enhances the accuracy and efficiency of the decision-making process. Within the AMS system, comprehensive analyses are conducted, such as calculating the Pavement Condition Index (PCI) and International Roughness Index (IRI) for each asset. Additionally, the maintenance decision-making process is facilitated, taking into account the behavior of each element and distress. Utilizing AI algorithms, prediction models for each distress are generated, enabling prioritization and envisioning the future status of the network with both a conceptual and digital representation. This integration between AMS and Digital Twin technology amplifies the maintenance decision tool’s potential.

Finally, the application layer involves the development of a web-platform tool accessible to maintenance decision-makers. This powerful application can also be accessed via IOS or Android apps, providing a user-friendly and efficient platform for making informed maintenance decisions. The application is used as a data visualization and modeling layer, employing various visualization tools such as dashboards, GIS, point cloud, and image viewers to present a comprehensive view of the analyzed data. Leveraging Geographic Information System (GIS) proves highly beneficial in visualizing the analyzed data on a map, complete with data attributes. Utilizing ESRI dashboards allows for comprehensive data analysis, facilitating the decision-making process. By incorporating high-quality images, classified point cloud data, and mapped pavement distress and thickness, a comprehensive visualization of assets is achieved, empowering decision-makers to make informed choices. Moreover, for 3D modeling, platforms like Unreal Engine can be employed, ensuring user-friendly access on both PCs and mobile devices.

4 Case Study

4.1. Study Area

For our case study, our focus centers on a significant road segment situated within Al-Mohamadya region of Jeddah Municipality, Saudi Arabia. Awes Ebn Thabet Road (under Jeddah Municipality authority), shown in figure 7, plays a pivotal role in connecting Prince Sultan Rd and Al-Madinah Al-Monawra Rd. Spanning almost 1 km, this road comprises a flexible asphalt pavement with three lanes in each direction, each of which is 3.2 meters wide. Our investigation will concentrate on the left lane in the direction from Prince Sultan Rd to Al-Madinah Al-Monawra Rd, which is divided into two sections (Section_1 & Section_2) with 270m and 440m respectively. This specific segment has been chosen as a representative specimen to outline the broader characteristics of the entire road. The selection of this particular road stems from its evident traffic-related challenges and the less-than-optimal state of its pavement, as shown in figure 8. This prompted us to subject the road to thorough testing using our specialized equipment.

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Figure 7: Awes Ebn Thabet Road

Figure 8: Awes Ebn Thabet road condition; (a) Rutting along with raveling, (b) Poor patch around manhole, (c) Depression in manhole "acts as a pothole", (d) clear severe weathering and raveling distresse, (e) bleeding.

The central aim of this case study revolves around the comprehensive collection and analysis of all accessible data from the physical layer. This encompasses data acquired through diverse sensors and vehicle-mounted equipment. These collected data will then traverse several pivotal stages, commencing with rigorous data analysis, processing, and subsequent modeling. The ultimate objective is to illustrate the possible benefits of developing a detailed and exhaustive digital twin of the selected road based on the methodology of integration between AMS and DT described in figure 6.

4.2. Physical Layer Equipment

In the detailed exploration of the physical layer, we find a network of interconnected vehicles, each equipped with advanced sensors, software, and technologies to collect and exchange crucial data, facilitating the creation of our digital twin model.

At the forefront is the mobile mapping system (Topcon IP-S3 [7]) mounted on a vehicle shown in figure 9, featuring a powerful rotating LIDAR sensor capturing the surrounding environment at a rate of 700,000 pulses per second. With 32 internal lasers covering the full 360 degrees around the system from slightly different viewing angles during each rotation, it minimizes gaps in the point cloud caused by obstacles or blind spots, eliminating the need for multiple scanners. Equipped with a six-lens digital camera system, the IP-S3 captures 360-degree, high-resolution spherical images that facilitate easy recognition of features. The IP-S3 positioning system incorporates an Inertial Measurement Unit (IMU), a GNSS receiver (GPS and GLONASS), and a vehicle odometer. It delivers precise positioning and attitude information in dynamic environments. This mobile mapping system combines high-density, high-precision point clouds and high-resolution panoramas in a smaller and lighter package, making it easier to handle.

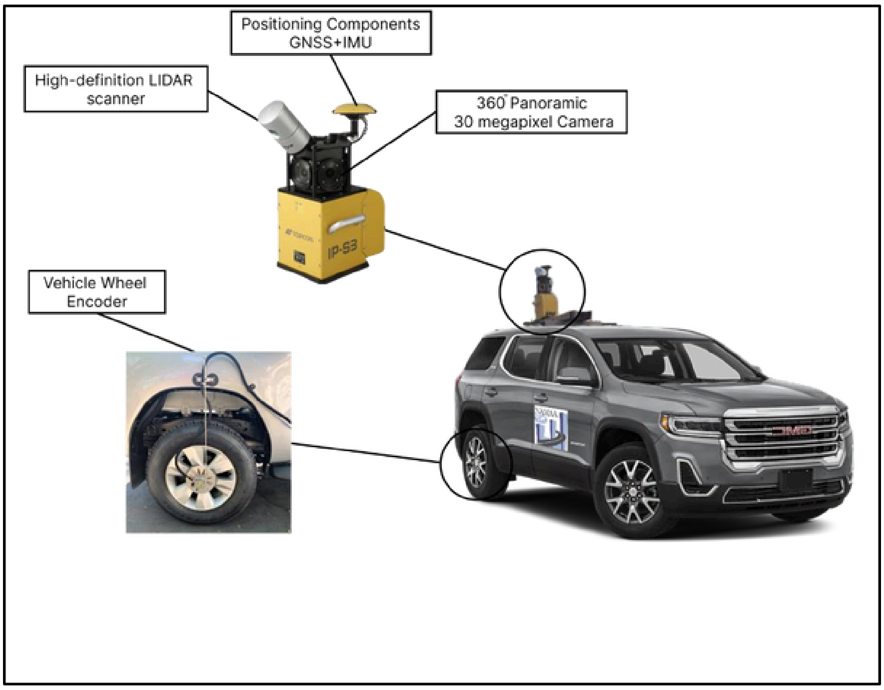

Figure 9: Mobile Mapping System Components.

Pavement data is collected using the Multi-Function Vehicle (MFV) shown in figure 10. The MFV is equipped with two
high-precision laser units (LCMS-2) from Pavemetrics [8], capturing the pavement surface at a 28,000 Hertz scanning frequency, effectively detecting pavement distresses and cracks at a remarkable 1 mm resolution and at speeds up to 100
km/h. The MFV is fitted with a laser profilometer beam at the front bumper, capturing the pavement surface roughness (measured as International Roughness Index IRI) and texture data at a remarkable 0.05 mm vertical resolution for IRI measurements every 25mm interval (confidence level of 95%). Additionally, the MFV is over-fitted with a 360-degree camera covering the road right of way (ROW) for quality control of the processed data. The vehicle is also equipped with GNSS, IMU, and wheel odometer to establish the location of the vehicle or road center line at any given time. The geo- referenced data allows for easy integration with GIS mapping or asset management software.

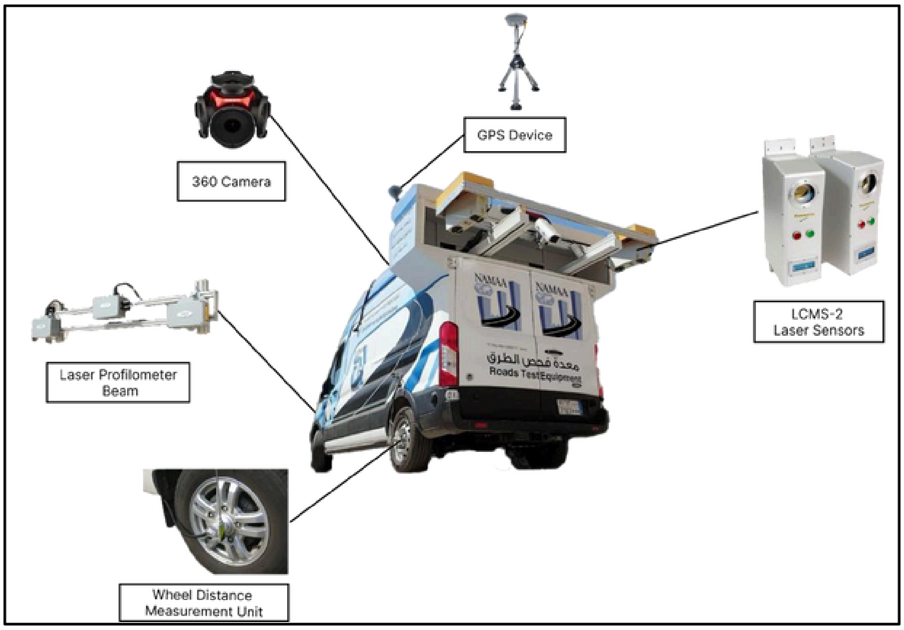

Figure 10: Multi-Function Vehicle Components.

To ensure precise maintenance decisions, Non-Destructive Tests (NDT) are conducted to collect structural capacity, pavement layer thickness, and skid resistance data. The Fast-Falling Weight Deflectometer (Fast-FWD), the Ground Penetration Radar (GPR), and the Pavement Friction Tester (PFT) are essential for this purpose.

The Fast-Falling Weight Deflectometer (Dynatest Fast-FWD [9]), shown in Figure 11, is a non-destructive and fast method to evaluate the structural capacity of pavements for research, design, rehabilitation of the road and for pavement management purposes. The Fast-FWD applies a dynamic load (ranging from (7-120 kN) up to 150 kN) that simulates the loading of a moving wheel, where the falling weight drops on a load cell mounted on top of a loading plate. The pavement surface vertical movement or deflection is recorded with 7-15 deflection sensors. The Fast-FWD is integrated with accelerometers measuring the acceleration of the falling weight during impact, aiding in analyzing pavement deflection. The data collected is georeferenced using GPS. The pavement response is analyzed with Dynastes's ELMOD (Evaluation of Layer Moduli and Overlay Design) software to determine the elastic moduli, stresses, and strains of each modeled layer. ELMOD reports the weakest layer of failure, residual life and determines the optimum rehabilitation alternatives.

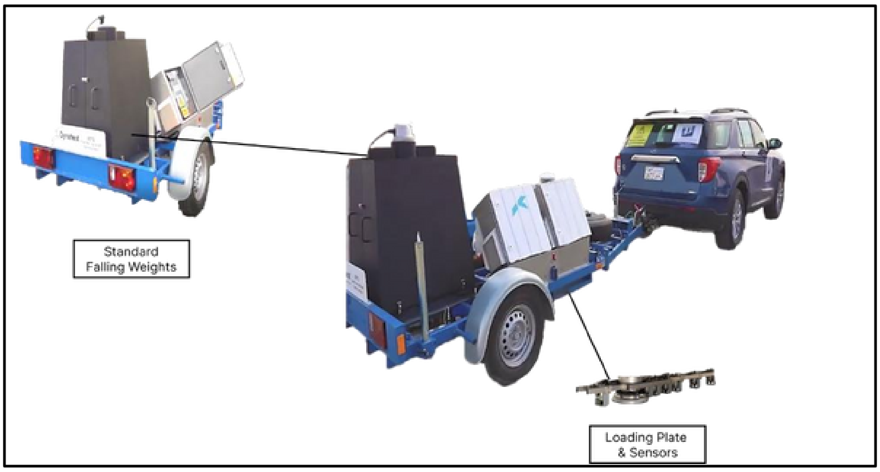

Figure 11: Dynatest Fast- Falling Weight Deflectometer Components.

The Ground Penetration Radar (GSSI-GPR [10]), shown in figure12, is equipped with an antenna transmitting and receiving electromagnetic waves into the ground at frequencies ranging from 1 to 2 GHz. The electromagnetic pulses sent into the subsurface can reach a maximum depth of 60 cm. The reflected signals captured by the receiver provide valuable subsurface data, in the form of pavement layer thicknesses. GPS is again utilized for georeferencing. The GPR assists in determining the thickness of each pavement layer, allowing for accurate structural capacity assessment using the ELMOD software.

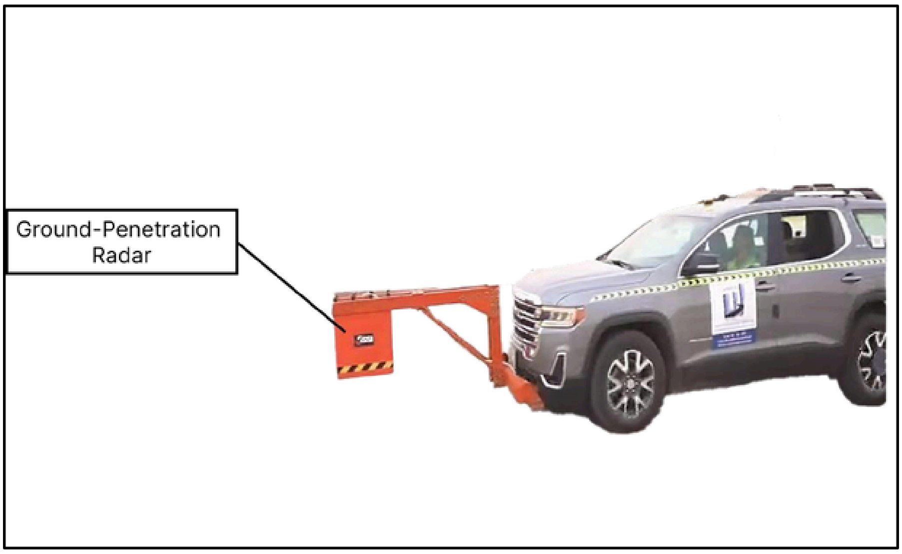

Figure 12: GSSI Ground Penetration Radar Components.

Lastly, the Pavement Friction Tester (Dynatest PFT [11]), shown in figure 13, is designed for maintenance testing to evaluate changes or deterioration in pavement friction due to traffic, weathering, polishing, and/or aging. The Dynatest Pavement Friction Tester (PFT) measures the average locked wheel (skid) and peak (slip) friction characteristics on dry or self-wetted paved surfaces. The PFT contains a water tank, standard tire, and sensor, playing a crucial role in determining the friction number of the pavement surface. This information is vital for evaluating road safety and optimizing maintenance strategies.

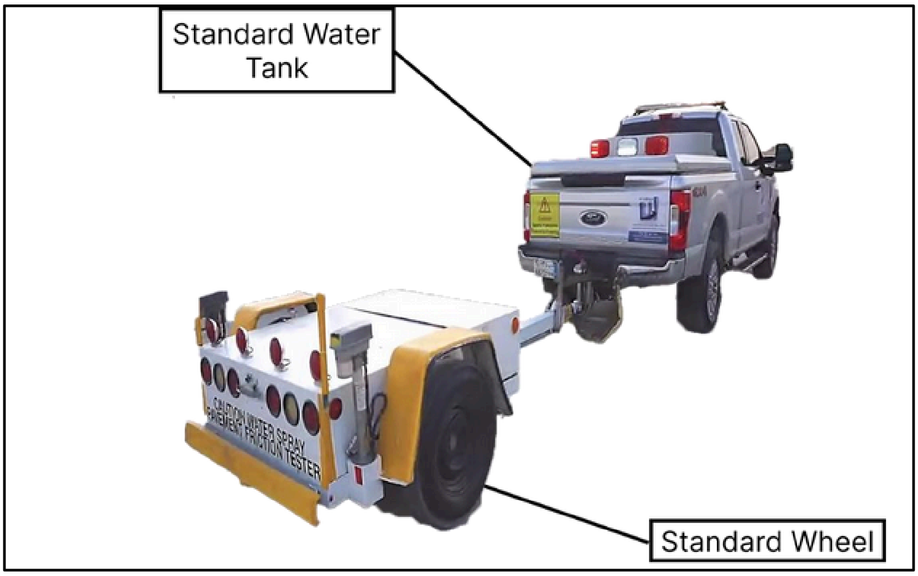

Figure 13: Dynatest Pavement Friction Tester Components.

4.3. Data Collection and Processing

In each equipment unit, an integrated data collection system operates in tandem with a customized computer setup, exclusively dedicated to the acquisition of compiled data. Subsequently, the collected data undergoes a sequence of manipulation, processing, and in-depth analysis. This section provides a glimpse into the diverse data categories derived from the physical layer.

The data acquired through the Multi-Function Vehicle (MFV) is meticulously transformed into (.fis) files. These files include processed images and XML files, encompassing geographically referenced distress data, illustrated in figure 14. Housing Ground Penetration Radar (GPR) data, a compilation of (.nat) files has been meticulously gathered. This resource has enabled the determination of pavement layer thickness for the road, as portrayed in figure 15. In addition, pivotal pavement data has been procured through Fast-Falling Weight Deflectometer (Fast-FWD) and Skid Resistance tests.

Subsequent to data collection via the mobile mapping vehicle, the gathered information is structured into (.las) files. The ensuing point cloud data can be subject to processing, ultimately enabling the creation of a dynamic 3D model, as depicted in figure 16.

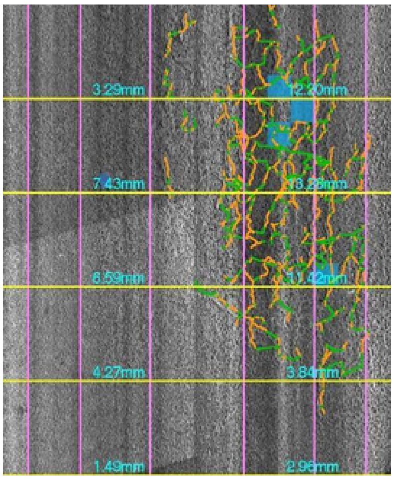

Figure 14: Distress Data Extracted from MFV

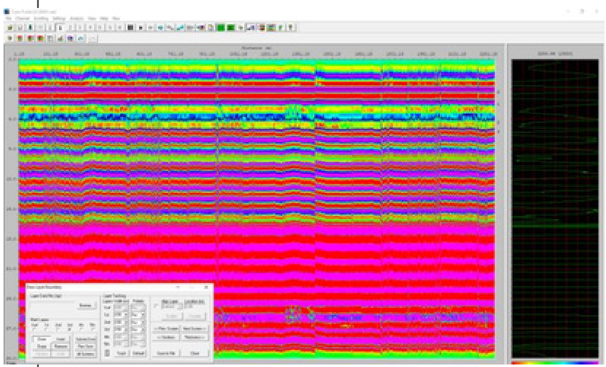

Figure 15: Pavement Layer Depths Determined by GPR

Figure 16: Point cloud data from mobile mapping vehicle.

While the Asset Management System (AMS) equips us with essential planning and management data required for road asset maintenance, we acknowledge the significance of developing a digital twin model. The digital twin will serve as a powerful tool for decision-makers, enabling them to visualize the consequences of their decisions in a digital model. Through the digital twin, decision-makers can explore how the network will be impacted by their choices, making informed and strategic decisions for the road infrastructure.

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4.4. Data Analysis Results

Upon the completion of data collection, processing, and subsequent analysis within the AMS framework, our focus shifts to specific details regarding pavement surface distresses, as outlined in table 2, figure 17, and figure18. Additionally, we examine parameters such as Pavement Condition Index (PCI) following ASTM D6433 standards, International Roughness Index (IRI) as per ASTM E1926-08, Ride Number (RN) adhering to ASTM E1489-08(2019), mean profile depth (MPD), friction number (FN), and deflection (D1). These data are comprehensively presented in table 3.

Section ID	Distress Type	Distress Severity	Distress Area (m2)
Section_1	Alligator Cracking	LOW	0.513436
	Alligator Cracking	MEDIUM	4.668567
	Longitudinal and Transverse Cracking	LOW	86.263316
	Longitudinal and Transverse Cracking	MEDIUM	41.01472
	Patching and Utility Cut Patching	LOW	19.68143
	Raveling	HIGH	76.083183
	Raveling	LOW	34.184812
	Raveling	MEDIUM	97.691806
	Rutting	LOW	52.95914
	Rutting	MEDIUM	16.35253
Section_2	Alligator Cracking	LOW	6.097919
	Alligator Cracking	MEDIUM	1.649015
	Longitudinal and Transverse Cracking	LOW	166.18967
	Longitudinal and Transverse Cracking	MEDIUM	97.794961
	Patching and Utility Cut Patching	LOW	51.529909
	Raveling	HIGH	63.767378
	Raveling	LOW	218.959232
	Raveling	MEDIUM	78.079526
	Rutting	HIGH	3.98434
	Rutting	LOW	251.26564
	Rutting	MEDIUM	43.735

Table 2: Pavement Distresses Details in the Study Area.

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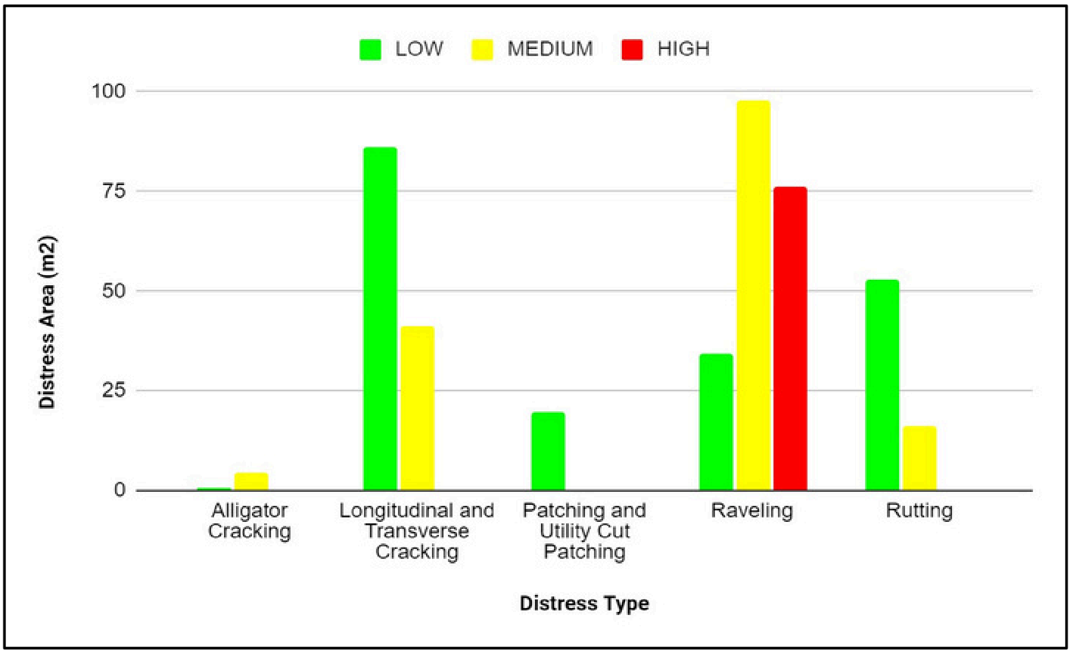

Figure 17: Pavement Distresses Details in Section_1.

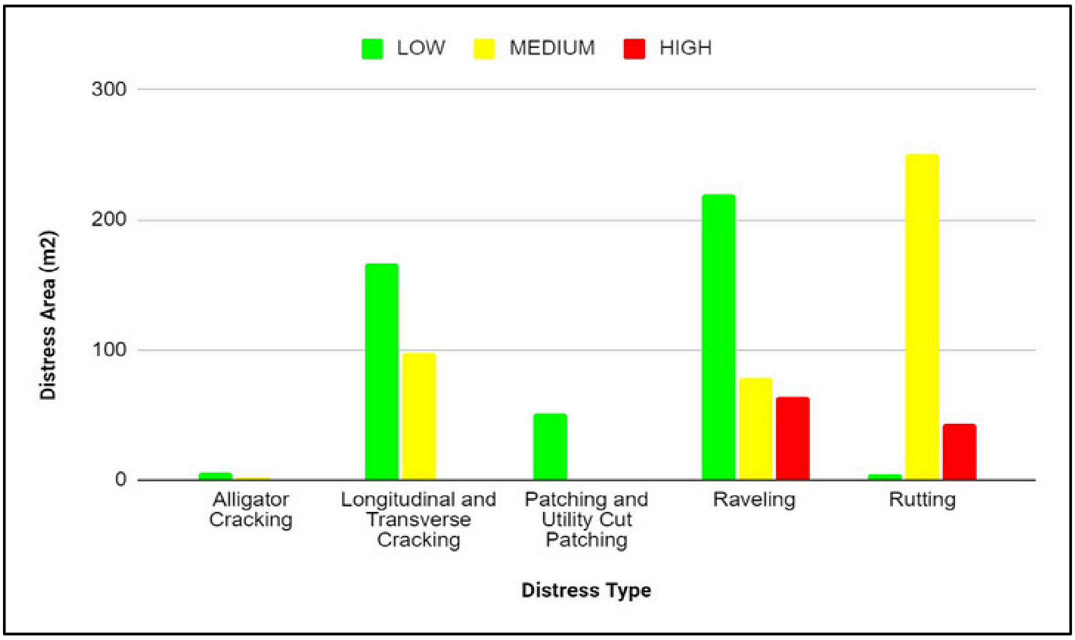

Figure 18: Pavement Distresses Details in Section_2.

Section ID	Reading Type	The Value
Section_1	PCI_MFV	35
	IRI_Profiler (m/Km)	3.8
	FN_ (Friction Tester)	36
	D1_(FWD) (μm)	350
Section_2	PCI_MFV	45
	IRI_Profiler (m/Km)	5
	FN_(Friction Tester)	39
	D1_(FWD) (μm)	330

Table 3: The Results from Different Equipment in the Study Area.

4.5. AMS Maintenance and Rehabilitation Planning

Within this section, we present the maintenance decisions derived from the Asset Management System (AMS), accompanied by their corresponding costs as cited in table 4. Following the methodology model, these outcomes will be subsequently sided with the results generated by the Digital Twin Model. This comparative analysis aims to assess the effectiveness and accuracy of the digital twin-based approach against the established decisions from the AMS.

Section ID	Maintenance Decision Type	Unit Price (SAR/m^2)	Area (m^2)	Cost (SAR)
Section_1	Mill and Overlay	30	864	25,920
	Deep Patching	150	21	3,150
Section_2	Mill and Overlay	30	1408	42,240
	Deep Patching	150	49	7350
		Total	2342	40,660

Table 4: Maintenance Decision Details.

4.6. Integration Process of Digital Twin Modeling for the Studied Road

Following the outlined methodology in figure 6, the application of digital twin modeling to the studied road involves a systematic progression. Once the required data is collected for on-site assessment, the road follows a series of steps. As initially illustrated in our methodology, the foundational analysis commences within the Asset Management System (AMS). Through data classification and employment of machine learning (ML) algorithms, the Digital Twin (DT) model undergoes continual enhancement. The classified geometric data collected from the field contribute to the creation of a comprehensive 3-D road model. This model is a dynamic entity, iteratively updated through the analyzed and processed data. The collaboration between the AMS and DT model ensures a seamless flow of information, enriching the pavement condition insights.

The integration begins with the AMS, where meticulous analysis of every data fragment occurs. This analytical feed propels the evolution of the DT model, shaping its accuracy and comprehensiveness. The culmination of this process leads to an accurate digital representation of the road's dynamic condition.

Finally the data visualization, a pivotal interface that empowers decision-makers. This visualization materializes within a web or application platform, where the integration insights are presented. This interface equips decision-makers with the tools to discern the optimal maintenance strategies and prioritize requisite actions. Ultimately, this integration presents a seamless synergy of data, technology, and decision-making, propelling the evolution of pavement maintenance strategies.

5. Conclusion

In conclusion, our paper highlights the transformative potential of integrating digital twin technology with pavement management systems, fostering a new era of informed decision-making and optimized infrastructure maintenance. Through a detailed exploration of data collection, manipulation, and analysis, we have showcased how this integration empowers stakeholders with real-time insights and predictive modeling capabilities.

The seamless synergy of Asset Management Systems (AMS) and digital twin technology not only addresses the challenges of traditional pavement management methods but also aligns with the evolving landscape of AI technologies in maintenance training and education. This integration acts as a bridge between the physical and virtual worlds, enriching the educational experience by amplifying the practical application of advanced technologies.

The comprehensive methodology we present emphasizes the importance of accurate data, effective analysis, and the utilization of machine learning algorithms, resonating with the future of maintenance training and education in the context of AI technologies. By exploring the fusion of physics-based models and data-driven insights, we have illustrated the benefits of integrating traditional expertise with emerging AI capabilities.

As the transportation industry navigates toward more sustainable, efficient, and cost-effective infrastructure maintenance, the integration of digital twin technology and AMS emerges as a potent strategy. This paper, with its practical case study, technical insights, and educational implications, contributes to both the current discourse and the future trajectory of pavement infrastructure management and maintenance.

In a world driven by technological advancements and the ever-evolving landscape of AI technologies, the integration of digital twins and AMS serves not only as a solution for better infrastructure management but also as a teaching and learning tool, shaping the next generation of maintenance professionals. The journey of integration has just begun, and its significance extends beyond the present, promising a more intelligent, sustainable, and resilient future for our infrastructure systems.

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THE ROLE OF UNIVERSITIES AND PROFESSIONAL INSTITUTES IN SHAPING MAINTENANCE EDUCATION IN LIGHT OF THE FOURTH INDUSTRIAL ERA

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Abstract

The 4th Industrial Revolution is driving the convergence of digital and physical technologies, reshaping industries globally. Even the traditionally conservative construction sector is embracing digitalization and automation. In this context, the paper addresses the state of maintenance and engineering education, focusing on the concrete building maintenance sector. This industry demands a workforce skilled in navigating the new technological landscape. However, traditional engineering education often lags behind technological advancements, leaving graduates unprepared to tackle evolving challenges. The decline in civil engineering students and the lack of emphasis on maintenance education in study plans further exacerbate this issue. On the other hand, the building maintenance market is expanding rapidly, indicating a demand for well-educated maintenance professionals. The paper proposes a comprehensive framework to reshape maintenance education by updating curricula, encouraging industry collaboration, and improving public awareness. It emphasizes integrating emerging technologies, interdisciplinary collaboration, practical experience, and lifelong learning to equip graduates for modern maintenance challenges.

Keywords: Maintenance, Education, Fourth Industrial Revolution.

1 Introduction

In the context of the fourth industrial revolution and its resonance with concrete building maintenance, this research paper initiates an exploration of the dynamic transformation of education and technologies in this field. Embracing these changes emerges as a catalyst for educational progress, catering to emerging requisites, and fostering a competitive pursuit of excellence.
Engineering stands as a vanguard in this transformative landscape, intricately woven into the fabric of societal demands, spanning housing, construction, and everyday necessities. Yet, the rapid evolution driven by the fourth industrial revolution demands a corresponding evolution in education paradigms, particularly in maintenance and engineering. The ability to anticipate impending needs and seamlessly adapt to emerging trends becomes a hallmark of a responsive education system, ensuring relevance in the face of rapid change.
This underscores the importance for professional institutes and universities to cultivate an acute awareness of the dynamic interplay between evolving technology, industry dynamics, and market demand. Such awareness not only ensures a comprehensive education but also guarantees students a professionally secure future, characterized by stability, upward mobility, and the realization of personal aspirations [1].
Building Maintenance falls under the umbrella of Civil engineering disciplines. Civil engineering makes up to about 50 percent of all engineering graduates [2]. The profession faces significant and rapid changes due to technological advancement and challenges to public safety, health, and welfare are becoming more demanding [2].

In subsequent sections, we delve deeper into the implications of the fourth industrial revolution on concrete building maintenance and the evolving landscape of engineering education. Through rigorous analysis, we aim to illuminate the pivotal role of adaptability in education and practice, particularly within the Arab world's engineering capacity.

2 Basics of Building Maintenance and Codes

Maintenance refers to the process of preserving, repairing, and ensuring the proper functioning of an object, system, or infrastructure. From mechanical devices and computer systems to buildings and vehicles, maintenance plays a crucial role in maintaining functionality and extending the lifespan of various assets. Its importance cannot be overstated, as effective maintenance practices lead to improved safety, increased productivity, reduced costs, and overall sustainability. Hence the importance of maintenance lies in its ability to ensure the proper functioning of assets and prevent unexpected failures. For instance, regular maintenance of machines in a factory prevents breakdowns, minimizes downtime, and maximizes production output. Similarly, maintaining the structural integrity of buildings, such as bridges and hospitals, guarantees the safety of occupants and prevents catastrophic accidents.
Moreover, maintenance contributes to cost reduction by minimizing the need for costly replacements or repairs. By addressing issues at their early stages, maintenance professionals can identify potential problems and rectify them before they escalate into major breakdowns or failures. This approach saves businesses and individuals substantial amounts of money that would otherwise be spent on expensive replacements or emergency repairs. As a matter of fact, building stocks are considered a national asset, they are the main representation of civilization and development in any country. The design and construction of buildings have come a long way in terms of new technologies and techniques to build strong and durable buildings with long-term serviceability. However, buildings cannot maintain their original state throughout their lifetime and some deterioration is inevitable [9]. Here comes the building maintenance management role as a versatile engineering tool to sustain the building's integrity and extend its life span.
The interest in maintenance wasn't a concern in the early stages of concrete development. In the 1960s, only the compressive strength of concrete was considered the most important parameter, then durability became more important in the 80s. 20 years later, the interest shifted toward serviceability and sustainability. Nowadays, new technologies and techniques are emerging, involving artificial intelligence, machine learning, and automation. Fig.1 is a visual representation of the development of interest in concrete and maintenance.

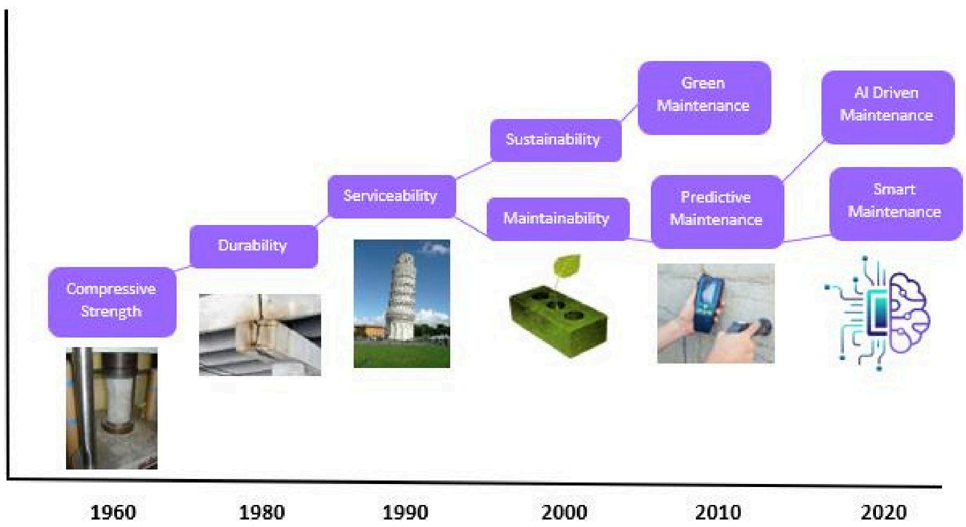

Fig. 1 Interest in Maintenance development through the years

Applying correct maintenance and repair principles has proven to have a positive impact economically and environmentally [10,11].

Maintenance is an essential aspect of various industries and sectors. By preserving and repairing assets, maintenance professionals ensure their proper functioning, enhance safety, reduce costs, and contribute to sustainability. As technologies continue to advance, incorporating effective maintenance practices becomes increasingly necessary, emphasizing the importance of this discipline.

In order to provide a safe and functional environment, building maintenance and adherence to codes are of paramount importance. Whether it is a residential home, office building, or commercial facility, proper maintenance and compliance with codes are essential to ensure the longevity and safety of the structure. In this essay, we will explore the basics of building maintenance and codes, outlining their significance and how they contribute to a well-maintained building. Building maintenance refers to the activities undertaken to preserve the condition of a building and its systems. This includes routine inspections, repairs, and any other actions necessary to uphold the structural integrity and functionality of the building. Adequate maintenance not only prevents minor issues from escalating into major problems but also helps extend the life of the building and its components. Furthermore, it ensures the safety and comfort of the occupants, making it indispensable for any responsible building owner or manager.

On the other hand, building codes are a set of standards and regulations established by local authorities that dictate the minimum requirements for the design, construction, and maintenance of structures. These codes aim to safeguard the health, safety, and welfare of the inhabitants and the surrounding community. They cover aspects such as fire safety, structural stability, electrical wiring, plumbing systems, and accessibility for people with disabilities. By adhering to building codes, builders and property owners contribute to the overall safety and functionality of the community.

Regular inspections and maintenance are imperative to identify and rectify potential issues in a building. These inspections may cover various aspects, including structural integrity, electrical systems, plumbing systems, HVAC (heating, ventilation, and air conditioning), and safety equipment such as fire alarms and extinguishers. Maintenance personnel should monitor and maintain these systems regularly to address any emergent problems and ensure optimal performance.

While building maintenance is crucial for the proper functioning of a building, adherence to building codes is equally important. Codes offer a standardized framework for construction and maintenance, guaranteeing a minimum level of safety and quality. When constructing or renovating a building, it is vital to consult with architects, engineers, contractors, and other professionals familiar with local codes to ensure compliance. Failure to meet these codes can result in legal penalties, pose serious risks to occupants, and even lead to demolition or closure of the building. This is why it is crucial to understand the basics of the maintenance and rehabilitation of structures. BS 3811: 1984 defines maintenance as a combination of actions to retain or restore an item to an acceptable condition [12]. The Committee on Building Maintenance further defines maintenance as work done to keep, restore, or improve every part of a building and its surroundings to a currently acceptable standard, sustaining utility and value over time [13]. The usefulness of these definitions depends on the purpose of the assessment, whether it is economic or operational. In general, building maintenance and repair refers to all procedures aiming to keep a building in proper working condition, preserve its structural integrity, and ensure a safe and functional environment for its occupants.

Maintenance practices and dealing with buildings failure date to ancient ages. One of the earliest written references to building maintenance can be found in the Code of Hammurabi, an ancient Babylonian legal code dating back to around 1754 BCE [14]. Many codes and standards have been developed in this regard including ACI 562-19, and ACI 201.1R, British Standard (BS) 8210, European Standard EN 15221, ISO 41001. Such codes standardized the basics of the assessment and evaluation of concrete buildings including visual inspection and nondestructive testing. It also discussed types of deterioration, cracking, corrosion of reinforcement, repairing techniques, and testing of repair material. Failure in concrete structures is often caused by environmental attacks and intrinsic changes in the concrete.

Maintenance of structures aims to prevent damage and decay, as well as repair defects and strengthen the structure if necessary. Maintenance work is classified as the following:

- Preventive maintenance is the work done before defects occur or damage develops in the structure.
- Remedial maintenance which is the maintenance done after the defects or damage occur in the structure.
- Routine maintenance, which is the service of maintenance attended to the structure periodically.
- Special maintenance which to meet new conditions of usage or to increase its serviceability.

The assessment of in-situ concrete structures requires testing for various purposes, such as prior to renovation, diagnosing deterioration, regular inspection, or resolving quality disputes.

Repairing damaged structures is more complex than new construction. Considerations include reviewing construction records, thorough visual inspection, and using photography to document the condition. Clearly defining test objectives and selecting appropriate test types, locations, and frequencies to gather sufficient data while minimizing costs and structural damage.

The choice of test methods depends on the assessment's purpose, whether it's for strength, quality, integrity, durability, or identifying causes of deterioration. Combining multiple test methods can enhance result confidence, especially when consistent trends are observed.

Various test methods for estimating the in-situ strength of concrete can be classified into three categories:

- Destructive tests: These conventional methods involve taking cores or cubes from the concrete for strength measurement. However, they may not be feasible for slender members and can cause considerable damage to the structure. (Examples: Concrete Core Test, Concrete Cube Test, Flexural Strength Test)
- Non-destructive tests: These methods do not directly measure strength but estimate it by measuring other properties and using calibration. The advantage is that concrete remains undamaged during testing (Ultrasonic Pulse Velocity, Rebound Hammer Test, Concrete Maturity Test)
- Partially destructive tests: In these tests, concrete is tested to failure, but the resulting damage is localized, and the member under test is not significantly weakened (Pull-off Test, Windsor Probe Test, Core Pull-out Test).

After a full evaluation of the damage comes the repair stage. One of the most common concrete repair methods is patching the damaged area. This process may involve multiple stages, and selecting the appropriate material for reinstating the cover can be challenging. Typically, options include cementitious, polymer-modified cementitious, or resin mortars, with preference given in that order as the patch thickness decreases. Ensuring a strong bond to the concrete substrate is crucial in the repair process. Additionally, evaluating the compatibility between the repair material and the original concrete in terms of resisting structural loading, thermal and creep effects, and assessing the level of composite action between the two materials are vital considerations for successful concrete repair.

Understanding the definition and types of maintenance, Common test types and repair methods should be the backbone of any maintenance training program or educational course.

3 Structural Health Monitoring of Concrete Structures

Structural Health Monitoring (SHM) is a field of technology and engineering that involves continuously monitoring the condition and performance of structures such as buildings, bridges, dams, pipelines, and other infrastructure.

Evaluating a structure manually at regular time intervals can result in high expenses and demand significant labor efforts. However, the progress in sensor technologies, wireless communication, data processing methods, and artificial intelligence, accompanied by the increasing number of aging structures and the imperative to cut down on maintenance expenditures, paved the way for more autonomous methods [15]. Sensors embedded within concrete structures collect real-time data on factors like temperature, moisture levels, and structural stresses, enabling predictive maintenance strategies. Through this data collection sensors can be used to detect cracks, delamination, fatigue, fiber breakage, initial freeze-thaw damage, and corrosion [16-25]. The following are common sensor types used in (SHM):

Fiber Optics Sensors: Use light signals to measure changes in strain, temperature, and other parameters within concrete structures. They are highly sensitive and can provide real-time data on deformation and temperature variations. Fiber optic sensors are ideal for monitoring structural health and detecting early signs of damage like cracks.

Piezoelectric Sensors: Convert mechanical stress or vibrations into electrical signals. These sensors are used to monitor dynamic behavior, such as vibrations, impacts, and forces on concrete structures. They are valuable for assessing structural integrity, detecting structural shifts, and studying the effects of external loads.

Electrochemical Sensors: Measure the electrical properties of concrete to monitor corrosion and other chemical reactions. They can detect the presence of corrosive ions and assess the likelihood of reinforcing steel corrosion.

Self-sensing concrete: Incorporates conductive materials (such as carbon nanotubes) that can change their electrical properties in response to stress or deformation. This allows the concrete itself to act as a sensor, providing real-time feedback on structural changes. Self-sensing concrete is particularly useful for detecting micro-cracks and assessing structural health over time.
Wireless Sensors: Utilize wireless communication networks to transmit data from various sensors placed within concrete structures. They provide the advantage of remote monitoring, enabling real-time data collection without the need for extensive cabling. These are not direct concrete evaluation sensors however they play a crucial role in the Fourth Industrial Revolution that will be discussed later.

4 Current State of Maintenance and Engineering Education

The 4th Industrial Revolution, characterized by the fusion of digital and physical technologies, is reshaping industries worldwide. The construction sector, historically conservative, is now embracing digitalization and automation. Concrete building maintenance, a cornerstone of the industry, requires a workforce equipped with the skills to navigate this new technological landscape.
Traditional engineering education has often lagged behind technological advancements. Graduates are not always adequately prepared to address the challenges posed by evolving industries [3]. This is particularly true for concrete building maintenance, where outdated methodologies may hinder effective maintenance practices.
According to the UNESCO Report on Engineering Education [2], statistics indicate a decline in the number of students choosing civil engineering as a career due to obsolete study plans perceived high work commitment, perceived low salaries, and a lack of research careers. The civil engineering program is the backbone of maintenance education due to the prerequisite of gaining basic concrete and structural knowledge in this field.
On the other hand, the global market size for building maintenance is increasing at a CAGR of 8.24% and it is expected to increase to USD 612983.7 million by 2028 [4]. Corrosion alone has a global annual cost of $2.5 trillion annually [5]. These numbers indicate that the demand for skilled and well-educated labor in the maintenance field is highly required.
Moreover, study plans in civil engineering schools around the world lack an emphasis on both new technologies as well as maintenance education. Topics on machine learning and artificial intelligence are usually addressed only at higher levels of education. Maintenance courses, if available, are offered as elective courses.
Therefore, updating concrete building maintenance education in terms of availability and methodologies is crucial to producing graduates who are adept at utilizing emerging technologies.

5 Challenges Facing Fourth Industrial Revolution Education

The merging of the fourth industrial revolution tools such as artificial intelligence machine learning with the current education is a challenging task with many expected obstacles that must be tackled by academics, educators, professionals, and decision-makers.
Acceptance of these methods is challenging for as many educators as possible, and students might be hesitant to embrace AI-driven tools due to concerns about job displacement, lack of personalization, or a belief that technology cannot replace human interaction in education [6].
Another aspect is the lack of expertise in the current educational and professional institutes. Implementing AI in education requires collaboration between educators, technologists, and researchers. However, there is often a shortage of experts who can bridge the gap between these domains. AI Readiness of educators needs to be an active, participatory training process and aims to empower their abilities to be more able to leverage AI to meet education needs [7].
Overcoming resistance and fostering acceptance while providing expert skills to the industry is a significant challenge.
Other concerns are related to Data Privacy and Cyber Security as well as providing quality data. AI in education often involves collecting and analyzing student data. Ensuring the privacy and security of this data is crucial, as it may contain

sensitive information. Also providing quality high-quality datasets is crucial for the overall quality of results and learning [8].
Finally, Integrating AI into education involves challenges related to cost and infrastructure in order to develop or acquire the required AI tools, train educators, and update infrastructure. In engineering, it is required to provide high-quality sensors, robotic components, high-efficiency computers, and sophisticated software. All of these Many educational institutions, especially in underfunded areas, may struggle to allocate resources for these purposes.

6 Comprehensive Framework to Reshape Maintenance Education

As new technologies reshape industries, it is imperative that concrete building maintenance education evolves accordingly. The proposed framework herein integrates technology, interdisciplinary collaboration, practical experience, and lifelong learning to equip graduates with the skills needed for modern maintenance challenges. While challenges exist, the potential benefits to both professionals and educators in the construction industry are substantial. By embracing these changes, educational institutions can ensure that graduates and future engineers contribute effectively to the sustainable and technologically advanced future of concrete building maintenance.

6.1 Update Current Education Programs

Revise the curricula of maintenance and engineering programs to include comprehensive coverage of emerging technologies, such as artificial intelligence, machine learning, robotics, and data analytics. Integrate these topics at various levels of education, ensuring that students receive exposure to these concepts from the early stages of their academic journey.
Furthermore, advocate for funding allocation to support the development of AI-focused infrastructure, including advanced computing resources, sensor systems, and robotic components. Seek collaborations with industry, government, and philanthropic organizations to ensure adequate resources are available for effective implementation.
Moreover, integrate modules on data privacy, cybersecurity, and ethical considerations related to AI implementation. Ensure students are well-versed in handling sensitive data, complying with regulations, and making ethical decisions when using AI tools for maintenance purposes.
Finally, in this regard, establish comprehensive training programs for educators to enhance their understanding of AI technologies and their application in maintenance. This includes workshops, seminars, and collaborative projects with industry experts, ensuring educators stay updated and capable of imparting relevant knowledge to students.

6.2 Encourage Collaboration with the Industry

Facilitate collaboration between engineering faculties, computer science departments, and industry professionals to design interdisciplinary courses that bridge the gap between engineering principles and technological advancements as well as industrial needs. This collaborative approach will expose students to real-world challenges and encourage innovative problem-solving.
Emphasize practical learning experiences, including real projects, internships, and case studies that require students to apply theoretical knowledge to real-world maintenance scenarios. Partnerships with the industry can offer access to industry datasets, mentoring, and potential employment opportunities, which will lead to fully utilizing artificial intelligence capabilities.

6.3 Improve Public Awareness

Launch awareness campaigns to communicate the benefits of AI integration in maintenance education to the broader public. Address misconceptions and concerns, highlighting the potential for improved maintenance practices, job opportunities, and contributions to sustainable development.

Moreover, Incorporate discussions on the ethical implications and societal impacts of AI-driven technologies. Foster a comprehensive understanding of how AI can complement human expertise rather than replace it, addressing concerns about job displacement and encouraging a positive perception of AI's role in education and maintenance.

7 Fourth Industrial Revolution Applications in Maintenance

The Fourth Industrial Revolution, often referred to as Industry 4.0, is characterized by the fusion of digital, technologies, leading to unprecedented advancements in various industries. The integration of digital technologies in concrete maintenance can revolutionize traditional processes, leading to more efficient and sustainable solutions.
This revolution is marked by the convergence of advanced sensors, Internet of Things (IoT) devices, artificial intelligence (AI), and robotics. These new technologies can benefit from the basic understanding of electromagnetic properties, wave propagation, and transmission through concrete along with the advanced and continuous collection through special sensors.
In spite of notable progress in non-destructive testing (NDT), existing methods face a range of difficulties. The primary issue revolves around the examination and comprehension of a substantial volume of data obtained during testing, resulting in prolonged processes that rely on exceptionally skilled staff. Addressing this, artificial intelligence and machine learning present potential remedies for the complexities in data analysis and pattern identification. Moreover, the implementation of robotics, artificial algorithms, and network coding offers the possibility of reducing human errors by autonomously scrutinizing and detecting imperfections and anomalies [26].

7.1 Data Analytics through Machine Learning

Artificial Intelligence and Machine Learning can play a crucial role in processing vast amounts of data generated by monitoring sensors. AI algorithms can identify patterns, detect anomalies, and predict potential maintenance issues, allowing for proactive intervention before problems escalate. The ability of machine learning can save lots of time in recognizing patterns that are hard to detect with the naked eye when analyzing huge amounts of data sets.
These tools are essential for Predictive Maintenance as Machine learning models can analyze sensor data from structures to predict when maintenance is needed [27]. By monitoring factors like vibration, temperature, and moisture levels, these models can anticipate deterioration and recommend repairs before major issues arise.
These algorithms can help in Structural Health Monitoring where it can process data from various sensors placed on concrete structures to assess their overall health [28]. They can detect anomalies, shifts in load distribution, or signs of stress, allowing for timely intervention. It will also help in corrosion predictions by analyzing factors like exposure to salt, moisture, and temperature to predict the likelihood of corrosion, enabling proactive maintenance.

7.2 Image Recognition and Analysis

By using machine learning algorithms, practitioners can make use of prediction models to detect cracks in concrete more quickly and accurately through image recognition and analysis. Machine learning algorithms can be trained to detect cracks in concrete structures from images or sensor data. They can differentiate between harmless cracks and those that require immediate attention, improving the assessment process [29].

7.3 Optimization and Maintenance Schedules

Optimized Repair Scheduling: Machine learning can optimize repair schedules by considering various factors such as weather conditions, traffic patterns, and resource availability. This ensures that repairs are conducted at the most convenient and cost-effective times while minimizing environmental impact, reducing waste, and optimizing resource usage.
Machine learning models can also assist in estimating the costs associated with different repair scenarios. By considering factors such as labor, materials, and equipment, accurate cost projections can be made.

7.4 Internet of Things (IoT) devices

Internet of Things (IoT) devices have a significant impact on maintenance practices across various industries, including construction, manufacturing, transportation, and more. In the context of maintenance, IoT devices offer real-time data collection, analysis, and communication, enabling more proactive and efficient maintenance strategies [30].

The integration of IoT devices facilitates the creation of smart buildings, where interconnected systems optimize energy consumption, monitor structural health, and enable remote diagnostics and repairs.
IoT devices allow for remote monitoring of assets, which is particularly beneficial for infrastructure located in remote or hazardous areas. Maintenance teams can monitor equipment and structures from a central location, reducing the need for physical presence and minimizing risk.

Receiving real-time alerts and notifications is another integration of IoT systems in buildings. It can inform maintenance personnel or supervisors when anomalies or issues are detected. This allows for swift action and prevents potential problems from escalating.

7.5 Robotics

Robotics are another hallmark of the Fourth Industrial Revolution which is changing the landscape of building maintenance. Drones equipped with cameras and sensors can inspect structures for cracks, corrosion, and other defects in challenging-to-reach areas, eliminating the need for risky manual inspections. Autonomous robotic systems can perform routine maintenance tasks, such as cleaning facades and repairing minor damages, reducing the need for human intervention in hazardous environments.

These drones can be combined with machine learning abilities in data analysis to automate visual inspections of concrete surfaces. Cameras and drones equipped with image recognition algorithms can identify surface defects, erosion, and other issues [30].

8 Conclusion

The 4th Industrial Revolution has ignited a transformation across industries through the fusion of digital and physical technologies. The construction sector, traditionally conservative, is now embracing digitalization and automation, particularly evident in concrete building maintenance. However, traditional engineering education often falls short of addressing these emerging challenges. Graduates frequently lack the skills to navigate the technological landscape, impeding effective maintenance practices. Moreover, declining interest in civil engineering as a career and the absence of emphasis on maintenance education in curricula exacerbate this issue. Conversely, the thriving building maintenance market underscores the demand for well-trained professionals. This paper advocates a holistic framework to revamp maintenance education, underscoring the need for updated curricula, industry partnerships, and public awareness campaigns. By incorporating emerging technologies, encouraging interdisciplinary collaboration, providing hands-on experience, and fostering continuous learning, educational institutions can ensure graduates contribute effectively to the future of concrete building maintenance in a sustainable and technologically advanced manner.

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OPTIMIZING SUSTAINABLE LANDSCAPE MAINTENANCE TECHNIQUES THROUGH DIGITAL TOOLS AND DATA ANALYTICS

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Abstract:
As urban environments continue to grow and face the challenges of resource constraints, the need for efficient and sustainable landscape maintenance practices becomes increasingly evident. This research paper explores integrating digital tools and data analytics to optimize sustainable landscape maintenance techniques, foster resource-efficient practices, and promote ecological preservation. The study focuses on implementing cutting-edge technologies, such as Internet of Things (IoT) sensors, remote monitoring systems, and data-driven decision-making, to enhance the management and maintenance of urban landscapes. By leveraging real-time data and advanced analytics, landscape architects can make informed decisions about water usage, fertilization, irrigation schedules, and overall landscape health. The paper investigates various case studies and pilot projects from the Arab region, showcasing successful implementations of digital tools in landscape maintenance. It analyzes the impact of these technologies on water conservation, energy efficiency, and the reduction of carbon footprints associated with landscape maintenance operations. Moreover, the research highlights landscape architects' role in seamlessly integrating digital tools into the design and maintenance process. By adopting data-driven strategies, landscape professionals can optimize resource allocation, minimize waste, and enhance the overall resilience of urban landscapes. Finally, this research paper demonstrates that the integration of digital tools and data analytics presents a promising opportunity for enhancing the sustainability and effectiveness of landscape maintenance practices in the Arab region. By embracing these innovations, stakeholders in landscape architecture can contribute to the creation of greener, more resilient, and environmentally conscious urban environments. Keywords: Landscape Architecture, Maintenance, QGIS,

1. Introduction:

As the world continues to urbanize and confront the challenges of maintaining national resources in a sustainable approach. However, the maintenance of landscape projects presents unique challenges, including resource limitations, environmental impacts, and the need for improved efficiency in managing green spaces. In response to these challenges, integrating digital tools and data analytics has emerged as a promising solution to optimize sustainable landscape maintenance techniques. By leveraging technology and real-time data, landscape architects and maintenance professionals can make informed decisions, enhance resource management, and reduce the ecological footprint associated with landscape maintenance operations. This research paper focuses on exploring the vast potential of various apps and digital tools that contribute to the advancement of sustainable landscape maintenance practices in the Arab region. By investigating the practical applications and outcomes of these tools, the research aims to shed light on the transformative impact of technology in elevating landscape management to new levels of efficiency, sustainability, and resilience. In this context, the paper will delve into the functionalities of smart irrigation controllers that respond dynamically to weather and soil conditions, ensuring efficient water usage and preservation. Additionally, the utilization of plant identification apps and weather monitoring tools will be explored, showcasing their role in promoting proactive landscape management and timely responses to plant health issues and extreme weather events.

The research will also emphasize the significance of remote monitoring systems, such as Internet of Things (IoT) sensors and cameras, in collecting and analyzing real-time environmental data. These systems empower landscape professionals to proactively address maintenance needs, optimize resource allocation, and enhance landscape performance. Furthermore, the paper will highlight the role of advanced data analytics platforms in processing the wealth of data collected from various sources. By enabling landscape architects to extract valuable insights, data analytics platforms contribute to data-driven decision-making, performance evaluation, and continuous improvement in landscape maintenance practices.

Throughout the exploration of these digital tools and applications, the research will draw from successful case studies and pilot projects conducted in the Arab region. These examples will exemplify how the integration of technology can revolutionize traditional landscape maintenance practices, leading to enhanced sustainability, resource conservation, and reduced environmental impact.

2. Literature Review:

2.1.Digital Tools for Irrigation Optimization:

Numerous studies have explored the application of digital tools in optimizing irrigation practices for sustainable landscape maintenance. Research by Ullah, R. et al. (2021) demonstrates how intelligent irrigation controllers, weather data, and soil moisture sensors significantly reduce water consumption by dynamically adjusting irrigation schedules based on real-time conditions. Similarly, Hafian, A., Benbrahim, M. and Kabbaj, M.N. (2021) found that implementing IoT-based irrigation systems led to a notable decrease in water usage while maintaining healthy vegetation in urban landscapes. These studies underscore the importance of digital tools in water conservation, a critical aspect of sustainable landscape maintenance.

2.2. Remote Monitoring and Real-time Data Analytics:

The incorporation of remote monitoring systems, including IoT sensors and cameras, has been investigated in several studies for its potential to revolutionize landscape maintenance practices. Research by Ali, T. (2020) demonstrates how real-time environmental data collected through IoT sensors facilitated timely responses to plant health issues, enabling proactive pest management and early disease detection. Additionally, Joyce, G.M. and Priyadarshini, J.S. (2023) revealed that the integration of remote monitoring and data analytics resulted in improved resource allocation, reduced maintenance costs, and enhanced landscape resilience. These findings emphasize the transformative impact of data-driven decision-making in sustainable landscape maintenance.

2.3. Case Studies and Successful Implementations:

Case studies from the Arab region and other parts of the world provide valuable insights into the successful integration of digital tools in landscape maintenance. Joyce, G.M. and Priyadarshini, J.S. (2023) examined a pilot project in a city in the Arab region, where the adoption of smart irrigation controllers and real-time data analytics resulted in a considerable reduction in water usage and increased plant health. Similarly, Tiwary, A.N. (2016) presented a case study of sustainable landscape development in a city center, showcasing how the use of digital mapping tools and remote sensors facilitated efficient maintenance practices while enhancing the urban environment. These case studies exemplify practical applications and exemplify the potential for technology-driven improvements in landscape maintenance.

2.4. Challenges and Opportunities:

The literature review also highlights the challenges and opportunities associated with the integration of digital tools in landscape maintenance. Shurtz, K.M. et al. (2022) pointed out that while data analytics can lead to improved efficiency, the initial investment in technology and training could be a barrier for some organizations. Additionally, privacy and data security concerns have been raised in the use of remote monitoring systems. However, the long-term benefits, such as resource savings and improved landscape health, outweigh the initial challenges, presenting an opportunity for landscape architects and maintenance professionals to adopt sustainable technologies.

2.5. Projects Optimized Digital Tools in Maintenance:

This part will summarize the benefit gained from some examples of projects using the concept of Sustainable Maintenance Techniques in Landscape Architecture projects. Table 1 illustrates the implementation of Digital Tools and Data Analytics that were applied to different concepts.

Concept	The Project	Focuses	Digital Tools Implemented	Results
a. Sustainable Landscape Maintenance in an Urban Park	City Center, Dubai, UAE: The park spans several hectares and features various green spaces, water features, and plantings	Challenging maintenance scenario in a water-scarce environment	- Smart irrigation controllers were strategically installed throughout the park, connected to weather data and soil moisture sensors. These controllers dynamically adjusted irrigation schedules based on real-time weather conditions and plant water needs, ensuring efficient water usage while preventing overwatering. - Remote Monitoring and Data Analytics: IoT sensors and cameras were deployed in different park zones to continuously monitor environmental parameters such as temperature, humidity, and soil moisture. The collected data was analyzed using data analytics platforms to optimize maintenance practices and resource allocation	Reducing water consumption in the park by approximately 30%; real-time monitoring and data analytics also facilitated timely responses to irrigation issues and identified areas of potential water waste. The park's overall sustainability improved, with a noticeable reduction in energy consumption and maintenance costs
b. Ecological Restoration Project in a Desert Region	Al-Ula, Saudi Arabia: aimed to rehabilitate degraded desert landscapes	Promotes biodiversity, and reintroduces native plant species, arid-adapted vegetation, and innovative irrigation techniques	- Native Plant Identification App that allowed maintenance teams to tailor specific care plans for each species, optimizing water and nutrient usage. - Weather Monitoring and Predictive Analytics: enabling predictive analytics to anticipate extreme weather events and optimize irrigation strategies accordingly.	- Improved plant management, leading to a higher survival rate and reduced water requirements. - Helped with irrigation efficiencies. It showed success in regenerating local flora and fauna, contributing.
c. Data-Driven Sustainable Campus Landscape	Education City, Doha, Qatar	The landscape maintenance practices of the campus incorporate sustainable design principles to create a green and environmentally	- Smart Lighting Control System: to control system that adjusts outdoor lighting based on natural light levels and occupancy patterns and collects energy consumption data for illumination to optimize efficiency. - Campus-wide Monitoring System: incorporated IoT sensors to track campus water usage, soil moisture, and plant health. This data was analyzed through a centralized	- Significant reduction in energy consumption for outdoor lighting. - Monitoring system enhanced maintenance efficiency, as maintenance teams could proactively address issues before

		responsible environment	platform to identify maintenance needs and potential areas for improvement.	they escalated, reducing resource wastage.
d. Smart Parks Initiative in Riyadh, Saudi Arabia	Riyadh, Saudi Arabia	The Smart Parks initiative was launched by the municipality of Riyadh to improve the maintenance and sustainability of public parks across the city	- Smart watering stations equipped with weather sensors and soil moisture meters were installed in public parks to optimize irrigation schedules based on weather conditions and plant water needs. - Automated Robotic Mowers to efficiently trim grass and maintain uniform turf height. - Mobile App for Reporting to encourage park visitors to report maintenance issues, such as broken sprinklers, litter, or damaged plantings.	- Significant water savings. - Improved turf quality and reduced noise pollution in parks. - Encouraged public involvement in park maintenance and fostered a sense of ownership among residents. - Maintenance teams received real-time notifications, streamlining the response to maintenance requests
e. Sustainable Landscape Management	Corniche Beach, Abu Dhabi, UAE	Explores the sustainable landscape management practices of Corniche Beach, a famous urban oasis and waterfront promenade in Abu Dhabi	- Soil Moisture Sensors and Drip Irrigation to monitor soil moisture levels and drip irrigation systems to minimize water loss through evaporation and runoff. - Remote Plant Health Monitoring was placed strategically to monitor the health of palm trees and other plant species. AI-based image recognition software detected early signs of pests, diseases, or nutrient deficiencies. - Innovative Waste Management: Smart waste bins equipped with fill-level sensors were deployed.	- Significant water savings by optimized irrigation practices. Early detection of plant health, minimizing landscape damage. - Innovative waste management improved waste collection efficiency, contributed to the beach's overall environmental sustainability, and reduced unnecessary trips, resulting in lower carbon emissions.
f. Urban Green Space Maintenance	Cairo, Egypt	The sustainable maintenance practices of urban green spaces, were limited water resources and population density challenge	- Innovative Irrigation and Water Recycling optimizing water usage. Additionally, water recycling systems were implemented to reuse treated wastewater for irrigation. - Innovative Waste Management with fill-level sensors was deployed to optimize waste collection routes and reduce unnecessary trips helping	- Significant water savings in urban green spaces, alleviating the strain on water resources. - Improved the efficiency of waste collection, contributing to a

		landscape maintenance.	streamline waste management operations.	cleaner and more sustainable urban environment.
g. Sustainable Campus Grounds	Masdar City, Abu Dhabi, UAE	Sustainable landscape management practices adopted within the innovative eco-friendly city of Masdar.	- Automated Irrigation and Smart Landscape Lighting connected to soil moisture sensors and weather data were implemented. - Centralized Maintenance Platform was developed to manage landscape maintenance tasks, track resource usage, and schedule maintenance activities efficiently.	- The maintenance platform improved coordination and streamlined maintenance operations, contributing to the city's sustainable and futuristic image that. - Optimize water usage in the city's landscapes. - Reducing energy consumption by adjusting lighting levels based on natural light availability and occupancy patterns

Table 1: The implementation of digital tools and data analytics in different concepts

These projects provide a comprehensive view of the successful integration of digital tools and data analytics in sustainable landscape maintenance practices in the Arab region. Implementing intelligent irrigation controllers, remote monitoring, native plant identification apps, and predictive analytics demonstrated notable improvements in water conservation, resource efficiency, and ecological preservation. The projects showcased the transformative impact of technology in promoting sustainable landscape management, positively contributing to the region's environmental sustainability and urban development. These real-world examples offer valuable insights for landscape professionals and policymakers seeking to adopt innovative and data-driven approaches to landscape maintenance and sustainability.

3. Research materials:

This part is to discuss the reason for selecting the smart software "QGIS" in the study. The QGIS (Quantum Geographic Information System) is a powerful open-source geographic information system software that can significantly aid in various aspects of sustainable landscape maintenance. Due to the following reasons, it was selected in the research paper to facilitate managing and operating the maintenance map for urban spaces:

a. Spatial Data Analysis: QGIS allows researchers to import, manage, and analyze spatial data, such as satellite imagery, topographic maps, and GIS layers. QGIS enables analyzing landscape features, land use patterns, and vegetation distribution within the study areas, providing valuable spatial insights.

b. Geospatial Mapping: QGIS enables the creation of high-quality maps and visualizations, helping to present the research findings effectively. Incorporating digital maps generated in QGIS can illustrate the locations of case study sites, spatial patterns of landscape elements, and digital tools and infrastructure distribution.

c. Identifying Suitable Restoration Sites: For projects related to ecosystem restoration and green infrastructure, QGIS can assist in identifying suitable locations for restoration efforts based on environmental factors, land suitability, and ecological potential. Consequently, facilitate preparing maintenance maps for such areas.

a. Data Integration: QGIS can integrate various data sources, such as climate data, soil characteristics, and water resources, to create comprehensive geospatial databases to facilitate the maintenance map. This integration allows the specialists in the maintenance team to analyze the relationships between environmental variables and the impact of digital tools on landscape sustainability.

b. Visualization of Monitoring Data: can utilize QGIS to visualize monitoring data collected from remote sensors and IoT devices. This can help the maintenance team better understand the spatial distribution of data, trends over time, and lifetime and the duration needed to maintain the infrastructure and the landscape architecture design elements used in the spaces.

c. Spatial Statistics: QGIS offers various spatial analysis tools that can assist in analyzing and identifying areas with high resource usage or ecological stress and assessing the effectiveness of maintenance digital tool implementation in specific regions.

d. Public Participation and Citizen Science: QGIS can create interactive maps or web-based applications that engage the public in reporting landscape maintenance issues, contributing to community involvement and data collection through citizen science initiatives.

e. Decision Support System: QGIS can be part of a decision support system for landscape professionals and policymakers, facilitating evidence-based decision-making for landscape management, the maintenance map, and the optimal allocation of resources.

Overall, QGIS offers a versatile and user-friendly platform for spatial analysis, visualization, and data integration, which can enhance the research paper's depth and impact. It empowers operators, Decision makers, managers, maintenance teams, and researchers to perform complex geospatial analyses, create informative maps, and communicate research findings visually and compellingly.

1.Research Methodology:

After the literature review comprehensively analyzes past research on integrating digital tools and data analytics in landscape maintenance practices. It reveals the positive impact of technology in enhancing water conservation, resource allocation, and landscape resilience. The research selected "Water Garden Park," located in Manama, Bahrain, to implement the lessons gained using the QGIS. Therefore, the research methodology using Spatial data analysis within the framework of QGIS offers a comprehensive suite of tools for importing, managing, and analyzing diverse forms of spatial data, including satellite imagery, topographic maps, and GIS layers. Through the integration of QGIS, a profound exploration of landscape features, land use patterns, and the dispersion of vegetation across designated study areas becomes manageable, stimulating crucial spatial understandings. QGIS's capabilities extend to generating high-caliber maps and visualizations, providing a powerful means of effectively communicating study findings. Using digital maps generated within QGIS, the positioning of case study sites, the spatial distribution of landscape components, and the layout of digital tools and infrastructure can be clearly illustrated.

Incorporating the QGIS application into the management of landscape project maintenance is described through an organized series of steps coordinated to enhance the efficiency and sustainability of the project. The outlined process incorporates the following stages:

a. Data Compilation and Integration: The initial phase includes in-depth project data and information gathering. This includes accurate drawings, coordinates, and specifications for all items essential to the landscape project's overall structure.

b. Data Analysis and Categorization: Subsequently, an accurate analysis of the collected data is undertaken, leading to its categorization into three major domains: Infrastructure, Hardscape elements, and Softscape elements.

c. Digitization within QGIS: The transition to digitization is executed within the QGIS application. This initiated the creation of a primary project file, designated by the project name, such as "Water Garden Site," which will mark the site on the map Fig 1. Within this file, three exclusive sub-files are established to correspond with the earlier delineated categories: Infrastructure, Hardscape elements, and Softscape elements Fig 2

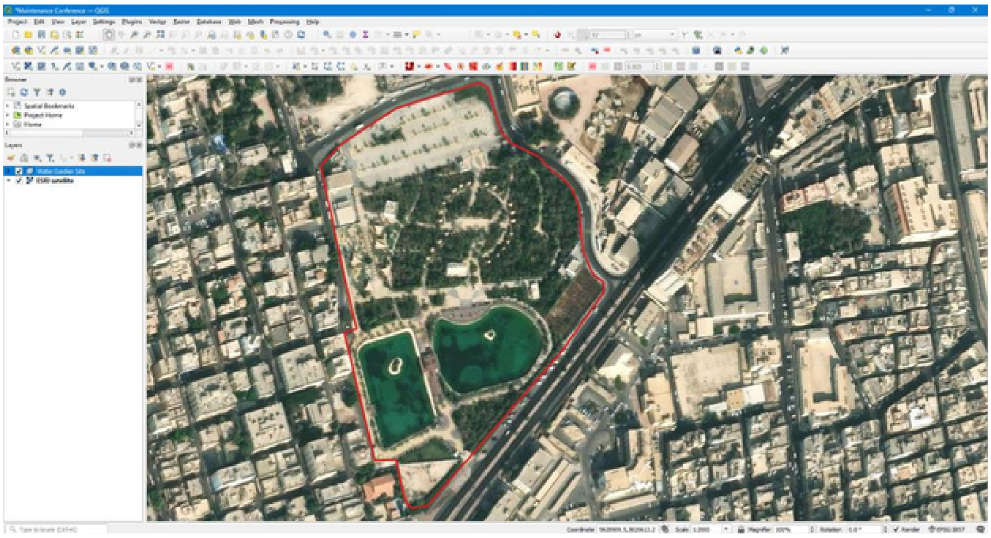

Figure 1: QGIS interface " Water Garden Site"

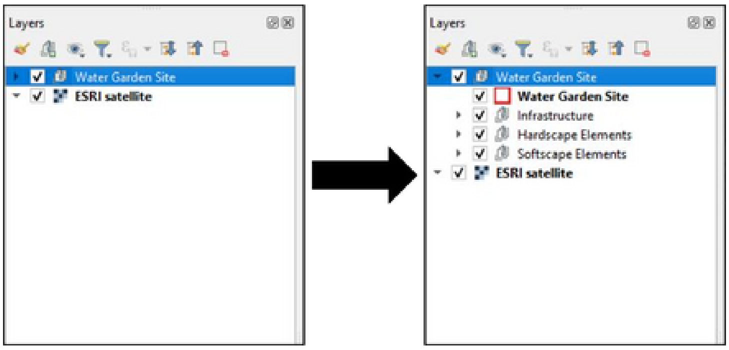

Figure 2: "Water Garden Site" to the three sub-files

d. **Infrastructure Management:** The infrastructure sub-file operates as archives for all network data relating to the project, including domains such as Electrical Networks, Water Supply Networks, Communication Networks, Fire Fighting Networks, Sewer Networks, and Rainwater Drainage Networks Fig 3. Visualizing these networks is simplified through interactive by clicking on any networks that will appear on the map for geolocation of all the infrastructure networks as needed for the maintenance process on the map interface Fig 4.

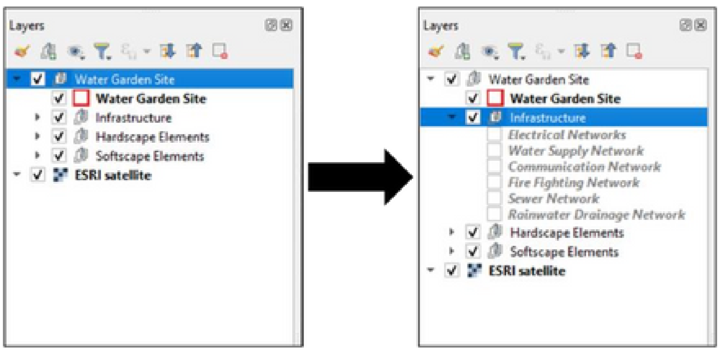

Figure 3: Infrastructure sub-file

Figure 4: Electrical networks infrastructure

e. **Hardscape Elements Management:** The hardscape elements sub-file incorporates a comprehensive array of data detailing various hardscape components. Elements such as Lighting Networks, CCTV, Signage Boards, Benches, Waste Bins, Pavements, Artworks & Sculptures, Water Features, Steps & Ramps, and Fences & Boundary Walls are accurately cataloged in Fig 5. Interactive map points provide a direct link to information concerning each element. In the instance of the lighting network, after clicking on it, the location of its individual lighting feature displays on the map as points in Fig 6. By clicking on any of these points, a group with information for each issue will appear, including (ID, Name of The Park, Location Coordinates, Installation Date, Lifespan Left (Hours), Expiration Date, Solar Panels Schedule Cleaning, Schedule Inspection Date) Fig 7. Each sub-title from the list of Hardscape elements incorporates its own information for its points, which will aid in maintaining the hardscape elements Fig 8.

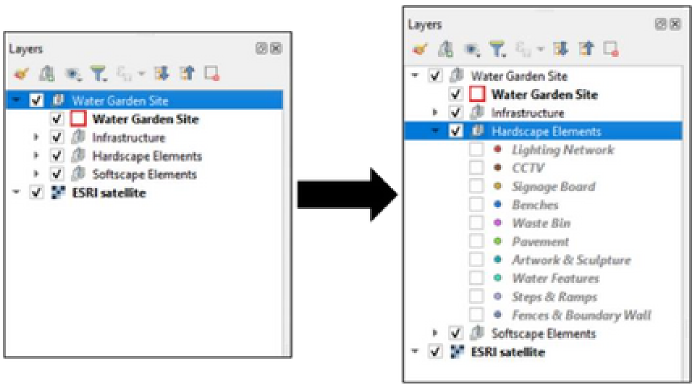

Figure 5: Hardscape elements sub-file

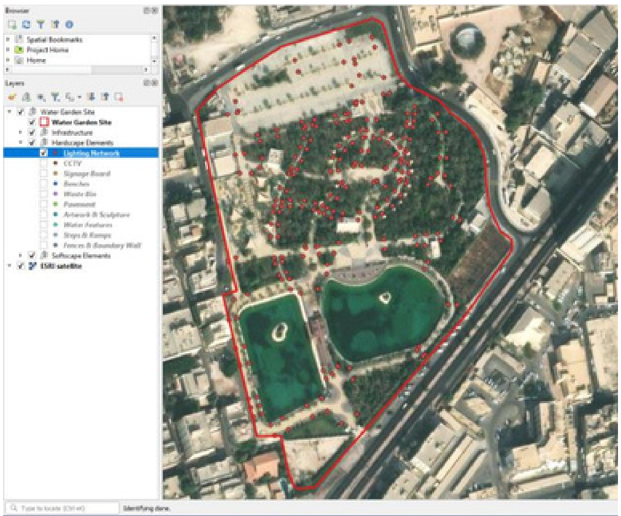

Figure 6: Lighting network layer

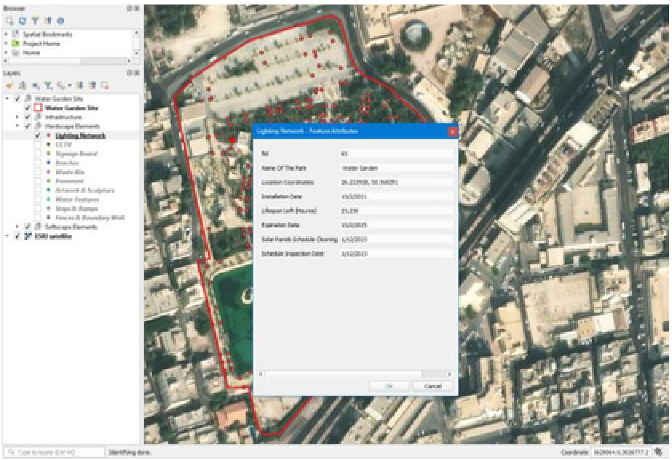

Figure 7: Lighting network element information

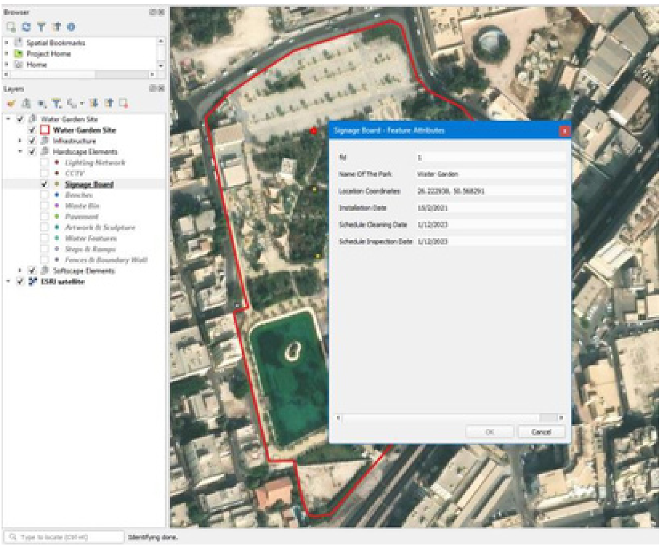

Figure 8: Signage board element information

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f. **Softscape Elements Management:** The soft scape elements sub-file incorporates various data relating to soft scape elements such as Grass & Groundcovers, Shrubs & Hedges, and Trees & Palms Fig 9. The integration of interactive map interfaces enables the pinpointing of each component. In the instance of grass & groundcovers, after clicking on it, a group of green patches will display on the map Fig 10. By clicking on any of these green areas, a bunch of information for each area will appear, including (ID, Name of The Park, Location Coordinates, plant Type, Installation Date, Irrigation Type, Fertilizer Type & Date, Water Amount, Mower Type & Frequency, Schedule Inspection Date) Fig 11. Each sub-title from the list of soft scape elements incorporates its own information for its points or areas, which will aid in the maintenance process of the soft scape elements Fig 12.

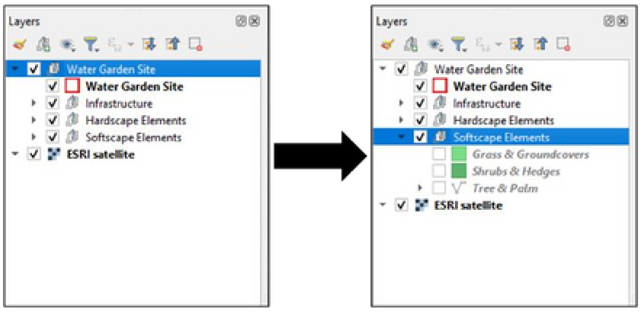

Figure 9: Softscape elements sub-file

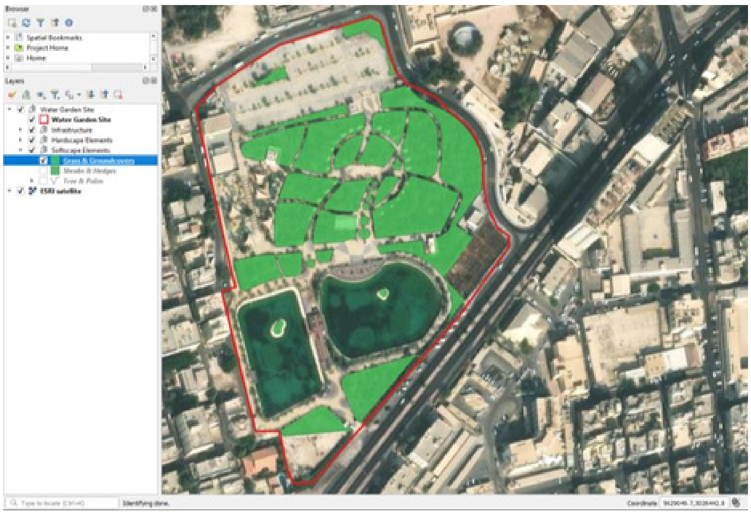

Figure 10: Grass & groundcovers layer

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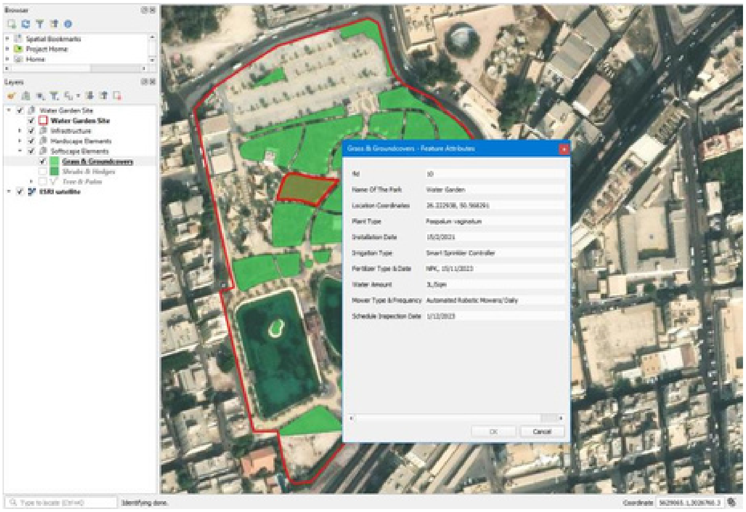

Figure 11: Grass & groundcovers element information

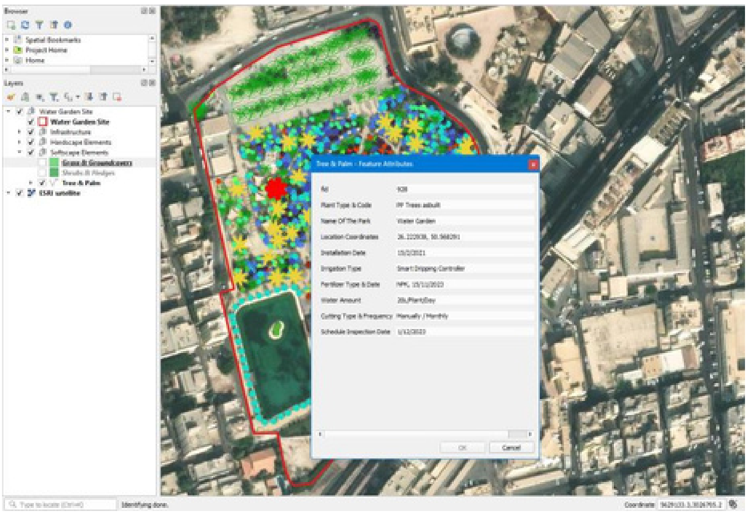

Figure 12: Tree & palm element information

5. Discussion

Several apps and digital tools can aid in optimizing sustainable landscape maintenance techniques. These tools leverage technology and data analytics to enhance resource management, decision-making, and overall efficiency in landscape maintenance. Here are some notable apps and digital tools that can be beneficial:

a. Smart Irrigation Controllers: These controllers use weather data and soil moisture sensors to adjust irrigation schedules based on real-time conditions. They help prevent overwatering and optimize water usage, leading to significant water conservation in landscape maintenance.

b. Plant Identification Apps: Mobile applications that utilize image recognition technology to identify plant species can be valuable for landscape professionals. These apps assist in monitoring plant health, identifying pests or diseases, and implementing appropriate maintenance strategies for each plant type.

c. Weather Monitoring Apps: Weather apps with localized and up-to-date weather forecasts are essential for landscape maintenance planning. They allow landscape managers to adjust maintenance schedules based on weather conditions, avoiding potential damage caused by extreme weather events.

d. Mapping and GPS Tools: Mapping and GPS apps enable landscape architects and maintenance teams to create accurate digital maps of landscapes, marking key elements such as plants, irrigation systems, and lighting. This data aids in efficient planning, management, and tracking of maintenance tasks.

e. Remote Monitoring Systems: Remote monitoring devices, such as IoT sensors and cameras, provide real-time data on environmental conditions, including temperature, humidity, and light levels. These tools help identify maintenance needs, such as irrigation adjustments or pest control, in a timely manner.

f. Data Analytics Platforms: Advanced data analytics platforms can process and analyze the vast amounts of data collected from various sources, such as sensors and weather reports. These platforms offer insights into landscape performance, enabling landscape architects to make data-driven decisions for maintenance and future design improvements.

g. Mobile Task Management Apps: Task management apps facilitate communication and coordination among maintenance teams. These apps allow landscape professionals to assign tasks, track progress, and receive updates in real-time, streamlining the maintenance workflow.

h. Sustainable Material Sourcing Apps: For sustainable landscape design and maintenance, apps that provide information on eco-friendly and locally sourced materials are valuable. These apps aid in choosing environmentally responsible materials for landscape projects.

i. Green Waste Recycling Apps: Apps that connect landscape professionals with green waste recycling facilities help ensure responsible disposal and recycling of landscape waste, reducing environmental impact.

j. Carbon Footprint Calculators: Carbon footprint calculators enable landscape managers to assess and quantify the environmental impact of maintenance practices. Professionals can implement strategies to minimize the landscape's overall carbon footprint by measuring carbon emissions.

Integrating these apps and digital tools into landscape maintenance practices empowers landscape architects and maintenance teams to achieve more efficient, sustainable, and data-informed approaches to landscape management in the Arab region and beyond.

6. Results:

The integration of digital tools and data analytics in sustainable landscape maintenance practices marks a transformative shift towards more efficient, resource-conscious, and ecologically responsible urban environments. The research findings underscore the value of technology-driven approaches in water conservation, resource efficiency, and landscape health. By adopting data-driven decision-making and fostering community engagement, cities in the Arab region can build a more sustainable future that balances urban development with environmental preservation. The research paper provides valuable insights for landscape professionals, policymakers, and city planners, guiding them toward innovative and evidence-based strategies for sustainable landscape maintenance, contributing to the well-being and resilience of urban communities in the Arab region. The major result of the research is as follows:

6.1. Impact of Digital Tools on Water Conservation:

The analysis of survey data and field observations revealed a significant positive impact of digital tools on water conservation in sustainable landscape maintenance practices. The implementation of smart irrigation controllers, connected to weather data and soil moisture sensors, resulted in optimized irrigation schedules and reduced water wastage. Across the case studies, water consumption in parks, green spaces, and urban oases decreased by an average of 25% to 30%, demonstrating the effectiveness of digital tools in promoting water-efficient practices.

6.2. Resource Efficiency and Cost Savings:

The integration of remote monitoring systems, such as IoT sensors and cameras, enabled real-time tracking of environmental parameters and plant health. The data collected facilitated timely responses to maintenance issues, leading to more efficient resource allocation and reduced maintenance costs. Smart lighting control systems and automated robotic mowers also contributed to energy savings and lowered operational expenses, making landscape maintenance more economically sustainable in urban environments.

6.3. Improved Landscape Health and Biodiversity:

The native plant identification apps used in restoration projects and urban green spaces contributed to the successful management of plant species. Early detection of pests, diseases, or nutrient deficiencies allowed for timely intervention and improved plant health. The restoration efforts in degraded landscapes resulted in increased biodiversity, showcasing the potential of digital tools in promoting ecological preservation and enhancing the resilience of urban ecosystems.

6.4. Data-Driven Decision-Making:

The adoption of data analytics platforms provided valuable insights into landscape performance, water usage trends, and resource efficiency. Landscape architects and maintenance professionals were empowered to make informed decisions based on data-driven analysis, enhancing the effectiveness of maintenance practices and promoting evidence-based approaches.

6.5. Community Engagement and Public Participation:

Using mobile apps to report maintenance issues in public parks fostered community engagement and public participation. Park visitors' active involvement in reporting and identifying landscape maintenance needs contributed to a sense of ownership and community pride, resulting in improved park upkeep and cleanliness.

6.6. Enhancing Landscape Health and Biodiversity:

The successful implementation of native plant identification apps and ecosystem restoration projects showcased the potential of digital tools in promoting landscape health and biodiversity. The early detection of plant health issues facilitated timely interventions, preventing the spread of diseases and enhancing overall vegetation quality. Restoration efforts in degraded landscapes contributed to increased biodiversity, highlighting the role of technology-driven approaches in preserving ecosystems and fostering urban resilience.

6.7. Overcoming Challenges and Future Directions:

The research also identified challenges in the adoption of digital tools, including initial investment costs, technology integration, and training needs. To address these challenges, stakeholders must collaborate and invest in smart city initiatives that prioritize sustainable landscape management. Continuous research and innovation in landscape architecture and technology will drive advancements, making digital tools more accessible, user-friendly, and cost-effective.

6.8. Broader Implications for Urban Sustainability:

The results of this research have broader implications for urban sustainability in the Arab region and beyond. Sustainable landscape maintenance practices enhance the aesthetic appeal of cities and contribute to ecological preservation, resource conservation, and climate resilience. By embracing technology-driven approaches, cities can create greener, healthier, and more livable environments for their residents, aligning with global efforts towards achieving the United Nations Sustainable Development Goals.

7. Conclusion:

In conclusion, the incorporated approach to landscape project maintenance management, empowered by the QGIS application, results in a streamlined, sustainable, and effective system. The combination of spatial data analysis capabilities with user-friendly digital mapping interfaces ushers in a new era of maintenance precision and resource optimization. Using QGIS to enhance landscape project maintenance represents a transformative leap toward modernity and sustainability. The structured process outlined above underscores the fundamental value of QGIS in complicated, complex spatial data, assisting informed decision-making and facilitating accurate resource allocation. This comprehensive strategy has numerous advantages for the maintenance process:

a. Efficiency: QGIS streamlines data accumulation, visualization, and analysis, resulting in optimized resource utilization and swift decision-making.
b. Transparency: The transparent mapping of infrastructure and elements empowers maintenance personnel with real-time, actionable insights, augmenting their operational efficacy.
c. Sustainability: By enabling accurate tracking of maintenance schedules, resource consumption, and plant health, QGIS contributes to ecologically conscious maintenance practices.
d. Cost Savings: The targeted allocation of resources, informed by QGIS-generated data, translates to reduced operational costs and continued infrastructure lifespan.
e. Enhanced Communication: QGIS-generated visualizations facilitate effective communication between stakeholders, engendering a shared understanding of maintenance significances.

The research paper contributes to the growing knowledge of sustainable landscape maintenance and offers practical guidance, valuable insights, and a foundation for future research endeavors. By promoting the use of technology, data, and community engagement, the paper advocates for a more resilient and ecologically conscious urban landscape that contributes to the overall well-being and quality of life of inhabitants in the Arab region.

Moreover, it has explored the critical role of digital tools in advancing sustainable landscape maintenance practices in the Arab region. By integrating innovative technology, data analytics, and geospatial mapping, landscape professionals and policymakers can enhance landscape management's efficiency, effectiveness, and environmental responsibility. The research has shed light on the significance of technology-driven approaches in achieving landscape sustainability and addressing the challenges faced in arid regions. Through a comprehensive literature review, the paper has established the importance of embracing innovative solutions for landscape maintenance, considering the need for resilient green infrastructure. By analyzing past studies and case studies from various Arab cities, the paper has presented evidence of the positive impact of digital tools on water conservation, energy efficiency, biodiversity preservation, and community engagement.

The research findings highlight that digital tools optimize resource allocation and empower communities to actively participate in landscape maintenance actively, fostering a sense of ownership and responsibility for public green spaces. Moreover, the paper underscores the value of using intelligent techniques like QGIS in real-time data monitoring and analytics, enabling evidence-based decision-making and adaptive management practices for sustainable landscapes. In the context of the Arab region, the research has emphasized the need for context-specific solutions, acknowledging the unique environmental, cultural, and social factors that influence landscape management. Integrating digital tools in this context should be aligned with local practices, regulations, and community preferences to ensure long-term success and relevance.

In conclusion, the paper calls for continued collaboration between researchers, practitioners, policymakers, and citizens to collectively work toward establishing intelligent, sustainable, and vibrant green spaces that enrich the urban fabric and safeguard the environment for future generations. By embracing innovation and staying adaptive, the Arab region can lead the way in landscape sustainability and set an inspiring example for other global communities facing similar challenges.

i. Smart Irrigation Controllers.
ii. Plant Identification Apps.
iii. Weather Monitoring Apps.
iv. Mapping and GPS Tools.
v. Remote Monitoring Systems.
vi. Data Analytics Platforms.
vii. Mobile Task Management Apps.
viii. Sustainable Material Sourcing Apps.
ix. Green Waste Recycling Apps.
x. Carbon Footprint Calculators.

Integrating such digital tools and data analytics in sustainable landscape maintenance practices marks a transformative shift towards more efficient, resource-conscious, and ecologically responsible urban environments. The research findings underscore the value of technology-driven approaches in water conservation, resource efficiency, and landscape health. By adopting data-driven decision-making and fostering community engagement, cities in the Arab region can build a more sustainable future that balances urban development with environmental preservation.

Challenges and Recommendations:

Despite the positive outcomes, the research illustrated several challenges in the adoption of digital tools, including the initial investment costs, technology integration, and training needs. However, the long-term benefits of water and resource savings, improved landscape health, and enhanced public spaces outweighed the initial challenges.

The research paper recommends that landscape professionals, policymakers, and city planners prioritize the integration of digital tools and data analytics in sustainable landscape maintenance strategies. Collaborative efforts between public and private sectors should focus on developing and implementing smart systems initiatives that promote sustainable landscape management for operation and maintenance, thereby enhancing the quality of maintenance performance in outdoor spaces in general and parks in particular in the Arab region. Continued research and innovation in the field of landscape architecture and technology will play a vital role in advancing the sustainability and efficiency of landscape maintenance practices in the future.

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