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Unlocking The Potential of Industry 4.0 Technologies in The Egyptian Industry

*Amro Abouzied[1] *, Medhat ElHadek [2] , Shady Aly [3] , Hanan Kouta [4]*

[1]Departement of Production Engineering and Mechanical Design Department, Faculty of Engineering, Port-Said University, Port Said, Egypt, email: amr.akram@eng.psu.edu.eg

[2]Departement of Production Engineering and Mechanical Design Department, Faculty of Engineering, Port-Said University, Port Said, Egypt, email: melhadek@eng.psu.edu.eg

[3]Department of Mechanical Engineering, Faculty of Engineering, Helwan University, Cairo, Egypt

email: shady_ali@h-eng.helwan.edu.eg

[4]Departement of Production Engineering and Mechanical Design Department, Faculty of Engineering, Port-Said University, Port Said, Egypt, email: hanan.kamel@eng.psu.edu.eg

**Corresponding author, DOI: 10.21608/PSERJ.2024.288785.1339*

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ABSTRACT

This research study aims to unlock the potential of Industry 4.0 technologies to enhance all sectors in industry in Egypt. The study conducted a use case in a medium enterprise which a plastic company located in Port-said operating through fully automated machines on the shop floor but with no connectivity or real time data acquisition. A modified digital transformation maturity assessment is utilized to develop a digital transformation strategy and digital infrastructure roadmap to upgrade the plant's industry 3.0 status to an industry 4.0 where everything is connected between IT and OT layers and enabling the adoption of a proper manufacturing execution system (MES) functionalities. The DTMA results revealed that the industry in Egypt is still in its infancy in terms of industry 4.0 adoption. Hence, this study aims to serve as a benchmark for other industries who wish to embark on their digital transformation journey. As a result of the DTMA, a proof of concept was implemented, utilizing the concept of a unified namespace (UNS) and its powerful capabilities to accelerate the digital transformation process, and overcome the barriers that industries face. The potential benefits of utilizing UNS can serve as a valuable reference for industries looking to implement similar initiatives. The results demonstrated the effectiveness of the UNS in connectivity, providing real-time data that can be utilized by other nodes to address production system issues such as downtime analysis and scheduling problems. The unified namespace facilitated data integration and enhanced data transparency, enabling data-driven decisions to improve processes.

Keywords: Industry 4.0, Digital Transformation Maturity Assessment, Unified Namespace, Small Medium Enterprise, Manufacturing Execution System.

1 INTRODUCTION

The Fourth Industrial Revolution, commonly known as Industry 4.0 (I4.0), refers to the integration of digital technologies into all aspects of industrial processes [1]. The aim of Industry 4.0 is to create a fully integrated business model where all software, assets, and human labor are connected within a digital infrastructure, with data being the primary commodity

for the business. This integration leads to smart factories where real-time data and information are used to improve the flexibility, productivity, and efficiency of production systems [2]. Furthermore, Industry 4.0 represents the transformation of data into real-time information, a journey that manufacturers take to upgrade their business processes from an industry 3.0 (I3.0) state to an I4.0 state.

The evolution of industrial revolutions marks a profound transformation in industry and production systems. The First Industrial Revolution, occurring in the late 18th and early 19th centuries, introduced mechanization through steam and waterpower, drastically changing hand production methods. The late 19th and early 20th centuries saw the Second Industrial Revolution, characterized by mass production and assembly lines powered by electrical energy, which significantly boosted production efficiency and volume. Moving into the late 20th century, the Third Industrial Revolution brought about automation with the advent of computers and electronics, further enhancing precision and efficiency in industrial processes. Currently, we are amid the Fourth Industrial Revolution, where cyber-physical systems, the Internet of Things (IoT), and cloud computing are integrating digital and physical technologies, creating smart factories that operate with unparalleled interconnectivity and autonomous decision-making capabilities [3] [4] [5].

Digital transformation (DT) refers to the integration and utilization of digital technology across an organization's operations, processes, and functions to fundamentally change the way it operates and creates value for its customers. It is a strategic process that aims to improve the organization's products, services, and processes by leveraging technologies such as cloud computing, artificial intelligence, big data analytics, and internet of things. The primary goal of DT is to empower people to become more efficient and productive by automating repetitive tasks and enabling them to focus on value-added work. DTs encompass a wide range of electronic tools and systems that generate, capture, store, or process data from both humans and machines.

It is important to note that digital transformation is not a one-time project or series of projects, nor is it about replacing human workers with automation. Instead, digitally transformed organizations work closely with their workforce to realign responsibilities and encourage self-managed teams. A successful digital transformation strategy requires continuous education at all levels of an organization and a scientific approach free from vendor bias. Additionally, organizations must continuously learn how digital technology is transforming them in comparison to other organizations in the market.

The manufacturing Industry with its different sectors is a crucial component of the Egyptian economy, accounting for a significant proportion of the country's Gross domestic Product (GDP) and providing employment opportunities for millions of people [6]. However, the industry faces several challenges, including limited access to modern technologies, inefficient production processes, and a lack of competitiveness in the global market. To address these challenges, there is a growing interest in digital transformation initiatives and the adoption of I4.0 technologies.

This research study aims to investigate the potential of I4.0 technologies to enhance industrial processes in Egypt. A case study was conducted in a plastic manufacturing plant located in Port-said/Egypt, the plant produces plastic rolls used for packaging, the plant consists of a fully automated machines, an enterprise resource planning (ERP) for enterprise processes, however there is no connectivity or real time insights to the shop floor. utilizing a digital transformation maturity assessment (DTMA), a framework to evaluate the plant's current state and identify areas for improvement as the first objective of the study. The DTMA acts as a roadmap and starting point for organizations to start their digital transformation journey towards I4.0 with confidence and eventually reach a state of a fully integrated business. The study also establishes a new way to integrate the business by building an Industrial Internet of Things (IIOT) ecosystem with a single source of truth in the middle, known as the unified namespace (UNS). The UNS refers to one centralized location for all nodes in the ecosystem, allowing for a more connected and efficient industrial environment where data from different sources can be easily integrated and analyzed [7].

The study's objective is to design a framework for all industries to follow to start their digital transformation journey, furthermore, to design an architecture centered around the UNS that is scalable and valuable.

The subsequent sections of the paper will provide an overview of the methodology and results of the study, which showcases the potential of I4.0 technologies and the benefits of a UNS for the industry in Egypt.

2 LITERATURE REVIEW

Digital Transformation has emerged as a key driver of growth and innovation in different industries, enabling organizations to optimize their operations, enhance their products and services, and create new business models. Despite the growing importance of digital transformation, many organizations in Egypt have yet to fully embrace digital technologies and continue to rely on traditional methods and practices [8]. This literature review explores the digital transformation in Egypt's different industries, identifying key barriers, and proposing strategies for successful adoption of digital technologies.

The current state of digital transformation varies across different industries and regions. However, in general, there has been a growing adoption of digital technologies in manufacturing and industrial sectors in recent years, driven by the desire to improve operational efficiency, reduce costs, and enhance product quality. According to a survey by Deloitte, only 5% of executives indicate significant progress in a connected, integrated approach to implementing industry 4.0 technologies [9].

Embedded within Egypt's national agenda, Vision 2030, is a strong emphasis on organization excellence and the transformative power of digital technologies. Recognizing the significance of the industrial sector as a driver of economic growth and job creation, Vision 2030 outlines a strategic vision to enhance the competitiveness and productivity of Egyptian industries. This includes fostering innovation, adopting advanced industry techniques, and leveraging digital transformation to optimize processes, improve efficiency, and drive sustainable development [10]. The National Structural Reform Program (NSRP) considers Industry 4.0 as one of its main pillars, with a focus on expanding the relative weight of the manufacturing, agriculture, and communication and information technology (ICT) sectors. The government has also launched initiatives such as the Digital Egypt ICT 2030 strategy and the National Artificial Intelligence (AI) strategy to upgrade digital connectivity and address regulatory frameworks. To foster digitalization in firms, the government has provided start-ups and other businesses with guidance and resources to develop I4.0 technologies, as well as fiscal incentives of up to 10%-20% of exported value-added digital services. The government has introduced numerous initiatives to increase the availability and financing of training for basic digital skills and advanced courses on information technologies among youth. The strategy aims to accelerate the pace of digitalization as a vehicle for development, particularly in the industrial and agricultural sectors, as well as the finance and energy sectors [11] [12]. Kristin et al. [13] identified several barriers in the digital transformation of the manufacturing industry, notably the lack of technical skills and the influence of organizational culture, which often lead to failed initiatives. They suggested that studying different companies implementing digital transformation could uncover additional research areas, offering a foundation for further investigation into these barriers. The authors emphasized combining their findings with case studies on overcoming these obstacles and developing best practices. However, their research was limited to articles published in the past three years, indicating that ongoing studies might address these issues. Also, study by Balasingham showed that IT-infrastructure and firm size have a positive correlation with implementation, while lack of financial resources, skills mismatches of employees, reluctance to change, and maturity stage have a negative correlation [14]. Additionally, the high cost of digital technologies and the associated infrastructure required for their implementation are also major barriers for many manufacturers, especially small and medium-sized enterprises (SMEs) as pointed out by a study made by OECD organization [15]. Despite these challenges, digital transformation offers numerous benefits for manufacturers, Peter et al. Peter et al. demonstrated that digital transformation and business model innovation significantly change consumer expectations, pressure traditional firms, and disrupt markets, identifying three stages (digitization, digitalization, and digital transformation) and emphasizing the need for specific organizational structures and performance metrics, while also proposing a research agenda for future studies. [16]. These benefits include increased operational efficiency, improved product quality and innovation, enhanced customer experiences, and access to new markets and revenue streams. Garcia conducted a detailed overview study on how I4.0 technologies can positively affect production systems and maintenance management in manufacturing companies, he described twelve different technologies and their different capabilities on increasing efficiency and decision making [17].

The concept of Industry 4.0 is transforming the way products are produced, leading to a new era of industrial systems that differ significantly from the current ones. For a successful implementation of I4.0, it is crucial for these systems to operate seamlessly and connect within the industrial environment. Industry 4.0 represents a turning point in the industrial landscape, where digital technology plays a vital role in shaping the future of production. Chuah's research emphasizes sustainability in Industry 4.0, highlighting innovative advancements that are set to revolutionize manufacturing processes. [18].

Germany's manufacturing industry, renowned for its expertise in innovative technologies and complex industrial processes, has positioned itself as a global leader, particularly in manufacturing equipment. Industry 4.0 aims to integrate the Internet of Things and Services into production lines, resulting in interconnected Cyber-Physical Systems (CPS). These CPS enable the emergence of smart factories, fostering customized production, optimized decision-making, and novel business models. I4.0 also addresses critical challenges such as resource efficiency and demographic changes. To effectively embrace this revolution, Germany must adopt a dual strategy by integrating technology into high-tech strategies and creating new CPS markets. Successful implementation requires dedicated research, development, and policy efforts. Key focus areas encompass standardization, broadband infrastructure, safety, work organization, training, regulation, and resource efficiency [19]. Furthermore, Industry 4.0 envisions a future state of industry characterized by extensive digitization of economic and production processes. It necessitates horizontal integration at every stage of production, where machines interact with one another. Vaidya et al. has identified and analyzed nine technological pillars of Industry 4.0. First, autonomous robots are becoming more independent and cooperative, capable of interacting with each other and learning from humans. Second, simulation enables 3D virtual models that mirror the physical world, allowing for testing and optimization before production begins. Third, horizontal and vertical system integration aims to interconnect organizations and their suppliers and customers. Fourth, the Industrial Internet of Things connects a greater number of intelligent products using standard protocols, enabling real-time responses. Fifth, cybersecurity becomes crucial as connectivity and communication protocols become the norm. Sixth, additive manufacturing (3D printing) is adopted for high-performance production of customized products, reducing transportation and inventory costs. Seventh, augmented reality tools provide real-time information to operators, aiding in decision-making and process improvement. Eighth, big data and analytics optimize production quality, energy savings, and services. The goal is to enable real-time decision-making [20].

Additionally, Qu and El-Sayed evaluated how I4.0 technologies can improve the monitoring and maintenance of equipment, reducing the risk of breakdowns and extending the life of equipment leading to cost reduction, quality improvement, flexibility, and increased productivity [21] [22]. Implementing digital transformation initiatives can be challenging, and failure to do so can be attributed to a variety of factors such as wrong strategy, lack of suitable infrastructure, and selecting the wrong partners. Therefore, it is important for manufacturers to carefully plan and execute their digital transformation initiatives, considering the unique challenges and opportunities that exist within their organization and the broader industry context. By doing so, manufacturers in Egypt can position themselves for long-term success and growth in the digital age.

Indeed, this literature review provides valuable insights into the current state of digital transformation in manufacturing industries in Egypt, highlighting the key challenges and potential solutions to help organizations successfully embark on their digital transformation journey. As the production systems and industrial processes in Egypt and beyond continues to evolve, it is becoming increasingly clear that digital transformation is not only a priority but also a necessity to remain competitive and achieve sustainable growth.

However, to ensure the success of digital transformation initiatives, it is crucial for organizations to adopt the right strategy, partner with the right stakeholders, and build the right infrastructure. By using this research paper as a starting point or framework, organizations can assess their current digital maturity score and state, identify their goals, and develop a tailored strategy to achieve them. With the right mindset and approach, Industrial companies in Egypt can leverage digital technologies to optimize their operations, enhance their products and services, and create new business models, driving growth and innovation in the industry.

3 DIGITAL TRANSFORMATION MATURITY ASSESSMENT

The digital transformation maturity assessment (DTMA) is a comprehensive evaluation that assesses the current state of the organization, which is a critical step prior to adopting I4.0 projects, as indicated by the literature review. Also, the DTMA will be used to design and recommend the appropriate digital strategy and roadmap to digitally transform the business and overcome challenges and barriers.

After reviewing several I4.0 projects in the Egyptian industry, the authors believe that a DTMA and road map planning must be the starting point for any digital transformation journey. This is because most digital transformation initiatives fail due to using the wrong technology, operating under the wrong strategy and roadmap, or lacking knowledge. In addition to assessing the current state of the organization, the DTMA also involves taking an inventory of all hardware and software used in the operation and process workflow and making recommendations on where to start the digital transformation process.

The DTMA methodology used in this case study is primarily based on the DTMA framework developed by 4.0 Solutions, a company based in the USA. However, the authors have made certain modifications and additions to the framework to ensure its suitability for small and medium enterprises (SMEs). These adjustments aim to adapt the DTMA approach to the specific needs and characteristics of SMEs in the context of digital transformation.

3.1 Theoretical Framework: Digital Transformation Maturity Assessment

The theoretical framework employed in this study is rooted in the recognition of the critical role of a digital transformation maturity assessment (DTMA) as a prerequisite for successful adoption of I4.0 projects. The DTMA serves as a comprehensive evaluation tool that evaluates the current state of organizations, enabling the design and recommendation of appropriate digital strategies and roadmaps to overcome challenges and barriers.

To ensure the validity and reliability of the DTMA methodology, various measures are taken. The chosen data collection methods, analysis techniques, and quality assurance processes are carefully selected to ensure accurate and consistent results. Ethical considerations, such as obtaining informed consent from participants and safeguarding data privacy and confidentiality, are also given due importance throughout the research process.

By following this structured and tailored methodology, this study aims to provide a comprehensive and reliable assessment of digital transformation maturity in SMEs within the Egyptian industry, facilitating successful adoption of I4.0 projects and enabling organizations to overcome challenges and achieve sustainable digital transformation.

3.1.1 Defining the scope and objectives

In this step, the scope of the assessment is clearly defined, outlining the specific areas of the organization to be evaluated. The objectives of the assessment are also established, identifying the desired outcomes and aligning them with the goals of digital transformation in the SMEs of the Egyptian industry.

3.1.2 Data gathering

The data gathering phase involves collecting comprehensive information about the organization's present state, including its technology infrastructure, workflows, processes, and human resources. This is achieved through a combination of surveys, interviews, documentation analysis, and observation to capture a holistic view of the organization's digital maturity.

3.1.3 Data analysis

The collected data is subjected to rigorous analysis to identify the organization's strengths, weaknesses, opportunities, and threats concerning digital transformation maturity. Various analytical techniques, such as quantitative and qualitative analysis, benchmarking, and comparative analysis, are employed to gain insights into the organization's current position in the digital transformation journey.

3.1.4 Gap and opportunity identification

In this step, the identified gaps between the current and desired states of digital transformation maturity are carefully analyzed. Opportunities for improvement and innovation are also identified through a thorough examination of the organization's internal and external environment, enabling the development of actionable recommendations to bridge the gaps and leverage the identified opportunities.

3.1.5 Roadmap development

Based on the findings from the previous steps, a digital transformation roadmap is developed. This roadmap outlines a clear and structured plan with well-defined steps, resource allocation, and realistic timelines necessary to achieve the desired state of digital transformation. The roadmap considers the unique needs and characteristics of SMEs in the Egyptian industry, providing a practical and customized guide for successful digital transformation initiatives.

3.1.6 Implementation and monitoring

The developed roadmap is put into action, and the digital transformation journey is initiated. During this phase, the implementation progress is closely monitored and assessed against the established milestones and performance indicators. Any deviations or challenges encountered are promptly addressed, allowing for necessary adjustments to keep the digital transformation journey on track.

3.2 Digital Transformation Maturity Pillars

To evaluate the digital transformation maturity of organizations, a scoring system based on ten pillars has been developed. This scoring system serves as a critical component of the DTMA methodology, providing a comprehensive overview of the organization's current state of digital maturity and identifying areas that require improvement. Prior to the scoring process, a field assessment of the process and material overflow is conducted, enabling a general understanding of the stages of the process and the industrial flow. This preliminary assessment sets the foundation for delving into the intricate details of all aspects of the organization's operations. To ensure a comprehensive evaluation, extensive and lengthy meetings were conducted with teams responsible for operations, engineering, quality, IT, and management.

During these meetings, specific questions were posed, covering each aspect of the organization's operations, from unit sales to production and shipment to customers. By engaging with the relevant teams, a detailed assessment was carried out, enabling the assignment of an accurate score to each performance pillar depicted in Figure 1. Within each pillar, a set of scoring criteria ranging from 1 to 5 is used to evaluate the organization's performance. These criteria provide specific guidelines for assessing the organization's level of maturity in each pillar. The scoring process enables a quantitative measurement of the organization's digital transformation progress and serves as a basis for identifying strengths and weaknesses within the different areas.

By applying the scoring system to the ten pillars, a comprehensive picture of the organization's digital transformation maturity is obtained. The scores highlight areas of excellence as well as those that require improvement, enabling the formulation of targeted recommendations and interventions.

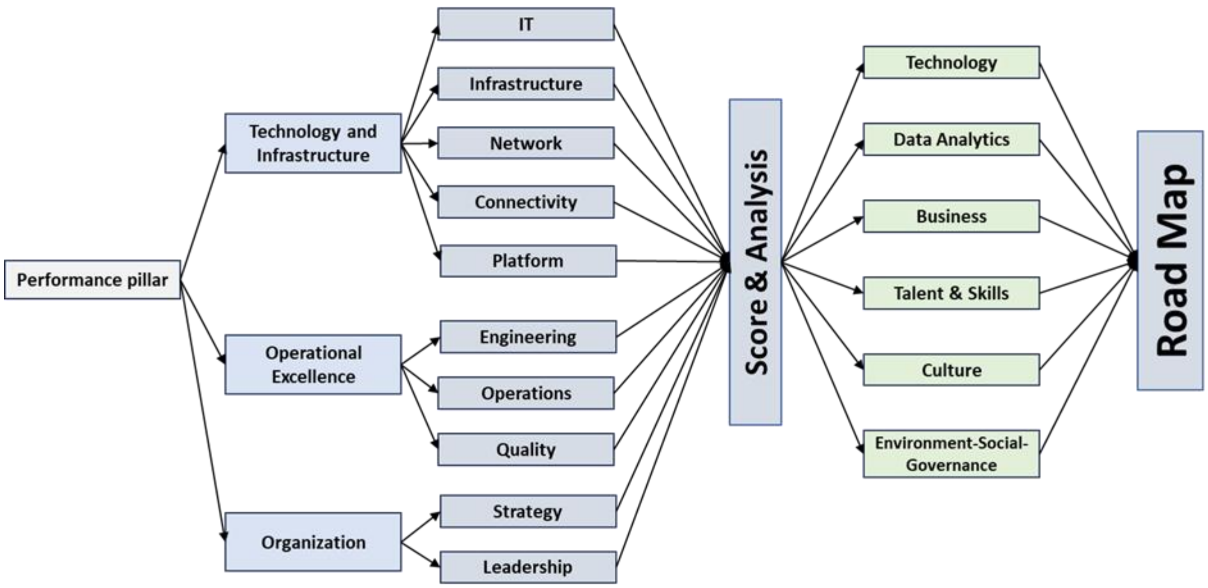

Figure 1: Digital Transformation Maturity Assessment Framework.

Overall, the combination of the DTMA methodology and the scoring system ensures a holistic assessment of digital transformation maturity, empowering organizations to make informed decisions and take strategic actions to drive their digital transformation journeys forward.

The scoring pillars within our Digital Transformation Maturity Assessment (DTMA) process are divided into three primary sections: Technology and Infrastructure, Operational Excellence, and Organizations. Each section comprises several pillars, which will be detailed in the subsequent section. This breakdown includes an explanation of the criteria for each pillar and its significance in the DTMA process, highlighting why each pillar is a crucial component of the overall assessment.

3.2.1 Operations

In the DTMA scoring system, the first pillar assessed is "Operations," which plays a crucial role in determining an organization's digital transformation maturity. The assessment of Operations involves assigning a score ranging from 1 to 5 based on the organization's level of advancement in real-time data utilization and digital manufacturing execution systems (MES). At Level 1, there is a lack of real-time data utilization, indicating a limited understanding and utilization of digital technologies in operations. Level 3 signifies the presence of Supervisory Control and Data Acquisition (SCADA) systems and partial implementation of real-time data, along with a partly digital MES. Level 5 represents the highest level of digital maturity in Operations, where organizations have achieved a single-pane-of-glass view and employ data-driven decision-making in real-time. Levels 2 and 4 denote the intermediate stages between the above and below levels, reflecting varying degrees of progress in real-time data utilization and digital MES implementation.

Several research papers support the importance of assessing Operations in the digital transformation journey. Studies have highlighted that real-time data utilization and digital MES play a critical role in optimizing operational efficiency, enhancing productivity, and enabling proactive decision-making [23]. The presence of SCADA systems and the ability to harness real-time data are often associated with improved visibility into operations, reduced downtime, and increased process control.

Furthermore, the attainment of a single-pane-of-glass view and data-driven decision-making in real-time have been linked to better operational agility, responsiveness, and the ability to leverage emerging technologies effectively. These research findings underline the significance of evaluating Operations in the DTMA and emphasize the need for organizations to prioritize and enhance their digital capabilities in this key area [24].

3.2.2 Information Technology (IT)

The DTMA assesses the "Information Technology (IT)" pillar, evaluating an organization's digital transformation maturity in terms of its IT capabilities and service orientation. Using a scoring system with levels from 1 to 5, different stages of IT advancement and service delivery are identified. At Level 1, organizations have basic IT capabilities primarily focused on security and compliance. Moving to Level 2, there is progress beyond the foundational stage, with efforts towards a service-oriented approach, although it may not be fully implemented yet. Level 3 signifies a moderate level of IT advancement, where the organization has established some service-oriented IT functions, although responsiveness and efficiency may still require improvement. Level 4 represents significant progress in IT capabilities and service orientation, with a well-defined service organization that delivers IT services more efficiently and responsively than at Level 3. Finally, Level 5 denotes the highest level of IT maturity, where the organization operates as a service organization, prioritizing the needs of data and information consumers and providing them with the desired resources in their preferred format and timeframe.

A strong IT infrastructure and service-oriented approach enable organizations to optimize processes, enhance collaboration, and enable data-driven decision-making [25]. Assessing the IT pillar within the DTMA framework helps organizations identify areas for improvement, strengthen IT functions, and align IT strategies with overall digital transformation objectives.

3.2.3 Engineering

This pillar focuses on the design and development of products or services, as well as the organization's ability to adapt to changing market needs. Engineering is about utilizing production, processes, and automation as well as leveraging tools used by maintenance to keep the equipment at high availability and at high efficiency [26]. The goal for engineering in an I4.0 organization is to be proactive with the ability to leverage real time digital data across process and business units to drive innovation, quality, and reliability.

3.2.4 Leadership

Leadership pillar within the DTMA evaluates an organization's digital transformation maturity based on its vision, strategy, and leadership approach. At Level 1, the organization lacks a clear vision and strategy for digital transformation, with a top-down leadership style. Moving up, Level 2 reflects progress towards establishing a vision and strategy, although they may not be fully defined or widely communicated. Level 3 signifies value capture with IIOT, but without a comprehensive digital transformation strategy. At Level 4, further advancement is made with a more defined vision and strategy, incorporating elements of digital transformation and technology adoption. Finally, at Level 5, the organization demonstrates a clear and concise digital strategy that aligns with overall business objectives. Disruptive, transformative and agile leadership is crucial for successful digital transformation, offering a clear vision, strategic direction, and empowerment of employees [27] [28] .

3.2.5 Infrastructure

The infrastructure pillar within the DTMA evaluates an organization's digital transformation maturity by assessing its technological infrastructure. Level 1 indicates either an air-gapped infrastructure or a lack of edge-to-cloud capabilities. At Level 2, the organization demonstrates progress in improving its infrastructure, addressing connectivity and functionality limitations while striving to enhance overall digital capabilities. Moving to Level 3, the organization aligns its infrastructure with the standard Purdue reference architecture, incorporating a Demilitarized Zone (DMZ). Level 4 signifies significant improvements, where advanced technologies are integrated, and connectivity and scalability are optimized. This sets the stage for a more robust digital ecosystem to support digital transformation initiatives. Finally, Level 5 represents a secure infrastructure that leverages virtual Ethernet networks, virtual machines, containers, and an edge user-driven deployment strategy. It ensures comprehensive network coverage, emphasizing robust connectivity and accessibility. Advancing infrastructure capabilities is essential for organizations to fully capitalize on digital transformation opportunities [29]. Many companies face challenges in implementing effective digital infrastructure. Simply focusing on technology alone can lead to the development of solutions that fail to align with business objectives, resulting in limited return on investment [30].

3.2.6 Platform

The Platform layer in the DTMA evaluates an organization's digital transformation maturity by assessing its technology components and their integration to drive innovation. A digital transformation platform incorporates technologies such as big data, analytics, AI, cloud computing, and machine learning [31].

At Level 1, the organization lacks an IIOT platform. Level 2 represents the adoption of a solution-centered platform which establishes a foundational framework for digital transformation. Progressing to Level 4, the organization embraces an IIOT platform that surpasses a solution-centric approach. This advanced platform emphasizes openness, edge-driven capabilities, and reporting by exception, enabling seamless integration and scalability. To achieve full maturity in the Platform layer, represented by Level 5, the organization requires an open, edge-driven, and report by exception IIOT platform. This technology-centric focus facilitates seamless integration and empowers organizations to drive innovation and gain a competitive advantage [32].

3.2.7 Network

Networks are vital in driving digital transformation as they facilitate the smooth transmission of data, communication, and connectivity across organizations and stakeholders. They serve as a foundation that enables information exchange, collaboration, and the integration of diverse digital technologies. Within the realm of digital transformation, networks play a critical role in ensuring the seamless flow of data, communication, and connectivity, enabling organizations to leverage the full potential of their digital initiatives [33]. The organization must possess a comprehensive network infrastructure that offers complete coverage while being scalable, flexible, and secure [34].

3.2.8 Connectivity

Connectivity represents the seamless integration across all layers of the business and the automation stack [35]. To achieve a highly developed connectivity pillar, it is imperative to establish network connectivity for all edge devices, ensuring they are interconnected and accessible over the network. This network integration plays a crucial role in facilitating efficient communication, data exchange, and collaboration throughout the organization's infrastructure [36].

3.2.9 Strategy

A robust digital strategy plays a pivotal role in aligning all aspects of an organization towards a shared objective and fostering sustainable growth. Digital transformation is not merely a standalone project but a series of interconnected initiatives that progressively build upon one another. As depicted in Figure 1, the initial outcome of the DTMA is the development of a digital strategy, which outlines the organization's approach to digital transformation endeavors [37] [38]. The strategy must be technology driven with stating the reasons for choosing to become a digital company. It will focus on different aspects of the organizations like technology, data analysis and data governance, business infrastructure, culture that enables innovation and problem solving and taking environment, social and cooperate governance into account.

3.2.10 Quality

Quality plays a vital role in the competitiveness and sustainability of manufacturers and companies, defined as the overall attributes that meet specified or implicit requirements, encompassing different quality management concepts such as Total Quality Management (TQM) and Zero Defects Concepts [39]. The integration of digital technologies presents significant opportunities for enhancing quality control procedures, resulting in increased operational efficiency, enhanced accuracy, and improved overall product quality [40]. Key elements encompass leveraging data-driven insights, implementing real-time quality control mechanisms, adopting predictive maintenance practices, fostering seamless integration and collaboration, ensuring traceability and compliance, and maintaining a relentless focus on continuous improvement and operating on real-time data and information.

4 UNIFED NAMESPACE (UNS)

The Unified Namespace architecture (UNS), a groundbreaking innovation in the digital realm, holds immense significance in today's interconnected world [41]. In an era characterized by an exponential growth of information and an increasing reliance on digital platforms, the adoption of the UNS architecture emerges as a crucial step towards creating order, efficiency, and seamless communication across diverse domains. The UNS is the transition from linear, deterministic integration into a single source of truth and a centralized hub, acting as the foundation a digital infrastructure [42]. By harmonizing and standardizing naming conventions, the UNS enables individuals, organizations, and systems to effortlessly navigate and interact with a vast array of data, resources, and services. This transformative approach not only simplifies information retrieval and sharing but also enhances interoperability, collaboration, and innovation on a global scale. As the world becomes increasingly interconnected, the adoption of the UNS architecture becomes paramount, empowering us to harness the full potential of our digital landscape and propel us towards a more connected, efficient, and inclusive future [43].

The UNS acts as a structured framework that brings together different layers of the automation stack such as PLCs, HMI, SCADA systems, MES, ERP, and cloud platforms into a cohesive and interconnected ecosystem. Figure 2 shows the UNS architecture and how all smart objects in the organization acts as a node in the ecosystem where all communication takes place, also, the UNS is the hub for all data and information in the business, it is the structure and events of the business.

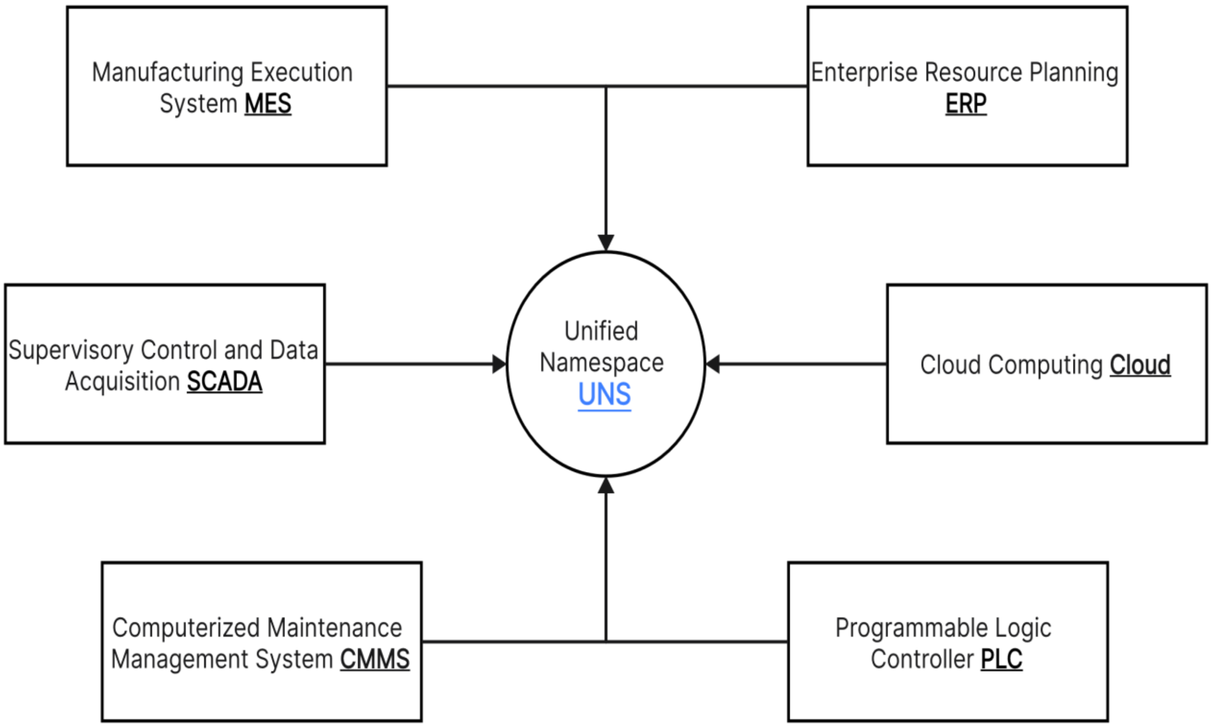

Figure 2: The Unified Namespace Architecture

Traditionally, integrating systems within the automation stack required a deep understanding of each layer's specific namespace and its internal structure. However, the UNS aims to simplify this process by providing a unified view of the entire business structure and events. ensure that any data or information exchange also gets published to the UNS. This way, anyone seeking a comprehensive view of the business's structure and events can find it in one place—the UNS.

In designing a unified namespace for IIOT systems, the workflow involves mapping the existing physical assets and devices, defining metadata for consistency and accuracy, and incorporating the functions and capabilities of different solutions within the UNS architecture.

5 RESULTS AND DISCUSSION

The motivation of this work was the interest from Prime-Pack manufacturing company in Egypt to use the factory floor to improve their process and to integrate all machines and software into one infrastructure. The current infrastructure on the plant floor doesn't give the ability to integrate the data generated by the machines and PLCs to a digital MES system and to the ERP system due to high cost of point-to-point integration, therefore, all the calculations of productivity and OEE is done by hand which then leads to technical gaps in the process and eventually the failure of any digital transformation initiatives.

The study encompasses two key aspects: a digital transformation maturity assessment and the development of a unified namespace using Message Queuing Telemetry Transport (MQTT) broker as the communication protocol between different layers in the automation stack (PLC/HMI/SCADA/MES/ERP). HiveMQ Broker was used as the central component. Additionally, various nodes such as Kepserver, Ignition, and Oracle ERP are incorporated to facilitate data exchange, enabling the plant to optimize its operations through real-time monitoring, analytics, and machine learning. This case study showcases the implementation of advanced technologies and integration strategies, including Apache Nifi, to ensure enterprise connectivity.

5.1.1 Maturity Assessment Results

To begin the process of digital transformation we must first inventory the business and the intelligence and know everything about our business and the capabilities and limitations of all available machines and software we have. Therefore, the first step was to do a digital transformation maturity assessment as described in the methodology and the output of this assessment will be

It acts as a schematic hierarchy, enabling different components to communicate and share data through the UNS. While direct communication between software components is still possible, the role of the UNS is to

the gate that will guide us through the digital transformation journey.

The manufacturing area that we are targeting consists of one compounding system and two identical lines that are responsible for producing plastic rolls used for packaging purposes. The final product varies depending on the recipe formulated in the compounding system, resulting in the production of different types of plastic rolls. After an extensive assessment of the plant processes and workflow, a maturity score matrix is conducted.

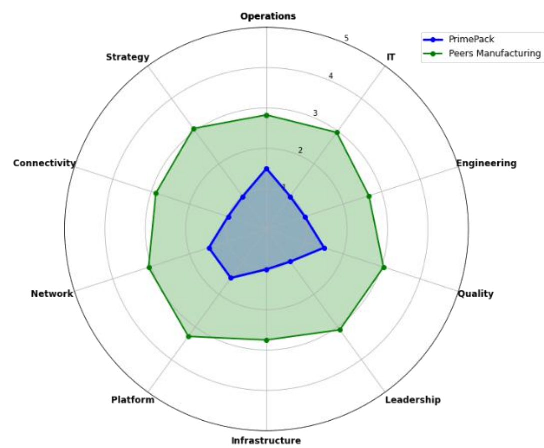

Figure 3: DTMA plant scoring compared to peers.

As evident from Figure 3, the packaging manufacturing plant lags in all 10 pillars of digital transformation maturity compared to other manufacturing plants scored and accessed by 4.0 solutions company. Highlighting several key areas that require attention and improvement. The assessment reveals notable shortcomings in the plant's operations and infrastructure.

Firstly, in terms of operations, the plant's score of 1.5 indicates a significant gap compared to the benchmark score of 3.08 which is the average score from over 1000 companies assessed by 4.0 solutions company. Manual OEE calculations pose a considerable challenge, as the plant relies on labor-intensive methods to measure and evaluate overall equipment efficiency (OEE). This manual approach not only consumes valuable time and resources but also introduces a higher risk of inaccuracies and delays in identifying production bottlenecks.

Furthermore, the plant experiences frequent unplanned machine breakdowns, resulting in disruptions to production schedules and reduced overall productivity.

These breakdowns may stem from inadequate maintenance practices, insufficient monitoring systems, or a lack of proactive measures to address potential equipment failures.

Another area of concern is the high changeover time between different product runs. Lengthy changeover processes can significantly impact production efficiency, leading to increased downtime and reduced throughput. Streamlining changeover procedures through standardized protocols, automation, and improved coordination between teams can help minimize these time-consuming transitions.

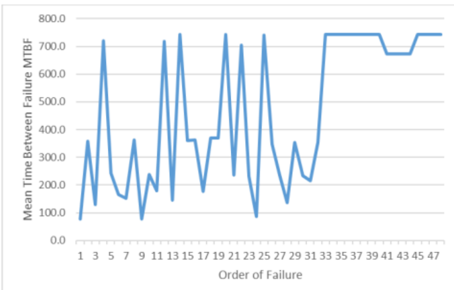

Figure 4: Mean Time Between Failures for the Rolling Machine.

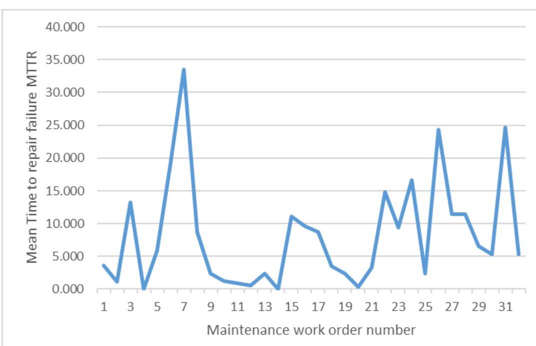

Figure 5: Mean Time to Repair Failures for the Rolling Machine.

Figure 4 provides a clear visualization of the challenges faced by the packaging manufacturing plant in terms of operational visibility. The absence of real-time data availability becomes evident, hindering the plant's ability to gain timely insights into its operations. Without access to up-to-date information on machine performance and production metrics, the plant struggles to make informed decisions and address potential issues promptly. Consequently, the lack of predictive maintenance machine learning exacerbates the situation, as failures occur repeatedly with varying time intervals between them. This repetition of failures leads to a cycle of reactive responses rather than proactive measures to prevent future occurrences.

Additionally, Figure 5 highlights another critical aspect: the impact of limited downtime analysis. Due to the absence of a comprehensive downtime analysis system, the maintenance team faces challenges in identifying the root causes of failures efficiently. As a result, the team spends excessive time investigating the reasons behind each failure, contributing to extended machine downtime, and negatively affecting overall productivity. The lack of clear visibility into the factors causing downtime further hampers the plant's ability to implement effective preventive or predictive maintenance strategies.

To address these issues, it is imperative for the packaging manufacturing plant to invest in real-time data acquisition and analytics solutions and that is one of the solution the authors provided for the plant floor; a downtime analysis solution based on the UNS and real-time information leveraging technologies such as IIoT devices, sensors, and data integration platforms, the plant collects and analyzes operational data in real-time. This enabled the plant to gain comprehensive visibility into its operations, identify patterns and trends, and make data-driven decisions.

Moreover, implementing predictive maintenance machine learning models can significantly enhance the plant's ability to anticipate and prevent machine failures. Leveraging historical and real-time data, ML models are built that can identify early warning signs and predict potential failures, allowing for proactive maintenance interventions and minimizing unplanned downtime. Furthermore, tracking and analyzing the duration and reasons behind each downtime event, the maintenance team can pinpoint the root causes more efficiently. This insight empowered the team to implement targeted corrective actions, reduce downtime, and optimize maintenance efforts.

In addition, the presence of data silos within the plant is a significant challenge. Lack of integration among different systems and departments hinders the seamless flow of information and inhibits effective data analysis. Integrating all nodes to the UNS resulted in more consistent information and reduced unnecessary duplication of meta data.

Addressing these downfalls requires a comprehensive digital transformation strategy that encompasses automation, predictive maintenance, process optimization, and data integration. The strategy is to operate on an open technology and shifting from solution-centric strategy, the authors considered the minimum technical requirements for any future solutions, any solution has to be report by exception, lightweight and edge driven. This transformative approach will pave the way for enhanced operational efficiency, reduced downtime, improved changeover processes, and optimized data utilization, ultimately positioning the plant for long-term success in a competitive manufacturing landscape.

The chosen strategy enabled the plant to operate from a unified and reliable data source, while the architecture should establish a cohesive ecosystem where all digital solutions and software act as interconnected nodes. This approach ensures seamless data flow and facilitates comprehensive visibility across the plant's operations.

To achieve this, the proposed starting architecture, as illustrated in Figure 6, encompasses key components and technologies. The HiveMQ broker is positioned as the central hub, serving as the single source of truth where all nodes publish their respective data and events. By consolidating data within HiveMQ, the plant can establish a centralized repository that ensures data integrity, accessibility, and consistency throughout the ecosystem.

Furthermore, the architecture incorporates Ignition as the data modeling component. Ignition plays a crucial role in normalizing and standardizing the data generated by various nodes within the ecosystem. This standardization facilitates consistent data representation and interpretation, enabling seamless integration and analysis across different systems and processes.

By adopting this proposed architecture, the packaging manufacturing plant can establish a strong foundation for its digital transformation journey. The unified namespace system, facilitated by the HiveMQ broker, ensures that all events and data pass through a central hub, enhancing data integration and enabling comprehensive monitoring and control. The integration of Ignition as the data modeling component further promotes data standardization and consistency, facilitating effective cross-functional analysis and decision-making.

Moreover, the inclusion of Apache Nifi as the data analytics tool offers advanced capabilities for leveraging machine learning techniques. This enables the plant to derive actionable insights, identify patterns, and optimize processes, ultimately leading to improved operational efficiency, reduced downtime, and enhanced overall performance.

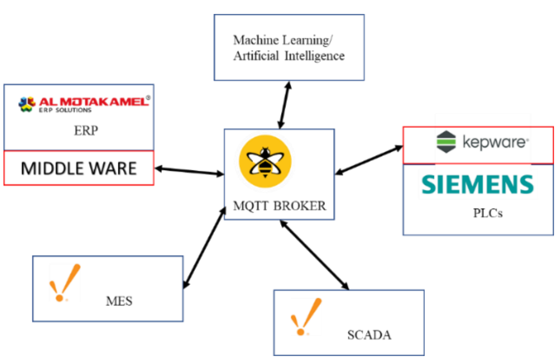

Figure 6: Digital Infrastructure for Packaging Plant

5.1.2 Unified Namespace UNS Implementation

The implementation of the Unified Namespace System (UNS) began with the design of the business structure, adhering to the ISA95-part 2 standard, as described in the methodology. This standard provided a framework for organizing and representing the hierarchy of the packaging plant. Figure 7 visually depicts the hierarchical structure of the packaging plant, as observed in the Ignition platform's tag browser. The enterprise is the company name (primepack), the area is the plants the company has, the company has 2 plants, 1 located in 10-Ramadan and 1 in Port-said. In Port-said there are 2 areas as shown in the figure. In the plastic roll area where the study took place, there were 2 lines.

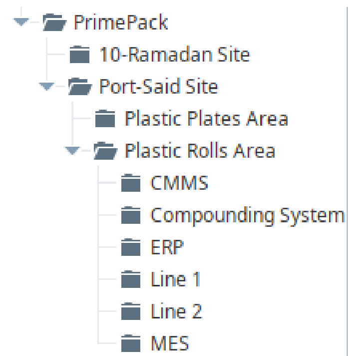

Figure 7: Prime-Pack Enterprise structure hierarchy in Ignition.

For the integration of the Enterprise Resource Planning (ERP) system with the MQTT broker, middleware was implemented to enable access to the backend of the ERP. Utilizing ORACLE ALMOTAKAMEL as the ERP system, the necessary data was configured to be published to the MQTT broker, establishing a reliable communication channel between the two systems. To facilitate seamless data exchange, the MQTT transmitter in IGNITION, the Data Modeling software, was employed to effectively subscribe to the published data from the ERP system. This integration achieved a streamlined flow of information between ORACLE ALMOTAKAMEL and the HiveMQ MQTT broker, allowing for enhanced efficiency and data management within the system.

Similarly, the Computerized Maintenance Management System (CMMS) software and the Manufacturing Execution System (MES) engine were integrated into the UNS architecture. The CMMS software was configured to publish relevant maintenance data to the MQTT broker, while the MQTT transmitter in Ignition subscribed to this data, enabling its inclusion within the UNS. Similarly, the MES engine followed the same integration approach, ensuring that the necessary data from the MES system was published to the MQTT broker and subsequently subscribed to by the MQTT transmitter in Ignition.

These integration efforts establish a cohesive ecosystem within the packaging plant, where the UNS acts as a central hub for data exchange and communication. The integration of the ERP system, CMMS software, and MES engine into the UNS architecture enhances the plant's ability to access and utilize real-time data, promoting improved visibility, streamlined operations, and informed decision-making.

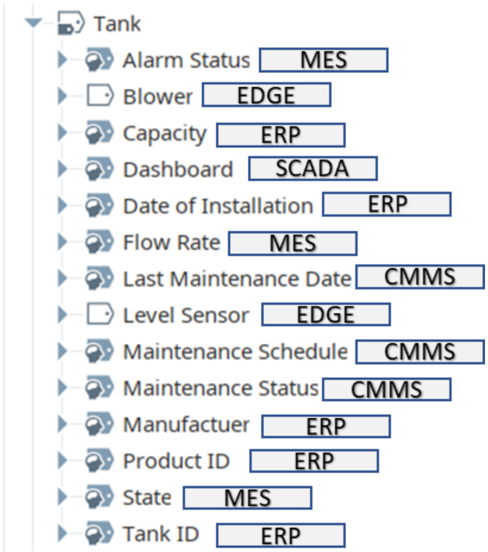

Figure 8: UNS tank datatype with data source.

In Ignition platform as shown in figure 8 a User-Defined Type (UDT) was created for a tank with various attributes such as ID, capacity, current level, and maintenance information. To provide context for each data point, the source of the data was identified such as ERP, MES, SCADA, PLC, sensors, and CMMS. This information helps to provide a clear understanding of where each data point originates from, making it easier to track and troubleshoot any issues that may arise. Additionally, it can also aid in making data-driven decisions for improving the tank's efficiency and maintenance schedule as all the information for this tank is one unified namespace. Overall, this data model provides a clear and concise representation of the tank and its associated data points, making it easier to manage and maintain.

The scientific implementation of the UNS and its integration with various software systems demonstrates a systematic and structured approach to digital transformation in the packaging plant. By following established standards and leveraging compatible technologies, the plant can effectively establish a unified data infrastructure, facilitating enhanced data exchange, analysis, and utilization.

To further understand the UNS architecture, figure 9 shows the connection between the MES namespace and other nodes in the ecosystem.

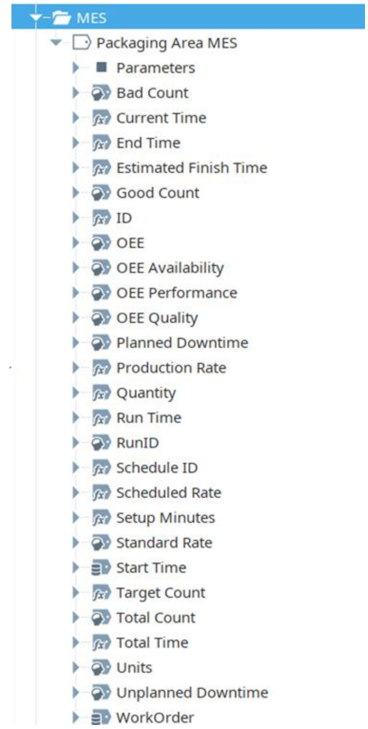

Figure 9: Manufacturing Execution System (MES) in UNS.

Moreover, all the visualizations or SCADA screens within the packaging manufacturing plant will be connected to and rely on the Unified Namespace System (UNS). An example of such a screen is illustrated in Figure 10, showcasing a digital display for Overall Equipment Effectiveness (OEE) that directly accesses and utilizes the data from the Manufacturing Execution System (MES) namespace.

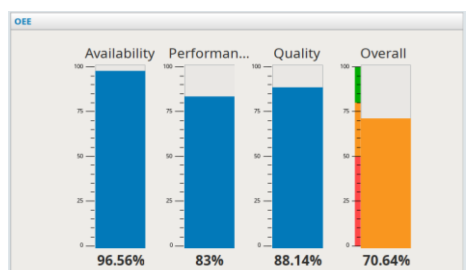

Figure 10: OEE Visual referencing the UNS

By integrating the UNS into the visualization systems, the plant can ensure that the displayed information accurately reflects the real-time data collected from various sources. In this particular example, the OEE screen provides comprehensive insights into the plant's equipment performance, highlighting key metrics such as availability, performance, and quality. The data used to calculate the OEE is sourced from the MES namespace, where it is continuously updated and synchronized with the UNS. The OEE is the multiplication of performance, availability and quality.

This unified approach allows operators and managers to monitor and analyze the plant's efficiency and productivity in a centralized and easily accessible manner. The OEE digital screen serves as a valuable tool for decision-making, enabling stakeholders to identify areas for improvement, detect bottlenecks, and implement strategies to optimize the overall equipment effectiveness.

By leveraging the power of the UNS and integrating it with visualization systems, the packaging manufacturing plant can enhance its operational visibility, promote data-driven decision-making, and drive continuous improvement across its production processes.

6 CONCLUSION

Based on the conducted DTMA, it is evident that the packaging industrial plant faces significant challenges in its current operations and infrastructure, which are hindering its ability to achieve optimal efficiency and productivity. The DTMA process revealed specific issues such as frequent machine downtimes, inefficient scheduling practices, and a lack of real-time data visibility, all of which are negatively impacting the plant's overall performance.

The implemented unified namespace (UNS) broker offers a promising starting point for the plant's digital transformation efforts. This architecture provides a unified and reliable data source, allowing seamless data integration, real-time monitoring, and advanced analytics. By leveraging the capabilities of the UNS, the plant can establish a robust ecosystem that operates from a single source of truth. This cohesive infrastructure will enable the plant to harness the full potential of its data, drive meaningful improvements, and make data-driven decisions across its operations.

In summary, the study highlights the following key points:

- **Prioritizing Key Areas of Improvement:** By addressing specific issues such as downtime reduction and scheduling optimization through the DTMA and implementing the UNS architecture, the packaging industrial plant can drive its digital transformation journey, enhancing efficiency, productivity, and competitiveness in the industry.

- **Growth Potential in Egypt's Industries:** The industry in Egypt is in its early stages of adopting Industry 4.0 (I4.0) technologies, indicating significant potential for growth and improvement.

- **Effective Framework for Evaluation:** The digital transformation maturity assessment (DTMA) served as an effective framework for evaluating the current state of the industry plant in Egypt and identifying specific areas for improvement.

- **Developing a Digital Transformation Strategy:** The DTMA results provided the foundation for developing a comprehensive digital transformation strategy and a digital infrastructure roadmap, guiding the plant's journey from Industry 3.0 to I4.0 state.

- **Capabilities of the UNS:** The concept of a UNS showcased its powerful capabilities in accelerating the digital transformation process by the integration between machines and software, which has always been a challenge.

- **Enhanced Data Integration and Transparency:** The UNS facilitated seamless data integration and enhanced data transparency, enabling manufacturers to make informed decisions and address critical issues such as downtime analysis and scheduling problems.

- **Importance of I4.0 Technologies:** The findings emphasize the importance of adopting I4.0 technologies, such as IoT sensors and predictive maintenance tools, to enhance industrial processes, improve operational efficiency, and achieve competitive advantages in the global market.

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Credit Authorship Contribution Statement

Amro Abouzied: Generating the idea, Collecting data, Methodology, Software, and preparing original draft.
Medhat Elhadek: Reviewing and supervision
Shady Aly: Reviewing, editing and supervision
Hanan Kouta: Reviewing, editing and Supervision

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper

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