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Chapter 6: Achieving real-time operational visibility using industrial IoT and digital twin technology

6.1. Introduction

In today's fast-paced and competitive business environment, achieving operational excellence is of key concern for organizations; this is especially true in industries such as manufacturing, oil and gas, and utilities whereby cost control, productivity, and product quality are critical success factors. Operational visibility is essential to achieving operational excellence. When we talk about operational visibility, we mean the ability to see the end-to-end process, the flow of material, information, and energy across multiple functions, departments, organizations, and enabling systems. It is difficult to achieve and sustain operational visibility as operations are often supported by a variety of disparate systems, are multi-faceted and data-intensive, traverse organizational boundaries, and are dynamic and continually changing (Chiarini & Kumar, 2021; Cui et al., 2022; Emon & Khan, 2024).

The need for operational visibility is underscored by the fact that existing methods and solutions generally provide a limited and constrained view of operations. For example, dashboards are often department- or function-centric and limited to KPIs such as production cycle time, OEE, and product quality. A siloed view can lead to poor decision-making as it does not enable managers to correlate performance between KPIs. Alerts rely on predefined rules, which cannot capture the dynamic nature of business operations. Reports are restricted to historical data and cannot be used to make real-time decisions. Such challenges increase the likelihood of problems going unnoticed, making the right decisions being difficult, and the right actions being taken too late. The decision to take corrective action is often subjective and can result in temporary fixes and increased rework. A room on the factory floor or a control room in a utility operate as 'information black holes' where data from various systems is pulled in to be analyzed by the people on the floor. These operations managers have a wealth of experience and knowledge but lack the tools that can help them make the best decisions in real-time or near real-time (Singh & Agarwal, 2021; Khan et al., 2024).

6.2. Understanding Industrial IoT

Industrial IoT (IIoT) plays a pivotal role in the digital transformation of various sectors including manufacturing, logistics, energy, transportation, and aerospace.

Fig 1 : Understanding Industrial IoT

Thanks to an ever-efficient global supply chain, competition is now fiercer than ever. The integration of IIoT technologies and methodologies in manufacturing has given rise to the concept of Industry 4.0, which promotes increased automation and information transparency in business processes. IIoT helps unprecedented visibility and understanding of business operations, facilitating better oversight and decision-making. Despite its well-acknowledged importance in enhancing and reshaping operations and infrastructure, IIoT is an elusive concept. In fact, the distinction between IIoT and IoT is subtle and often confused. In this section, we present a more pragmatic point of view by presenting the components of Industrial IoT, discussing its applications, and presenting its challenges and limitations. We hope this will help provide a concrete foundation for the subsequent chapters which delve deeper into how Industrial IoT and digital twin technologies can be integrated to provide better business visibility and decision-making.

6.2.1. Definition and Key Components

The Industrial Internet of Things (IIoT) is one of the main components of Industry 4.0. The IIoT has evolved from connecting a few machines or devices that send simple alarm signals to Remote Monitoring from Centralized Control Rooms into ubiquitous and pervasive connectivity of all devices, machines, tools, and equipment across the manufacturing enterprise that enables the collection of data on a continuous basis. Treatment and analysis of this large volume of data enable actionable insights to improve productivity, safety, and costs; make products better; and even create new revenue streams. By harvesting this data goldmine, manufacturers can eliminate the current "hit or miss" decision-making and instead rely on data-driven decision-making. The IIoT is a large, diverse ecosystem of components and technologies that provides the connectivity backbone and infrastructure to enable data collection; business processes; applications, including cloud; and enterprise functions like enterprise resource planning, product lifecycle management, and engineering workstations. The IIoT connects machines, sensors, devices, products, and people to the cloud. Embedded with sensors, devices, and components capable of real-time connectivity, machines can collect and share building data and provide real-time insight into on-site and remote performance. Analyzing this data enables proactive decision-making based on equipment performance, optimizing available data, assessing operational risk, predicting or avoiding shut-down periods, reducing equipment-related safety issues, minimizing losses, and improving overall building design and quality. At an even higher level, the IIoT combines specific applications, data, and technology with processing and storage through a cloud computing resource. Cloud services have the ability to process large volumes of data and automate decision-making, allowing personnel to focus on core competencies and improving performance.

6.2.2. Applications in Industry

The ubiquitous nature of Industrial IoT, and the wide range of applications in industry, can be well understood by analyzing the three main areas of its contribution: wireless access to process data, wireless access to supervisory applications, and wireless collaboration. The increasing availability of cheaper sensors, actuators and data storage is allowing users to monitor almost every aspect of their business, from individual pieces of equipment to enterprises as a whole.

The new sensors function by bridging the physical world and the Internet. Physical effects such as temperature, humidity, light, sound, movement, electricity, or motion can be sensed and converted into a digital format that can be accessed remotely and stored in the cloud. Surveillance, monitoring and control loops can also be established combining these sensors with actuators that are also Internet-enabled, such that physical actions can be performed from a distance and not just monitored. Application examples include atmospheric pollution monitoring and control; air pollution monitoring; smart agriculture; smart city; smart grid; smart home; smart logistics; smart water; structural health monitoring.

On the other hand, the integration of wireless sensors and actuators into the Industrial IoT will enable neighborhood interactions of smart entities near a particular equipment, as well as collaborative interactions among workers or other participating entities, through shared mobile and cloud-based collaboration tools. These collaborative tools can be employed on a daily basis to support workflow and task automation, thereby driving operational efficiency, when executed ad-hoc according to procedure, habitual for disciplined organizations. Task automation of the Industrial IoT can also be used to help reduce human error, for example in logistics operations or equipment supervision.

6.2.3. Challenges and Limitations

The digital twin concept introduces new challenges and limitations regarding data management. Digital twins require a bridge to the real physical asset, which can be identified within a hierarchy of systems in production, security, and economic domains. Due to the different characteristics of each available data source, the types of data that the digital twin will merge are numerous. Some data sources are time sensitive, of different types, updated only periodically, or will require manual merging with other types of digital information and, often, will not be trustworthy.

The various limitations linked to the exchange, integration, interactivity, and correlation of data can affect the creation and implementation of an operational, dynamic, complete, and trustworthy digital twin. Most challenges lie in the first layer of the framework. The system will not be able to provide if it cannot get trustworthy information about what is happening in real-time without affecting operations. Often, the information topology is not versatile enough to allow for specified and dynamic interaction between the various systems. Within each of these data sources, data come in different formats and must at least be preprocessed before being merged through semantic web or linked data technologies. And some applied technologies must be able to support the link to distributed cloud-based data. The problem intensifies as the complexity of the enterprise grows. Such complexity can be expressed through the number of people involved in business operations, the number of products, and the number of sites or warehouses working together.

6.3. Digital Twin Technology

Representing a real-world entity in a virtual (digital) world is the fundamental concept of a digital twin, the latest digitalization technology that supports Cyber-Physical Systems and Industrial Internet of Things. Digital twins are virtual representations of physical objects or systems in our real-world. These physical systems not only encompass an industrial perspective such as a factory, machine, or assembly, but also incorporate objects from nature and social systems. Moreover, these twins can operate at different levels of abstraction, or hierarchy, for example: a single factory can be represented by a higher hierarchical virtual asset while the composition of physical machines in that factory are represented by lower level virtual factories. Digital twins are much more than a simple model of their counterpart. First and foremost, the importance of the creation of the digital twin is linked to an individual physical entity for which its twin(s) exist. In this perspective, an individual digital twin is a mirror and a unique digital service representation of that asset.

Digital twins are merging the physical and digital worlds. They add to the physical asset data and information about the physical asset. In fact, a digital twin becomes a service rendering agent that contains all sorts of information to monitor, test, prognose or service the physical asset. For example, a digital twin of the assembly could access the models and color code services to help the workers operate within their Blue Zone. They interact and communicate with each other, exchanging their artificial Data. This includes real time updates on the current state in the physical world, information about underlying physical properties, nonstop monitoring of the physical processes with fault detection diagnostics and control, communication about upcoming planned tasks. That is to say, digital twins can perform all sorts of preemptive management of the physical object such as remote testing, prediction, guidance, and diagnostics.

6.3.1. Concept and Framework

Digital Twin (DT) technology is a novel concept that uses mapping and simulation techniques to create a virtual clone (or twin) of a physical object or entity, coupled in such a way that changes in one are reflected in the other in real time. As a new concept, the "digital twin" is defined variably, causing confusion about the concept, features, standards, and applications. A Digital Twin is a digital application enabling ecosystem that maps P-World objects, processes, and actors and the digital universe’s corresponding virtual world (V-World), where the digital application constantly visualizes and simulates selected real-world objects, processes, and actors (and their interaction), in order to allow understanding and support of those processes ongoing in the real world. We provide this definition because: (i) It is encompassing. Any P-World object can be modeled with one or more digital applications, giving diverse relationships and links that allow the multiple simulation, modeling, ethical and relationship dimension applications, if the public/private both actors agree; ii) It is an application platform concept, recognizing that Digital Twins themselves generate useful information and analysis when collaboration these software ecosystem applications along the Digital Twin Architecture framework that we propose below.

6.3.2. Benefits of Digital Twins

The benefits of utilizing Digital Twins can be manifold and can cover multiple different areas, such as the customers' experience and satisfaction as well as safety, availability, performance, and reliability, all leading up to diminishing operational costs. Digital Twins can enable the extension of product lifecycles through condition monitoring, predictive maintenance, and upgrades and modifications to products in situ, decreasing the need for physical prototypes. Digital Twins can enhance the physical product's performance through benchmarking and recommendation functionalities. These recommendations can be operational, for instance, when the product is largely automated by AI and can suggest better ways of operation to improve KPIs. The Digital Twin could also suggest modified operation instructions to a human operator. The recommendation could also come down to suggested operational parameters to achieve better KPIs. Through product observation, Digital Twins can be utilized for identification of product design or component issues. And there is the possibilities of testing different configurations and mods of the system virtually before deciding on how to perform it physically. Since operational tasks are not typically carried out by the Digital Twin itself, it does not need to directly interact with the real-world product, although it can be listening to event alerts to help in its visibility of the operation.

Looking further into details, the Digital Twin can contribute to each part of the Product Lifecycle and increase sustainability of both the product and its functioning: Ideally, it can provide useful feedback at each stage of the Lifecycle so that energy and materials are not wasted on unnecessary tests, prototypes, and physical models. A Digital Twin can enhance the design process, helping designers understand how their configuration choices can affect lifecycle energy consumption and global warming. Once in production, the twin can suggest optimization of the manufacturing operations to achieve smaller ecological footprints. In the use phase, the twin can provide insights on how the product can consume less resources. Whenever applicable, the twin can seek to prolong the product lifecycle, by suggesting when maintenance is needed and if so, how to perform it. Finally, when the device has reached its end of life, it could also suggest the modes of parting to minimize environmental impact.

6.3.3. Integration with IoT

Digital twins leverage real-time data for timely and relevant insights. This requires data that is up to date and synchronized in the twin models, in terms of time and parameters. Different domains use different parameters and methods of measuring change and which values are considered updated and synchronized, but in general there are two types of data that will lead to recommendations or action: data about 'twin use' – how the real twin is being used – and data about 'function' – the parameters representing current actual function. Data about twin use usually comes from sensors, regarding machine use – internal sensor signals indicating machine loading or recline, as well as external data from camera or proximity sensors indicating part options, part dimensions, proximity sensing indicating potential jamming of objects, or which type of object would best optimally use the current machine capabilities; and functions data comes from sensor signals linked to parameters that indicate actual machine capability as well as sensor data indicating the actual demands affecting either supply or demand optimization decisions.

The twins synchronize these two data sets and use them for recommending action at the real twin level – for exercise in Collaborative TWIN Ecosystems self-optimizing at the multi-partesian-corporate, regional and corporate-wide levels. These recommendations will focus on suggesting that the real twin react or not – taking its unique parameters of use and function into account – to certain user demands, or messages from another user whose optimum candidate real twin for that demand has been chosen. When that enterprise model decides on an offer or a counter-offer, the data combination for that enterprise pair gets used to check its potential reaction effect. In addition, during the course of twin enterprise collaboration, the twin models continuously adjust the effect parameters to optimize any specific enterprise pair.

6.4. Real-Time Data Processing

Despite differences in architecture and computing resources, all Industrial IoT systems need algorithms and protocols for real-time processing of potentially large databases. In an industrial context, real-time data processing techniques can be categorized into two types: (i) data collection techniques and (ii) data analytics and visualization techniques. Data collection techniques enable effective collection of physical variables of interest from the factory shop-floor, environmental, or product tags, in as close to real-time as possible. Data analytics and visualization techniques enable integration of disparate Industrial IoT data with existing enterprise data, perform advanced analysis to derive information and knowledge about the operational state of the smart factory, and enable propagation of knowledge to the appropriate stakeholders in the enterprise.

Examples of different data collection techniques include data query optimization, multitiered data collection architectures, compressed sensing for image data, high-throughput sensor technology for RGB and thermal image data capture, and lossless data compression techniques. Examples of data analytic techniques include algorithms for sensor fusion, time-series pattern matching, detection of user-defined events and anomalies, classification algorithms for variable/parameter misalignment in connected subassemblies, neural networks for RGB and thermal image data analysis, graph-based algorithms for visibility data connectivity, and reinforcement learning for task-oriented generation of visibility data. The analytical techniques can often utilize supervised, semi-supervised, or unsupervised machine learning models built from industrial large databases containing simulation outcomes, model outputs, and historical and learning data from real-world operations.

Dynamically and intelligently merging and blending Industrial IoT and other process data streams can create greater insight for engineers and managers responsible for operational and strategic decision-making in an industrial environment. Propagation of information and knowledge should be done in the right context to the right decision-maker at the right time with the right level of abstraction.

6.4.1. Data Collection Techniques

The demand for real-time processing of Industrial Internet of Things (IIoT) data is growing exponentially from the industrial sector, due to the rapid adoption of Connected Smart Factories and the advancement in many of Industry 4.0 including Big Data, Artificial Intelligence and Machine Learning technologies. In this section, we combine the aforementioned use cases, and present an IIoT data processing architecture that is built on modern data collection, transport and decision-making frameworks. The architecture leverages leading open-source technologies to make the real-time processing solution easy to use and deploy. The architecture expands the edge-to-cloud concept, and ingests data from multiple manufacturing sources including machines, sensors, automation and supply chain, and then universalizes the data into a format that can be analyzed for easy decision making by engineers and management. This section discusses data collection from both the edge and cloud systems, and the high-level use of capabilities from tools in simplifying the data ingestion, transport and staging requirements. The section presents edge device and cloud systems that push data periodically into a transport pipeline, along with a general decision-making process end-users may want to deploy as part of a digital twin with real-time data analytics and event detection. We also discuss some common data collection techniques from an operational visibility and readiness perspective, and provide a sensitivity analysis on the strengths and weaknesses of both remote telematics systems and internal sensors themselves, placed strategically on the industrial assets.

6.4.2. Data Analytics and Visualization

Access to real-time use case data requires analytics and visualization. Developers must ingest large amounts of raw data to build rules and models for static and streaming data. With streaming features, they can create new events or alerts on top of rules and models for event creation. These rules or models run every second to create higher-level events such as "Device ID is hot." Developers define categories for events and set up associated notifications with dynamic content creation templates, which automatically get populated to create user alerts in emails or other notification outputs. These events are visualized in dashboards showing raw data, created event alerts, and categories, with alerts conditional on event truth.

Event dashboards allow hierarchical alerts, such as "Database contains 100 hot devices (where hot <= X)" or "For Device ID 112233, alert every second if Feature ID 654321 is hot." Adaptive tolerance such as alerts for hot, but for short time or plus X more in last Y minutes (recent event detection on rolling time windows) is configured. Alerts are sent out after smoothing, meaning Device ID 112233 should be hot plus X or more for longer time Tspan.

For event alerting, templated reports allow reports that generate like "This report tells me every day at 9 am what device IDs are hot today. Enable alerts to DT Internals for Device ID 112233 every second to see exactly when it gets hot." Define the schedule, and the data outputs go out every day, month, or week into reports. These templates provide customized reports for visualization to help other units like application developers subscribe to learning groups.

6.5. Operational Visibility

Operational visibility allows people to see what is happening with operations within the factory in real-time. What does it mean? It means being aware of needed and useful information and acting on it at the right time. In a highly automated and connected factory, a number of connected devices can deliver vast amounts of real-time data from devices, machines, tools, and test equipment. Smart and connected devices enable intelligent production processes to see what is going on, how they are influenced by real-time conditions, and how to adapt and respond to those conditions and challenges. In enabled systems, timely, complete, and accurate information can be automatically generated to enable rapid reaction and response. This capability is extremely important for efficient and effective operations in a manufacturing system.

With the digital twin already enabling optimized and predicted designs, when coupled with an enabled operational visibility of real-time performance, the ability to act on that generated data becomes highly effective. The digital twin coupled with real-time visibility becomes a true “digital thread” for the real-time enterprise, where the ability to act on the generated data is built and what was planned can be efficiently and effectively executed in real-time. Simply put, the digital twin supports the design aspect of operations, while the real-time visibility connects the in-depth real-time inspection of operational performance and semantic capture of ongoing activities with real-time response capabilities. It is also important to note that different types of manufacturing processes create different views of operations and related performance metrics.

6.5.1. Importance in Manufacturing

Digital transformation is becoming more and more important for stakeholders and leaders of manufacturing organizations. Typically, they focus on optimizing cost, resource utilization, and capital expenditures. However, nowadays stakeholders and leaders of manufacturing enterprises are asking for all outcomes of a digital transformation to be reviewed. These positive outcomes include Annual Operating Expenses, revenue, and Return on Investment - the effectiveness of the changes. Decision makers want to understand the concepts to be implemented, how they would be implemented, what the investment and operating costs are, timing for realization, and impacts on the organization. They want to see economic justification for the digital transformation investment projects introduced. Investment projects implementing Digital Twin and Industrial IoT are quite promising in terms of impact both in short run and long run.

An economical justification for these kinds of investment projects can come from understanding the impact of reducing unplanned maintenance, which is a relevant goal of a digital transformation. Roots for unplanned maintenance are in operations that were planned or forecasted to happen, but due to unexpected conditions did not happen. In the very harsh manufacturing environment, every manufacturer expects his shop to produce 24/7. Unplanned maintenance directly impacts Availability - the KPIs mostly associated with the OPEX of any manufacturer. Availability shows what percentage of the time is a machine available for its primary purpose - production. Unplanned maintenance increases time that machines are unavailable for their primary purpose. Therefore, manufacturers are attempting to reduce, but do not see how.

6.5.2. Key Performance Indicators (KPIs)

To understand the basic concept of operational visibility presented in this work, it is greatly helpful to establish a good understanding of Key Performance Indicators (KPIs). From a technological aspect, KPIs are challenging to define, but it is crucial to understand the KPIs when deciding upon which technology path an implementation will go because it will dictate a lot of the choices made by the engineers responsible for the technical architecture, the functional architecture, and the processes that will support the technical implementation of the KPI. Regardless of how many available tools there are to enable an implementation, a solution provider must also decide upon what metrics to consider KPI values and which ones to consider caveats. All these requirements and details will eventually dictate how the implementation can be technically thought out since KPIs will represent priority items needing to be architectured in a way that enables feedback control. A false assumption could lead to a mistaken dataset selection or signal processing that supports the design of the technical architecture.

Defining KPIs can be a daunting task because the concept behind KPIs is large and complex in almost every industry. This can be attributed to the fact that KPIs capture the essence of what makes companies or production lines for different types of companies or products unique. In most cases, these companies operate in specialized niches in which they may have invented their own unique process, and KPIs have to be defined based on specific requirements. Hence, this section will present a general methodology, and following that, the user will find illustrative examples and variations. Before any specific KPI is presented, users will be exposed to the general methodology, followed by the various aspects to be considered for determining possible KPI values. After the presentation of the methodology, dedicated sections will detail a few selected KPIs.

6.6. Case Studies

Over the past few decades, the use of Industrial IoT technologies and digital twin models in real-world industrial applications has seen a significant increase. Various industries have deployed such models for monitoring their assets during their operational phase. Digital twins have emerged as the enabling technology with the potential to reshape the industry economy significantly. These advances have inspired us to explore the research and industrial community's interests in using Industrial IoT technologies and digital twin models in real-world industrial applications to support the current economy. In this section, we summarize three case studies where physical systems possess a digital twin counterpart, namely, the manufacturing industry, supply chain management, and the energy sector.

The contribution of the manufacturing industry to the overall GDP has increased over the past several decades. However, due to the high cost of operations, the contribution of the manufacturing sector is continuously under threat from both large multinationals and the emerging economies. Currently, manufacturers are now realizing that they cannot hide the long-standing flaws in their operations. Manufacturers are realizing that achieving incremental changes in their operations is no longer sufficient. With massive competition growing from overseas, manufacturers must begin to rethink how they run their businesses in order to realize substantial improvements from breakthrough ideas, business models, and processes. To compete successfully, manufacturers will have to implement innovative new ideas—faster than their competitors can copy them.

Today's world's economy is increasingly interconnected, and the management of the global supply chain has become the new standard for businesses. Pressure from globalization is causing companies, more than ever before, to streamline their operations and reduce costs. This means not only the use of just-in-time logistics, lean manufacturing, and total quality management, but also a creative approach to integrating all components along the supply chain—from manufacturing and delivering products to providing information and services to consumers. Supply chain integration is the interconnecting of all the links in the supply chain—from product development through sourcing and manufacturing through distribution and installation, and ultimately through supply chain management itself. It requires solving complicated problems using various decision-making activities, such as forecasting and demand management, strategic planning, product design, sourcing and purchasing, transportation, production, inventory, warehousing, and facility management.

6.6.1. Manufacturing Industry

Real-time operational visibility of the shop floor is on the verge to becoming a reality, thanks to the advances in Industrial Internet of Things and digital twin technology. Using unique IIoT capabilities, such as the ability to address all machines and man, the physical-to-digital connection can be achieved for previously disconnected machines as well as people and information locked in individual silos. The contribution of IIoT is twofold: IIoT provides the fundamental technology, and digital twin technology provides a framework that integrates, interprets, and presents the connections and relationships. The result is a dynamic digital representation of the shop floor that can be used to achieve operational excellence. Dynamic shop floor visibility provides previously unseen insights into key performance metrics, such as machine availability, utilization, performance, and quality. Such insights are crucial for identification of issues, and immediate resolution is imperative. The proposed IIoT architecture addresses the needs for real-time resolution of performance issues through fast electronic visibility of the alerts. Machine monitoring IIoT solutions deliver frequent updates about machine status, usually at least once per minute, much faster than the traditional push systems of shop floor control. The proposed digital twin framework, with its focus on the integration, interpretation, and presentation of data from multiple sources, enables faster localization and resolution of shop floor issues, warehouse operation issues, and scheduling delays. The pulse of the digital twin is also discussed: the ability to push electronic alerts about production delays, using standard electronic protocols.

6.6.2. Supply Chain Management

Supply Chain Management (SCM) is an important domain for many industries, responsible for ensuring operational performance while also minimizing costs. However, it is also a complex task, which often pulls together distributed information from many sources and aims to ensure timely availability of products, as well as support internal functionalities, e.g., finance, and delivery capabilities, while also managing external ones, like demand and service levels. In recent years, Supply Chain management has increasingly adopted Industrial Internet of Things (IIoT) technologies to improve the quality and availability of information. IIoT provides a way to interconnect products, facilities, suppliers, and other stakeholders which make up supply chains and interconnects them to create data pipelines, thereby adding to the benefits of traditional capabilities, such as Coordinated Supply Networks, 4D Demand Management, Flexible Ownership Management, Real-Time Support, Financial Alternatives Management, Service and Knowledge-Based Offering Development, Supply Chain Tracking and Tracing Technologies, and Supply Chain Disruption Management.

The paper discusses four case studies which provide best practices related to the implementation of IIoT supply chains with support from IIoT and Digital Twin technology. The first two are from the automotive and food and beverage industry and demonstrate both infrastructure effects and end product effects. The last two are on organizational support and information tools, respectively. In summary, it is shown that Interconnectivity of products, systems, and services enhances information flows interconnected by electronic highways and optimizes SCM. The enhanced visibility improves integrated automation for physical product flows but also supports supply chain triggers, for example, pull control to logistic service capacity, and manage Linked sequential and parallel production operations.

6.6.3. Energy Sector

The function of an up-to-date and responsive monitoring activity is fairly evident in the energy sector where energy production is dependent on an adequate climate condition and energy demands significantly vary during the day, week, month, or season. Traditionally, for an effective global balance, energy transmission and distribution networks are characterized by their ability to ensure rapid cross-border energy transfers replacing local shortages, caused by momentary mismatches in energy production and consumption. In addition, as Client-Side Management Systems are evolving and being deeply integrated with services for User-Interface, there is a growing request for up-to-date and reliable novelty energy services.

The Wind sector may serve as an example as it has been monitoring energy production and analyzing performance in real-time for detecting the onset of malfunctioning operation conditions or just the energy production magnitude, verification of the functioning magnitudes of the energy turbine for decades. Currently, many issues are evolving, as the offshore wind section is moving to its maturity, with the continuous increase of the number of installations on the sea and several projects coming into operation also in Deep Water sites. The request for more and more competitive tariffs are driving Wind Power Operators to increase and extend the operational time period at nominal working conditions of the installed windpower units and at the same time to reduce the Energy Produced Lost due to unexpected malfunctioning events that usually involve long down times.

6.7. Implementation Strategies

Recognizing the capabilities offered by Industrial IoT and Digital Twin technologies, manufacturers can identify the degree of operational visibility they previously lacked and the urgency in transforming their operational challenges into competitive advantages. While consuming digital twin technology adoption services may be the least painful option — and an ideal first step for those manufacturers that lack the required expertise — enlisting the help of advanced technology experts will be necessary for implementation of the most complex IIoT and DT technology stack deployments. However, the most common strategy consists of building internal capabilities by gradually implementing project work with the help of external partners, while training operations staff.

With the previously discussed IIoT and DT technology stack components, manufacturers can realistically set the foundational elements for a multi-phase implementation of operational visibility capabilities, including a rich, user-friendly library of insightful operational performance applications. However, the exact content of these applications may be based on models built by advanced technology services partners, manufacturers' business experts, or a collaborative effort. A critical success factor for the final user experience design and usability is to involve downstream users from all impacted front line operations in the process as much as possible. Moreover, providing the final users with improved application prototypes during the design process for feedback can also significantly improve the usability of the created applications. This is especially true for the user experience of the manufacturing execution systems running on shop floor equipment for operational visibility.

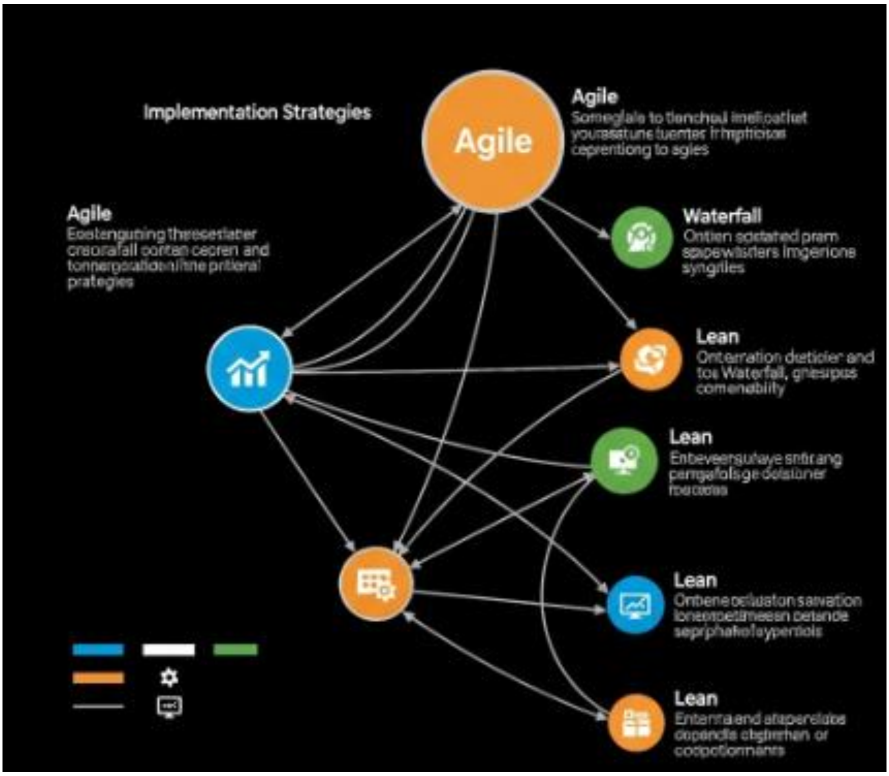

Fig : Implementation Strategies

Planning is an essential step in ensuring Industrial IoT and Digital Twin Implementations for Real-Time Operational Visibility deliver maximum value, while remaining on-track and on-budget. Specifically, physical limiting factors – impossible to overcome during deployment – must be first identified. These limiting factors relate to IT infrastructure, core platforms and methods, as well as on-premise and cloud-based data management and data storage capabilities. After that, resource availability must also be considered.

6.7.1. Planning and Design

Another aspect that should be accounted into consideration before implementing technology-based operational visibility solutions is the planning and design phase. Visualizing and modeling the current as-is operational processes, wiring, and systems help better understand what is going to be connected to what in the implementation stage. The as-is model also permits the future model of the optimized operational process or the process that is reliant on the newly implemented technology to be elaborated upon, revealing potential operational inefficiencies and points to be made more optimized. In conjunction with the as-is and the future modeling design, a gap analysis will help clarify the core requirements of the operational visibility solution, revealing the potential risks while also enabling the technology to be mapped to the requirements. Furthermore, understanding the volume of data from multiple connected systems would also help choose the effective way of storing and storing. A design phase would also help in choosing whether one specific technology will be used to connect all factory systems or if other different technologies may be optimized for other equipment and systems. Proper planning and design will not only permit a smoother implementation process and help with identifying points to request potential suppliers to elaborate technical and operational proposals to respond to visibility needs but also help with ensuring optimized design and configuration from a cost perspective.

6.7.2. Technology Selection

At the Technology Selection phase of implementation of the Real-Time Operational Visibility solution, the following need to be evaluated from the perspective of the Enterprise Digital Twin Architecture in order to arrive at a specific technology stack for the implementation – Quality, and Maturity of the Technology, Technology Components and their Maturity and Interoperability, Time to Deploy, Cost to Deploy, Organization's Technology Stack, Ecosystem Support & Availability of Skills, and Availability of Standards and Best Practices. These topics are elaborated below.

Quality and Maturity of Technology: The organization needs to evaluate the specific technologies that would help fulfil the requirements of Enterprise Digital Twin Architecture from angles of quality and maturity of technology. This would include technologies that directly tie into specific components of the architecture such as data ingestion components, models for to-be and as-is analysis, simulation components, visualization components, and their coupling. It will also include aspects of the quality of the final solution delivered by the technology stack in the context of functional and non-functional characteristics.

Several edge computing or cloud platforms exist that provide support for development of the Digital Twin solution but each has its independence not necessarily sharing components with each other. Organizations need to carefully analyze each specific component and their coupling as part of the evaluation process. If model-based solutions exist for creation of the Digital Twin solution, these provide additional benefit in terms of reduced development time, increased accuracy through utilization of best practices, modularity, and long-term maintenance and improve quality. Such model-based solutions typically fulfil specific qualities and maturity dimensions.

6.7.3. Change Management

After determining what new capabilities to add to their organization and executing their plan, the greatest challenge may still lie ahead for IoT program sponsors. Enabling new machines or systems to deliver increased information visibility is one matter. Figuring out how to modify existing work processes to take advantage of that new visibility is often far more difficult, and there are many examples of IoT initiatives failing for exactly this reason. This is true not only in situations where front-line employees must alter their behavior, but with IT departments as well and their work to ensure smooth, uninterrupted system operation.

IoT programs at an enterprise level do not succeed simply because a new dashboard or other data visualization asset is created. Nobody is going to look at a new visual on a regular basis if it never contributes to bridge long-standing issues or change specific work practices. The most successful efforts drive and enable a measurable change in how people work, and get business units to sign off in advance on that new work design. People need to be asking themselves continually: "How do the new, real-time insights I am gaining from the IoT network change what I do, and if so, how can I do my job better? What should I do differently today, given the information I'm now receiving on the health or performance of the asset?"

6.8. Future Trends

A continual increase in the volume of data and acceleration in the adoption of the IoT connected future has created new challenges and opportunities in how data is used. Operational visibility has historically focused on monitoring equipment health. Although this is still critically important in reducing unplanned equipment failures, it is only one of myriad use cases that are solving some of business problems. Load balancing is one of the key concepts in digital manufacturing, both from the perspective of sustainable and predictable production operations, as well as highly efficient use of production assets. Of the variables that impact load balancing, manufacturing inefficiencies associated with:

- Production bottlenecks

- Variability in production quality or yield

- Variability in production cycle times

have traditionally been addressed through the application of structured improvement methods. Each of these approaches relies heavily on offline or periodic data collection using a combination of direct observations and group studies that leverage statistical analysis to identify and quantify inefficiencies. Continuous Data Driven Improvement represents the continued evolution of research in both the fields of IoT and Artificial Intelligence. From the IoT perspective, a variety of new sensors are coming to market, many designed for industrial applications, that are more accurate while being lower cost, smaller, and easier to install and maintain.

6.8.1. Evolving Standards and Protocols

They work seamlessly with near and far edge platforms that have both standardized interfaces with cloud hosted data lakes, but also edge capabilities for the real-time processing of time-series data that are needed to enable lower latency use cases. From the AI perspective, researchers have been working for decades to solve the problem of high dimensionality. Given a specific use case where historical data has been collected, labeled, and used to train an AI algorithm, the accuracy becomes nearly perfect. What has not been easy is identifying effective algorithms for use cases where labeled, high dimensional data does not exist. The computing power of the cloud and the development of innovative techniques around deep learning are having a dramatic effect at lowering the barrier of entry and improving the ability of untrained staff to implement sophisticated AI algorithms to be run at scale.

6.8.2. Advancements in IoT and AI

Recent years have seen a rapid acceleration in technological innovations enabling new capabilities, knowledge, and systems that promise greater efficiencies, safety, reliability, and security. The progress in artificial intelligence (AI) is a key enabler of the Industrial Internet. By making it affordable to deploy machine learning (ML), natural language processing (NLP), image recognition, and deep learning algorithms at scale, AI provides the means for discovering opportunities for optimization and the tools for interpreting or contextualizing the flood of information being generated by the rapidly increasing number of Industrial Internet systems and the growing ecosystem of devices that they connect with and communicate through – edge devices, sensors, gateways, and clouds.

AI, when combined with the rapidly dropping costs of the Industrial Internet foundations – embedded computing power, cloud computing, sensors, connectivity, and developer tools – provides the ability to characterize and optimize processes not just in factories and power plants but throughout the operational environment: the factory, plant, or rig; the interior and exterior of machines and equipment; the vehicles that service equipment and transport materials; the supply chain and logistics networks within and around industrial operations; and the actual processes that these assets are performing. The increasing size and sophistication of AI models are finding many practical applications for the technologies – for example, the use of large language models to curate and optimize tasks for workforces. Both the size of the models and the demand for cloud computing resources to train and deploy them are, however, raising concerns about the sustainability of current development and deployment patterns.

6.8.3. Evolving Standards and Protocols

According to a report, recent technology innovation and the accelerating evolution of standards and protocols are paving the way for a growth in demand for industrial wireless connectivity. For example, industrial recommendations for WLAN technology are evolving to address industrial use case requirements for wireless connectivity, leveraging the benefits of WLAN architecture to add new capabilities for large networks with high bandwidth, low latency, robust security, and mission critical reliability.

Fig 2 : Evolving Standards and Protocols

Next generation Wi-Fi will add support for a range of new industrial applications, improving radio technology with multi-gigabit data rates, lower cost point to point connectivity over longer distances, lower latency and power for waiting to sleep, and much higher reliability and real-time performance of critical mission data. The challenge is to evolve to a capable industrial technology while also addressing the demanding large scale infrastructure and management requirements mandated by the industrial applications for use of WLAN in factory and enterprise settings.

Bluetooth Low Energy offers a lower complexity implementation path with lower cost and power, targeting the sub-1 Mbps data rates of sensing support and small packet M2M connections. BLE has become the de facto standard for consumer and enterprise indoor positioning and proximity use cases, including everything from phone app capabilities for shopping and venue use, to enterprise scale services that allow precision location tracking of assets and people. BLE in the industrial space will leverage improvements driven by Bluetooth's industrial working group in collaboration with other organizations evolving Wireless Sensor Network protocols for industrial, pro-AV, medical device and automotive applications.

6.9. Conclusion

Large-scale real-time visibility of operational performance indicators, decentralized or centralized, has eluded many industries even today. The centuries-old challenge can now be overcome by adopting scalable architectures, achievable through the distributed computing capabilities offered by the ecosystem and digital twin services. Efforts have been hampered due to lack of architectural understanding, models, methods and experience. This chapter provided insight to the concept that enables digital twins to achieve large-scale operational visibility while maintaining firm linkages to physical operational states and actions, revealing unique capabilities and features. We also demonstrated implementation viability of the approach using proof-of-concept experiments and ongoing use case development in various industries and domains. While operational visibility is achieved through constant monitoring and visibility techniques, operational monitoring is more than visibility. Measurements of performance indicators of various classes are carried out to monitor changing behavior. What is monitored and how is defined by indicator specifications. Measurements provide signatures to the monitored indicators that capture the signatures of physical state changes, to detect abnormal operating conditions, check performance, validate predictive models, detect errors in action implementation, discover modifications to optimal or best-practice action recommendations, while providing input all other digital twin functions such as prediction, optimization, and learning and management of policy/action orchestration. An orchestration policy guides execution, ensuring consistent and repeatable implementation of design objectives specified by digital twin stakeholders. Thus, not only digital twins are the essential technology for achieving real-time, large-scale operational performance visibility and information convergence in operations, they are equally essential for operational monitoring through performance signature measurement.

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