Utilizing Extended Digital Twin to Enable Interactive Business Intelligence Services in Prefabricated Building Components Manufacturing Facilities

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***Abstract*— *Digital Twin (DT) has emerged as a transformative technology across various industries, enabling the creation of virtual replicas of physical entities for real-time monitoring, analysis, and optimization. The integration of DT in industrial settings, particularly in building management and manufacturing, has proven to be a significant advancement. This study aims to investigate the utilization of the so-called eXtended Digital Twin (XDT), a holistic concept of DT able to enhance sustainability in logistics, energy consumption, communications, planning, safety, security, internal mobility, and liveability. The XDT presented in this paper is analyzed and implemented in industrial buildings, including, but not limited to, offices and factories to enable business intelligence, enhancing operational efficiency and decision-making processes within prefabricated building components manufacturing facilities. This paper presents the methodology adopted, and the opportunities and challenges that emerged regarding implementing XDT.*

Keywords*—*EXtended Digital Twin, Industrial building, Metadata, BIM model, Digital Platform

I. Introduction

In recent years, Digital Twin (DT) has garnered significant attention across various industries due to its potential to revolutionize operational efficiency and decision-making processes [1],[2]. A DT is a virtual representation of a physical entity, created by integrating real-time data and advanced simulation techniques [3]. This digital replica allows for continuous monitoring, analysis, and optimization of the physical counterpart, enhancing performance and reducing costs [4]. The state-of-the-art applications of DTs in industrial settings exemplify the versatility and impact of this technology [5]. Integrating this technology with data analytics, interoperable platforms, and measurable metrics could induce the DT into a new era of proactive building management and optimization. Currently, most of the research and developed DT is referred to as a single-building typology, however, the increasing complexity of industrial facilities, often encompassing both office and factory spaces, necessitates a holistic approach to building management. Extended Digital Twin (XDT) [6] aims to improve not only energy efficiency but also to define a holistic view of the building leveraging sustainability for topics such as logistics, energy consumption, communications, planning, safety, security, internal mobility, and liveability. This emerging approach enables data integration establishing data relations and insights from multiple building systems into a unified platform. The opportunity of this approach is to streamline operations, improve energy efficiency in factories and offices, enhance occupant comfort, and drive business growth, thereby enhancing productivity while simultaneously maintaining a comfortable and energy-efficient office environment, enhancing operational efficiency, reducing costs and emissions, and improving user experiences and interfaces [7],[8],[9]. The XDT for industrial buildings also represents an efficient enabler for boosting sustainability targets, therefore facilitating the management of the building's consumptions including but not limited to energy, material waste, and transportation production processes [10], [11]. The complexity of manufacturing facilities for prefabricated building components arises from the various layers that need to be managed, aiming to represent a complex sector involving several variables to address and manage sustainability goals. There are some examples of XDT in industrial sectors on-market as the one developed by Bosch for its Wuxi plant that encompasses both the production areas and the office spaces [12],[13]. A similar example is the Siemens' Amberg plant, which is realized an XDT covering production lines and office areas. This XDT facilitates the simulation and optimization of manufacturing

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workflows, the monitoring and management of energy consumption, and indoor climate in office spaces [14], [15].

In this context, the research reports the preliminary results for the implementation of the XDT deployed in a prefabricated building components manufacturing facility property of Focchi S.p.A. company [16]. The use case novelties for XDT are in the complexities represented by the business activities based on the engineering-to-order (ETO) process [17]. Although the XDT is implemented in a manufacturing company, the company works in the construction sector offering a prefabricated building component within a unitized curtain wall system, engineered by each customized project and consequently with a low degree of replicability of the products. Therefore, the maturity level of the facility is far from product-based companies (like Bosh or Siemens). The complexity of implementing the XDT in a prefabricated building components manufacturing facility is due to multiple actors involved and components that are different for each project.

The main objective of this study is to investigate the opportunities and challenges in developing XDTs to integrate multiple systems to enable business intelligence for this type of industrial company. This involves examining the current IT infrastructures, identifying key areas for improvement based on potential stakeholders' needs, and exploring how XDTs can leverage more informed insights and drive the improvement of different KPIs to produce prefabricated building components. This research contributes in new applications of XDT technology developed within the European project titled DigiBUILD (HE-GA 101069658) [18],[19] aims at addressing the challenges of massive data generation in many sectors including construction by developing innovative digital building frameworks to transform traditional, costly, and space-consuming data storage methods into more efficient digital solutions, while enhancing data accessibility and reducing costs and emissions. This paper within the project demonstrates how data, BIM models, and analytic services in the building sector can offer valuable and positive impacts on complex processes and daily lives.

II. Methodology

The methodology developed in this research follows a systematic structure based on several key steps, each contributing to the comprehensive development and deployment of the XDT:

- Definition of users and services (A): identifying the users/stakeholders who can interact and benefit from the XDT development and utilization. User analysis is adopted to understand their needs and expectations to meet their specific requirements. Based on the user's requirements, a set of possible business intelligence needs are defined and used to define XDT's services to be deployed.
- Analysis of IT and data set (B) - considering the users and their requirements, an in-depth analysis of the available data is conducted to understand the interoperability, accessibility, and reusability of the data. The data set is classified in a data inventory to ensure all relevant data are categorized and analyzed for the XDT platform development.
- A scalable cloud platform (C) - As the XDT continuously receives real-time data on various parameters, it requires robust infrastructure to process this data efficiently. A scalable cloud platform is designed as it provides the necessary computational power and storage capacity to handle these large datasets without compromising performance.
- Development of the XDT for services deployment (D) - the development of the XDT includes the following steps:
  (1) BIM model and management - development of a digital representation of physical facilities including architectural, and structural elements together with production equipment and sensor integrations;
  (2) Sensor's integration - Sensors are integrated throughout the facility to collect real-time data. Identifying critical parameters to be monitored (e.g., temperature, humidity, occupancy, equipment status), selecting appropriate sensors and placement locations, and ensuring connectivity and data flow from sensors to the DT platform;
  (3) Metadata storage and retrieval - Metadata associated with the BIM model and the integrated sensors need to be meticulously stored. This includes detailed information about sensor types, their locations, calibration data, and the specific parameters they monitor. Efficient retrieval mechanisms are crucial for accessing metadata when needed. This involves implementing a structured approach to query and extract relevant data from the knowledge graph or database.
  (4) Early warning engine - monitoring real-time sensor data to detect anomalies and trigger alerts for facility management. It sends notifications and can activate automated controls to address issues like temperature fluctuations or equipment malfunctions. Integrated with the DT, it ensures informed responses, enhancing the building's safety and efficiency.

III. Result

The above-mentioned methodology has been used for the implementation of the XDT in the Focchi headquarters which is owned by the company, and houses offices and facilities that can accommodate up to 350 employees. Focchi is an Italian company that designs, manufactures, and installs bespoken curtain wall-building envelopes. The headquarters consists of two main sections: the office section, which is a two-story building featuring a fully glazed facade with a double glass

Figure 1 - Focchi headquarters (building (1) - an extension of 2100 m^2 and factories (2) - an extension of 13.325 m^2)

stick system, and adjacent to the office space, the factory and warehouse, which stretch across 50,000 square meters.

Focchi is committed to sustainability in its manufacturing processes, requiring 1MW of energy, and has plans to install a photovoltaic (PV) system in two stages over the next three years - 1,500 square meters in the first phase and 1,500 square meters in the second (Figure 1). In alignment with Focchi strategic goals, the initiative also includes sustainability KPIs, productivity, and comfort targets.

A. Definition of users and services

The first step of the methodology is to define the platform's users who could benefit from the XDT. This defines the users and categorizes their objectives for the specific business role helping define the requirements for the specific services. For XTD implementation, the users selected are:

- Facility manager (FM) – The facility manager aims to ensure the efficiency of equipment, maintenance, and safety of office and production buildings. Currently, the facility managers have multiple systems to monitor the building technologies, equipment, cleaning according to the standard regulations and company targets. With the implementation of XDT the facility manager will expect to control the main KPI and gain unprecedented insights into their building's operations, leading to significant improvements in energy efficiency, predictive maintenance, and overall maintenance optimization. In particular, the interoperability of data from multiple platforms is expected through a unique platform dashboard as the user interface.
- Sustainability manager (SM) - The sustainability manager aims to implement strategies to minimize environmental impacts and promote sustainable practices throughout the company. Based on company specificities, the sustainability manager would like to track information for façade typology produced to provide this data to the client. Another objective is to have a dashboard to track KPIs to track sustainable targets requested by certification entities and reduce the time for their collection. With the implementation of XDT the sustainable manager will expect to control the office and production's sustainability metrics, and facilitate the operation to tackle sustainability targets.
- Production manager (PM) - The production manager oversees and optimizes the production processes to ensure efficient output in line with the variability of the façade's components and prefabricated façade manufacturing in line with ETO production organization. The objectives are to keep the quality control of the products and time delivery. With the implementation of XDT the production manager expects to monitor better operational activities for CNC machine productivity, time support production plan, and avoid machine malfunctioning.

Once the platform's users are identified, the next step is the business intelligence activities definition to be implemented in the XDT. In this research, the identified users participated in a co-creation methodology to articulate their needs. Figure 2 shows a schematic representation of the users and the desired services. The key outcome from user interviews in the Focchi use case was identifying common services for both building types.

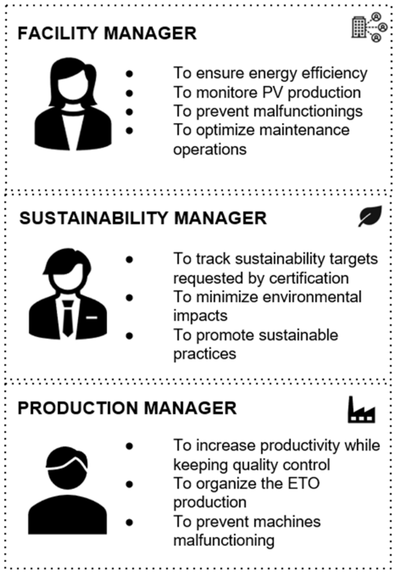

Figure 2 - Definition of users and their needs (facility manager, sustainability manager, and production manager)

In some instances, these services overlapped, such as in controlling energy consumption and monitoring environmental factors like CO2 emissions. Specifically, the factory emphasized monitoring PV production and overall management to prevent failures or facilitate microgrid creation. In contrast, the office focus included indoor comfort, building BMS management, managing meeting room reservations, and integrating data from IoT sensors embedded within the façade.

Based on these business intelligence services requested by the users, key services for the XDT are identified. These services are based on the need to unify databases that consolidate all data and information from various proprietary systems in a unique data lake. This would enable users to share data, detect more informational patterns, and manage diverse issues more effectively. The services defined based on users' needs can be summarized as follows:

- S1 - Interoperability/data quality service
- S2 - AI-based services for finer-grained energy profiling and forecasting
- S3 - Enhanced comfort and well-being
- S4 - Comfort performance contract
- S5 - DT for designing future buildings.

B. Analysis of IT and data set

The dataset encompasses seven distinct collections sourced from office and factory settings (Table 1), primarily capturing variables related to PV generation, energy demand, indoor environmental quality (IEQ), room occupancy, and comfort parameters. Data collection intervals vary by dataset, occurring every minute or 15 minutes, while data storage frequencies range from hourly to daily. This variability highlights the diverse availability of data important for the defined services. Additionally, data accessibility is facilitated through multiple interfaces, including Modbus TCP/IP and API connections. An important task was to define the already existing technologies to the ones to be implemented during the research. The technologies already installed in the Focchi facility are Environmental and energy data (temperature, humidity, wind velocity, flow rate, PV production, energy consumption) collected for Focchi headquarters, including specific data for CNC and silicone machines. For these technologies, historical data were available facilitating the definition of patterns.

TABLE 1 - FOCCHI DEFINED DATASET

#	Dataset name	Data Origin	Variables description	Storage format	Communication
D1	PV Panel (Production and Status)	Monitoring platform	PV production, PV performance, energy consumption	.csv	API
D2	Energy demand (factory)	Monitoring platform	Voltage [V], Current [A], Frequency [Hz], cos(fi), active power [W], Energy consumption for two manufacturing lines and a compressor	.csv	API
D3	Energy demand (CNC machines and silicone machines)	Monitoring platform	Energy consumption for CNC machines and silicon machines (ECf (CNC and silicone machining)	-	
D4	Environmental data (ground floor office)	Monitoring platform	Indoor and Outdoor parameters (T-C°, H-%, C02, Wind, Weather condition, Lux, Radiance	.csv	modbus tcp/ip or API
D5	Energy consumption and indoor/outdoor parameters (meeting room)	BMS	Indoor and Outdoor parameters (T-C°, H-%, C02, Wind, Weather condition, Lux, Radiance, and Feedback from the actuators	.csv	modbus tcp/ip or API
D6	Reservations management (meeting room)	Google Calendar	Data about reservation	-	-
D7	IoT embedded within the façade modules in offices	Monitoring platform	Comfort data, feedback from the users, C02 saved in terms of energy consumption, the productivity of the users	-	-

The dataset implemented during the project was the data from the monitoring of indoor/outdoor parameters (temperature, humidity, CO2, brightness) and energy consumption (monitored for a meeting room), alongside reservation management and IoT sensors embedded in the facade as comfort/productivity data for office and sensors (brightness, temperature, and relative humidity) for the factory.

TABLE 2 – FOCCHI SERVICES

#	Service name	Outputs / Objectives	Involved service systems	Associated datasets
S1	Interoperability data quality services	1. Improve data quality 2. Reduce uncertainty	IoT embedded in the facade - outputs and controls	D7
			PV System	D1
			HVAC + Gas Boilers	D4
			Manufacturing Lines	D3 D2
			Indoor Office Building sensors	D7
S2	AI-based services for finer-grained energy profiling and forecasting	1. Better energy performance	IoT embedded in the facade - outputs and controls	D7
			PV System	D1
			HVAC + Gas Boilers	D4
			Manufacturing Lines	D3 D2
S3	Enhanced comfort and well-being	1. Increase the comfort of the building users 2. Integrate comfort and health-related issues as a key component of energy-related issues	IoT embedded in the facade - outputs and controls	D7
			Indoor Office Building sensors	D4 D7
S4	Comfort Performance Contract	1. Provide insight into expected consumption and real-time to support the business model	IoT embedded in the facade - outputs and controls	D7
			Indoor Office Building sensors	D4
S5	DT for designing future buildings	1. Test the implementation of the building DT solution introduces advanced data analytics for energy, comfort, and well-being analysis.	IoT embedded in the facade - outputs and controls	D7
			PV System	D1

C. *Scalable cloud platform*

The technical solution proposed is a vertical application of the Digital Enabler [20], keeping the following peculiarities on the top:

- A middleware layer to process and harmonize data.
- An open and highly scalable cloud platform
- A dedicated web application for the actors of the solutions
- Standard, interoperability, and security by design.

The DigiBUILD Reference Architecture (Figure 3) is adopted, and it involves tools and technologies that support the creation and management of XDT Services. Moreover, the XDT suite is designed to interact with the other layers of DigiBUILD architecture responsible for providing services related to Data Acquisition and Harmonization (Business Intelligence) and the DigiBUILD Smart Services, other services deployed within the project.

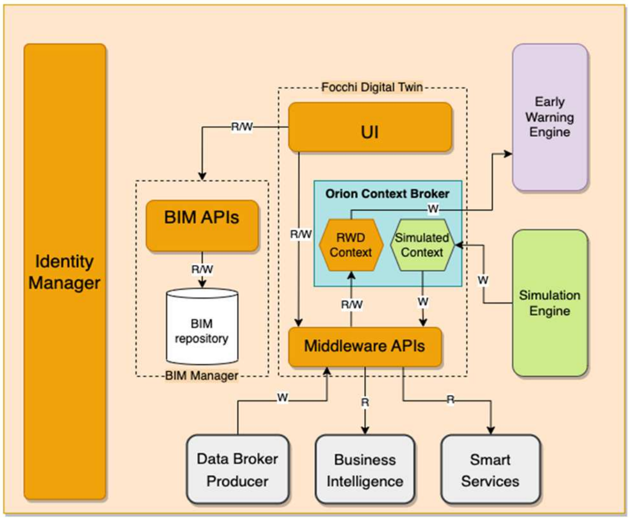

Figure 3 - The DigiBUILD Reference Architecture

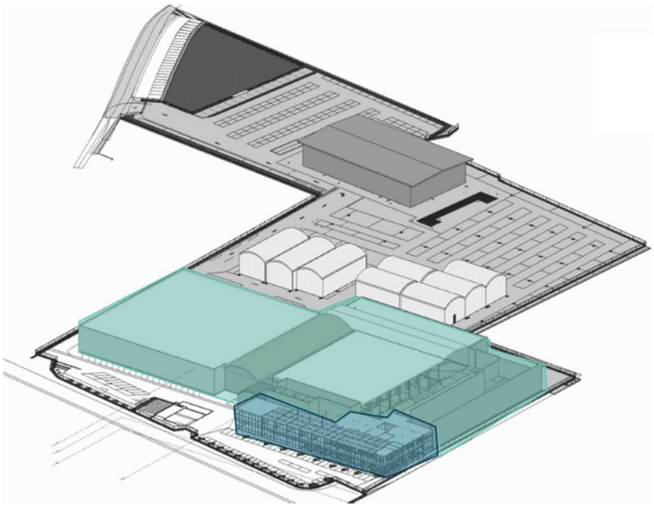

Figure 4 - The BIM model was created using a specific semantic procedure, with designated areas grouped into zones. The finalized version is exported as an IFC file.

The interoperability with both layers is achieved through the development of the Middleware designed to allow the XDT components to retrieve new telemetry (Data Broker Producer), historical and forecast data from the Data Lake (Data Sharing Service) and DigiBUILD Smart Services (Serving Framework).

The XDT architecture for the use case encompasses several components that work collaboratively. These components include the Early Warning Engine, Simulation Engine, Context Broker, Middleware, BIM Manager, BIM Repository, Identity Manager, and User Interface. This architecture promotes modularity, deployment, and updates, while enabling seamless integration and interaction between the services, empowering stakeholders to make informed decisions, optimize performance, and enhance collaboration.

D. *Development of the XDT for services deployment*

The development of the 3D representation of the XDT is imperative to fully enable interactive business intelligence services. By handling the BIM model, sensor integration, metadata storage, and retrieval, the XDT not only provides a comprehensive digital replica of the physical environment but also facilitates real-time monitoring and predictive analysis. Furthermore, the incorporation of an early warning engine enhances the decision-making process by predicting potential issues and providing actionable insights.

1) *BIM model and management*

The data area aggregated in a Building Information Modelling (BIM) has become a cornerstone in managing industrial facilities, providing a detailed and dynamic representation of physical structures. In this research, an advanced application has been developed by Digital Enabler allowing managers to store the latest BIM versions seamlessly [20]. This capability ensures that the DT, a virtual replica of the physical facility, always reflects the most up-to-date information. Real-time BIM loading is a key feature the management application provides, allowing for the immediate incorporation of new data as changes occur within the facility including but not limited to sensors and spaces.

This means that any modifications to the physical structure, such as renovations or updates to equipment layouts, are instantly mirrored in the BIM model (Figure 4). The benefits of this approach are manifold. Firstly, it enhances the accuracy of the DT, making it a reliable tool for monitoring and managing the facility. The application developed in this research leverages the power of BIM to create a dynamic and accurate DT of industrial facilities. By integrating real-time data from sensors and production equipment, the BIM model becomes a living document that enhances the accuracy of the DT, improves decision-making processes, facilitates predictive maintenance, and supports collaboration among stakeholders. This innovative approach optimizes facility management while paving the way for smarter and more efficient industrial operations.

2) *Sensor's integration*

The integration of sensors is a critical component in developing an XDT. Our approach leverages an event-driven architecture and message brokers to efficiently transfer, parse, store, and display real-time data from sensors deployed throughout many facilities [21]. This architecture is designed to handle the continuous data flow from sensors, ensuring that it is processed and made available to the DT platform without delay. By adopting an event-driven model, we can respond to data changes instantaneously, which is crucial for maintaining an accurate and up-to-date digital representation of the facilities and their internal state. This system enables proactive monitoring and management, allowing facility operators to make informed decisions based on real-time

Figure 5 - The BIM model shows the most current view of the facility with real-time sensors.

insights. The sensors integrated into the facility monitor a wide range of critical parameters, including but not limited to temperature, humidity, and luminosity levels. Each sensor continuously collects data and transmits it to the central system, where it is parsed and stored in a structured format. The real-time data is displayed on the DT platform, providing a comprehensive and current view of the facility's environment (Figure 5).

This integration allows for detecting anomalies and trends that may indicate potential issues, such as equipment malfunctions or environmental conditions that deviate from optimal levels. By having immediate access to this information, facility, sustainability, and production managers can take action to address any problems, thereby preventing minor issues from escalating into major disruptions.

3) Metadata Storage and Retrieval

Metadata associated with the BIM model and the integrated sensors must be meticulously stored to ensure the efficient and accurate operation of the DT. In this research we utilize a Knowledge Graph to visualize and manage this metadata, providing a robust and scalable solution for organizing complex information [22]. The Knowledge Graph allows for the detailed storage of metadata elements including but not limited to sensor type, location, relationship relative to a facility, attributes, and operational status. By structuring metadata in a Knowledge Graph, we create a comprehensive, interconnected data model that reflects the relationships between different entities within the facility. This model enables seamless integration and querying, supporting multiple applications and ensuring all relevant metadata is readily accessible. Efficient retrieval mechanisms are crucial for accessing metadata, enabling real-time monitoring, predictive maintenance, and performance analysis by each stakeholder. We implement a structured approach to query and extract relevant data from the Knowledge Graph using SPARQL, a powerful query language designed for querying RDF (Resource Description Framework) data stored in the graph. This retrieval process involves:

- SPARQL Queries - Using SPARQL queries to map the metadata and connect it to the correct building, room, and sensor. These queries are crafted to efficiently locate and extract specific metadata based on various criteria, such as sensor type, location, or operational status.
- Contextual Mapping - Mapping the retrieved metadata to the appropriate contextual elements within the DT. This ensures that the data is correctly associated with the physical and functional components of the facility, providing accurate and relevant information.
- Integration with Orion Context Broker [20], [23] - Leveraging the Orion Context Broker to manage context information and ensure real-time updates. The Orion Context Broker facilitates the integration of metadata with other systems and applications, enabling dynamic data exchange and real-time insights.

4) Early Warning Engine

Digital Enabler's Early Warning Engine plays a pivotal role in the real-time monitoring and management of facilities by leveraging data from integrated sensors [20].

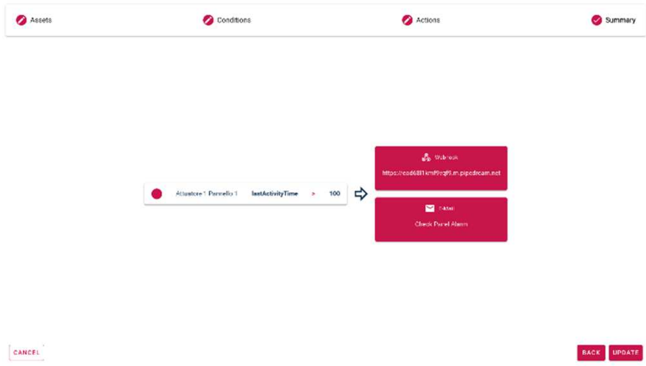

Figure 6 - The Early Warning Engine Rule Overview

This system ensures timely alerts and enables control mechanisms to maintain optimal conditions within the building.
Sensors distributed throughout the facility continuously collect data on critical parameters such as temperature, humidity, and luminosity.

These sensors are the primary data sources for the early warning engine, providing real-time information on the facility's conditions which could affect the overall productivity and quality of the manufacturing. The secondary source of information is retrieved from the company's Google Calendar by seamlessly integrating the API to monitor specific spaces and their occupancy to make smarter rules for action triggers.
The early warning engine is programmed to recognize specific events and anomalies based on predefined thresholds and patterns. For example, it can detect deviations in temperature, CO_2, or humidity. The engine continuously analyses incoming sensor data to identify these events promptly. Upon detecting an event, the early warning engine triggers alerts to notify Sustainability or Production managers. Alerts can be communicated via various channels such as emails, SMS, or push notifications on a dedicated application (Figure 6). The alerts are designed to provide detailed information about the event, including the location, nature of the anomaly, and recommended actions. Beyond alerting, the early warning engine can also activate control mechanisms to mitigate potential issues. For instance, it can adjust HVAC settings to regulate temperature and humidity in specific rooms before an important meeting or conference.

IV. DISCUSSION AND CONCLUSION

Based on the activities conducted at this stage, some early considerations emerge. It is confirmed that the integration of technological data within the XDT framework for manufacturing facilities that produce prefabricated building components presents significant potential for supporting industrial facility management. The research demonstrates that the solution designed for the XDT incorporates real-time data from various sensors and systems, as well as static data information, so that the XDT can provide a comprehensive and dynamic representation of the facility. This integration supports the deployment of business intelligence to enhance decision-making, predictive maintenance, operational efficiency, comprehensive monitoring, and improved collaboration. In particular, the real-time data integration and alert demonstrates to allow for immediate insights into the operational status of the facility, leading to improved efficiency and responsiveness. Continuous data collection and analysis facilitate the prediction of equipment failures before they occur, significantly reducing downtime and maintenance costs. Beyond these operation services, additional services are implemented by monitoring critical parameters such as temperature, humidity, occupancy, and luminosity, so that the XDT helps to optimise energy usage and people comfort. Above all these aspects the aggregation of these data works for environmental conditions, resulting in better resource management and cost savings. The XDT confirms to provide a holistic view of the facility, ensuring that all aspects of operations are visible and manageable, and supports better collaboration among stakeholders by providing access to the same real-time data.

While the potential benefits of technological data integration are substantial, several critical points and challenges must be addressed to ensure successful implementation. The accuracy and reliability of the data collected from sensors are paramount; inconsistent or inaccurate data can lead to incorrect insights and decisions. Ensuring high-quality data involves regular calibration and maintenance of sensors and data validation mechanisms. Data security and privacy are also significant concerns, as the integration of extensive data from various sources must protect sensitive information from unauthorized access and ensure compliance with data protection regulations. Achieving seamless interoperability between different systems and sensors, which may use various protocols and formats, is another technical challenge that requires standardized data formats and communication protocols. A relevant aspect for the implementation of the XDT emerged to be the security requested by the IT company standard. Being the XDT, a cloud-based platform specific security protocols must be planned to avoid any risk breach of data breach in company IT systems in case of promiscuity among IT infrastructure for company's core business and data collectable from non-core activities. This issue opens the need to separate the IT infrastructure in two different infrastructures to support cloud communication without any risk for company security breach and to easily deploy XDT in facilities. Scalability is a crucial consideration as the facility grows and more sensors are added. The XDT system must be scalable to handle increasing volumes of data, requiring robust infrastructure and efficient data management practices to ensure the system remains responsive and reliable.

Integrating and processing real-time data from numerous sensors can be resource-intensive, so ensuring that the XDT platform can process and display real-time data without significant delays is essential for maintaining its effectiveness. User training and adoption are also critical; for the XDT to be effective, facility managers and other stakeholders must be trained to use the system proficiently. Ensuring user adoption and addressing resistance to new technology are necessary for maximizing the benefits of data integration. Finally, integrating the XDT with existing systems in many industrial facilities can be complex and may require significant adjustments to workflows and processes.

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