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Designing Digital Twin with IoT and AI in Warehouse to Support Optimization and Safety in Engineer-to-Order Manufacturing Process for Prefabricated Building Products

Alessandro Pracucci 

Focchi S.p.A., Via Cornacchiara 805, 47824 Poggio Torriana, Italy; alessandropracucci@gmail.com

Abstract: Engineer-to-order manufacturing, characterized by highly customized products and complex workflows, presents unique challenges for warehouse management and operational efficiency. This paper explores the potential of a digital twin as a transformative solution for engineer-to-order environments in manufacturing companies realizing prefabricated building components. This paper outlines a methodology encompassing users' requirements and the design to support the development of a digital twin that integrates Internet of Things devices, Building Information Modeling, and artificial intelligence capabilities. It delves into the specific challenges of outdoor warehouse optimization and worker safety within the context of engineer-to-order manufacturing, and how the digital twin aims to address these issues through data collection, analysis, and visualization. The research is conducted through an in-depth analysis of the warehouse of Focchi S.p.A., a leading manufacturer of high-tech prefabricated building envelopes. Focchi's production processes and stakeholder interactions are investigated, and the paper identifies key user groups and their multiple requirements for warehouse improvement. It also examines the potential of the digital twin to streamline communication, improve decision-making, and enhance safety protocols. While preliminary testing results are not yet available, the paper concludes by underlining the significant opportunities offered by a BIM-, IoT-, and AI-powered digital twin for engineer-to-order manufacturers. This research, developed within the IRIS project, serves as a promising model for integrating digital technologies into complex warehouse environments, paving the way for increased efficiency, safety, and ultimately, a competitive edge in the market of manufacturing companies working in the construction industry.



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Keywords: digital twin; engineer-to-order manufacturing; warehouse management; internet of things; building information modeling; artificial intelligence; safety; optimization; customization manufacturing; built environment

1. Introduction

The advent of Industry 4.0 [1] has spurred a surge of interest in digital transformation across various manufacturing sectors and the advancement to Industry 5.0 is going beyond, also including in the technology deployment the impact on people in line with human-centric approach [2]. Industry 4.0, characterized by the integration of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and cloud computing, is revolutionizing the manufacturing landscape [3,4]. Small and medium-sized enterprises (SMEs) in the construction industry, often constrained by limited resources, are increasingly recognizing the potential of digital transformation to enhance their competitiveness, efficiency, and sustainability [5]. The implementation of digital tools and processes has been demonstrated to streamline operations, reduce costs, improve quality, and enable data-driven decision-making [6–8]. Also, in the construction sector the interest in digital technologies is growing every year, but their penetration into the construction industry is currently slow and limited [9]. The reasons are multiple, including a lack of awareness and understanding of the technologies, high implementation costs, and concerns about

data security. Furthermore, the industry's fragmented nature, traditional practices, and resistance to change often create barriers to digital transformation in the construction industry. However, in the last few years, the integration of Industry 4.0 technologies, such as Building Information Modeling (BIM), Internet of Things (IoT), and artificial intelligence (AI), has been demonstrated to offer significant opportunities for construction companies. These technologies can streamline processes, enhance collaboration, and enable data-driven decision-making, leading to improved efficiency, reduced waste, and safer working environments. While challenges exist, the potential benefits of embracing digitalization and adapting to a "Construction 4.0" mindset are immense, promising a more sustainable, efficient, and innovative future for the construction industry.

This slow, but inexorable, introduction of Industry 4.0's technologies in the construction industry can be particularly relevant for companies focused on manufacturing building components, and for the manufacturing of customized prefabricated building products. These manufacturers challenge standard critical aspects [10], but also the complexity of engineer-to-order (ETO) processes, where customization and rapid response to market demands are paramount. In this context, manufacturing companies realizing customized prefabricated building products within the construction industry are challenging the adoption of these enabling technologies due to the specificity of their contribution to the market, focused on a by-design product delivery based on a specific building project design and specification. The main difference between the ETO model and others in warehouse activities is due to the absence of a pre-existing inventory. Indeed, traditional manufacturing companies have on-shell products manufactured based on selected materials: the Make-to-Stock (MTS) model is based on forecasts of customer demand and are stored in inventory until ordered; the Make-to-Order (MTO) model is based on product manufacturing after an order is received, but based on standard designs; and the Configure-to-Order (CTO) model is based on pre-defined options selectable by the customers, who can choose from a set of options to configure a product to their liking. In opposition, ETO manufacturing is characterized by highly customized products and complex production processes, presenting unique challenges for optimization and efficiency of the inventory due to the components and materials having a low replicability and high variability. These challenges are particularly evident in warehouse management, where the constant flux in inbound logistics, internal warehouse operations, and outbound logistics of bespoke components and materials demand adaptable solutions. To manage this complexity, digital twin (DT) technology, a virtual replica of a physical asset or system, has already emerged as a promising tool for warehouses [11], and research analysis and implementation are addressing ETO challenges [12,13]. By integrating real-time data from IoT devices with BIM and AI, recent research has highlighted the potential of DTs in various industrial contexts, including manufacturing, construction, and logistics. Studies have demonstrated the benefits of DTs in streamlining production processes [14,15], improving supply chain visibility [12,16], and enhancing predictive maintenance [17,18]. However, the specific challenges of ETO manufacturing, such as the high variability in product manufacturing and demand fluctuations, necessitate tailored DT solutions and open a space for deeper investigation. This is also interesting in the context of providing new software to improve the very mature Warehouse Management System (WMS). Indeed, DT development can evolve the WMS through the integration of BIM information and IoT data in manufacturing, highlighting the potential for improved information management and collaboration in asset management as well in operations support [19,20]; in the same way, the integration of AI capabilities to analyze complex warehouse data and generate actionable insights remains a nascent area of research which can exploit the data set fusion guaranteed by DT deployment [10,11]. Additionally, the role of DTs in enhancing safety protocols within ETO warehouses has received limited attention.

Despite the research conducted, DT application in ETO environments remains relatively unexplored and this paper aims to contribute to this research field by presenting ways of understanding and designing the DT implementation conducted within the IRIS

project [21]; this research was funded by the European Union's Horizon 2020 research and innovation program within the framework of the Change2Twin (C2T) [22] project's cascade fundings (grant agreement No 951956). The DT for a warehouse in the ETO model is defined for the warehouse of Focchi S.p.A., an ETO manufacturer of high-technological prefabricated building envelopes. The project aims to develop a DT that leverages the IoT, BIM, and AI to optimize warehouse operations and enhance worker safety. By analyzing Focchi's specific production processes and user requirements, this research seeks to uncover the opportunities and challenges associated with DT adoption in ETO manufacturing. The findings will inform the development of tailored DT solutions that can improve efficiency, safety, and ultimately business intelligence in warehouse management. This research evaluates how DTs can offer unprecedented visibility into warehouse operations, facilitating data-driven decision-making, process optimization, and risk mitigation to improve safety measures. This research allows for the support of the design implementation of a digital twin with technologies such as IoT and AI, demonstrating the potential of the solution implementation in comparison with conventional on-the-market products for warehouse management for engineer-to-manufacturing models. This research allows the evaluation of the effectiveness of DT technology in optimizing warehouse management within ETO environments, highlighting the benefits of a DT by integrating IoT, AI, and BIM for real-time visualization, predictive production planning, and data-driven decision-making. Beyond the technical contributions, the originality of this research lies also in the user-centric design approach, incorporating user stories and KPIs to align with specific workforce needs and business strategies, ultimately enhancing operational efficiency, quality control, and certification alignment, thus demonstrating the transformative potential of a DT in ETO warehouse management.

2. Materials and Methods

This section describes the methods and materials adopted for the implementation of the research activities presented in this paper.

The methods are focused on the approach adopted for the DT definition, with the following methodologies adopted:

- **User-Centric Design:** The project follows a user-centered design (UCD) methodology, prioritizing the needs and expectations of warehouse personnel throughout the development process [23,24]. This approach involves close collaboration with stakeholders through interviews, workshops, and user acceptance testing to ensure that the final product aligns with their requirements and workflows. With the interview, the warehouse processes, material flows, and data exchange procedures are mapped to identify pain points, inefficiencies, and opportunities for improvement. User stories were created based on the gathered requirements. These stories outlined the specific needs, goals, and expectations of different user groups within the warehouse environment.
- **Data-Driven Approach:** The project analyzes the opportunity for the adoption of a data-driven approach to inform decision-making at every stage. This involves analyzing existing data sources [25,26] to support further evaluation, different tracking technologies based on quantitative metrics [27], and using real-time data from IoT sensors to monitor and optimize warehouse processes [14]. Data sources and flows of the use case's softwares are analyzed to identify relevant data points for integration into the DT.
- **Digital Twin Framework:** The development of the digital twin is based on the integration of data from Building Information Modeling and Internet of Things technologies, a well-established approach in the literature [28], and includes manufacturing software's data in Enterprise Resource Planning (ERP). The development of optimization algorithms in the DT draws on research on operations and artificial intelligence to find optimal solutions for complex problems in real time.

The materials used for the IRIS digital twin design are:

- Use case: Focchi S.p.A. manufacturing company, which produces prefabricated building envelopes, is based in Poggio Torriana, Rimini (Italy) and is adopted as the use case. Focchi S.p.A. is a family-owned company founded in 1914 and has established itself as a leading player in the construction industry, specializing in delivering high-tech architectural building envelopes for the construction industry based on an engineer-to-order model. Focchi's expertise lies in crafting bespoke façade solutions for unique buildings, blending craftsmanship with cutting-edge technology. Within the construction value chain, Focchi is engaged in the activities of engineering, manufacturing, and installing building envelopes with the purpose of overseeing the stages from design concept validation to final on-site installation (Figure 1).
- Company assets: the physical and digital assets are listed as follows:
 - Physical assets: three kinds of physical assets are evaluated in the digital twin design:
 - Built environment: the Focchi HQ premises is the physical space of the warehouse to be used in the DT. This research focuses on warehouse and external spaces used to store inbound materials and components and outbound prefabricated façades.
 - Means of transportation: bikes and forklifts used by warehouse operators will be in the DT.
 - Stillages for components storage: stillages, pallets, and iron steels will be tracked in the DT (Figure 2).
 - Digital assets: three kinds of digital assets are evaluated in the Digital Twin design for data-driven analysis:
 - ERP: this software centralizes and manages various business processes and data, including inventory and orders.
 - Production Planner: integrated with the ERP and operations, this tool is used by an operator to schedule production processes based on production loads and material inventory analysis. The solution is manually handled.
 - BIM (Building Information Modeling): this model maintains a digital representation of the physical and functional characteristics of the Focchi facility and its warehouse.



Figure 1. Focchi S.p.A. headquarters in Poggio Torriana, Italy. The facility is composed of an office and factory, and it will be modelled by BIM with data for the warehouse (area locations and georeferencing) to be used in the DT.



Figure 2. Outdoor warehouse in Focchi S.p.A. The ETO model requires a warehouse with a high variability and low replicability of materials and components.

3. Results

The methodology presented above was implemented with the following activities: Interviews and Workshops. These activities gathered information from warehouse personnel to understand their daily tasks, challenges, and requirements for the digital twin.

3.1. Warehouse Process Analysis and User Story Identification

The mapping of Focchi S.p.A.'s ETO warehouse processes was conducted using the user-centered design methodology to identify the key stages of the activities of the warehouse, user groups, and explicit their needs through user stories. This approach facilitated the definition of the process of ETO and the definition of user requirements, and their subsequent translation into technical requirements, aligning with the research objectives. User stories were further utilized to collaboratively establish Key Performance Indicators (KPIs) with warehouse personnel through individual interviews, ensuring a user-centric validation process. Table 1 reports the process within the use case of Focchi S.p.A. but considers a reference of a similar ETO model for customized prefabricated building products. The manufacturing and warehousing processes in an ETO company project involve multiple stages with various stakeholders participating within a flow which supports the identification of users and information to be managed and organized. The process goes from the reception to the management of materials, components, and stillages within the warehouse to the end-product management before shipment. The stages report these activities, and they are used as a reference for a further data-driven approach in DT design. The table summarizes the stages, the tasks, and the users involved. Based on this process analysis, the users are identified for further workshops and interviews. Eighteen employees, representing both Office (O) personnel ($n = 6$) involved in warehouse operations and Warehouse (W) operators ($n = 12$) are engaged in logistical and production line supply activities. These diverse groups provided valuable insights into the current challenges and desired improvements. Analysis of these stories, excluding those beyond the scope of DT implementation, revealed key pain points and areas for improvement. A comprehensive list of user stories and their associated outcomes is available in Appendix A. These findings informed the preliminary definition of technical specifications and business intelligence KPIs to be incorporated into the digital twin. Through a series of workshops and interviews, the process was defined and a diverse set of user stories was compiled.

Table 1. The table reports the state of the art in warehouse management and technology adoption (BIM, IoT, AI, and DT) across industries.

Technology/Approach	Adoption in Warehouse Management	Goals	Advantages	Limitations	References
Conventional WMS	Widely adopted in many industries	Efficient inventory management	Established technology, reliable inventory tracking	Limited real-time capabilities	[29–32]
IoT-based WMS	Increasing adoption	Real-time monitoring and tracking	Real-time data, immediate issue alerts	Requires robust network infrastructure, high maintenance costs	[33–36]
AI-enhanced WMS	Emerging adoption	Optimization through data insights	Advanced analytics, predictive maintenance	High computational requirements, need for quality data	[37,38]
BIM integration in WMS	No or limited adoption in warehouses	Enhanced planning and design	Improved spatial planning and visualization	Requires relevant BIM data	[39–41]
Digital Twin Approach in WMS	Emerging trend	Real-time visualization, predictive maintenance	Comprehensive integration of IoT, AI, and BIM, enhanced decision-making	High implementation costs, data privacy concerns, integration challenges	[11,33,42,43]

These stories encapsulated the specific needs and expectations of different stakeholders. The user stories highlighted the need for a solution, deployable in a digital twin, that could provide real-time data, improve communication, and automate tasks with functionalities which can be summarized in the following needs:

- Enhanced materials, components, and stillages visibility and tracking:
 - Real-time visibility of vehicle traffic, warehouse access points, inventory levels, package locations, and personnel/vehicle locations.
 - Unique identification and tracking of materials, components, and stillages.
- Improved Efficiency and Optimization:
 - Optimized route suggestions for material transport.
 - Efficient packages search functionality.
 - Streamlined check-in process and optimized storage locations.
 - Faster and more productive work through better task assignments and organization.
 - Real-time task status updates and efficient task allocation.
 - Optimized warehouse layout and clear traffic routes.
 - Real-time updates on production schedules and task prioritization.
- Enhanced Safety:
 - Real-time location tracking of personnel and vehicles for collision prevention.
 - Improved visibility for pedestrians and bikers in warehouse areas.
- Communication and Collaboration:
 - Real-time communication platform for information sharing and collaboration.
 - Clear communication of schedules and priorities.
- Resource (personnel and space) Management:
 - More available storage space for prepared materials and components.
 - Effective management of outbound logistics without hindering inbound logistics.
 - Planning of deliveries and arrivals of materials (including forecasting and reservations).

The user requirements are used to define technical requirements. With the purpose of designing a DT using IoT and AI, the technical requirements are aggregated in the following:

- IoT technologies:
 - Sensors for real-time tracking: These would be placed on pallets, forklifts, bicycles, and potentially on workers (privacy concerns to be addressed) to capture location data. These sensors should be supported by IoT antennas to connect the wireless device to communications networks.
 - Proximity sensors: These could be used to detect proximity between objects or people, triggering alerts for potential collisions. This is particularly relevant in the case of promiscuity paths between forklifts and bicycles to reduce the risk of blind spots for the forklift operators.
- AI algorithms:
 - Search algorithms: To enable efficient search and location functionality for packages and materials.
 - Routing algorithms: To optimize routes for forklifts and other vehicles, reducing travel time and improving efficiency.
 - Workload balancing algorithms: To automate task allocation and ensure efficient distribution of work among warehouse operators.
 - Data analysis and visualization tools: To process and display real-time data from IoT sensors in a meaningful way, allowing for quick decision-making.
- Digital twin platform:
 - Three-dimensional layout visualization: To provide a visual representation of the warehouse layout, allowing for better spatial understanding and planning.
 - Integration BIM data with IoT data: To overlay real-time data from IoT sensors onto the BIM model and geolocation, providing a comprehensive view of warehouse operations.
 - Real-time location tracking display: To show the current location of pallets, vehicles, and personnel within the warehouse.
 - Task management system: To assign, track, and prioritize tasks for warehouse operators. The solution should be supported for the production line as well as for the forklift utilization.
 - Communication and collaboration tools: To enable real-time communication and information sharing between workers.
 - Safety alerts and notifications: To provide audible alerts (and/or visual for forklift operator) for potential hazards, such as proximity to forklifts or unauthorized areas.
- Digital twin business intelligence:
 - Dashboard visualizations: To display KPIs in an easy-to-understand format. Dashboards must be developed specifically for office users (desktop) and for warehouse workers (mobile and table) to support tasks and data deployments.
 - Reporting tools: To generate reports on warehouse efficiency, safety, and other relevant metrics.
 - Predictive analytics: To forecast future warehouse occupancy and potential issues in production based on real-time data and production planning.

An analysis of KPIs with the users helps to categorize two main topics of interest to be addressed in warehouse improvement:

- Efficiency and Optimization KPIs:
 - Vehicle turnaround time: The time it takes for a truck to enter the warehouse, unload/load, and exit.
 - Warehouse utilization rate: The percentage and/or sqm of available warehouse space being effectively utilized.
 - Production line downtime: The amount of time that production lines are not productive due to lack of materials or components.

- Inventory accuracy: The degree to which the recorded inventory levels match the actual physical inventory.
- Non-compliance records (NCRs) due to loss: The number of incidents where materials or components are lost or misplaced.
- Picking time and cost: The time and resources required to locate and retrieve items from the warehouse.
- Task allocation and completion time: The time it takes to assign and complete various warehouse tasks.
- Operator efficiency: A measure of how effectively warehouse operators are performing their assigned tasks. The KPIs cannot include operator identification, but they include aggregated data for operators working in similar tasks.
- Overtime hours: The number of hours worked beyond regular shifts due to workload demands.
- Adherence to production schedule: The percentage of tasks completed on time according to the production schedule.
- Time spent on logistics tasks: The total time dedicated to logistics-related activities.
- Safety KPIs:
 - Incident rate related to stress: The number of incidents or near-misses attributed to worker stress or fatigue.
 - Worker satisfaction surveys: Feedback from workers on their perception of safety and well-being in the warehouse.
 - Incidents/near-misses: The number of accidents, near-misses, or unsafe situations occurring in the warehouse.

By tracking these KPIs before and after the implementation of the DT, an ETO company can assess the effectiveness of the system and organization adopted in achieving its goals of optimizing warehouse operations and enhancing worker safety.

3.2. Data Flow and Source Analysis

Interviews revealed that communication gaps between warehouse operators and production line personnel were a primary source of inefficiency at Focchi S.p.A. The lack of real-time visibility into inventory levels and locations further hindered effective decision-making. Additionally, the reliance on manuals, paper-based systems, and siloed data management increased the risk of errors and delays. Analysis of Focchi's existing data infrastructure highlighted a complex landscape of interconnected systems useful to meet the DT's requirements (Table 2) and classified in a data inventory (Table 3). While the company's Enterprise Resource Planning (ERP) system includes a Warehouse Management System (WMS) (data set #1) module for material tracking, it remains underutilized due to perceived time constraints. Currently, information management relies heavily on the ERP system, which is customized for Focchi's manufacturing process and covers a timeframe of up to two months from material acceptance to production line utilization. Product information, including the traceability of raw materials, components, and finished products based on the bill for the materials, is managed within the ERP. In addition to the ERP, Focchi has developed proprietary tools and software, some of which are integrated with the ERP for data input. These tools support production planning (data set #2), inventory checks, and production order scheduling. They can be used in the design of the DT exploiting the IoT, and these new designed data sources can also be used with BIM information (data set #3) and its visualization (Figure 3). Data inventory revealed that real-time data are not essential for most warehouse operations due to the extended storage duration and assembly times. This is also understandable due to the sampling frequency of one every 12 h. However, safety measures, currently lacking data support, necessitate real-time (tenth of a second) interactivity to prevent collisions. This integration can be facilitated through the DT and IoT design and implementation. Data inventory rises are also issues related to challenges of data format, protocol variations, and closed systems (as is the case with ERP). These issues must be addressed by supporting raw data aggregation and analysis in the DT, leveraging existing data sources for their current scope, and simplifying the process

for system integration and software development. The aggregation of these data will be part of the DT implementation with specific database definitions.

Table 2. ETO warehouse activities. The process, analyzed with involved users, presents the sequence of the activities, the tasks and users involved, and the usual duration.

#	Stage	Tasks	Duration	Users (Warehouse Workers)	Users (Office Employees)
1	Material Reception	Unload and inspect incoming materials, verify against BoM, create internal handling unit	1/2 day	Worker in packages Worker in reception	Operations Manager Q&H&S Manager Safety Manager
2	Storage and Inventory	Store materials in warehouse, update inventory records	1–5 days for inventory 3–25 days for storage	Worker in packages Sequencer (Forklift operator)	Operations Manager Facility Manager Q&H&S Manager Safety Manager
3	Production Planning	Create production schedules and orders based on site installation planning and material availability	updated daily	N/A	Production Manager Q&H&S Manager
4	Material Picking	Pick materials from storage based on production orders	1 day	Sequencer (Forklift operator)	Operations Manager Sequencer Q&H&S Manager
5	Production	Assemble components into finished products according to specifications and drawings	1–2 days	Production line workers	Operations Manager Production Manager Production Engineers Q&H&S Manager
6	Packaging and Shipping	Pack finished products, create shipping labels, prepare for transport	5 days	Worker in packages Forklift operator	Operations Manager Shipping Coordinators Q&H&S Manager
7	Delivery	Load products onto trucks for delivery to customers or construction sites	1/2 day	Warehouse workers Forklift operator	Operations Manager Logistics Coordinators Q&H&S Manager

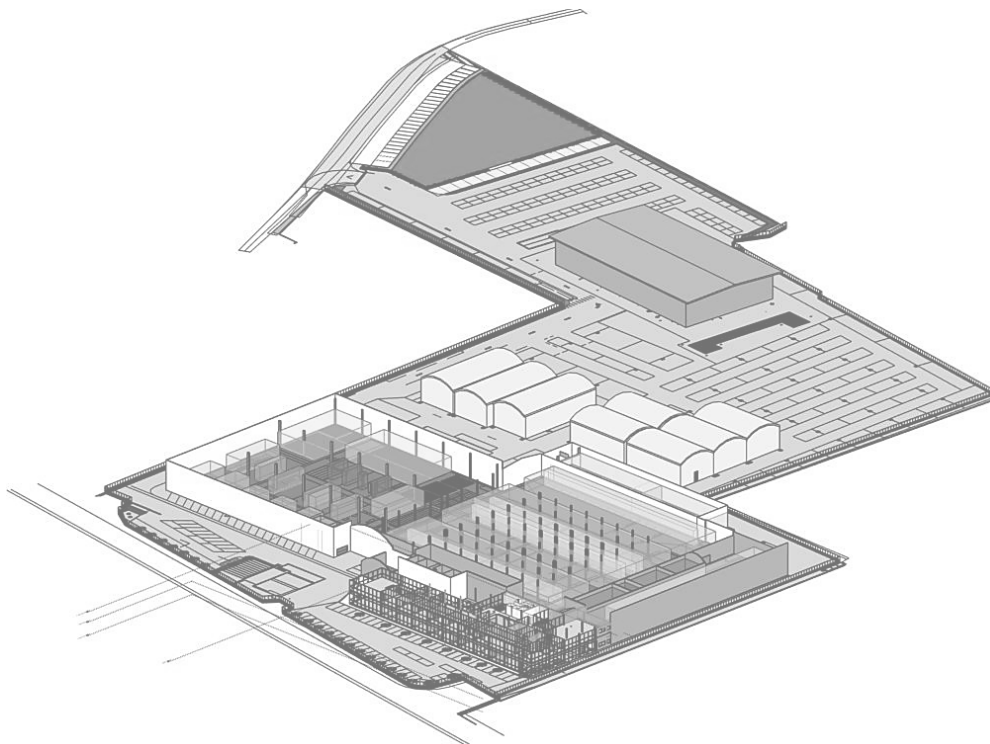


Figure 3. BIM model of Focchi headquarters. The BIM model is used as a 3D model for the digital twin and its georeferenced data and warehouse locations will provide information to be linked to IoT network.

Table 3. Data inventory for useful data and data sources.

Dataset Number	Dataset Name	Data	Type of Data	Data Origin	Storage Methodology	Sampling Frequency	Storage Format	Storage Frequency	Read Frequency	Update Frequency
1		Available quantity	Static	ERP	SQL in on-premise server	12 h	xml	2 times/day	2 times/day	2 times/day
		Description								
		Handling Unit								
		Item								
		Item list								
		Number of production orders								
		Product ID								
		Project								
		Pallet ID								
		Warehouse location (EMPTY) Work ID								
2		Working Center	Static	Production planning	SQL in on-premise server	12 h	xml	2 times/day	2 times/day	2 times/day
		Year								
		Year of production order								
		End data of production								
		Starting data of production	Static	Production planning	SQL in on-premise server	12 h	xml	2 times/day	2 times/day	2 times/day
		Work ID								

3.3. Digital Twin Design and Development

Based on the activities conducted, the design of the DT can be funded. To support the data listed in the existing data inventory and the development of the DT, IoT systems will support the data generated to meet user requirements and related technical requirements for the following concerns:

- Pallet for location in the warehouse: the IoT system aims at optimizing the warehouse, involving geolocating pallets stored in the outdoor warehouse and enhancing tracking capabilities.
- Forklift and bicycle transport routes: the IoT system aims at enabling real-time monitoring of transport routes, encompassing forklifts and bicycles, to ensure efficient and safe movement within the factory.
- Verification of the use of means of transport such as forklift and bicycles by authorized personnel: the IoT system ensures that only authorized personnel use specific means of transport, such as forklifts and bicycles, to enhance safety and control.

The data collected in the DT will be used to support algorithm implementation for:

- Warehouse task optimization: AI aims at using data to define the most productive scenarios and task assignments.
- Real-time collision risk alerts: AI aims at supporting on-board, real-time alarms on forklifts which will alert drivers to potential collision risks with bicycles in unauthorized areas, thus acting as a preventative measure against possible incidents.
- Asynchronous feedback for safety management: AI aims at communicating with safety operators in the factory, who will receive asynchronous feedback to identify areas with the highest levels of criticality, enabling them to take proactive measures to enhance safety.

The BIM model provides a visual representation of the warehouse and geolocation, while the IoT sensors provide real-time data and GPS tracking on assets. The use of a cloud platform for data aggregation and analysis aligns with current trends in digital twin technology, ensuring scalability and accessibility.

Based on the digital twin architecture in the literature and a previous project within the Focchi company [44], the architecture of the digital twin for the ETO company is designed in line with user requirements, technical requirements, the KPIs defined, and the existing data inventory (Figure 4). This design is based on the following:

- Data source:
 - ETO field systems include existing dynamic data sources used by the company to support engineer-to-order processes such as ERP and product scheduling. A BIM-based 3D model of the warehouse is used, providing a visual representation of the physical layout and enabling spatial analysis. The BIM includes a georeferencing of the facility as well as the definition of warehouse areas, locations, and pedestrian paths.
 - IoT field systems are designed to collect real-time data on pallet locations and forklift and bicycle movements.
- Data interoperability:
 - The communication layer moves from data sources to a Data Lake using on-site gateways or a connector with API or MVC solutions.
 - The Data Lake has multiple Data Bases (DBs) related to data sources.
 - The data integration layer connects data from DBs for dynamic data representation and data visualization and analytics tools, and to manage BIM in the DT.
 - The business intelligence layer contains a dashboard for the business intelligence analysis of the Data Lake.
- ETO AI services, with their intelligent layer, are deployed in the DT algorithms to meet user requirements for warehouse optimization and safety.

- The ETO digital twin includes the front end with the user interface and the visualization engine for desktop and mobile.

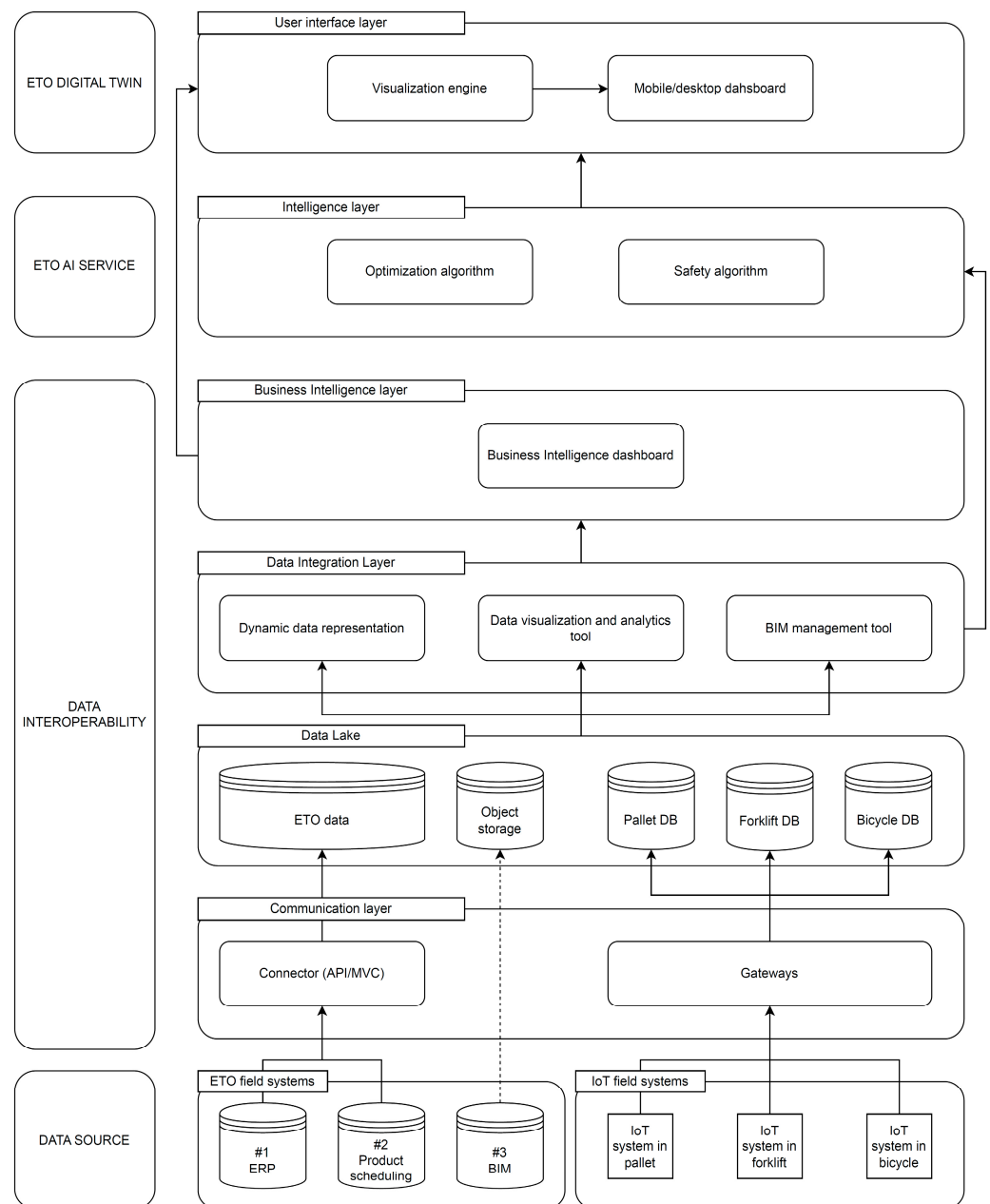


Figure 4. ETO company digital twin architecture. The DT design collects and orders the activities conducted for its definition.

4. Discussion

The insights gained from these results can inform the development of tailored DT solutions for other ETO manufacturers, paving the way for a more agile, responsive, and competitive manufacturing landscape. This research, conducted within the IRIS project focus on addressing the distinct challenges of engineer-to-order manufacturing in the context of warehouse management through a digital twin approach, reveals several key findings with broader implications for the field. The implications of this research are methodological, to define a common approach to support DT implementation in an ETO business model, as well as architectural, to define a comprehensive vision of DT opportunities in this specific use case. Based on the state-of-the-art analysis described

in Table 1, Table 4 reports the results achievable for the digital twin in the ETO process compared with other approaches and with further in-house system integration.

Table 4. The results of the research compare the achievable results in ETO digital twin designed with state-of-art alternative solutions.

Key Achievement	ETO Digital Twin Design	Comparison with Conventional WMS	Comparison with IoT-Based WMS	Comparison with AI-Enhanced WMS	Comparison with BIM Integration in WMS	Opportunity for Further Systems Integration
Improvement of inventory management	Dynamic inventory, real-time organization of warehouse areas and production planning	Static inventory	Dynamic inventory	Warehouse optimization of static inventory	Static visualization	Seamless integration with ERP and production planning, providing a holistic view
Real-time information	Real-time visualization	Lacks real-time capabilities	Comparable, but DT offers better integration	Comparable, but DT integrates spatial data better	Comparable, but DT integrates IoT and AI	Seamless integration with ERP and production planning, providing a holistic view
Predictive production planning risks	Enhanced production planning	Limited predictive capabilities	Limited predictive capabilities	Comparable due to integrated AI models	Limited predictive capabilities	Integration with AI for advanced predictive analytics and production planning
Decision-making support	Data-driven decision-making	Manual and less data-driven	Improved, but lacks comprehensive integration	Comparable due to integrated analytics	Improved, but not as comprehensive	Enhanced by integrating data from ERP and production planning for better decision support
Operational efficiency	High operational efficiency	Efficient but not optimized	Improved, but lacks comprehensive integration	High but depends on data quality	Improved, but lacks comprehensive integration	Enhanced by integrating data from ERP and production planning for better operation efficiency
Cost considerations	High initial costs, long-term savings	Lower initial costs	High maintenance costs	High computational costs	High initial and management design costs	Potential for cost reduction through integrated and optimized systems
Integration challenges	Complex but comprehensive	Simple but limited	Moderate, needs robust infrastructure	High, needs quality data	Simple but limited	Integration with ERP and production planning for comprehensive system management
User-centric design	Aligns with user needs and KPIs	Not/slightly user-centric	Partially user-centric	Partially user-centric	Partially user-centric	Uses user stories and KPIs to ensure alignment with business strategy and operational needs

The initial analysis of Focchi's warehouse processes underscored the complexities inherent in ETO environments. The high degree of product customization and frequent

changes in components lead to unique challenges in inventory management, communication, and overall efficiency. The role of ERP and the production scheduling tool adopted are a key component for warehouse optimization. Indeed, these software already have key data which can be integrated in a DT to boost the collaboration among users as well as support warehouse task organization and optimization in line with materials and products in-house, orders to be delivered, and the production time slot.

An analysis of the result and methodology, replicable in similar use cases, reveals clearly some key steps for the design of the DT for the ETO process. By tracking the implementation and evaluation of features based on user stories, this study contributes to the body of knowledge on the effectiveness of UCD methodologies in industrial settings, supporting the adoption of I4.0 and I5.0 based on a bottom-up approach. The development of user stories through a collaborative process with diverse stakeholders proved crucial for aligning the DT with the specific needs of the workforce in the ETO environment. This user-centric approach, advocated for in DT research, not only fosters acceptance of new technologies in the early stage, as demonstrated by the interactive process, but also ensures that the system delivers tangible benefits to those who interact with it daily. This is also particularly relevant for the collaborative approach to define with the users measurable and verifiable performance metrics. The KPIs identified in the user stories, such as truck turnaround time, picking time, and NCRs due to loss, helps users to understand what they would like to achieve while providing a basis for quantitative assessment of the digital twin's impact on warehouse performance and the implementation of specific business intelligence activities with the data interoperated within the DT.

Another result is that analyzing the user stories by user group can reveal patterns in requirements and priorities, highlighting the unique needs of different stakeholders. It appears that for all the users groups the KPIs are more oriented toward optimization and efficiency (19 of 26 user stories, 73%) to avoid time-consuming activities and inefficiency, while safety KPIs for prevention measures and control have a minor relevance for the current organization (7 of 26 user stories, 27%).

A further interesting analysis, not conducted within the scope of this research, is related to the prioritization of user requirements and, consequently, technical ones. The user stories can be used to prioritize the development of specific technical features within the digital twin based on their potential impact on user satisfaction and overall warehouse performance. For this activity, the involvement of middle and top management is also a key step to have an alignment between the DT and business strategy based on performance productivity, certification acquisition, or other strategic parameters. Indeed, this KPI monitoring in the DT also helps it to be aligned with company activities across the project delivery process, such as quality control—the goal is to ensure that all prefabricated building envelopes meet the highest quality standard—and the company project management for the production activities—the goal is to deliver prefabricated façades on time, and in line with projects milestones. Additionally, the adoption of KPIs has emerged to be aligned with opportunities for certification improvement to guarantee quality control and track improvement year by year in the already-achieved certifications such as ISO 9001 [1], to assess and improve the quality management system, ISO 14001 [2], to assess and improve the environmental management system, and ISO 45001 [3], to assess and improve the safety management system.

The processes and user identification presented in the results will help also to address further platform implementation at different stages, defining user interfaces (UI) and user experience (UX) related to specific tasks and requirements defined by the users. The implementation of this UI is not in the scope of the present paper, and it will be analyzed during platform implementation.

The integration of BIM, IoT, and AI within the DT architecture confirms the novelty of the approach to warehouse management; to support the integration of BIM and IoT in manufacturing with the incorporation of AI algorithms for real-time analysis and decision-making is a distinct advancement. The potential for AI to optimize warehouse layouts,

predict production line needs, and enhance safety protocols aligns with the broader vision of Industry 4.0.

Although preliminary testing results are not yet available, the findings suggest that DT technology can effectively address the unique challenges of ETO manufacturing by providing a comprehensive data-driven platform for warehouse management. The ability to visualize complex processes, track assets in real time, and generate actionable insights has the potential to transform the efficiency and safety of ETO warehouses.

5. Conclusions

The IRIS project offers a compelling framework for leveraging DT technology to address the complex challenges inherent in engineer-to-order manufacturing. By integrating IoT, BIM, and AI capabilities, the DT architecture can support warehouse management in customized prefabricated building product manufacturers, as in the case of Focchi S.p.A., creating a more efficient, safe, and data-driven environment. The DT architecture design serves as a practical blueprint for the implementation of digital twin technology in ETO manufacturing environments. By integrating IoT, BIM, and AI, the DT appears to offer a comprehensive solution for optimizing warehouse operations, enhancing worker safety, and streamlining complex workflows. The project's findings can be directly applied to similar manufacturing contexts where customization and rapid response to construction site demands are comparable. The developed framework, encompassing data collection, analysis, and visualization, can be adapted to various warehouse layouts and production processes. The focus on user-centric design ensures that the resulting DT is intuitive and user-friendly, promoting widespread adoption and maximizing the benefits of digital transformation. Moreover, this research's emphasis on safety protocols and risk mitigation strategies can serve as a model for other industries seeking to improve workplace safety with digital technologies. A key remark is that this research underscores the importance of a user-centric approach in DT design, as exemplified by the meticulous collection of user stories and requirements. By tailoring the DT to the specific needs of warehouse personnel, this research demonstrates the potential for technology to empower workers and improve their daily experiences. Despite these achievements, a limitation of this research lies in the replicability evaluation. The current methodology and design were assessed for a single, specific use case. While this use case may be representative for ETO companies in building product manufacturing, a broader validation across companies with similar ETO manufacturing requirements is needed to demonstrate the effectiveness of the proposed design to check the potential risks associated with scaling this solution in the future. Even though this DT design represents a significant first step towards integrating such solutions within the engineer-to-manufacturing process for building products, its scalability remains a concern. This initial assessment serves as a valuable foundation, but further investigation is necessary to determine the solution's applicability to other similar companies within the building product industry, as well as in adjacent industries with comparable characteristics.

While implementation of DT architecture is ongoing, and consequently subject to testing activities, the design and development phases of a DT for ETO manufacturers have highlighted the transformative potential of a digital twin. The integration of real-time data, 3D visualization, and AI-powered analytics can unlock new levels of efficiency, optimize resource utilization, and enhance safety protocols. However, the design validation should be confirmed with DT implementation focusing on rigorously quantifying its impact on key warehouse KPIs defined with the users. This will provide concrete evidence of the DT's efficacy in ETO environments. This will serve to demonstrate design methodology effectiveness for DT implementation in the specific ETO context. Further research should investigate the scalability and adaptability of this approach to other industries and manufacturing models, potentially leading to standardized DT frameworks for broader adoption. This validation is even more interesting considering the understanding of the impact of the DT on worker behavior and decision-making, crucial for long-term success. Future

studies should investigate the human–machine interaction aspects of DT implementation, ensuring that the technology complements and empowers the workforce.

Overall, the DT integrating AI and IoT in the ETO environment could represent a significant step forward in the application of digital technologies. By addressing the unique challenges of this market segment, this research offers some insights for both researchers and industry practitioners seeking to leverage digital transformation for increased competitiveness and improved operational outcomes.

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Appendix A

The table below reports the user stories and the related user requirements, technical requirements, and KPIs.

User Unit	As a . . . <Type of User>	I Want to . . . <Perform a Task>	So That I Can . . . <Achieve This Goal>	User Requirement	Technical Requirement	KPI
O	Facility Manager	Monitor transit flows and times	Manage access for cleaning/services Optimize space	Real-time visibility of truck traffic and warehouse access points	IoT sensors Real-time data collection and analysis platform	Truck turnaround time Service downtime Warehouse utilization rate
O	Operations Manager	Support in searching packages	Reduce time and cost for picking	Efficient package search functionality	AI search algorithm Real-time location tracking	Picking time Picking cost
O	Operations Manager	Optimize route routing	Reduce time and cost for picking	Optimized route suggestions	Routing algorithm Real-time location data	Picking time Picking cost
O	Operations Manager	Update package locations	Reduce time and cost for storing and picking	Real-time location updates for packages	IoT sensors Real-time tracking	Picking time Picking cost
O	Production Manager	Have more reactive production lines	Efficiently manage inventory emergencies	Real-time inventory visibility and alerts for low stock levels	IoT sensors Real-time inventory tracking AI-automated alert system	Production line downtime Inventory accuracy Emergency response time
O	Production Manager	Have unique locations for stillages	Decrease non-compliance records (NCRs) due to material loss	Unique identifier for each stillage, accurate tracking	RFID/barcode scanning Real-time location tracking system	NCRs due to loss Time spent locating materials
O	Production Manager	Improve acceptance control and storage	Material does not stay in unload areas for long	Efficient check-in process, optimized storage locations	Digital checklists Real-time inventory updates AI optimized storage algorithm	Material unloading time Storage utilization rate

User Unit	As a . . . <Type of User>	I Want to . . . <Perform a Task>	So That I Can . . . <Achieve This Goal>	User Requirement	Technical Requirement	KPI
O	Quality, H&S Manager	Increase visibility of pedestrians/bikers	Reduce the risk of collisions with vehicles	Real-time location of personnel and vehicles	IoT sensors Proximity detection Real-time alerts	Near-miss incidents Accident rate
O	Safety Manager	Improve material positioning in the layout	Reduce time and cost for storing and picking	Optimized warehouse layout	3D layout visualization AI simulation algorithm	Trip/fall incidents Collision incidents
O	Safety Manager	Improve traffic routes (pedestrians, vehicles, etc.)	Reduce risk of tripping and collisions	Clear traffic routes and signage	Digital twin visualization AI route optimization	Trip/fall incidents Collision incidents
W	Sequencer	Have a larger warehouse for prepared materials/components	Manage outbound logistics efficiently without hindering inbound logistics	More storage space for prepared materials/components	Warehouse expansion or reorganization	Outbound logistics processing time Number of outbound logistics delays
W	Sequencer	Share information in real-time with colleagues	Manage production line requests better	Real-time communication platform	Instant messaging Collaborative tools integrated in DT	Production line response time Number of requests fulfilled on time
W	Sequencer	Share information in real-time with colleagues	Avoid wasting time	Real-time task status updates	Task management system Visual progress tracking	Time spent on tasks Number of tasks completed on time
W	Sequencer	Share information in real-time with colleagues	Avoid unnecessary overtime	Efficient task allocation and prioritization	AI-automated workload balancing Real-time task assignment	Overtime hours Number of tasks completed within regular working hours
W	Sequencer	Share information in real-time with colleagues	Improve safety by reducing stress due to more efficient planning	Clear communication of schedules and priorities	Shared calendar Real-time updates on delays or changes	Incident rate related to stress Worker satisfaction surveys
W	Sequencer	Automate the search for materials/components/stillages	Reduce time spent searching and placing items	Efficient search and location functionality	AI search algorithms Real-time location tracking Visual search tools in DT	Time spent searching for items
W	Sequencer	Assign tasks to warehouse operators	Improve efficiency and reduce redundant interactions	Digital task assignment and tracking	Task management system in DT	Task completion time Operator efficiency
W	Sequencer	Have tools to support timely logistic operations	Perform tasks efficiently and align with production planning	Real-time updates on production schedules, task prioritization tools	Integration of production schedule data in DT AI task prioritization features	Time spent on logistics tasks Adherence to production schedule

User Unit	As a . . . <Type of User>	I Want to . . . <Perform a Task>	So That I Can . . . <Achieve This Goal>	User Requirement	Technical Requirement	KPI
W	Sequencer	Have designated storage spaces for materials/components	Ensure materials do not remain in unload areas and are traceable	Organized storage with clear labels	Storage visualization in DT Inventory tracking	Time spent locating materials Storage utilization rate
W	Sequencer	Plan deliveries and arrivals of materials/components	Forecast arrivals/departures, improve safety, reduce congestion	Scheduling and reservation system	Appointment scheduling software Integration with DT	Truck waiting time Congestion incidents
W	Worker in packages	Have better-defined tasks and roles	Work faster and more productively	Clear task assignments and role descriptions	Workflow management system Task management system in DT	Task completion time Productivity
W	Worker in reception	Have waterproof, high-visibility protective clothing	Improve visibility and protection	Provision of appropriate safety gear	IoT sensors Real-time tracking	Incidents/near-misses in loading/unloading areas
W	Worker in reception	Have a device to read QR/bar codes on supplier packing lists	Auto-fill outgoing packing lists	QR/bar code scanning and data extraction	Mobile device or tablet with QR code reader Integration with packing list system	Time spent creating packing lists Packing list accuracy
W	Worker in reception	Share information in real-time with colleagues	Better manage production line requests and avoid wasting time	Real-time communication and information sharing platform	Instant messaging Collaborative tools integrated in DT	Communication efficiency Time saved on communication
W	Worker in reception	Optimize traffic flows	Increase safety and speed	Real-time tracking of vehicles and personnel	IoT sensors Real-time location tracking DT visualization	Incidents/near-misses Time spent searching for materials
W	Worker in reception	Have well-signposted roads and clear signs	Improve safety and organization during loading/unloading	Clear signage and markings	DT visualization of signage Augmented reality navigation	Incidents/near-misses in loading/unloading areas

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