FlexSim-Based Digital Twin Framework for Smart Warehouse Monitoring and Performance Optimization

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***Abstract*—This study presents a Digital Twin–based warehouse monitoring system developed under the Industry 4.0 framework, focusing on enhancing operational efficiency through real-time visualization and intelligent decision support. The proposed model integrates 3D simulation using FlexSim with Asset Administration Shell (AAS) standardization to achieve bidirectional communication between physical and digital assets. The system implements a Nearest Storage Finding Strategy (NSFS) to optimize material handling, minimize travel distance, and improve throughput performance. Key warehouse components, including transporters, conveyors, operators, and storage racks, are modeled to mirror real operations dynamically. Simulation results demonstrate that the proposed system achieves high transporter utilization (82–88%), reduces unnecessary movement, and enhances throughput under varying load conditions. The findings confirm that the NSFS-based Digital Twin framework enables efficient warehouse management through intelligent path selection, dynamic monitoring, and improved resource utilization.**

***Index Terms*—Asset administration shell (AAS), digital twin, flexsim, nearest storage finding strategy (NSFS)**

I. Introduction

The Fourth Industrial Revolution, commonly known as Industry 4.0 (I4.0), focuses on the digitalization of manufacturing processes to improve flexibility, adaptability, and transparency, enabling industries to meet highly diverse customer demands and respond rapidly to changing market conditions [1], [2]. Cyber–physical systems and digital twins have emerged as key enablers of I4.0, providing a digital representation of physical assets that allows real-time, bidirectional exchange of information, predictive analysis, and enhanced decision-making. Despite their potential, existing digital twin implementations are often bespoke, static, and limited to unmovable assets, lacking standardization, dynamic visualization, and direct control capabilities. These limitations hinder interoperability, restrict integration across different systems, and prevent effective optimization of industrial processes [3].

The AAS addresses these challenges by providing a standardized digital representation of each physical asset, encapsulating its properties, functionalities, and lifecycle information while enabling communication between assets for monitoring, control, and optimization. By offering a common structure and interface, AAS ensures seamless integration with other Industry 4.0 technologies and supports the development of dynamic digital twin [4], [5].

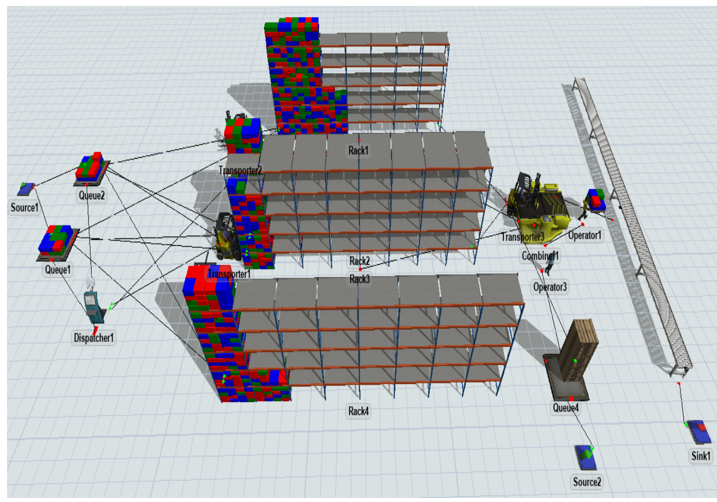

Fig. 1: Proposed 3D simulation model of warehouse operations in FlexSim

Building on these concepts, this study proposes a simulation-based dynamic digital twin framework using AAS and flexSim software. Each physical asset in a smart warehouse including conveyors, Transporters, operators, and storage racks is modeled with generic and asset-specific submodels. Real-time data from IoT sensors are captured and mirrored in a 3D simulation, enabling dynamic visualization, performance monitoring, and bidirectional control. Furthermore, multi-objective optimization is integrated into the framework, demonstrated through flexsim, while a dynamic dashboard provides actionable insights for decision-making under uncertainty [6]. This approach not only enhances operational efficiency but also advances digital twin standardization and Industry 4.0 adoption in smart manufacturing environments.This study makes the following key contributions to the development and application of digital twin technology in smart warehouse environments under the Industry 4.0 framework: (1) Development of a dynamic digital twin using 3D simulation. (2) System integration architecture and bidirectional communication with AAS standardization for warehouse. (3) Demonstration of simulation-based optimization and dynamic dashboards for operational decision support.

II. Proposed System

The proposed system presents a Digital Twin–based warehouse monitoring framework designed to evaluate a storage allocation strategie the nearest storage finding strategy. The goal is to analyze how each approach affects warehouse efficiency in terms of material handling time, storage utilization, and overall system throughput. The system employs a simulation-driven digital twin model of a smart warehouse that continuously mirrors real-time operations. Core assets such as storage racks, conveyors, transporters and operators are modeled in a 3D simulation environment using FlexSim Fig.1.

a) Dynamic Digital Twin Development: A 3D simulation-based digital twin is created using flexSim to mirror real warehouse operations involving conveyors, transporters, storage racks, and operators. The simulation model replicates real-time processes such as receiving, storage, and order picking, enabling visual monitoring and analysis of system performance.

b) AAS-Based System Integration: Each asset was represented through an AAS to ensure interoperability and standardization. OPC UA and AutomationML (AML) were employed for communication and data exchange, allowing bidirectional connectivity between physical assets and their digital counterparts for both sensing and control functions.

c) Simulation-Based Optimization and Dashboard: A multi-objective optimization was integrated into the simulation to improve storage planning, balancing throughput and energy efficiency. Additionally, a dynamic dashboard was developed to display key performance indicators such as transporter utilization, operator activity, and total throughput in real time, providing decision-makers with enhanced visibility and control.

III. Performance Analysis

The performance analysis of the proposed warehouse monitoring system using the NSFS demonstrates significant improvement in operational efficiency. The simulation results indicate high transporter utilization, balanced operator activity, and minimized travel distances due to optimal path selection. The results in Fig. 2 indicate that transporters achieved an average utilization of 82–88%, with Transporter 1 showing the highest utilization at 87.6%, reflecting optimized routing and minimal idle time. Operators maintained an average active rate of around 22%, indicating balanced coordination between manual and automated activities. The total travel distance for transporters averaged about 2100 meters, confirming that the NSFS effectively reduces unnecessary movement by assigning the closest available storage locations. Furthermore, the system achieved a noticeable increase in throughput, reaching its maximum efficiency under high-load conditions. All performance metrics were obtained through the flexSim dashboard, which provides real-time visualization and quantitative analysis of transporter and operator performance. Overall, these results confirm that the NSFS-based digital twin framework enables improved resource utilization, reduced travel distance, and enhanced real-time warehouse performance through intelligent path selection and task allocation.

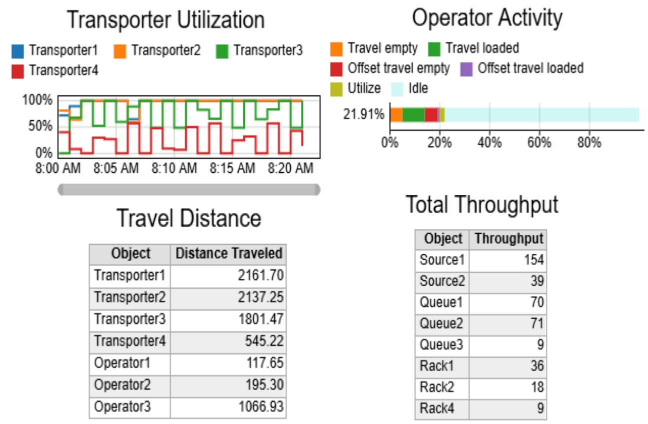

Fig. 2: Operational performance of transporter utilization, operator activity, travel distance, and total throughput

IV. Conclusion

This paper proposed a simulation-based digital twin framework for smart warehouse monitoring and optimization using the NSFS. The developed model effectively integrates 3D simulation with standardized AAS communication, enabling real-time synchronization between physical and digital environments. Performance evaluation results indicate significant improvements in transporter utilization, travel distance reduction, and throughput efficiency, proving the effectiveness of the NSFS in optimizing warehouse operations. The digital twin model provides a scalable and interoperable solution for Industry 4.0 environments, allowing flexible performance evaluation and dynamic control of warehouse processes. Future work will focus on integrating predictive analytics and additional storage strategies to further enhance automation and decision-making in intelligent warehousing systems.

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