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A ROADMAP TOWARDS A DIGITAL TWIN FOR AUTOMATED STORAGE AND RETRIEVAL SYSTEMS

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ABSTRACT

Automated warehouses have been playing a central role in contemporary supply chain operations, offering significant advantages over traditional systems. This research project aims to develop a digital twin (DT) for automated storage and retrieval systems. The study explores the value of DT proposing an architectural framework and investigating the main development steps. A discrete event simulation model was developed and integrated with a dynamic-programming optimization algorithm to generate the sequence of storage and retrieval missions for the handling machines. Validation against a small-scale warehouse setup demonstrated the model reliability in predicting operational times. A gated recurrent unit-based metamodel coupled with a particle swarm optimization algorithm was developed to solve the order picking sequencing problem. The study contributes to the theoretical understanding of DT by offering a structured approach to their development and integration. In practice, the DT serves as a powerful decision-support tool by providing real-time insights and predictive analytics.

1 INTRODUCTION AND RESEARCH BACKGROUND

Intralogistics is a term that refers to the management, control, and optimization of material and information flows within a facility. It encompasses a wide range of activities, including storage, handling, and transportation of materials (Drissi Elbouzidi et al. 2023). In this context, the last decades have seen rapid advances in the field of automated storage and retrieval systems (AS/RSs), which play a pivotal role in supporting modern supply chain processes (Ferrari and Mangano 2023). With the recent global developments and the resulting increased pressure on supply chains, intralogistics and AS/RS have been required to be more and more flexible to handle the day-by-day operations (Kembro and Norrman 2019). In the context of Industry 4.0, the new technology called Digital Twin (DT) emerged. DTs are defined as simulation-based virtual counterparts of a physical system, which exploits real-time data synchronization to optimize the actions undertaken by the physical system (Kritzinger et al. 2018). The implementation of DTs offers significant advantages, such as for instance the ability to simulate what-if scenarios to evaluate the impact of different operational strategies to be directly applied in the physical system (Braglia et al. 2019). Despite the clear benefits of DTs and the growing attention they have been receiving in recent years, their application to intralogistics processes and more specifically to AS/RS has been largely overlooked. Therefore, this study aims to explore the significance and potential applications of DT technology in AS/RSs, by proposing a comprehensive architectural framework and by delineating the principal stages involved in its development and implementation. This work focuses on a specific AS/RS configuration called multi-level shuttle (MLS) system, designed for industrial contexts that require high performance but characterized by limited spaces (Ferrari et al. 2024).

2 RESEARCH METHODOLOGY

The research project started with the development of a DT architecture, in order to define the various components of a MLS system and their interactions. Once defined the general architecture, the digital model (DM), serving as the virtual counterpart of the physical warehouse, was created. The system was conceptually modelled using a Unified Modelling Language class diagram, and then a discrete event simulation model was developed in AnyLogic to predict time and energy consumption metrics. Time and energy consumption models were adapted from existing literature and enhanced by incorporating additional variables to more accurately represent the system behavior. The DM was also supported by a dynamic programming algorithm used to generate the optimal sequence of storage and retrieval missions required to complete a given number of tasks. It was developed in Python and interfaced with AnyLogic through the Pypeline library. Once completed the implementation of the DM, it was calibrated and validated comparing its predictions with the performance of a small MLS system installed in Politecnico di Torino (Ferrari et al. 2024). The integration of artificial intelligence (AI) within the DT framework for an AS/RS represents a significant advancement in enhancing the system capabilities and overall efficiency (Ivanov 2023). Thus, an AI module for the DT was developed. A gated recurrent unit-based neural network (NN) was constructed, trained, and evaluated on synthetic data generated by the DM in order to predict the makespan to complete a set of picking orders. To solve the order sequencing problem, a swap-sequence based particle swarm optimization (SSBPSO) was coded. In the algorithm, the fitness function was evaluated using the previously trained NN. The AI module capabilities were then evaluated in different scenarios, determined by order sets of different dimensions and different warehouse capacity values.

3 CONCLUSIONS

This research contributes to the deeper theoretical understanding of DTs for AS/RS by providing a detailed and structured approach to their development and integration. Moreover, the developed DM integrates simulation and optimization, which has been demonstrated to be an effective approach to study and manage automated warehousing systems. By defining a structured approach to validate such DM, this work has also made some progress in the development of DM oriented to DT. Finally, by demonstrating the effectiveness of the combination of NN with advanced optimization algorithms such as SSBPSO, new, powerful methodologies to extend DT capabilities and address the challenges of automated warehouse operations are introduced. From a practical standpoint, implementing the DT has the potential to significantly enhance operational efficiency in automated warehouses, serving as a powerful decision-support tool by providing real-time insights and predictive analytics. The proposed architecture can assist managers in customizing the development of a DT for their specific system needs. Additionally, the implementation steps outlined in this work offer logistics companies valuable guidance in identifying potential challenges when implementing a DT in an industrial setting. The next phase of this research will focus on the comprehensive integration of all DT components into a unified framework. The first step will be to ensure uninterrupted data flow between the physical warehouse, information technology systems, DM, and AI components.

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