Digital Twin for Intralogistics

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1. Introduction

As companies strive to meet customer demands, they are beginning to embrace the concept of Industry 4.0. With a goal of achieving smart factories, Industry 4.0 centers on increasing automation through the application of technologies including digital twin (DT) simulations, the Internet of Things (IoT), sensors, and advanced communication systems. A key component of this is the development of smart intralogistics.

Faced with increasing demand, ever shorter lead times, labor challenges, and world events (such as pandemics, natural disasters, geo-political conflicts, etc.), reliable, agile, and sustainable intralogistics are needed to minimize and avoid supply chain disruptions. To address this, digital twin for intralogistics is a tool that is gaining strength to enable better decisions making and more efficient intralogistics.

The term, *digital twin,* was coined in the early 2000's by Michael Grieves [1] and refers to the virtual representation of a physical object, system or process, which can be used to simulate, monitor, and optimize its real-world performance. Establishing a crucial benchmark for digital twins, NASA highlighted "a need for a paradigm shift from conventional approaches to digital twins for increased safety and better reliability for future generations of NASA and U.S. Air force Vehicles" [2]. Since then, the use of the term digital twin has grown exponentially. As evidence of this, a search for "digital twin" on Google Scholar shows the number of yearly publications has increased dramatically from 88 in 2013 to over 21,500 in 2022 (see Figure 1). Research in digital twin has been applied in various applications including engineering, physics, material science, manufacturing, healthcare, automotive, and supply chain.

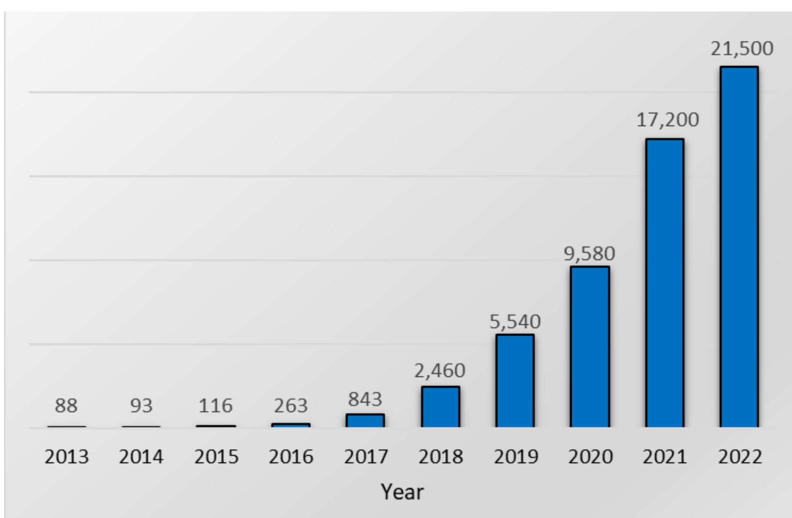

Figure 1. Digital twin research publications (Source: Google Scholar).

Furthermore, the term, digital twin, has evolved in many directions to have a meaning that seems to vary based on the context in which it is being used. In this paper, we define a digital twin for intralogistics to be a virtual representation of the end-to-end operation of a material handling facility in the form of a dynamic simulation model. The digital twin mimics the flow of material through the facility and is used to evaluate alterative system designs, aid in planning decisions, and optimize operational performance.

2. Why DT for Intralogistics?

A common digital twin example is a digital twin of a product such as a jet engine [3]. In this type of digital twin, physics-based models are used to represent the moving parts in relations to one another and their impact on the surrounding environment. For example, a model may simulate the turning of gears and turbine in a jet engine resulting in air displacement and thrust. Just like the jet engine, an intralogistics system consists of a complex set up components (people, equipment, products, etc.) moving and interacting within a facility. A digital twin can be used to understand the operations of the system, identify system constraints, compare alternatives solutions, and evaluate decisions in a virtual environment.

A case study presentation involving intralogistics digital twin modeling and analysis for internal warehouse management [4] illustrates the problems, methods, and benefits of digital twin simulation. The digital twin represents the end-to-end flow of a warehouse including truck unloading, product scanning, rack replenishments, and shipments. The simulation considers stock levels, rack capacity, worker and machine capacities and schedules, processing times for operations, and product picking time and prioritization.

Some reasons given in the case study for why digital twin simulation is important for warehousing include the ability to:

- Analyze complex scenarios and identity areas of improvement through a data-driven process;
- Provide end-to-end warehouse operational results;
- Provide results in terms of relevant key performance indicators;
- Assess uncertainty and risk; and
- Examine multiple alternative scenarios to support business decisions before making major investments.

Although not quantified the expected benefits from utilizing the warehouse digital twin include direct savings associated customer service; reduction in operational costs; decrease in total warehouse personnel; and increases in performance [4].

Some examples of specific issues that the warehouse digital twin can be used to address include the following [4]:

- How can receiving capacity be increased?
- Should dedicated storage be used?
- What is the impact of integrating co-bots in picking?
- What is the impact of introducing robotic arms in packing?
- What types of automation could be introduced to increase throughput?
- Where will new bottlenecks form if particular improvements are made?

Another benefit of the digital twin simulation is the ability to run "what-if" scenarios to assess uncertainty and the robustness of various systems configurations. Some examples of the areas that could be evaluated include assessing the inbound processes such as the number of docks, and scanning process; testing various number of resources (forklifts, workers, etc.) and shift configurations; testing product placement strategies and rack layouts; and evaluating alternative picking strategies and prioritizations [4].

This case study illustrates just some of the potential problems that can be addressed and potential benefits that can be gained from digital twin in the area of intralogistics. In the next section, we provide a digital twin framework for intralogistics and discuss some of the details involved in creating a digital twin.

3. DT for Dynamic Intralogistics Simulation Analysis

Intralogistics is a complex system involving a wide range of functions including receiving, storage and retrieval, picking, kitting, packing, palletizing, labeling, and shipping, among others. In addition to these functions, there are a many management and support functions that utilize sophisticated equipment and control strategies including asset tracking, inventory management, scheduling, and maintenance. Furthermore, the material handling and processing tasks can involve a combination of methods including operator-driven forklifts, automated guided vehicles (AGVs), conveyors, autonomous mobile robots (AMRs), drones, robots, people, etc. all with varying capabilities, capacities, and limitations. Finally, the system includes the facility itself and the related infrastructure and utilities required to operate.

Given the all of the interactions and interdependencies among the components of the intralogistic system, we need a tool such as simulation that is uniquely capable analyzing such systems. Simulation allow for modeling the behaviors system components and dynamically representing the behavior of the system as the components interact over time. Furthermore, the goal of a digital twin simulation is to provide a virtual dynamic replica of the physical intralogistic system to enable decision support resulting in operational efficiency.

Next, we present a framework for digital twin simulation and discuss approaches for applying digital twin simulation to intralogistics.

3.1 Digital Twin Framework

A conceptual digital twin framework for intralogistics is depicted in Figure 2. The framework consists of three main components: a) the physical intralogistic system; b) the data and control systems; and c) the digital twin. The digital twin itself consists of two main components, the simulation model and an analysis/testing component [5].

The physical intralogisic system includes all of the actual components of the system that interact within the facility as well as those components that provide inputs and outputs from the facilities such as delivery trucks. Within the facility, there are active components such as forklifts, people, products, etc. as well as stationary components such as racks and aisles. The components within the system are equipped with sensors that can generate data about the current state of the system including tracking of forklifts (position, velocity, load, etc.); tracking of unit loads; tracking of people (task, pick rate, movement, etc.), among others.

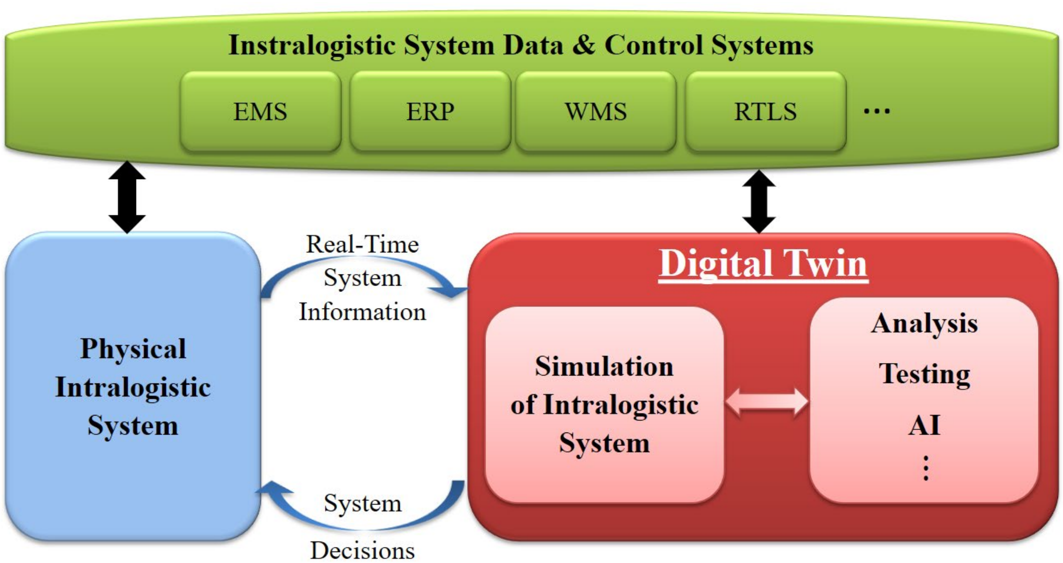

Figure 2. Digital twin for intralogistics framework (adapted from [5]).

The intralogistic system data and control systems store system information about the operational aspects of the company and can be used to manage the intralogistics.

These systems, although they may vary among companies, can include an enterprise management system (EMS) and/or an enterprise resource planning system (ERP) for managing asset and operational information such as customer orders, etc.; a warehouse management system (WMS) for managing inventory and warehouse assets; and a real time location system (RTLS) for actively tracking asset location and movement within the facility.

The digital twin consists of a simulation model and an analysis module. The digital twin simulation is a virtual representation of the physical system. Provided the sensor information and the relevant information from the data and control system, the digital twin simulation should represent the current state and behavior of the physical system. As the state of the system changes over time, the information about the performance of the system can be analyzed. Through the analysis component, the digital twin simulation model can be used in serval ways for analysis including the following:

- Forensic Analysis - The history captured by the digital twin can be used to help identify how/why a situation occurred;
- Predictive Analysis – Given the current state of the system, simulate the near term future to identify any issues that may need to be addressed;
- Alternative Analysis – Utilize the simulation model to evaluate system design/configuration alternatives;
- Capacity Analysis – Conduct a stress-test of the system using the simulation model to determine capacities, bottlenecks, and constraints;
- What-if Analysis – Explore opportunities and improvement scenarios in the virtual simulation environment; and
- AI Development – Utilize the simulation model to train/test artificial intelligence (AI) methods that could be implemented in the physical system.

Additional examples of how digital twin can be applied for intralogistics will be discussed in section 4.

3.2 DT Simulation Approach and Data Acquisition

Data acquisition is perhaps that most critical and challenging aspect of digital twins that are used for operational decisions. Some of the key aspects to consider when building the digital twin are – how will the digital twin be used; and what type of questions will the digital twin be expected to answer? The answers to these questions can impact the type, quantity, and frequency of data that will be needed to be collected from the physical system. For example, if the digital twin is primarily going to be used for system design, planning, and operational decisions such a facility layout, the number of vehicles to operate, worker scheduling, etc. a discrete-event or agent-based simulation modeling approach may be appropriate and data associated with asset locations, processing times, travel times, etc. will need to be obtained from the physical system. However, if the analysis is going to center around equipment capabilities and limitations (e.g., robotic arm movement; forklift kinematics; etc.) then a physics-based simulator will need to be integrated into digital twin and the associated data will need to be collected from the physical system.

The bright side of data acquisition is the rapid expansion of IoT. As devices themselves are being equipped with sensors and in some cases computational power, devices are able to share information about their current status through the cloud (see Figure 4). With that said, the communication protocols used may be proprietary or require special methods to obtain and transform the data into a form that can be utilized by the digital twin simulation. Additional details about data acquisition for digital twins can be found in [6,7].

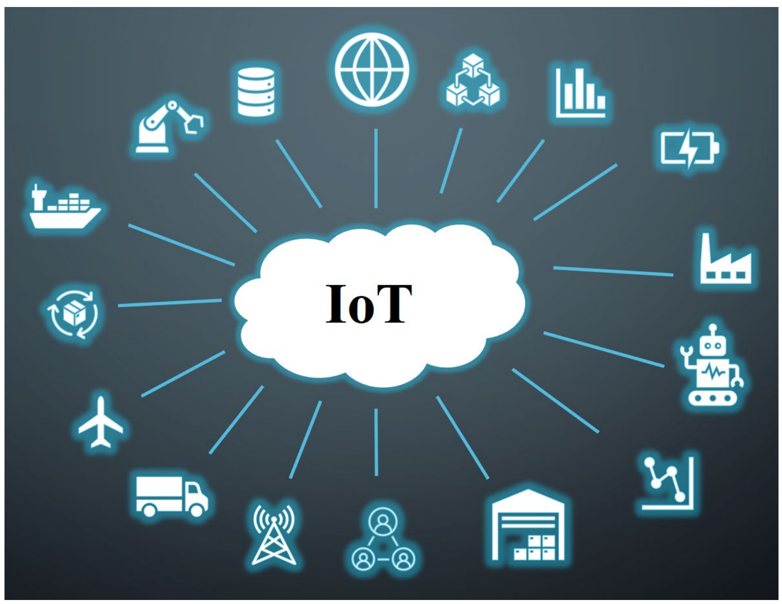

Figure 4. Internet of Things (IoT) for intralogistics data.

In addition to data acquisition, reliable, low-latency, communication and networking is critical to successful digital twin implementation. The digital twin requires a robust and reliable communication and networking infrastructure to receive data from sensors and transferring information to the data acquisition and processing system, particularly when attempting to use the digital twin for real-time (or near real-time) decision making [8].

The communication network could include include wired or wireless networks, cloud-based platforms, and edge computing devices. Furthermore, it is important that the communication system be secure, so that transmitted data is that of the physical system and not that of a malicious hacker.

Finally, the digital twin needs to provide a user-friendly interface that allows operators, engineers, and other stakeholders to access, visualize, and interact with the data and the model of the system. This can include web-based portals, mobile applications, and other tools that can be used to monitor the system status, troubleshoot problems, and optimize system performance [9].

4. Applications of DT in Intralogistics

The application of digital twin in intralogistics are many fold. To illustrate some of these applications, we will look at decisions as they may occur in the life of a facility (or the life of a digital twin) as illustrated in Figure 5. In particular, we will discuss applications related to facility design or redesign (strategic decisions); virtual commissioning; operational planning; and real-time control. Finally, we discuss the use of digital twin for training with the use of AR/VR technology.

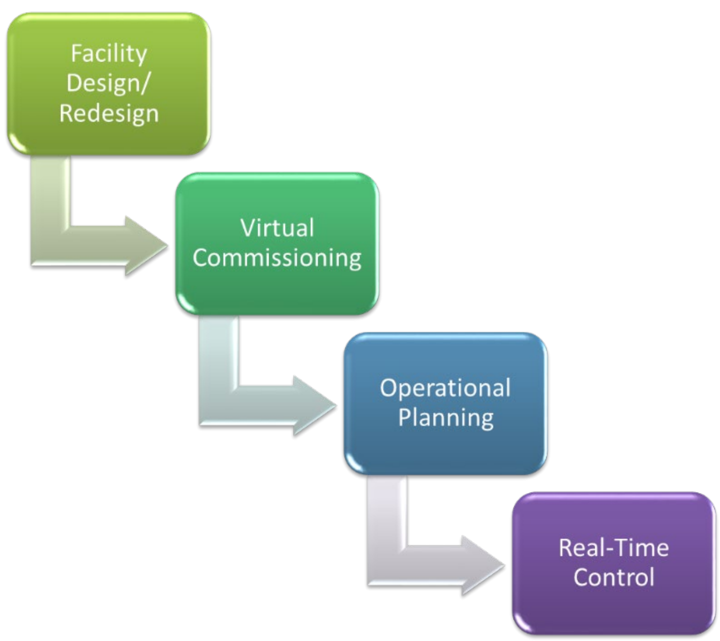

Figure 5. Applications for digital twin in intralogistics.

4.1 Facility Design/Redesign

The design of a new facility or the redesign of an existing facility for a new business can be a highly impactful application of digital twin for intralogistics. More generally, this could be thought of as digital twin for strategic decisions. As facility design typically involves a substantial capital investment, making sure the facility is the right size and will be designed to maximize operational efficiency is critical. In particular, a digital twin can help optimize the layout of the facility and the configuration of storage and retrieval systems.

In the case of facility design, the system does not yet exist, therefore the inputs to the simulation model will need to estimated based on manufacturer specifications for equipment speeds, capacities, etc. If possible, contacting the manufacturer to see a deployment of the system similar to the facility under consideration can be valuable to establishing realistic estimates for the model input.

The digital twin for the facility design can be constructed to address a full range of issues including (to name a few):

- Dimensions and layout of the facility;
- Storage alternatives (racks, bulk storage, AS/RS, etc.);
- Number and type of material handling equipment;
- The level of automation to incorporate;
- Processing areas for picking, packing, labeling, etc.;
- Shipping/receiving docks and locations;
- Utilities (electricity, water, lighting, etc.);
- Communication infrastructure;
- Sustainability; and
- Safety.

Investing in a digital twin at this stage has the benefit of ensuring that the money is not wasted due to under-sizing or over-sizing the facility, and that the company will be able to hit the ground running when construction is complete as the operational aspect of the system would have already been tested. Further, once the facility design stage is finished, the digital twin model can be reused in the next phases of the facility lifecycle.

4.2 Virtual Commissioning

When designing a new facility or introducing equipment into an existing facility, commission is an important step to ensuring productivity and safety measures are met Virtual commissioning allows for the testing and optimization of systems before they are built or installed – improving efficiency and reducing costs. This process is often done through a digital twin simulation model where the digital twin can take data from the physical system (if it exists) and insert the digital representation of the equipment that is to be installed. Through this process, the expected performance of the system can be evaluated, and if there are issues or changes need to be made, they can be addressed before the equipment is installed. (See also, [10]).

4.3 Operational Planning

A digital twin that is developed for operational planning decisions can be used in several ways including forensic analysis, predictive analysis, comparing alternatives, and what-if analysis. Note that each of these analysis goals can be used with the same digital twin of the physical intralogistic system. The difference is in how the digital twin is used.

For a digital twin that is connected to the physical system and the current state is updated in real-time as the state of the physical system changes, the digital twin can be set to record the history of the physical system over time. Then, at some point, if there is a situation that arises (good or bad), forensic analysis can be conducted where the history of the digital twin can be replayed in attempt to determine the conditions that resulted in the situation of interest. In the case of a bad situation, the forensic analysis can be used to determine the cause and then alternative methods for preventing the situation can be examined in attempt to keep the situation for occurring again in the future.

Another use for the digital twin is predictive analysis. In predictive analysis, the digital twin starts at the current system state and can be used to simulate forward into the near-term future to determine if any issues are predicted to arise. If so, the simulation can be used to identify alternative solutions to prevent the event from occurring, reduce the likelihood of the event, or mitigate the effects of the event.

To illustrate how digital twin could be used for predictive analysis in short-term operational planning decisions, consider a fulfillment center that, under typical demand, has an on-time shipping performance of greater than 99%. Each day, the digital twin simulation model is run to predict the near term performance of the system. The current state of the system including known orders, shipping dates, personnel, inventory, etc. is used to initialize the simulation model. On a particular day, due to a *flash* sale on the company website there is a spike in orders. Utilizing the digital twin, the company identifies that under the current staffing plan, starting tomorrow afternoon, on-time shipping performance will begin to drop dramatically. Identifying and quantifying the severity and persistence of the impending issue is the first benefit of utilizing the digital twin. The next benefit comes from utilizing the digital twin to efficiently resolve this issue. Once again, running the digital twin starting with the current system state, alternative staffing configurations can be evaluated to minimize or even eliminate negative impacts to the shipping performance metrics at minimal cost.

In addition, the digital twin can be used to compare alternatives for potential changes to a system. For example, a company may be interested in introducing autonomous robots to preform picking operations and wants to determine the number and type of robots to purchase. In addition, they may want to compare the productivity of the picking robot with human pickers at various experience levels. Digital twin provides an excellent environment for making this comparison. The system performance estimates obtained from the digital twin simulation can then be combined with other decision factors such as cost, stainability, and other factors that are needed to make a data-driven decision.

Finally, the digital twin can be used to conduct what-if analysis. This type of analysis is useful for preparing for events that may occur at some point in the future. For example, what if a storm causes the facility to lose power for several hours; or what-if two forklift driver call in sick on the same day; or other scenario. What-if analysis allows the company to develop contingency plans that will ensure the robustness of their system.

4.4 Real-Time Control

Real-time control is perhaps a long-term (not too long) goal of digital twin. That is, how can we utilize the digital twin for real-time decision making and control of the physical system? This real-time control could take the form of decision making using artificial intelligence. In this case, the digital twin simulation model can be used to train an AI algorithm to make good decisions based on the current state of the system. Further, as the system evolves over time, the digital twin can be used to continually retrain or refine the AI algorithm as additional data are observed.

One area where AI is being studied for intralogistics is AMR dispatching. In particular, given a set of pickup and delivery tasks and a fleet of AMRs, when an AMR becomes available, how should the AMR be assigned to a task so that the set of tasks can be completed as efficiently as possible? For example, a novel task assignment and path planning method called Risk-based A* has been proposed for AMR dispatching in attempt to minimize travel distance while avoiding conflicts with other AMRs [11].

As digital twin simulation models become more prevalent, the ability to generate realistic data for the development of AI algorithms, will (I predict) advance the application of AI for real-time decision making.

4.5 DT for Training

Finally, a potential use for digital twin for intralogistics is training. By integrating augmented reality or virtual reality (AR/VR) into the digital twin framework, a worker could be immersed in the virtual environment taking on the role of a picker or forklift driver, for example, and learn to effectively work in the system without the risk of injury to the worker or disruption of the system. By using AR/VR a worker could come up to speed on the basics of the task they need to perform, experience and learn how to deal with issues that may arise in the real system, and be better prepared when starting their position on the floor.

5. Conclusion

In this paper, we discussed the use of digital twin for intralogistics. In particular, we provided a motivation for the use of digital twin in intralogistics. We then discussed the use of simulation as a dynamic digital twin including a conceptual digital twin framework that illustrates the relationship among the physical intralogistic system, the data and control systems, and the digital twin. Furthermore, we discussed the process of data acquisition, IoT, and the need for secure, reliable, low-latency communication between the physical system and the digital twin. Finally, we presented a series of applications for digital twin in intralogistics including facility design, virtual commissioning, operational, planning, real-time control, and virtual reality.

Given the rapid advancement in digital twin technology, it is clear that digital twin will play a key role in the advancement of intralogistics into the future. However, there are still some technical challenges that will need to be overcome for broader digital twin adoption including the development of robust methods for synchronization between the digital twin and the physical system; methods for addressing system uncertainty; and computationally efficient methods for real-time decision making [12]. Despite these challenges, driven by the supply chain pressures and a limited workforce, automation and digital twin will be at the forefront supply chain innovation.

References

[1] Grieves, M. (2015). Digital Twin: Manufacturing Excellence through Virtual Factory Replication (White paper). https://www.3ds.com/fileadmin/PRODUCTS-SERVICES/DELMIA/PDF/Whitepaper/DELMIA-APRISO-Digital-Twin-Whitepaper.pdf [Accessed May 11, 2023]

[2] Glaessgen, E., & Stargel, D. (2012). The digital twin paradigm for future NASA and US Air Force vehicles. *53rd Structures, Structural Dynamics, and Materials Conference*. American Institute of Aeronautics and Astronautics. 1-14.

[3] Tiwari, A., S. K. Singh, and A. K. Tripathi, (2019) Development of digital twin for jet engine, In *2019 International Conference on Advances in Mechanical and Robotics Engineering (ICAMRE)*. 1-5.

[4] Buil, R., M. Servitja, A. Ruiz (2022) *Accenture – Warehouse Digital Twin* (Presentation), Simio Sync Conference [Virtual], Video available at https://youtu.be/lddjDBdIzaM [Accessed May 11, 2023].

[5] Kuhl, M.E., S.S. Bhattathiri, R. Bhisti, M.P. Li (2022) Warehouse Digital Twin: Simulation Modeling and Analysis Techniques. In *Proceedings of the 2022 Winter Simulation Conference.* B. Feng, G. Pedrielli, Y. Peng, S. Shashaani, E. Song, C.G.

Corlu, L.H. Lee, E.P. Chew, T. Roeder, P. Lendermann, eds. Institute of Electrical and Electronics Engineers: Piscataway, NJ. 2947-2956.

[6] Gao, W., Y. Liu, and Y. Chen, (2018) A review of sensors and actuators for smart manufacturing, *IEEE Transactions on Industrial Informatics*, 14(2), 558-569.

[7] Liu, Y., Y. Chen, and W. Gao, (2018) Data acquisition and processing techniques for smart manufacturing systems, *IEEE Transactions on Industrial Informatics*, 14(3), 1291-1302.

[8] Wang, J., Y. Liu, and Y. Chen, (2018) Communication and networking for smart manufacturing systems, *IEEE Communications Magazine*, 56(8), 104-110.

[9] Liu, Y., Y. Chen, and W. Gao, (2018) Human-machine interface for smart manufacturing systems," *IEEE Transactions on Industrial Informatics*, 14(5), 2279-2289.

[10] Barbieri, G., Bertuzzi, A., Capriotti, A. et al. (2021) A virtual commissioning based methodology to integrate digital twins into manufacturing systems. *Production Engineering* 15, 397–412.

[11] Li, M.P., M.E. Kuhl, R. Ballamajula, C. Hochgraf, R. Ptucha, A. Ganguly, A. Kwasinski (2020) Risk-based A* : Simulation Analysis of a Novel Task Assignment and Path Planning Method, In *Proceedings of the 2020 Winter Simulation Conference*, K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, eds. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers. 563-571.

[12] Kuo, Y.-H., F. Pilati, T. Qu, and G. Q. Huang. 2021. “Digital Twin-enabled Smart Industrial Systems: Recent Developments and Future Perspectives”. *International Journal of Computer Integrated Manufacturing* 34(7-8), 685–689.