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DIGITAL TWIN ARCHITECTURE FOR A FLOW SHOP ASSEMBLY SYSTEM

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ABSTRACT

This paper proposes a digital twin architecture for a flow shop assembly line to maximize productivity and reduce quality costs. The proposed digital twin architecture consists of five major modules; Synchronization module to synchronize a real factory and the digital twin, Monitoring module to provide intuitive information visualization, Event calendar initialization module to initialize the factory state at any given time to the starting point of the CPS (Cyber-Physical System) simulation, CPS simulation module to identify potential production losses, and Decision-making module to take proactive actions to avoid anticipated production losses. The proposed digital twin architecture has been implemented for a home appliance factory of LG Electronics Co., Ltd. In South Korea, and shows significant improvements in terms of productivity, quality cost, and energy efficiency.

1 INTRODUCTION

To stay competitive in today's manufacturing landscape, a manufacturer must enhance both the quality of their products and the efficiency of their production system, which converts inputs like material, information, and energy into the specified product. The concept of a smart factory has emerged to enhance the competitiveness of a manufacturing factory. Although there are many definitions of a smart factory, it generally can be defined as a digitized factory that uses connected devices, machinery, and production systems to continuously collect and share data (monitoring). In other words, a smart factory requires a digital twin enabling the continuous monitoring and simulation of the manufacturing system (Escorsa 2018; Tao et al. 2019; Lee et al. 2015; Zhong et al. 2017; Soderberg et al. 2017).

There are many studies on digital twin architectures and frameworks in manufacturing. Lee et al. (2015) introduced a unified 5-stage architecture for implementing cyber-physical system (CPS), focusing mainly on equipment-based CPS and enabling self-awareness and self-prediction through data sources. Ribeiro et al. (2017) addressed system-level configuration and interaction design challenges in integrating modular cyber-physical production system (CPPS) by considering the interaction between CPS formulation and industrial components. Alam and Saddik (2017) proposed a digital twin architecture for cloud-based CPS, offering a control decision-making system based on Bayesian networks and fuzzy logic. Zhou et al. (2020) proposed a general framework for a knowledge-based digital twin manufacturing cell that enables autonomous manufacturing through intelligent perception, simulation, prediction, optimization, and control

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strategies. These studies have explored and presented the applicability of CPS and digital twins in various aspects of manufacturing, considering their implementation and interaction to enhance the field of manufacturing.

There are cases where digital twins have been applied in a real factory. Zhong et al. (2013) proposed a real-time manufacturing execution system (MES) based on radio frequency identification (RFID). They applied it to a large-scale customized production company in China, aiming to visualize and manage the progress of operations on the production line. However, real-time tracking of the work progress and prediction of future anomalies proved challenging. Similarly, Frontoni et al. (2018) introduced a novel CPS architecture for real-time visualization, successfully enhancing visibility across manufacturing operations and improving product quality. Ding et al. (2018) proposed the RFID-enabled social manufacturing system (RFID-SMS) for real-time monitoring of inter-enterprise production and transportation tasks. They have implemented and evaluated the system in an actual printing company. Furthermore, Ding et al. (2019) employed CPS and digital twin technologies to establish a connection and interoperability between the physical production line and cyberspace, supporting decision-making in the physical world through simulations conducted in cyberspace. Park et al. (2020) developed a cloud-based digital manufacturing system utilizing data schema, offering real-time monitoring and predictive simulations. Small and medium-sized enterprises have used this system. Park et al. (2023) proposed a digital twin-based CPPS framework. Through verification in a secondary battery production site, they achieved synchronization between the actual production line and the digital twin, preventing performance degradation during production through simulations.

Figure 1: A flow shop example of conveyors, turn tables, and lifters.

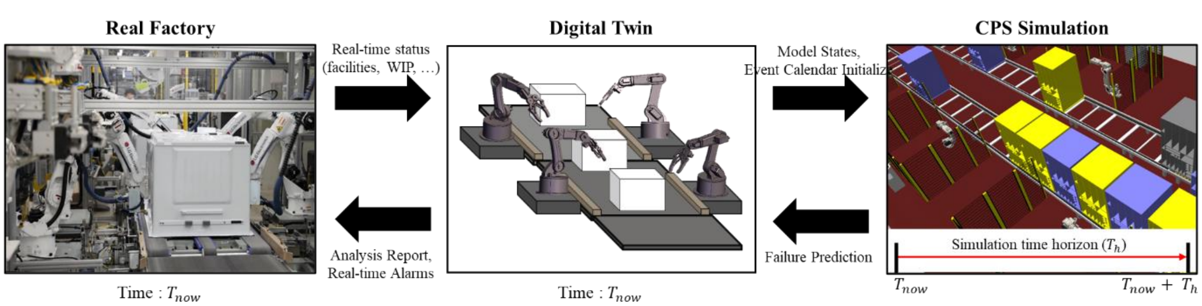

Figure 2: Digital twin & CPS simulation.

This paper selects the flow shop assembly system as the target system. Previous research has not yet proposed a digital twin that focuses on the flow shop assembly system. Nevertheless, a digital twin architecture targeting a flow shop assembly system is important. This is because flow shop layouts are commonly adopted in many manufacturing production lines. The contributions of this study are as follows: 1. Real-time synchronization technique between real factory and digital twin, 2. Simulation technique to predict potential production losses.

Most of the logistics systems in the flow shop assembly system are composed of conveyor systems that consist of conveyors, turn tables, and lifters, as shown in Figure 1, which often have wide sensor spacing and lack sufficient sensors for product detection. This makes it to track the real-time positions of products within the factory accurately. Consequently, one of the critical requirements of a digital twin, 'real-time synchronization', becomes difficult. To overcome this, we propose a methodology to synchronize the positions of workpieces more accurately within the constrained sensor tracking environment.

In a flow shop assembly system, if a product is taken out of the line due to quality problems during production, it causes problems because the production sequence is changed. This may result in instability of productivity. In this paper, we propose a methodology that makes predicting and responding to potential production losses possible by using CPS simulation in the digital twin.

As shown in Figure 2, the real-time synchronization enables the CPS simulation, which predicts future problems for a given time horizon (T_h) from now (T_{now}). The CPS simulation can identify potential future problems (production losses), such as availability losses, performance losses, and resource consumption losses. In a smart factory, once problems are identified, proactive actions should be made to prevent such production losses (Ko and Park 2014; Ko et al. 2013; Lee and Park 2014).

The proposed digital twin architecture is described in the following section. Section 3 introduces a digital twin construction example for a home appliance factory of LG Electronics Co., Ltd., in South Korea. Finally, concluding remarks are given in Section 4.

2 DIGITAL TWIN ARCHITECTURE FOR A FLOW SHOP

Because the digital twin needs to synchronize the real factory situation in real time, the layout data with the factory structure to be used as the target system must be identified as shown in Figure 3. The layout data must contain information about the location and orientation of physical elements in the factory, their physical properties, and the connection between each element. The location, direction, physical properties, and connection relationship between each element can be identified as nodes, links, resources, and sensors for physical elements in the real factory. Node data is the entry point and exit point of the unit assembly line, and link data is the relationship between nodes and means of the material flow. Resource data includes which assembly line the resource is connected to and the processing time. Sensor data contains information on which assembly line it is attached to. After loading the factory layout data from the digital twin and having the same specifications as the real factory, five modules can be used to perform real-time synchronization and predictive simulation with the real factory.

As shown in Figure 4, a digital twin is essential to realize a smart factory by preventing various production losses, which can be identified through CPS simulation. The proposed digital twin architecture consists of five major components; 1) 'Synchronization module' to synchronize a physical system (real factory) and a cyber system (digital twin), 2) 'Monitoring module' to provide intuitive information visualization of the actual production system situation to users, 3) 'Event calendar initialization module' to initialize the factory state at any given time to the starting point of the CPS simulation, 4) 'CPS simulation module' to identify potential production losses by performing a CPS simulation for a given period at the beginning point (the initialized event calendar), and 5) 'Decision making module' to take proactive actions to avoid anticipated production losses through the CPS simulation.

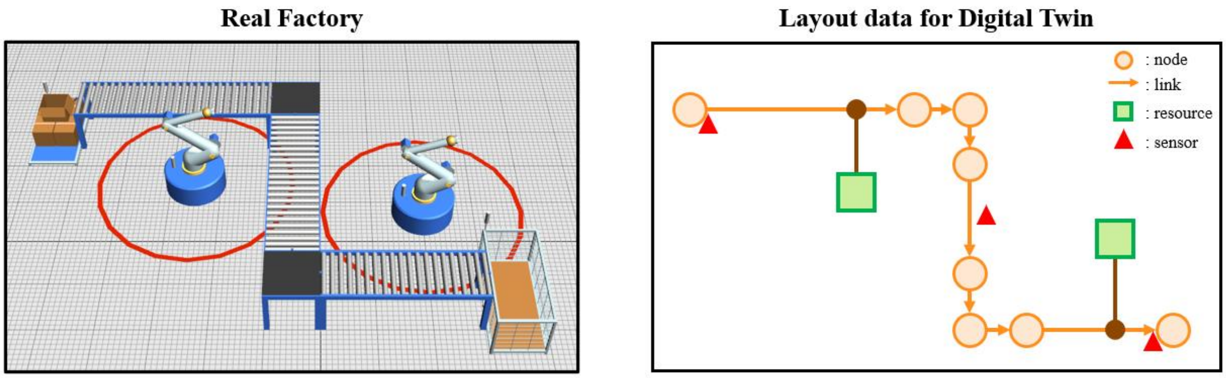

Figure 3: Identification details for digital twin construction.

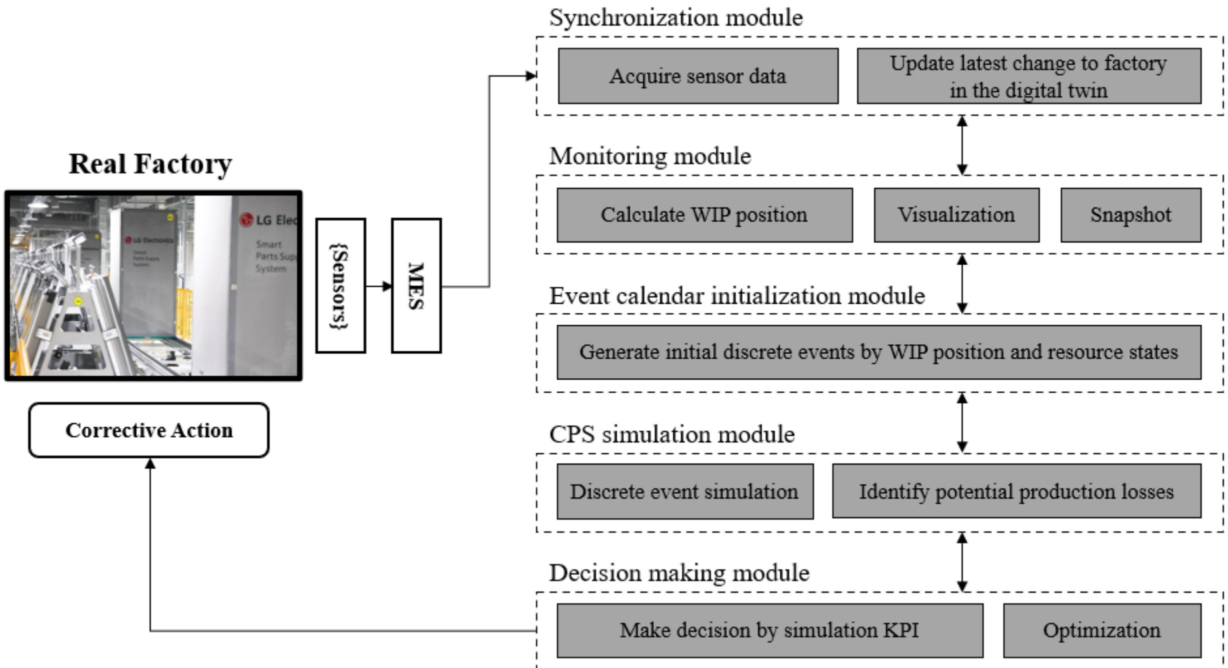

Figure 4: Digital twin architecture for a flow shop.

2.1 Real-Time Synchronization Technique Between a Real Factory and a Digital Twin

Real-time synchronization of the real factory situation to the digital twin is shown in Figure 5. The 'synchronization module' periodically acquires data from the MES and synchronizes the location of products in the real factory to the digital twin as shown in Figure 5-(a). A flow shop assembly system finishes products through repeated manufacturing processes. At this time, while the product flows along the line, a sensor is attached to each specific location, so when the product passes the sensor location, the sensor detects the product and reports the time, sensor location, and information about the detected product to the MES. Therefore, the synchronization module can identify the latest location of products in the real factory by periodically acquiring data from the MES. However, it is difficult to determine the real-time location of a product in the digital twin because it takes some time for a product to be detected by the next sensor when the distance between the sensors is considerable. This is because the product flows along the line in a real factory, whereas in a digital twin, the product position cannot be updated until the next sensor detects it. In order to solve the shaded area for the distance between sensors, the monitoring module plays a role in calculating the real-time position of the product in the digital twin as shown in Figure 5-(b). The real-time position of the product within the digital twin is calculated by considering the sensor's location where the product was last taken and the logistics control logic of the line where the product is currently located (Adam et al. 2011). Also, if the line includes resources, as shown in Figure 5-(c), product's position is calculated considering the processing time. If the product is not synchronized with the next sensor yet, it waits at the position behind it, as shown in Figure 5-(d). This makes the products in the digital twin appear to move along the line as they do in real-time. Through the monitoring module, the real-time location of all products flowing in the real factory can be expressed and visualized on the digital twin as it is.

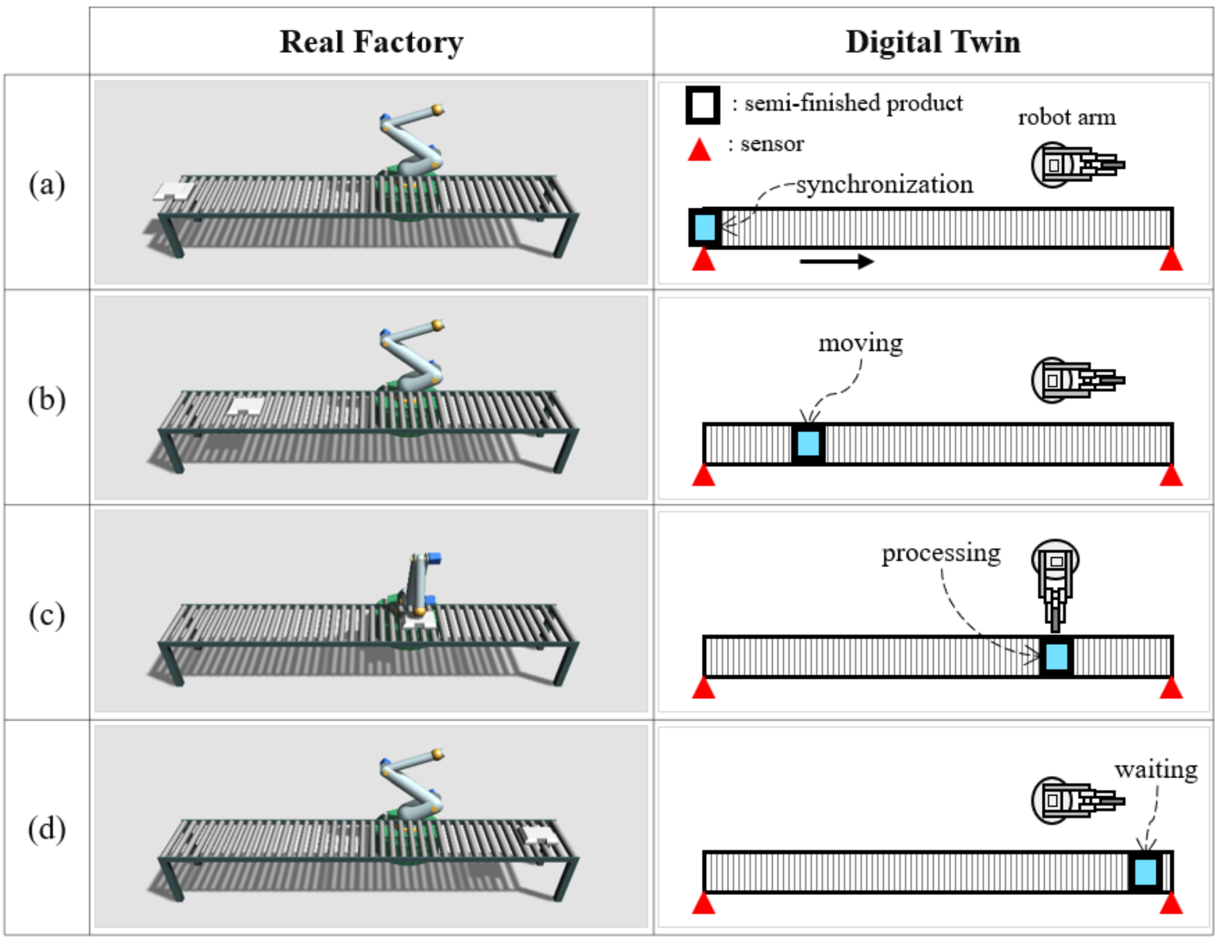

Figure 5: Real-time synchronization in the digital twin.

2.2 Simulation Technique to Predict Potential Production Losses

Snapshot data on the location and status of products/resources can be exported and converted into CPS simulation input data at any point in time from the digital twin, which can understand the real-time location of products on the line. The event calendar initialization module generates an initial event calendar before performing CPS simulation through snapshot data. By generating an initial event calendar and performing a simulation, it is possible to predict future situations based on any point in time. In this paper, CPS simulation is performed as a discrete event simulation, and discrete events are generated based on snapshot data. When event calendar initialization is completed, discrete event simulation is performed through the

CPS simulation module. While the simulation is performing, key performance indicators (KPI) are collected and observed for potential production losses. The decision-making module can proceed with decision-making and optimization through the simulation KPI collected after the simulation is completed. In addition, by considering these contents, the correct action can be reflected in the real factory.

To predict future production losses during rapidly changing production, the CPS simulations need to run periodically at regular intervals (T_{delta}). Each CPS simulation predicts potential production losses that may arise in the future after a certain period, so-called the time horizon of a CPS simulation (T_h), as shown in Figure 6. To implement the architecture, it is necessary to determine two parameters; the CPS simulation interval (T_{delta}) and the time horizon (T_h). Although the longer time horizon (T_h) provides the ability to look farther ahead, the longer time horizon requires more computation time (T_{com}) for the CPS simulation (Klingstam and Gullander 1999; Ko et al. 2014; Park et al. 2013; Park et al. 2009). For any flow shop assembly system, it is recommended that T_{delta} be the average tact-time for the product to input the factory, and T_h is determined depending on the characteristics of the production system, However, it is recommended to set T_h as an appropriate time (product cycle time) to predict future potential production losses.

At this time, we need to observe a constraint that the computation time must be shorter than the CPS simulation interval ($T_{com} < T_{delta}$), as shown in Figure 6. Note that the computation time (T_{com}) can be shortened by upgrading the hardware capabilities of the computing system. Considering the opinions of factory management experts within the scope of satisfying the given constraint ($T_{com} < T_{delta}$), it is necessary to determine the CPS simulation interval (T_{delta}) and the time horizon (T_h).

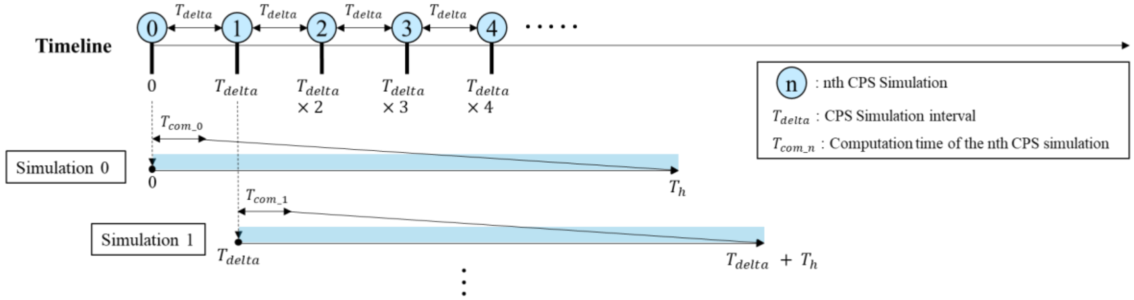

Figure 6: CPS simulation interval and the time horizon.

3 DIGITAL TWIN CONSTRUCTION FOR A HOME APPLIANCE FACTORY

This section introduces a digital twin construction example for a home appliance factory of LG Electronics Co., Ltd. in South Korea. The products that the factory produces include high-end refrigerators, washing machines, and dishwashers. The factory can be classified as a flow shop and is located in Changwon, Korea. In a flow shop, the processes are arranged in the sequence that the parts are processed, and all work steps are repeated within a short time.

The primary purpose of the digital twin in the Changwon factory is to predict & minimize the 'production losses' in the factory. An assembly line consists of multiple workstations and adds parts as the semi-finished assembly moves from workstation to workstation, where the parts are added in sequence until the final assembly is produced. For digital twin construction, we used commercial software Pinokio developed by Carlo, Republic of Korea.

In order to ensure efficient operations, flow shop assembly systems commonly employ just-in-sequence (JIS). JIS is a supply chain management approach that aims to maximize the efficiency and accuracy of the production process by providing components and materials in the correct sequence and timing. The JIS system considers the correct order of supplied components and follows the basic rule of preplanned assembly sequence, based on the First-In, First-Out (FIFO) principle (Meissner 2010). If there is a line interruption, defect, or omission, the assembly sequence needs to be rearranged, resulting in unstable order lead times. Therefore, the JIS system requires high synchronization between customers and suppliers regarding quality and monitoring, achieved through responsive, inventory-minimized production. This necessitates a high standard for the entire production system (Wagner and Silveira 2011).

In the Changwon factory, the chronic problem was the 'matching delay of parts', as shown in Figure 7, where parts must arrive simultaneously for assembly. This problem leads to production losses and occurs because the factory produces various products in a mixed flow, and parts are occasionally discarded during production due to defects. Semi-finished products travel along the main-line line, arriving sequentially at the matching location, while the supply box is placed in the buffer and waits. Assembly proceeds when a semi-finished product and a supply box containing parts simultaneously arrive at the matching location. The buffer dispatches a supply box of the same product type as the arriving semi-finished product. Each color in the shape of semi-finished products and supply boxes represents a product type. The blue supply box in the middle column moves to match the blue semi-finished product in the main-line (Figure 7-(a)). After matching, the robot arm assembles parts (Figure 7-(b)). If a supply box in the buffer is blocked by other types of supply boxes, it cannot move until the other boxes are relocated, causing the main-line to halt until the same type of supply box is exported (Figure 7-(c, d)).

To minimize the matching delay problems, it is crucial to utilize the digital twin technology, which enables the real-time detection of evolving scenarios (disposal of parts due to unexpected defects) and accurate future predictions. As mentioned earlier, the digital twin implementation requires five major modules; 1) synchronization module, 2) monitoring module, 3) event calendar initialization module, 4) CPS simulation module, and 5) decision-making module. To minimize the production losses in the factory, the CPS simulation module identifies any possible matching delay cases in advance, and the decision-making module takes proactive actions to avoid anticipated production losses. As a result of building the digital twin, tact-time decreased by 25%, warehouse area decreased by 30%, and downtime improved by 30%.

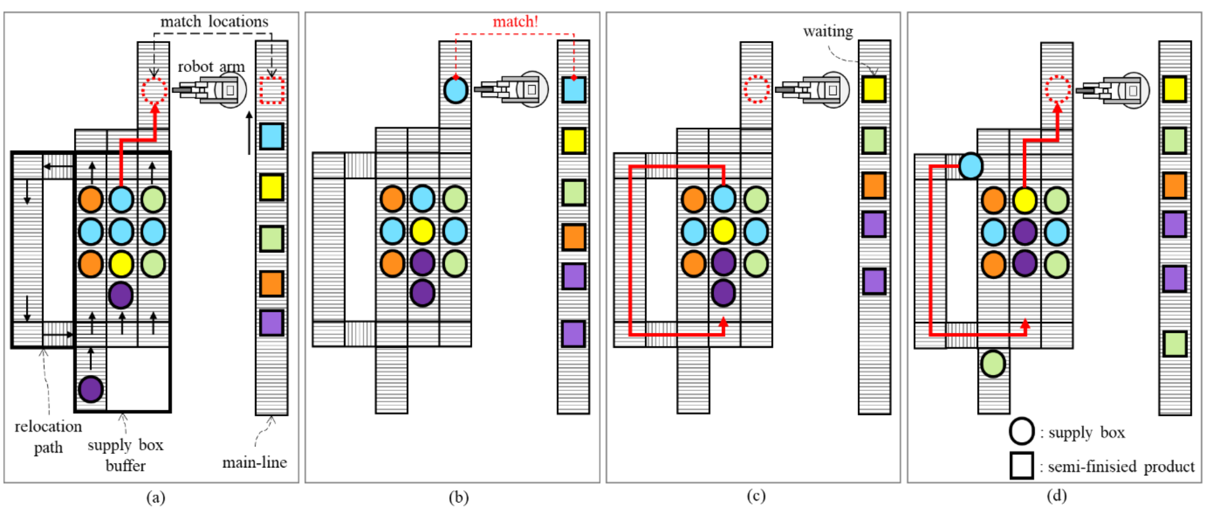

Figure 7: Matching delay problem in an assembly line.

4 DISCUSSION AND CONCLUSIONS

The definition of a digital twin in manufacturing is a virtual copy of a real-world factory. Although the meaning of the digital twin is simple, it is not so simple to identify the explicit purpose of using the digital twin. The purpose of using the digital twin is different depending on manufacturing domains, and even within the same domain, the purpose can be very diverse. Because a digital twin cannot and should not be completely identical to the real object, it is important to identify the purpose of the digital twin.

This paper proposes a digital twin architecture for a flow shop assembly line to minimize the 'production losses' in the factory, mainly caused by matching delay problems. To prevent matching delay, it is necessary to have five major modules; Synchronization module, Monitoring module, Event calendar initialization module, CPS simulation module, and Decision-making module. The proposed digital twin architecture has been implemented for a home appliance factory of LG Electronics Co., Ltd. in South Korea. It shows significant improvements in terms of productivity, quality cost, and energy efficiency.

The leading cause of matching delay problems may be defects within the production line and insufficient quantities of parts supplied to the factory. Because the scope of the proposed digital twin in this paper is limited to the factory, it is challenging to recognize issues caused by a lack of parts delivered to the factory. Future research is underway to consider expanding the scope of the digital twin to encompass the entire process from part suppliers to the delivery of parts to the factory. This expanded scope will enable much earlier detection of issues occurring within the factory.

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