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# Operation Twins: Synchronized Production-Intralogistics for Industry 4.0 Manufacturing

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**Abstract.** The widespread adoption of Industry 4.0 technologies in factories are transforming manufacturing operations management. Multiple resources are interconnected, massive data are real-timely collected by smart devices to provide visibility and traceability. It is generally acknowledged that real-time data are beneficial for manufacturing operations management. How to utilize these data for facilitating production and intralogistics (PiL) operations management is an emerging challenge. This study proposes a new concept, operation twins, for achieving synchronized PiL operations based on three dimensions of synchronization (cyber-physical synchronization, spatial-temporal synchronization, and data-driven decisions synchronization).

**Keywords:** Operation Twins, Production-Intralogistics Synchronization, Production and Operations Management, Real-Time Visibility and Traceability, Industry 4.0, Smart Manufacturing

## 1 Introduction

Industry 4.0 promises next-generation smart manufacturing. The emerging technologies that enable this revolution and their applications have attracted widespread attention from both scholars and practitioners in the last decade, such as Internet-of-Things (IoT), Digital Twin (DT), Cyber-Physical Systems (CPS), Big Data Analytics (BDA), Additive Manufacturing (AM), Blockchain [1-3]. In contrast, methodological research is rare in the context of industry 4.0 manufacturing, although advanced technologies are revolutionizing production and operations management [4]. For instance, the production and intralogistics (PiL) in a shop floor are inherently coupled by physical flow (e.g., raw materials, WIPs). In conventional management mode, the PiL operations are organized and performed separately by different divisions without considering the overall benefits because it is hard to collect and share the data among the divisions for making coordinated decisions [5, 6].

The advent of various Industry 4.0 technologies provides a promising direction forward and paves the way for the PiL synchronization. Multiple smart devices are deployed in the physical shop floor to capture real-time data, advanced analytics and decision services are integrated into the cyber shop floor [3, 7]. Traditional manufacturing resources are upgraded to smart resources augmented with identification, sensing, and networking capabilities [2]. Hence, how to fully tap the potential of visibility and traceability in Industry 4.0 environments to manage the complexity and uncertainty of PiL operations for better production performance becomes a new challenge [8].

Real-time/online simulation is an effective tool integrated in new production planning and control approaches that can make use of real-time data. Real-time system status is captured as the input, and online simulations are performed to generate new optimal policy or decision [9-11]. These simulation tools connect the information flow and decision flow to implement a closed-loop control for the whole system. The effectiveness of real-time simulation is widely appreciated, while it is too general to abstract the manufacturing systems into two dimensions. For example, the production flow and intralogistics flow in a manufacturing system are highly coupled with complex interactions.

This study proposes a novel concept, operations twins, to achieve PiL synchronization by leveraging advanced Industry 4.0 technologies and methodologies. Section 2 presents the concept of operation twins and how the production flow, intralogistics flow, and information flow are managed via vertical twinning and horizontal twinning. Three dimensions of synchronization (cyber-physical synchronization, spatial-temporal synchronization, and data-driven decisions synchronization) are summarized as the basis for operation twins in Section 3. Finally, a simple example is presented to illustrate the application of operation twins in manufacturing.

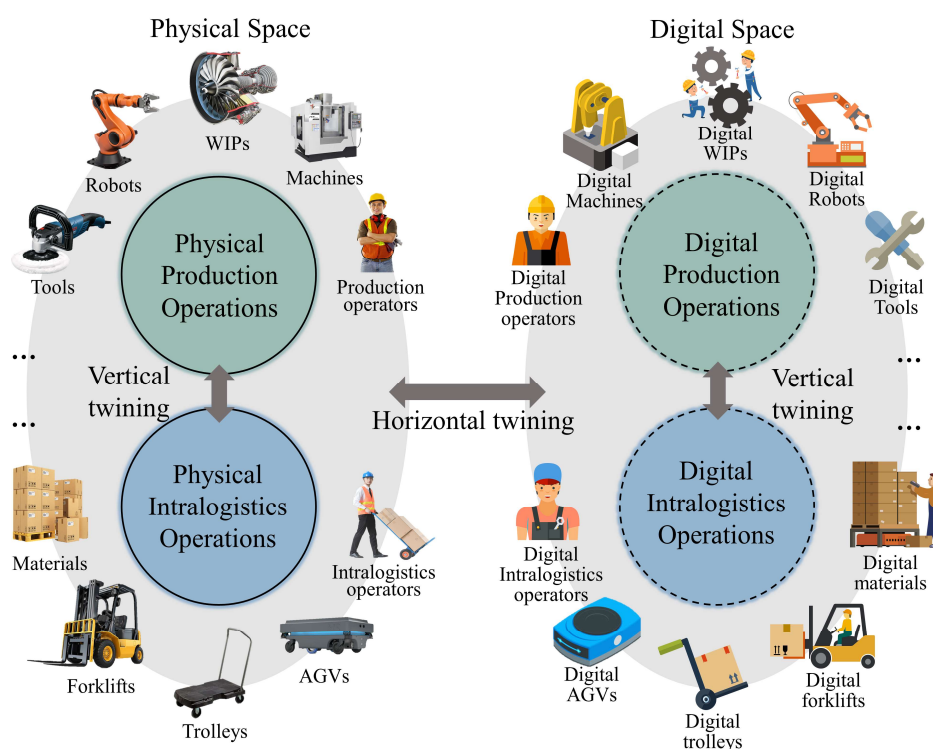
## 2 The Concept of Operation Twins

Fig. 1 depicts the conceptual framework of the proposed operation twins. Manufacturing operations hold a dominant position in this framework. Production operations (PO) convert materials and components into products by utilizing production resources such as operators, machines, robots, and tools. Intralogistics operations (LO) correspond to the delivery of required resources such as materials, finished products within the plant using forklifts, automated guided vehicles (AGVs), trolleys, etc. With the adoption of frontier Industry 4.0 technologies, the physical operations and resources are mapped to the digital space. The operation twins concept mainly includes two aspects: vertical twinning and horizontal twinning.

### 2.1 Vertical Twinning

Vertical twinning involves the twinning of production and intralogistics operations and related resources. The PO and LO are inherently complex because they are coupled and entangled by physical flow (materials, WIPs, or finished products). In traditional management mode, PO and LO are managed by different departments to reduce complexity.

The information is usually inaccurate, incomplete, and hard to be shared among different departments. The workflow is fluctuated even disrupted due to various disturbances (e.g., material delay, machine failures, stochastic operational time) on the shop floor. Cutting-edge technologies such as IoT and data analytics remove the barriers and promote information sharing within the plant. Hence, it is possible to manage the PO and LO in a coordinated and synchronized manner to improve the overall operational resilience and resource utilization.



**Fig. 1.** The conceptual framework of operation twins.

## 2.2 Horizontal Twinning

Horizontal twinning refers to the twinning of physical and digital operations and related resources. Massive real-time manufacturing data are collected, transmitted, and analyzed thanks to the deployment of Industry 4.0 technologies. All related production and intralogistics resources can be digitized to form corresponding digital representations for real-time simulation and control. PO and LO can also be formulated in digital space with extended visibility and interoperability. Pre-planned operations can be proactively adjusted, ongoing operations can be real-timely monitored, and finished operations can be thoroughly evaluated. Besides, by analyzing the real-time data, the digital space provides real-time feedbacks to support decisions and operations execution in physical space to cope with various uncertainties and enhance efficiency and accuracy.

### 2.3 The Practical Applicability of Operation Twins

It is noteworthy that the concept of operation twins is closely related to existing concepts such as digital twin [12] and real-time simulation [13]. On the one hand, digital twin is object-oriented; it aims at creating digital representations of manufacturing objects (human, machine, materials, etc.) for real-time monitoring. The concept of operation twins is operations-oriented; manufacturing objects are considered as resources for performing operations, which means operation twins can be more naturally applied in production planning and control processes in practice. On the other hand, real-time simulation focuses on the information flow and decision flow to form closed-loop control of the system. The input system status is usually abstracted so that the interactions and dynamics among the system are often overlooked. For example, in practice, the production and intralogistics for material supply are managed by separate departments that have different KPIs. The concept of operation twins provides a new approach to manage the production flow, intralogistics flow, and information flow in a synchronous and coordinated manner.

## 3 The Three Dimensions of Synchronization in Industry 4.0 Production-Intralogistics Systems

To establish the operation twin for production-intralogistics synchronization, an overall architecture of synchronized production-intralogistics system is proposed with three dimensions of synchronization, namely, cyber-physical synchronization (CP-Sync), spatial-temporal synchronization (ST-Sync), and data-driven decisions synchronization (DD-Sync), as shown in Fig. 2.

### 3.1 Cyber-Physical Synchronization (CP-Sync)

The CP-Sync aims at synchronizing the physical shop floor and cyber shop floor to achieve cyber-physical visibility and traceability of the whole plant. As shown in Fig. 2, all physical resources are equipped with smart tags (e.g., RFID, iBeacon, sensors), which can be uniquely sensed, identified and traced by smart gateways, mobiles, industrial wearables, or readers. With the deployment of multiple smart devices, the plant is characterized by hyperconnectivity among physical resources, high-quality real-time data acquisition and transmission. Cyber-physical agents (CP-Agents) are employed to handle various industrial standards/protocols of smart devices and process heterogeneous data from multiple sources to create digital representations with basic facts (e.g., ID, type, quantity), status (e.g., processing, waiting, transferring), spatiotemporal trajectory and so on. Therefore, all manufacturing resources are real-timely monitored and simulated in cyber space to generate insightful feedbacks to physical space, so that cyber space and physical space are seamlessly synchronized. Great interconnectivity of resources, smooth circulation of manufacturing data/information flow, and cyber-physical visibility and traceability serve as solid foundations for further analysis and decision-making.

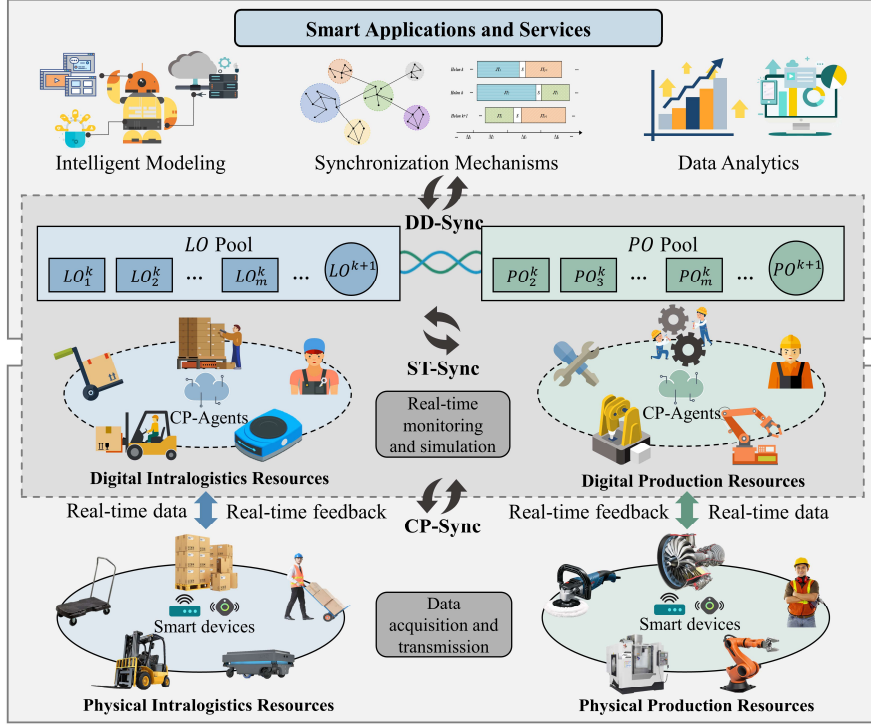


Fig. 2. The Three dimensions of synchronization in production-intralogistics systems.

### 3.2 Spatial-Temporal Synchronization (ST-Sync)

The ST-Sync aims at ensuring smooth operations execution by synchronizing the required resources within a narrow spatiotemporal window and governing the interactions among smart resources inside. The onsite production execution is subject to the availability of multiple resources (e.g., materials, machines, and humans). Resources-related uncertainty is one of the major challenges in manufacturing execution. Thanks to the cyber-physical visibility and traceability built by CP-Sync. The onsite shop floor situation and detailed information (e.g., the estimated arrival time of materials, machines/operators status) can be easily accessed through smart devices, so that the pending operations in the pools can be organized and executed on a dynamic basis to avoid unreasonable stalls/waits and improve processing efficiency and resource utilization. ST-Sync guarantees the pre-decided production/intralogistics plans/schedules can be completed smoothly under stochastic manufacturing environments (e.g., uncertain operational time, material delays).

### 3.3 Data-driven Decisions Synchronization (DD-Sync)

The DD-Sync corresponds to the decision-making process via developing intelligent modeling, synchronization mechanisms, and data analytics. Intelligent modeling

establishes the operational logic for critical resources in the PiL process. With embedded algorithms, smart resources can sense and analyze, take actions and interact with each other to enhance overall efficiency. Synchronization mechanisms are designed to coordinate the PO pool and LO pool for supporting decisions based on real-time data (e.g., resource availability, demand change). By incorporating real-time data, the mechanisms will be more resilient and efficient to handle various disturbances and minimize the resulting adverse effects. Besides, data analytics are widely applied, such as data fusion that integrates data from multiple sources to give more accurate results, data mining that uncovers patterns to gain underlying knowledge, etc. For instance, recognizing the frequent spatiotemporal trajectory of materials and humans to facilitate better management and status monitoring. Finally, driven by production data, the combination of these techniques can make the system smarter.

#### 4 An Illustrative Example of Operation Twins

The section presents an illustrative example of the application of operation twins. Considering a simple scenario, there are two orders that request different products,  $Order\ 1 = \{B_1, C_1\}$  and  $Order\ 2 = \{A_1, A_2, C_2\}$ . The original schedule is generated as  $\{C_1, C_2, B_1, A_1, A_2\}$  based on the setup requirement and order arrival time.

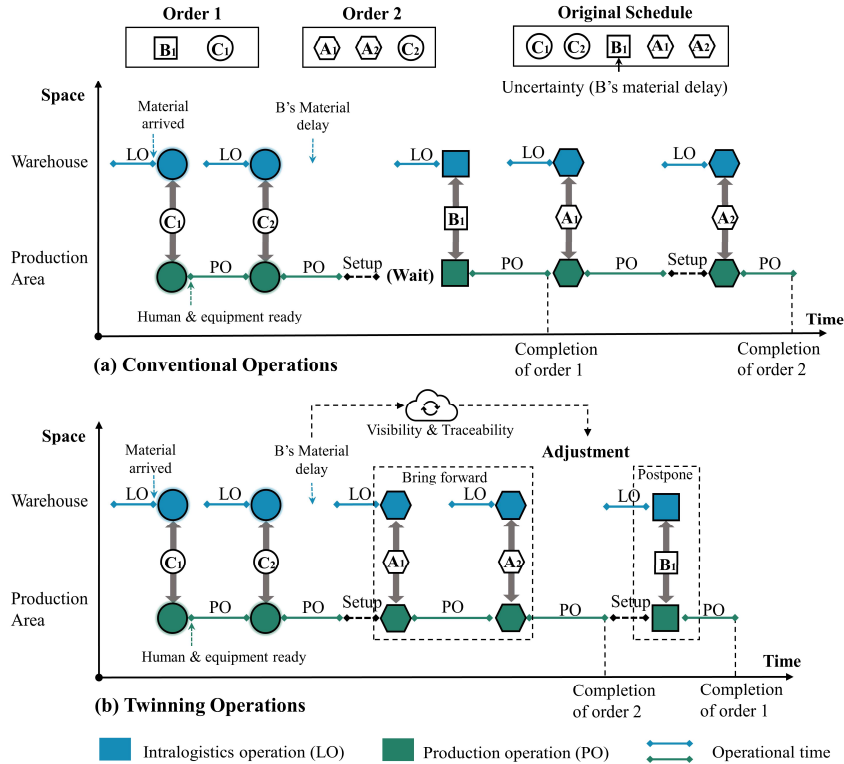


Fig. 3. An illustrative example of operation twins.



When uncertainty (B's material delay) occurs, the following operations have to be postponed and prolong the production process and cause backlog orders. Because in conventional mode (see Fig. 3 (a)), it is hard to identify the uncertainty accurately and quickly, the corresponding information cannot be shared with related departments rapidly so that it is impossible to make decisions to cope with these uncertainties, and the overall production performance deteriorates.

In the twinning operation mode (see Fig. 3 (b)), the uncertainty (B's material delay) can be accurately detected via smart devices, the data and information will be updated in cyber space and shared with intralogistics and production departments (CP-Sync). Based on the information (e.g., estimated delay), corresponding decisions can be made to adjust the operations (DD-Sync). In this example, the operations of  $A_1, A_2$  are brought forward and  $B_1$  is postponed. Finally, onsite operators will perform the adjusted operations accordingly. All required resources will be synchronized into corresponding spatiotemporal windows to ensure smooth execution (ST-Sync). In this way, the adverse effects of uncertainties are minimized.

This simple example is only for illustrating the underlying logic of operation twins in a complete way and how three dimensions of synchronization play a role in the whole process. More comprehensive numerical analyses or case studies will be carried out in the future to verify the superiority of the proposed concept.

## 5 Conclusion and Future Perspectives

This paper proposed a new concept, namely operation twins, to achieve production-intralogistics synchronization in Industry 4.0 manufacturing environments. The manufacturing operations are vertically and horizontally twinned through cyber-physical synchronization, spatial-temporal synchronization, and data-driven decision synchronization. This study contributes to the methodological research for production and operations management in the era of Industry 4.0. However, how emerging technologies reshape operations management in manufacturing deserves further in-depth discussions. And also, there still are several challenges to fully implement operation twins in practice.

- **Challenges in Cyber-Physical Synchronization.** Massive real-time operational data can be captured from multiple sources with the deployment of IoT devices [14]. How to effectively process these heterogeneous data considering the balance between the granularity of real-time visibility/traceability and computational efficiency, how to faithfully map the physical and digital operations as well as corresponding resources considering their distinct attributes and complex relations among them, are major challenges in CP-Sync.
- **Challenges in Spatial-Temporal Synchronization.** Real-life manufacturing systems are always subject to a certain degree of stochasticity [15]. Uncertain events such as stochastic operational time, machine failure will inevitably have negative effects on operation execution even the overall production efficiency. How to design a mechanism to manage the operation pools on a dynamic basis to achieve spatial-

temporal synchronization for enhancing the overall execution resilience, is a crucial topic in operation twins.

- **Challenges in Data-Driven Decision Synchronization.** Real-time data collection and information sharing make it possible to coordinate and synchronize the decisions of different decision authorities/stakeholders (e.g., production and intralogistics departments in a manufacturing plant) for the global optimum [8]. Therefore, how to formulate novel decision support mechanisms that can fully leverage the potential of abundant IoT data for the coordination of decision-making in manufacturing operations, deserves further explorations.

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