Synchroperation in Industry 4.0 Manufacturing

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Abstract

Industry 4.0 connotes a new industrial revolution with the convergence between physical and digital spaces, is revolutionizing the way that production operations are managed. The requirement of increased productivity, improved flexibility and resilience, and reduced cost in Industry 4.0 manufacturing calls for new paradigms that comply with the changing of production and operations management. In this paper, a concept of manufacturing synchroperation, refers to *"synchronized operations" in an agile, resilient and cost-efficient way, with the spatiotemporal synchronization of men, machines and materials as well as data-driven decision-making, by creating, establishing and utilizing cyber-physical visibility and traceability in operations management*, is proposed as a new paradigm of production and operations management for Industry 4.0 manufacturing. A Hyperconnected Physical Internet-enabled Smart Manufacturing Platform (HPISMP) is developed as a technical solution to support manufacturing synchroperation. Graduation intelligent Manufacturing System (GiMS) with "divide and conquer" principles is proposed to address the complex, stochastic, and dynamic nature of manufacturing for achieving synchroperation. An industrial case is carried out to validate the effectiveness of the proposed concept and method. This article provides insight into exploring production and operations management in the era of Industry 4.0.

Keywords: Industry 4.0; production and operations management; manufacturing synchroperation; Graduation Intelligent Manufacturing System (GiMS)

1. Introduction

Industry 4.0 connotes a new industrial revolution with the convergence between physical and digital spaces, which is triggered by the confluence of disruptive technologies, such as Internet of Things (IoT) (Xu et al., 2014), cyber-physical systems (CPS) (Lee et al., 2015), cloud computing (Xu 2012), big data (Kusiak 2017), digital twin (Tao et al., 2018), etc. With the support of these emerging technologies, traditional manufacturing resources have been converted into smart objects augmented with identification, sensing and network capabilities (Korteum et al., 2010). Thus, the dynamic production operations could be organized and managed in an integrated, optimized and synchronized manner with real-time information sharing and visibility (Guo et al., 2020a). The hyper-connection, digitization and sharing in the context of Industry 4.0 have the potential to revolutionize, or at least change, the way that production operations are done and therefore, how operations should be managed (Olsen and Tomlin, 2020).

The production and operations management has been shifted over the past fifty years, and three paradigms, including manufacturing collaboration, manufacturing interaction and manufacturing interoperation, can be classified with the enabling technologies and changing market. The paradigm of manufacturing collaboration aims at automating shop-floors by integrating different types of machines within a manufacturing company, which has rendered the feasibility of developing flexible manufacturing system (FMS) and computer-integrated manufacturing system (CIMS) (Buzacott and Yao, 1986; Mcgehee et al., 1994). Take the interaction of cross-organizational activities into account, the paradigm of manufacturing interaction extended production operations from a manufacturing company to a supply chain in a close-to-reality manner within a dynamic environment, which acts as key principles in agile manufacturing (AM) and networked manufacturing (NM) (Gunasekaran, 1999; Montreuil et al., 2000). More recently, to optimize the efficiency of production operations in the network, the paradigm of manufacturing interoperation is introduced, in which distributed manufacturing resources/capabilities can be interoperable in a close-loop network with timely production information exchange, which is the essence of cloud manufacturing (CM) and ubiquitous manufacturing (UM) (Xu 2012; Lin and Chen, 2017).

These paradigms for production and operations management are widely appreciated (Yin et al., 2018; Koh et al., 2019; Ivanov et al., 2020). The requirement of customized demand, increased productivity, improved flexibility and resilience, and reduced cost calls for more synchronized production and operations management that complies with changing business climate in Industry 4.0 manufacturing. Paving the way for transformation and implementation of Industry 4.0 manufacturing, major challenges still exist as follows.

(1) How to identify key characteristics for transformation and implementation of Industry 4.0 manufacturing, and derive a paradigm of production and operations management in the era of Industry 4.0 from these characteristics?

(2) How to leverage advanced technologies in the era of Industry 4.0 for developing effective architectures to support the transformation of the new production and operations management paradigm?

(3) How to cope with the complex, dynamic and stochastic nature of manufacturing by proposing effective methodologies to support the implementation of the new production and operations management paradigm?

The challenges mentioned above motivated this study and, therefore, the concept of manufacturing synchroperation is proposed as a new paradigm of production and operations management in the era of Industry 4.0 with cyber-physical synchronization, data-driven decision synchronization and spatio-temporal synchronization. A Hyperconnected Physical Internet-enabled Smart Manufacturing Platform (HPISMP) assisted with digital twin and consortium blockchain, is developed as a technical solution to support the transformation of manufacturing synchroperation. With the support of the HPISMP, Graduation Intelligent Manufacturing System (GiMS) with “divide and conquer” principles is proposed to address the complex, stochastic, and dynamic nature of manufacturing for achieving synchroperation. An industrial case from an air conditioner manufacturer is carried out to illustrate the potential advantages of manufacturing synchroperation.

The remainder of this paper is organized as follows. Related research streams are briefly reviewed in Section 2. In Section 3, the concept of manufacturing synchroperation is introduced. A HPISMP is developed in Section 4. Section 5 presents GiMS with “divide and conquer” principles for achieving synchroperation. An industrial case from an air conditioner manufacturer is carried out in Section 6. Section 7 concludes the paper with some remarks on possible directions for future research.

2. Literature review

Many companies devote themselves to Industry 4.0 manufacturing. Siemens cloud-based IoT open operating system, MindSphere, connects products, plants, systems, and machines to enable industrial customers to harness the wealth of manufacturing data for decision-making (Siemens, 2020). GE IIoT platform, Predix, provides a complete solution for industrial data monitoring and event management, combining asset connectivity, and edge-to-cloud analytics processing to improve operational efficiency (GE, 2020). SAP cloud platform is designed to realize intelligent manufacturing that enables industrial customers to accelerate integration across the value chain while staying flexible and agile (SAP, 2020).

Industry 4.0 manufacturing with hyper-connection, digitization and sharing is revolutionizing production and operations management. This section briefly reviews the evolution of manufacturing paradigms based on enabling technologies and changing market at that time. Manufacturing paradigms can be classified into three types according to the principle of production and operations management. And challenges of these existing paradigms are then discussed and new requirements for transforming to Industry 4.0 manufacturing are proposed.

2.1. *Manufacturing collaboration*

Typical manufacturing paradigms has been developed to facilitate collaboration within a manufacturing company, including FMS and CIMS.

FMS refers to an integrated, computer-controlled complex of numerically controlled machine tools, automated material handling devices and computer hardware and software for the automatic random processing of palletized parts across various workstations (Buzacott and Yao, 1986). FMS utilizes the flexibility of job shops to simultaneously machine several part types to attain the efficiency of well-balanced, machine-paced transfer lines (Stecke, 1983). Eight types of flexibilities are summarized, including machine, process, product, routing, volume, expansion, operation and production flexibility, to design an FMS (Browne et al., 1984).

CIMS refers to the harmonious connection and integration of automation equipment within a manufacturing facility (Mcgehee et al., 1994). CIMS utilizes computers and communication network to transform islands of enabling technologies into highly interconnected manufacturing system (Nagalingam and Lin, 1999) through a solution using STEP and STEP-NC for the integration of CAD, CAPP, CAM and CNC (Xu et al., 2005). CIMS improves data exchangeability and promotes adaptability of companies.

The key features in this era are: (1) They focus on a manufacturing company; (2) They aim at the automation of shop-floors by integration and collaboration of different types of machines; (3) They rarely integrate humans into manufacturing systems.

2.2. *Manufacturing interaction*

In the interaction era, typical paradigms are AM and NM. AM, originated from lean manufacturing, refers to the capability of surviving in a competitive environment of continuous and unpredictable change by reacting quickly to changing markets, driven by customer-designed products and services (Gunasekaran, 1999). The agility of manufacturing is provided through integrating reconfigurable resources with best practices in a knowledge-rich environment (Yusuf et al., 1999). A virtual enterprise is a typical application to characterize the global supply chain of a single product. It establishes the interaction with little liaison between companies to structure the whole system for agility (Martinez et al., 2001).

NM is the extension of agile manufacturing, and aims to collaboratively plan, control and manage daily activities and contingencies in a close-to-reality manner within a dynamic environment (Montreuil et al., 2000). NM increasingly focuses on information sharing that aims to create business relationships at different levels of shared information on price and capacity based on a distributed collaborative vision (D'Amours et al., 1999). Thus, standard information technology infrastructure is investigated to support cross-organizational activities for effective interaction (Akkermans and van der Horst, 2002).

The key characteristics in this era are: (1) The scope is extended from a company to a supply chain, and multiple companies are collaborated to manufacture a type of products; (2) Information exchange plays a crucial role in the interaction between them; (3) Knowledge and wisdom of human are considered an important part of manufacturing systems.

2.3. *Manufacturing interoperation*

Recently, many manufacturing paradigms (e.g. IoT-enabled manufacturing, CM, and UM) have been designed to realize manufacturing interoperation using various technologies, such as IoT and cloud.

IoT-enabled manufacturing is an advanced principle where manufacturing resources are converted into smart ones able to sense, interconnect, and interact with each other to automatically and adaptively carry out manufacturing logics (Zhong et al., 2017). IoT provides manufacturing resources with the ability to exchange data and information real-timely (McFarlane et al., 2003). Open-loop networked manufacturing is thus closed, and tedious and error-prone manual data collection is eliminated, so that manufacturing resources can work together effectively (Huang et al., 2009). IoT lays the foundation of interoperation. Huang et al. (2008) utilize wireless manufacturing to manage work-in-progress inventories in job shops to retain existing operational flexibility while improving efficiency and capacity. Zhong et al. (2013) present a RFID-enabled manufacturing execution system to track and trace manufacturing resources and collect real-time data for making planning and scheduling decisions.

CM uses the network, cloud computing, service computing and manufacturing enabling technologies to transform manufacturing resources into services that are managed and operated in a unified way to share and circulate manufacturing resources (Zhang et al., 2014). Interoperability is the prerequisite for CM, because manufacturing resources need to be described, virtualized and integrated in a manufacturing cloud before sharing (Wang and Xu, 2013). Chen and Chiu (2017) find the smooth operation on cloud is hampered by interoperability when different cloud services are utilized. Wang et al. (2018b) classify interoperability in CM into four levels: data level, computing service level, manufacturing process level and CM service level. At manufacturing process level, a costing-based, generic deployment model is designed to identify the key process parameters that influence the interoperability of CM (Mourad et al., 2020). Also, synchronization as the extension of interoperation is proposed to address dynamics in production logistics activities (Qu et al., 2016).

UM enables on-demand network access to a shared pool of configurable manufacturing resources but emphasizes the mobility and dispersion (Lin and Chen, 2017). Interoperability is also one of core characteristics, which closes the loop of production planning and control for adaptive decision-making (Zhang et al., 2011). Thus, manufacturing knowledge representation and data structure in UM need to be standardized, so that diversified UM systems are interoperable (Wang et al., 2018a). Wang et al. (2017) propose a function block-based integration mechanism to integrate various types of manufacturing facilities for interoperability in UM. Luo et al. (2017) present the synchronized production and logistics via ubiquitous computing to make real-time decisions within a factory.

The key characteristics in this era are: (1) Manufacturing resources worldwide are interoperable (Newman et al., 2008); (2) IoT facilitates information and data exchange to close the open-loop production process; (3) synchronization as an extension of interoperation is explored relying on real-time data to handle dynamics.

2.4. *Challenges*

From the literature, factors related to manufacturing paradigms in three eras are summarized in Table 1. Several key challenges are thus proposed for Industry 4.0 manufacturing. The first is what the general principle is and what its key characteristics are. Although Industry 4.0 has been applied to different application scenarios with various objectives, the essence of Industry 4.0 is rarely considered. The second is how state-of-the-art technologies can be fused and integrated to provide a technical solution for Industry 4.0 manufacturing. Many advanced technologies are proposed to support Industry 4.0 manufacturing, but the fusion of them is scarcely reported. The third is what approaches can be leveraged to address the complex, dynamic and stochastic nature of manufacturing optimization problems. As manufacturing systems become increasingly complex and stochastic, traditional methods can hardly provide optimal solutions timely in the context of Industry 4.0. Thus, this paper proposes the concept of synchroperation, introduces enabling technologies, and designs a methodology for synchroperation.

Table 1. Summary of manufacturing paradigms

Category	Manufacturing collaboration	Manufacturing interaction	Manufacturing interoperation
Production mode	Flexible production	Mass customization	Mass customization
Society needs	Variety of products	Customized products	Customized products
Market	Demand>Supply	Supply>Demand	Supply>Demand
Product volume	Small volume demand	Smaller volume demand	Fluctuating demand
Scope	Machine- machine level	Factory-factory level	Supply chain level
Business model	Push	Pull-Push	Pull
Technology enabler	Computer	Information technology	IoT, cloud computing

3. Manufacturing Synchroperation

3.1. *Concept of manufacturing synchroperation*

The requirement of customized demand, increased productivity, improved flexibility and resilience, and reduced cost calls for efficient production and operations management that complies with changing business climate in Industry 4.0 manufacturing. On the basis of the evolution of production and operations management paradigms, and from a manufacturing point of view, we understand synchroperation as a new paradigm of production and operations management in the era of Industry 4.0 as follows.

Synchroperation refers to "synchronized operations" in an agile, resilient and cost-efficient way, with the spatiotemporal synchronization of men, machines and materials as well as data-driven decision-making, by creating, establishing and utilizing cyber-physical visibility and traceability in operations management.

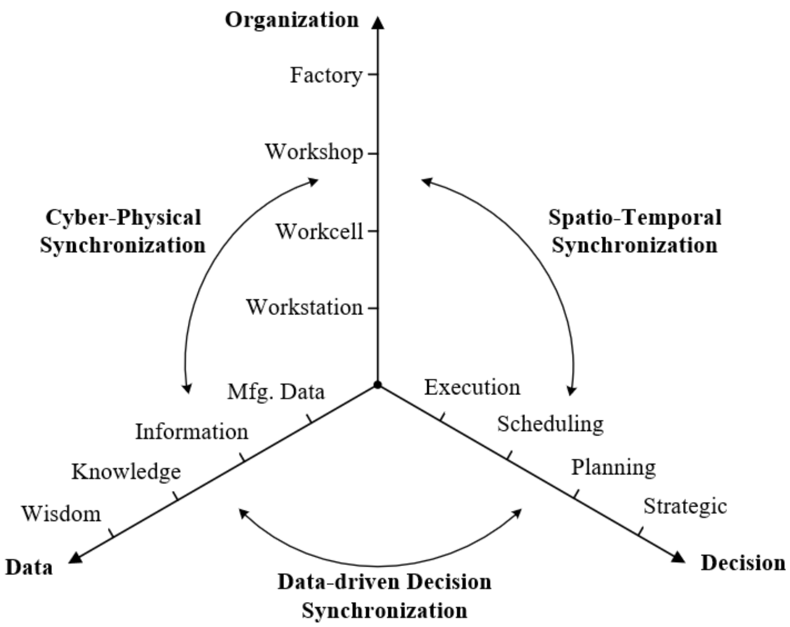

Fig.1. Overall framework for manufacturing synchroperation

Fig.1 shows the overall framework of manufacturing synchroperation with three key characteristics, including cyber-physical synchronization, spatio-temporal synchronization and data-driven decision synchronization. Cyber-physical synchronization focuses on the synchronization between cyber space and physical space through information visibility and traceability. The IoT and digital twin enabled ubiquitous connection, digitization and information-sharing in the context of Industry 4.0, present an opportunity for creating a digital equivalent representation of the physical entity (e.g., from small as a workstation, a workcell, to big as a workshop, a factory) and synchronizing them between cyber space and physical space with real-time information sharing.

Data-driven decision synchronization focuses on coordinated and global optimal production decisions benefiting from information sharing and data analytics. With enormous manufacturing data collected and shared in the cyber-physical system, valuable information and knowledge could be derived from the hidden patterns and correlations based on data mining, big data analytics and AI technologies. Thus, the coordinated, global optimal and even autonomous decision-making can be made for both short-term (e.g., scheduling and execution) and long-term (e.g., strategic and planning) production strategies.

For achieving successful implementation of these production strategies derived from data-driven decision models, spatio-temporal synchronization is crucial as it focuses on decomposing complex production environment and operations into spatio-temporal units and synchronizing them in a "divide and conquer" manner. It not only ensures that the required production resources (e.g., men, machines and materials) could be allocated and utilized in the right place at the right time with synchronization of production operations, but also in turns decouples the decision models towards practical industrial application by significantly reducing the uncertainty, randomness and complexity.

3.2. *Synchroperability measures*

Following the concept of synchroperation, we define synchroperability as the ability of a manufacturing system to achieve synchronized operations. Synchroperability is a measure for synchroperation in manufacturing. Three important aspects of measures for synchroperation, including simultaneity, punctuality and cost-efficiency are derived from the literature, and will be considered comprehensively in this section.

Table 2. Measures for synchroperability

Measures	References	Environment	Major aims	Indicators
Simultaneity	(Hsu and Liu, 2009)	Job shop	Reduce finished product inventory level	Flow time
	(Luo et al., 2017)	Flow shop	Improve overall performance of production and logistics	
	(Chen et al., 2019)	Flow shop	Improve production efficiency	Waiting time
	(Guo et al., 2020b)	Job shop	Improve the synchronization degree between manufacturing and logistics	
Punctuality	(Chen et al., 2015)	Flow shop	Improve production lead time and shipment punctuality	Earliness and tardiness
	(Fazlollahtabar et al., 2015)	Job shop	Improve the performance of material handling system in production	
Cost-efficiency	(Qu et al., 2016)	Flow shop	Improve production-logistics resources utilization	Utilization
	(Lin et al., 2018)	Flow shop	Improve production efficiency	Setup time
	(Luo et al., 2019)	Flow shop	Improve overall performance of production and warehousing	Makespan
	(Lin et al., 2019)	Flow shop	Improve production efficiency	

As listed in Table 2, synchroperability measures are divided into three categories: simultaneity, punctuality and cost-efficiency. Simultaneity is one of the most important aspects of measures for synchroperation, and indicators for simultaneity, such as flow time and waiting time have been adopted in specific applications (Hsu and Liu, 2009; Luo et al., 2017; Chen et al., 2019; Guo et al., 2020b). Simultaneity concerns variation in completion times of jobs within the same package or order, which can be used to reduce finished product inventory level as well as improve production efficiency. Simultaneity could be considered as a measure in the production system that sensitive to job flow time or waiting time. For example, for producing large-size or fragile products, it is sensitive to job waiting time as holding such a product is quite expensive, which requires a measure of simultaneity in this production system (Guo et al., 2020c). Punctuality is another important aspect of measure that focuses on earliness and tardiness (Chen et al., 2015; Fazlollahtabar et al., 2015). Punctuality could be considered as a measure in the production system that advocates JIT production, as it can reduce the production lead time, inventory level and shipment punctuality (Chen et al., 2015). Cost-efficiency is a common aspect of measure for synchroperation, most of the literature deals with such regular indicators as makespan, utilization and setup time (Qu et al., 2016; Lin et al., 2018; Luo et al., 2019; Lin et al., 2019). Cost-efficiency could be used as a measure in a complicated production environment that involves across multi-echelon and inter-organizational production activities. For example, for achieving overall optimization of make-to-order production and cross-docking warehouse, Luo et al (2019) proposed a synchronized production and warehouse decision model to minimize the overall makespan.

4. Synchroperation Platform for cyber-physical traceability and visibility

To achieve the cyber-physical visibility and traceability serving for synchroperation, a HPISMP, leveraging various IoT technologies, digital twins, big data techniques and consortium blockchain, is proposed in this paper. The overview of the technical framework is shown in Fig. 2.

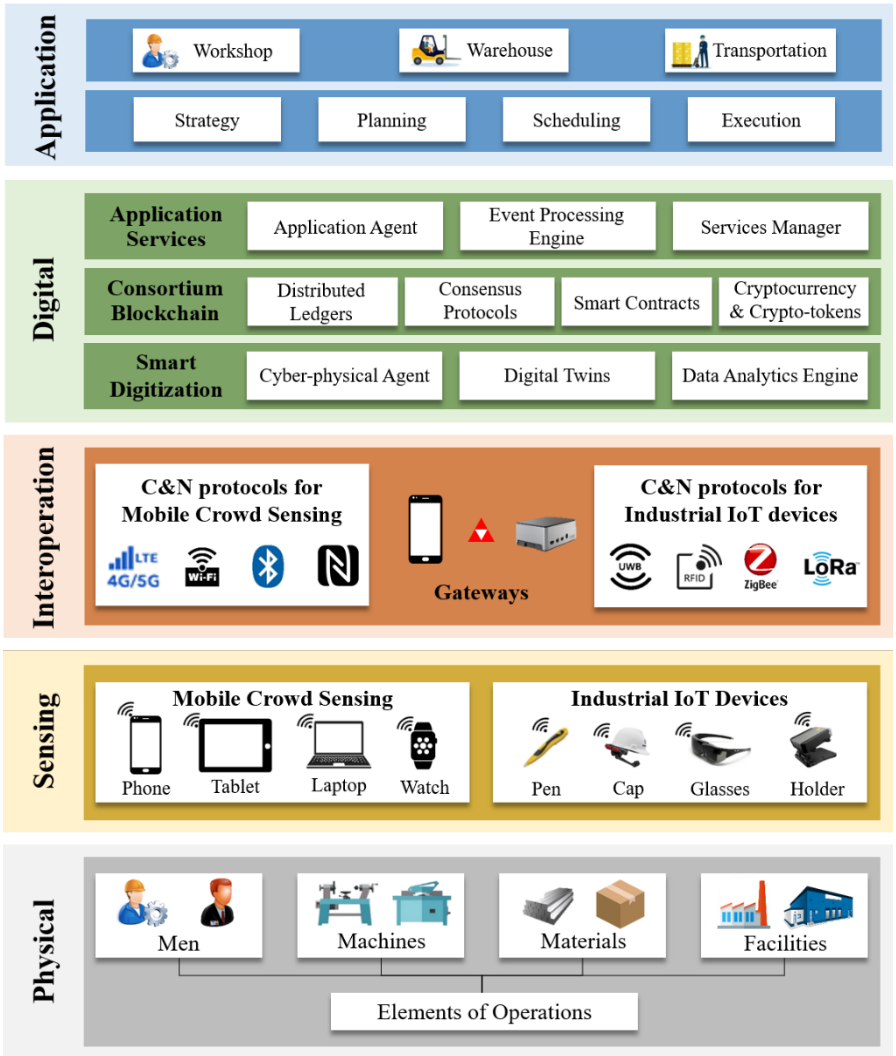

Fig. 2. Overview of hyperconnected Physical Internet-enabled smart manufacturing platform

The platform is divided into five layers, from bottom to top, namely physical, sensing, interoperation, digital, and application layer. Each layer is designed to connect, interact, and interoperate with each other so as to reinforce the overall synchroperability for production.

The first physical layer concerning men (e.g., managers and onsite operators), machines (e.g., production machines, vehicles and tools), materials (e.g., raw materials, Work-In-Processes (WIPs) and finished products), and facilities (e.g., production workshops and warehouses) that are fundamental elements of operations in manufacturing. Each type of element owns several categories classified by roles, functions, or phases. In line with actual demand, those elements may be equipped with electronic tags that contain a trickle of information primarily for identification in the cyber space, which can be captured passively or broadcast proactively (Zhao et al., 2017). Under this condition, it endows each element with capability of communication and interaction.

The second sensing layer includes a variety of IoT equipment that is used to enable physical objects with sensible, interactive, and intelligently reasoning capabilities. To be specific, mobile crowdsensing (MCS) is to collectively gather sensing data from nearby sensors via ubiquitous mobile devices, such as smartphones, tablets, laptops, and smartwatches (Ganti et al., 2011). Besides the application of MCS, Industrial Internet of Things (IIoT) devices are also widely deployed for the real-time data collection and transmission (Kong et al., 2020). Notably, wearable devices for men and machines enjoy high favour in the industry attributing to hands-free carry and convenient handling. For example, machines furnished with tag readers, like smart holders, are capable of detecting adjacent objects and triggering relevant events to facilitate operations. Else, men tend to carry smart devices to connect with peripheral objects and maintain responsive communication, such as versatile smart pens, caps, and glasses. Data or extracted information secured in this layer will be uploaded to the next layer for further processing.

The third interoperation layer aims to synchronize cyber-physical spaces and realize timely and seamless dual-way connectivity and interoperability between manufacturing objects and different application systems. It encompasses gateways and wireless communication and networking (WC&N) protocols. WC&N protocols serve as a data carrier to link with smart objects and the digital world (Zhang et al., 2011). In this platform, diversified wireless communication technologies are devised to be applied, such as 4/5G, LTE, Wi-Fi, Bluetooth, and NFC, which are typically provided in smartphones and personal wearables, and others like UWB, RFID, ZigBee, and LoRa that are preferably harnessed in the industry. All those protocols are embedded in gateways. Besides acting as a hardware hub, the gateway also offers a suite of software services, named gateway operating system, including definition, configuration, execution, and monitoring (Fang et al., 2013). Concretely, it can define the flow of data collection from heterogeneous devices and the cloud, configure essential setups and environmental conditions, execute data processing, information aggregation and exchanging, and, finally, monitor the entire operations for the malfunction detection. In addition, gateways have two types. One is the stationary gateways that are mounted at appointed spots and work in a plug-and-play way to ease the deployment. Another is the mobile gateways that are moveable and even portable since ubiquitous devices, like smartphones, can install dedicated applications to serve as a gateway, which significantly extends the channel of data collection and reduces development cost.

The fourth digital layer is the cyberspace, in the form of the cloud or servers in reality, that replicates the physical world and adopts services-oriented governance. The main function of smart digitization (Lin et al., 2019) converts physical objects into cloud assets (Xu et al., 2018) and applies data analytics for different purposes. Thereinto, the cyber-physical agent acts as a gate of cyberspace to receive data from gateways. Based on those informative data, physical objects are mapped to digital twins under predefined logics. Else, the data refinement or pre-processing is implemented in the data analytics engine. The second module consortium Blockchain (Li et al., 2017) is used as a backbone to build up a database, facilitate workflow management, and ensure traceability, accountability, and transparency. In detail, the distributed ledgers serve as distributed databases where digital twins are stored and transactions recorded, and consensus protocols is a globally-agreed rule for distributed computing to control the access to the database and make sure ledgers trackable and irreversible. Any kind of codified procedures that refer to a series of real-life workflows are encrypted and stated in smart contracts to trigger events in order. Cryptocurrency or crypto-tokens working as an incentive mechanism is granted proportionally according to the quality and punctuality of task completion. The goal of the third module application services is to host and manage services committed to users. The application agent acts as another gate of the digital world to interact with user applications. Calling functions or taking responses pursuant to manipulations in the application behaves in the event processing engine. The services manager is devoted to administrating fundamental components of services and configuring logics between services.

The fifth application layer provides decision support systems and visualization tools to help conduct operations for participating stakeholders, including workshops, warehouses, and transportation in manufacturing. Each stakeholder is principally concerned with four kinds of applications, namely strategy, planning, scheduling, and execution. Additionally, applications are developed in forms of desktop and mobile terminal so that office staff can make decisions in front of the desktop, and operators simply bring mobile devices to accomplish tasks. Furthermore, those applications allow individuals from different departments to manipulate separately without interference but for the same goal among the whole factory in real time so as to synchronize operations. For example, when a batch of parts is being produced, an urgent order crops up, the production manager goes to adjust the schedule, the warehouse prepare the material, and the logistics initiate a shipping task accordingly via each application. Hence, the next production job could be launched as punctually as possible.

Synchroperation in manufacturing anticipates high demand for a traceable and visible system that can synchronize the cyber and physical world greatly regarding organization, data, and decision. For the cyber-physical synchronization, IoT technologies play an essential role in digitizing physical objects to provide a foundation for information traceability and visibility. For the spatio-temporal synchronization, objects in operations are highly intertwined concerning time and space since the flow of men, machines, and materials in the factory are much frequent and intricate. To model and visualize these operations, a spatio-temporal analytics method is designed to segment space and time of operations for local dissolution and then integrate them to reap the overall effects. For the data-driven decision synchronization, consortium blockchain provides an effective solution to sharing information among the platform safely and helping users easily track and trace. Based on data analytics engines, different applications are developed for data visualization to assist operators in making decisions. In this case, the visibility and traceability of the system get considerably enhanced.

5. Graduation Intelligent Manufacturing System for Synchroperation

This section proposes the GiMS with “divide and conquer” principles, to address the complex, stochastic, and dynamic nature of manufacturing for achieving synchroperation. The basic form and principles of GiMS can be found in previous research (Lin, et al., 2019; Guo et al., 2020a). As shown in Fig. 3, this paper presents the five key phases to implement GiMS in factories.

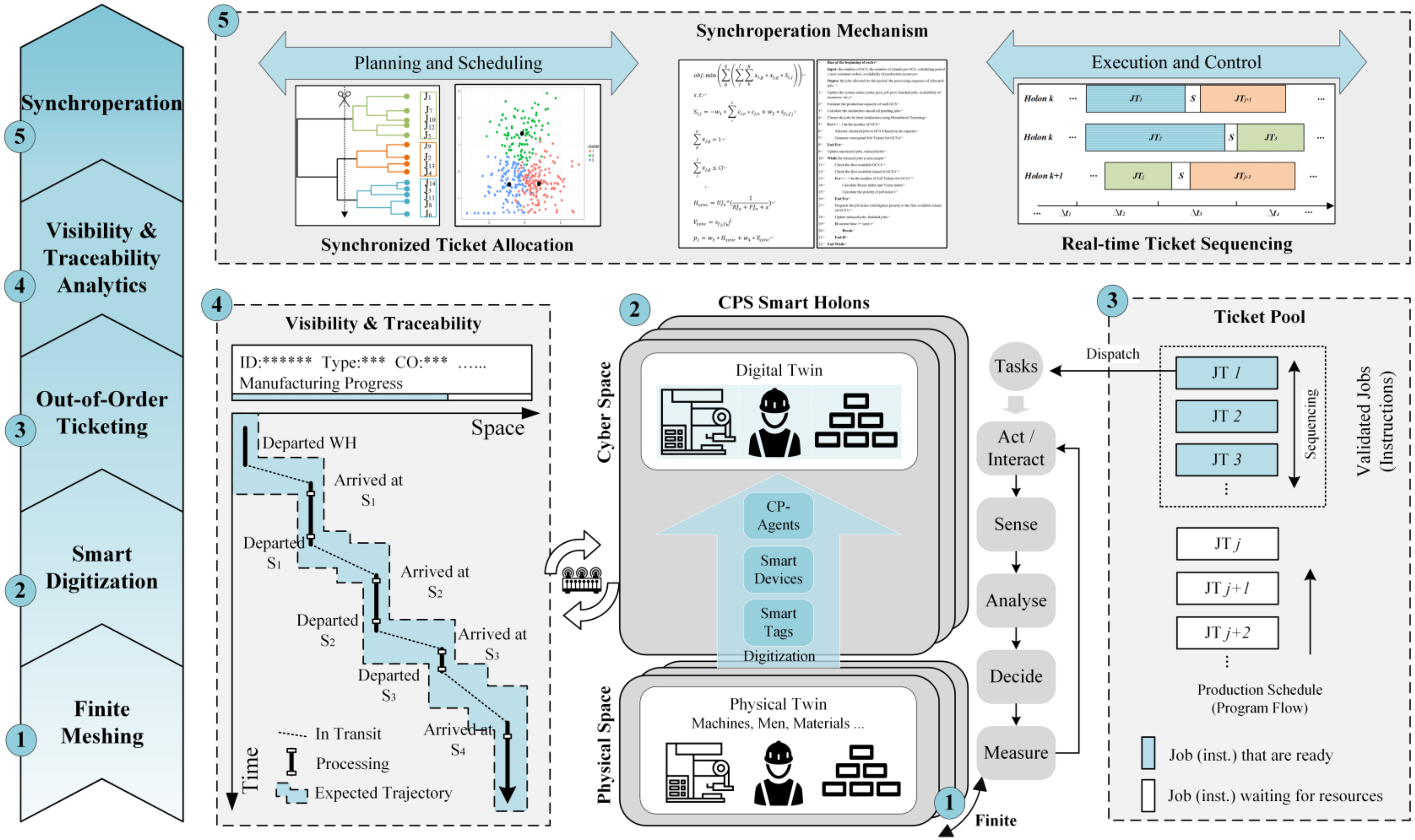

Fig. 3. Five phases of GiMS

Phase 1: Finite Meshing

This phase involves spatially dividing the factory organization and temporally discretizing the decision horizon into an equivalent system of finite “Graduation Ceremony Stages (GCS, a space unit in a time period)”, to minimize complexity and localize uncertainties. Operation elements (men, machines, materials) are defined for all “stages” as physical twins.

The space scope of a factory contains various production, logistics, and storage facilities and areas that can be divided into smaller space units. The decision horizon is discretized into multiple shorter time periods (Balakrishnan and Cheng, 2007; Torkaman et al., 2017). Because the space unit and time period of GCS in meshing are small enough relative to the original system, the subproblem size is limited, and a straightforward decision model can be built. All the uncertainties that occur during the current period can be considered in the next period with negligible loss of service quality. There are different rules to generate the mesh: (1) Meshing according to absolute space and time. Usually, the factory is divided into finite space units based on their absolute spatial positions; the decision horizon can be discretized into multiple time periods representing a working shift or several hours. (2) Meshing based on functionality. This rule divides the factory into GCS with different functions. For instance, logistics facilities and production workstations belong to separate GCS. Production area can be further divided based on their functions and responsibilities (threading, heat-treating, etc.) to obtain finer granularity. Correspondingly, the time scope should be discretized with the characteristics of different function areas taken into account. (3) Meshing on a dynamic basis. This rule dynamically adjusts the granularity of spatiotemporal mesh based on the real-time situation. This usually requires a high level of visibility and traceability throughout the fast-changing supply chain.

Phase 2: Smart Digitization

Phase 2 is to digitize the operation elements at all GCS for generating digital twins with the enabling technologies. A highly visible, transparent, and interconnected Cyber-Physical Factory (CPF) with real-time visibility and traceability is built through smart digitization. This phase constructs the data dimension of physical twins, and the cyber-physical synchronization is achieved through smart gateways.

With the deployment of mobile crowdsensing, IIoT devices, and cyber-physical agents, all physical entities in the factory are digitized for generating cyber avatars. The physical twins combine with corresponding digital twins to form CPS smart holons (CPS-SHs) that are decentralized and of autonomy to some extent. All CPS-SHs are physically independent but digitally interconnected by the tasks. The capabilities of CPS-SHs include: 1) sense the environment, such as how it connects with other holons and the status of task pool; 2) analyze the real-time production data and information; 3) autonomously make decisions based on the status of tasks and the state of itself; 4) take actions accordingly and interact with each other; 5) finally measure the key production performance (e.g., holon utilization, efficiency). Relevant applications, services, and analytics are integrated into the cyber space. Smart gateways are deployed to synchronize cyber and physical spaces, analyze the status of smart holons, and support visibility and traceability analytic between smart holons.

Phase 3: Out-of-Order Ticketing

This phase implements an Out-of-Order (OoO) ticketing for smart holons to facilitate smooth onsite execution and flexible control of production progress with enhanced resilience. OoO ticketing guarantees the data-driven decision synchronization at the operational level.

Three kinds of tickets, including job ticket (JT), setup ticket (ST), operation ticket (OT) and twined logistics ticket (LT) are critical in GiMS. Smart tags serve as the carriers of digitalized tickets. JTs are designed for permitting the right jobs to produce in one batch considering demand and capacity. STs are designed to control flexible setups between different job families so that the setup can be informed in advance and performed at the right time. OTs and twined LTs are designed to synchronize operation and JIT delivery. These tickets are real-timely generated and allocated to the ticket pools of each GCS. OoO is a paradigm used in modern CPUs to avoid stalls and improve processing efficiency (Hwu & Patt, 1986). OoO allows the processor to execute instructions in an order governed by the availability of input data and execution units. By analogy, the OoO ticketing in factories allows jobs to be processed in an order governed by the availability of materials, machines, and men. That is, smart holons look ahead in the ticket pool and find those that are ready to be processed. When a disturbance like material deficiency/loss or machine failure occurs, the smart holon can decide to process other ready jobs or using other available machines rather than wait. OoO ticketing organizes the onsite production operations with simplicity and resilience, and offer a robust and straightforward logic to tackle frequent uncertainties in the real-life shop floor.

Phase 4: Visibility and Traceability Analytics

In phase 4, the cyber-physical visibility and traceability (CPVT) analytics is utilized to identify and establish the dependencies and connectivity of GCS and smart holons, and to mitigate the spatiotemporal uncertainties. Besides, this phase also serves as the foundation for spatio-temporal synchronization and higher-level data-driven decision synchronization.

The holonic dependency and connectivity usually refer to the logical relationship between holons, such as how the state of ticket pools update over time, and how the tickets flow between holons. The CPVT is the key tool to real-timely monitor ticket pools and to establish the connectivity from two aspects. Firstly, how the states of holons update over time: The input of one holon at the beginning of the current time unit consists of two parts. The first part is the output of that holon in the previous time unit; the second part contains new information that occurs in the previous time unit; these two parts are also strongly influenced by various uncertainties such as stochastic processing time, machine failure, absence of operator, etc. Secondly, how the tickets flow between holons: Completing a production job usually requires performing several operations. These operations and their intrinsic sequencing and spatial constraints are defined in the tickets. The jobs whose operation at the current holon in the previous time unit has been completed, will be transferred to the following holons. And the jobs transferred to the current holon in the current time unit, are the union set of jobs whose operation in the previous holon has been completed. These real-time data and information are vital for supporting decision-making within GCS and connecting all holons.

Phase 5: Synchroperation

This phase designs the synchroperation mechanism under GiMS to facilitate upper-level planning and scheduling and lower-level onsite execution and control. Spatio-temporal synchronization and data-driven decision synchronization are achieved in this phase.

In the upper-level planning and scheduling, the overall planning horizon T is discretized into multiple shorter scheduling periods t. Based on the real-time demand (e.g., product type, quantity) and production constraints (e.g., capacity, resource) in period t, the job ticket allocation mechanism aims to generate schedule for period $t+1$ on an aggregate basis for families of jobs and allocate job tickets. The similarity among jobs is usually measured from the aspects of setup, material requirement, operator skill requirement, correlative orders and so on. In the lower-level execution and control, as the jobs allocated to a single period are similar, the rigid sequence of these jobs is less significant. Thus, OoO ticketing of tickets is adopted. At the beginning of t, job tickets are released to each GCS task pool, the operation tickets and logistics tickets for this job are activated. A job ticket is validated once all required resources are available. When there is a vacancy in the workstation buffer, and the priorities of validated tickets are calculated based on real-time data, the job ticket with the highest priority will be dispatched. The priorities are usually computed based on horizontal synchronization, vertical synchronization, and the matching degree of the job and workstation (job type, machine type, operator skill etc.). The bi-level synchroperation mechanism promises both optimized decisions at the managerial level and resilience execution, flexible control at the operational level.

6. Case study: Synchroperable hybrid assembly line Based on GiMS

In this section, the GiMS is applied to a novel manufacturing layout named hybrid assembly line (HAL). This layout is adopted by a world-leading air conditioner manufacturer G to face the fast-changing market with high flexibility. First, the GiMS enabled HAL is introduced, and then a comprehensive numerical analysis is carried out to verify the effectiveness of the proposed method. Results show that GiMS can obtain significant performance improvements regarding synchroperability measures.

6.1. *GiMS enabled HAL*

Fig. 4 presents the GiMS-enabled HAL. The HAL consists of a series of assembly stations. Each station has the space for equipment, materials and tools. All operations for one product will be processed and completed on an assembly trolley. The operators move the assembly trolley along the assembly line for assembly operations. After handling the final product, the operator moves the assembly trolley back to the first station for next assembly job. In the assembly process, the job finished early can overtake the ones in front. For example, in the real time job pool part of the Fig. 4, the job #3 is completed faster in station 1, and it will become the first job in next station. Operators in the same station share the same job pool and always take the first job from the job pool. Each operator can only process one job at a time and preemption of jobs is not allowed.

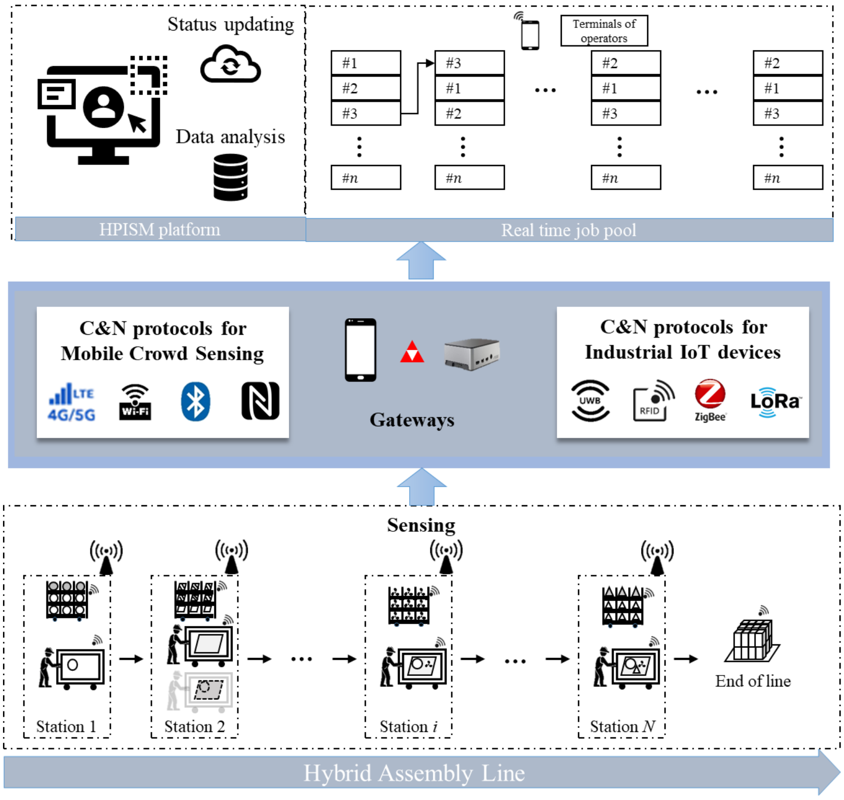

Fig. 4. GiMS enabled HAL assembly process

The PI infrastructure is deployed for creating the hyperconnected cyber-physical manufacturing environment. The production data and information are real-timely captured and transmitted to cyberspace through smart gateways with cyber-physical visibility and traceability. The whole factory is meshed spatially and temporally with the proposed meshing rules in section 5. In this process, each HAL is regarded as a GCS and there are multiple homogeneous GCSs in the factory. From the temporal perspective, different strategies including integral time units such as 1 hour or the average processing time can be applied. Smart tags (e.g., RFID tags) are attached to the corresponding machine, materials, and tools, and all elements are digitalized for generating cyber avatars. The CPS-SHs are formed from cyber avatars and their digital twins. Finally, the entire factory is discretized into CPS-SHs.

The job allocation and execution process under HAL is formulated mathematically to ensure the synchroperation in the whole assembly process. The customer order o_i is denoted by

$$o_i \triangleq \left(at_i, d_i, n_{i,p}\right)$$

The at_i and d_i represent the arrival time and due date of the ith order, and $n_{i,p}$ donates the required amount of product type p. Each product is represented by an assembly job ticket.The assembly job tickets are released dynamically based on the comprehensive priority (CP). The CP_j of job j is calculated with V-sync and H-sync proposed in GIMS and due date priority (DP):

$$CP_j = w_H \cdot norm\left(HS_j\right) + w_V \cdot norm\left(VS_j\right) + w_D \cdot norm\left(DP_j\right) \tag{1}$$

$$HS_j = \left(\frac{UJ_i}{\alpha}\right)^{\frac{1}{\left(\frac{RJ_i}{\alpha}\right)+\beta}} \tag{2}$$

$$VS_j = \frac{b_{p_j,p_l}}{1 + \prod_{l' \in L-l} b_{p_j,p_{l'}}} \tag{3}$$

$$DP_j = d_i - t \tag{4}$$

The job with smaller CP_j has higher priority. HS_j represents the production progress of the order that contains job j. UJ_i and RJ_i denote the unreleased jobs and released jobs of order i respectively, ε is an arbitrary small real number in case RJ_i is equal to 0. α and β are positive real number used to smooth the HS_j value. As setup is required for changeover between different product types, VS_j reflects the matching degree of the job j and the available line l (whether setup is required). p_j and p_l denote the product type of job j and the setup condition of line l left by previous job. b_{p_j,p_l} is a Boolean function and takes the following form:

$$b_{p_j,p_l} = \begin{cases} 0 & if\ p_j = p_l \\ 1 & otherwise \end{cases} \tag{5}$$

For DP_j, d_i and t are the modified due date of order i and current time. The normalization function takes the following form:

$$norm(x) = \frac{x - min}{max - min} \tag{6}$$

Where the maximum and minimum can be derived from all unrealised jobs in the system. Then, the objective in the release process is to allocate the jobs with higher priorities

$$\text{Minimize} \sum_{j=1}^{J} CP_j x_j$$

s.t.

$$\sum_{j=1}^{J} x_j \leq N \tag{7}$$

$$x_j \in \{0,1\} \tag{8}$$

N represents the maximum number of jobs released to each HAL and depends on the operators in each station, time period t and average job processing time. Then, a batch of jobs with higher priorities will be released to the job pool of the first station in the HAL. Then, in each assembly line, assembly job tickets are handled under the OoO ticketing. Notations used in the system are summarized in Table 3.

Table 3. Notations used in the system

Index	
i	customer index
j	job index
l	HAL index
Parameters	
I	total customer orders
J	all unreleased assembly jobs
t	time period
o_i	customer order i.
d_i	order i's due date.
$n_{i,p}$	the required amount of product type p in order i.
CP_j	comprehensive priority of job j.
HS_j	H-sync priority of job j.
UJ_i	unreleased jobs of order i.
RJ_i	released jobs of order i.
VS_j	V-sync priority of job j.
DP_j	due date priority of job j.
α, β	positive real numbers.
p_j	denote the product type of job j and the setup condition of line l
p_l	the setup condition of line l.
N	the maximum number of released jobs in each releasing decision.
c_j	the complete time of job j
r_j	released time of job j
TST_l	the total setup time of line l.
Decision variable	
$\boldsymbol{x_j}$	if job $\boldsymbol{j}$ is released

6.2. *Numerical Study*

Several experiments are conducted to evaluate the performance of GIMS in the HAL case. Several synchroperability measures are used in the experiments. For the simultaneity measure, the average flow time (AFT) is adopted, which considers the time duration from the first assembly job starts processing on the HAL to completion of all jobs. The AFT is calculated by

$$AFT = \frac{\sum_{i=1}^{I}\left(\max_{j\in o_i} c_j - \min_{j\in o_i} r_j\right)}{I} \tag{9}$$

Where c_j and r_j represent the complete time and released time of job j. The average tardiness (ATD) is used as the punctuality measure and takes the following form:

$$ATD = \frac{\sum_{i=1}^{I}\left(\max\left(0, \max_{j\in o_i} c_j - d_i\right)\right)}{I} \tag{10}$$

The makespan (MS) and average setup time (AST) are adopted as the cost efficiency measure of the whole plant. The AST can be calculated as follows:

$$AST = \frac{\sum_{l=1}^{L}(TST_l)}{L} \tag{11}$$

TST_l represents the total setup time of line l. The parameters for generating test instances are set as the values in Table 4.

Table 4. Experimental data

Parameters	Value
Cell	5
HALs	5
Operators	4
Average processing time in each station (min)	$N(10,2)$
Average setup time (min)	10,20, 30, 40
Customer orders	50
Number of jobs per order	5
Average orders inter-arrival time (min)	15,25,35
Due dates of orders	U [7, 13] ×order inter-arrival time
Products	3, 6, 9,12
Released job numbers	4
Time period	100

The operation time for each job in each station follows a normal distribution with mean 10 and standard deviation 2. The number of customer orders is set to 50. The time period, setup time, and types of products are set to several fixed numbers. The order inter-arrival time is generated from a Poisson process with mean 15, 25 and 35. The inter-arrival time which balances the output rate and job arrival rate of the entire plant. When the value becomes smaller, which means that orders come to the system more frequently and can be considered as the peak season. Similarly, a smaller value means the offseason. The type of products are set to {3, 6, 9, 12} respectively. The due date of each order is set to 7~13 times of average orders inter-arrival time (min) after the order arrives. 4 job are released each time and the time period is set to 100.

The performance of GiMS is compared to several common scheduling rules with different numbers of orders. Then the sensitivity analysis is conducted to investigate the effects of two crucial factors: product type and setup time. To compare the performance, the following three common rules are adopted: first-come-first-serve (FCFS) rule (Schwiegelshohn and Yahyapour, 1998), Shortest processing time (SPT) (Pickardt and Branke, 2012) and Earliest due date (EDD) (Baker, 1984). In this case, SPT considers that the order with less unreleased jobs has higher priority. The setup time is set to 30 and product type is set to 6.

At the beginning of the production horizon, each HAL holds the same number of jobs with the same product type. The inter-arrival time is gradually increased from 15 to 35 in steps of 10 and there are 50 customer orders. Under each number of orders, the experiments for the four rules are carried out individually for 100 times, which is large enough to give statistically reliable results. Table 5 shows the average values of the results.

Table 5. Synchroperability measures performance of HALs under different rules

Inter-arrival time	**Rules**	**Measures**			
		AFT	**ATD**	**MS**	**TST**
15	GIMS	**217.3851**	**72.3005**	**1216.085**	**1785.572**
	FCFS	221.9514	76.75619	1371.398	2157.09
	SPT	221.3701	76.37134	1363.869	2156.957
	EDD	221.8738	76.64523	1372.187	2157.06
25	GIMS	**211.2348**	**5.708845**	**1208.925**	**1824.576**
	FCFS	219.4813	7.7747	1596.651	2204.133
	SPT	219.8993	7.905285	1575.59	2203.765
	EDD	219.6664	7.769687	1567.685	2203.273
35	GIMS	**208.4382**	**0.005619**	**1506.978**	**1827.535**
	FCFS	214.5554	0.173307	1586.747	2171.051
	SPT	214.3138	0.13862	1583.864	2171.605
	EDD	214.6878	0.146956	1602.94	2171.842

Numerical results show that GIMS achieves lower values in all measures. Especially, GIMS achieves a 15%~18% reduction in TST compared to other rules. This means that GiMS can effectively reduce the setup operations can help the manufacturer achieve cost-efficiency and higher synchroperability. Another key observation is that GiMS achieve less ATD when the inter-arrival time is 15 and enable orders to be finished simultaneously. This means that during peak seasons, GiMS can reduce setup cost without sacrificing the punctuality performance.

The sensitivity analysis is conducted to the product type and setup time. First, the product type is increased from 3 to 12 in steps of 3 with the setup time is 30. Also, FCFS policy is used for comparison. The results are shown in Fig. 5. And then the setup value is increased from 10 to 40 in steps of 10 with 6 product types. The results are shown in Fig. 6.

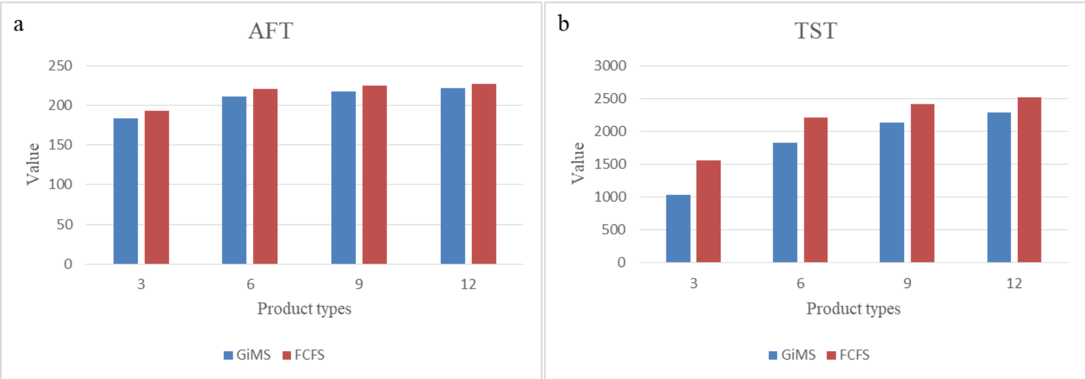

Fig. 5. Measures of GiMS and FCFS policy under different product types

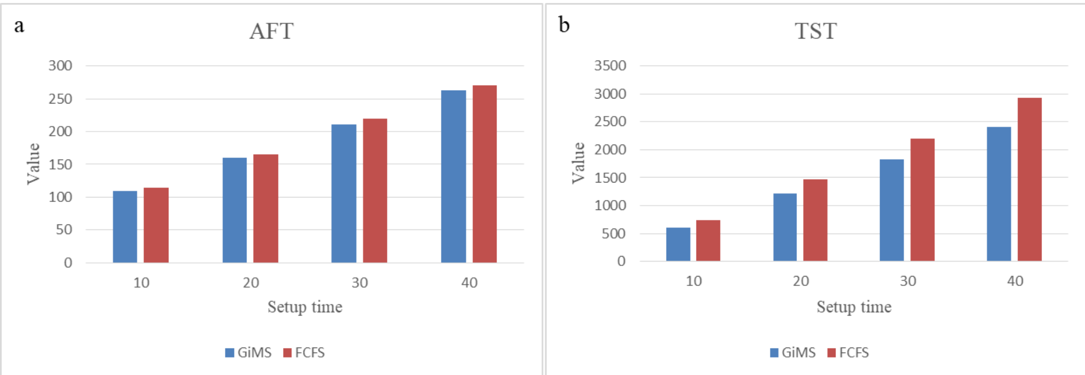

Fig. 6. Measures of GiMS and FCFS policy under different setup times

Fig. 5 shows that GiMS has less AFT and TST compared to FCFS policy in each instance. This implies that GiMS can achieve better performance in a wide range of regimes. When product types is 3 and 6, GiMS outperforms FCFS in AFT. For TST, it can be seen that GiMS also has a better performance in the case with less product types. In Fig. 6, GiMS has less AFT and TST compared to FCFS policy under each setup time. For AFT and TST, GiMS has a greater advantage over FCFS when the setup time increases. Besides, the TST has been significantly reduced compared to AFT. This indicates that GiMS can help manufacturers to reduce the setup time significantly especially when the setup time is larger.

The management insights can be summarized as follows: GiMS can achieve higher synchroperability and significant performance improvement for HAL. With the deployment of HPISMP, real-time status of operators, equipment, and materials is available for decision making. This enables a global optimization of decisions.

7. Conclusions and Future perspectives

Industry 4.0 connotes a new industrial revolution with the convergence between physical and digital spaces, which are currently revolutionizing the way that production operations are managed. To explore the evolution of production and operations management paradigms in the era of Industry 4.0, a concept of manufacturing synchroperation with enabling technologies and associated methodologies are proposed for transformation and implementation of Industry 4.0 manufacturing.

The main contributions of this paper can be concluded as follows: (1) A concept of manufacturing synchroperation with cyber-physical synchronization, data-driven decision synchronization and spatio-temporal synchronization, is proposed for Industry 4.0 production and operations management. (2) A HPISMP assisted with digital twin and consortium blockchain is developed as a technical solution to support the transformation of manufacturing synchroperation. (3) GiMS with “divide and conquer” principles is proposed as a methodology to address the complex, stochastic, and dynamic nature of manufacturing for achieving synchroperation. (4) The potential advantages of implementation of manufacturing synchroperation are illustrated with an industrial case from an air conditioner manufacturer.

This paper presents a new paradigm of production and operations management in the era of Industry 4.0-manufacturing synchroperation. The research is still in its infancy, and there are abundant research opportunities in this topic. Further research efforts on principles, methodologies, and support technologies for transforming production and operations management to Industry 4.0 manufacturing are necessary. Several possible research directions with related research questions are listed as follows.

RQ1: How manufacturing synchroperation reshapes the way manufacturer do business with their customers? How to establish adaptive business models for manufacturing synchroperation in the era of Industry 4.0?

Industry 4.0 manufacturing is revolutionizing the way that production operations are managed and done, which also has the potential to revolutionize the way manufacturer do business with their customers and suppliers. The concept of manufacturing synchroperation provides an insight for manufacturers to re-evaluate and develop their business model to capture and maximize the value of the customer in the Industry 4.0 manufacturing environment. More innovative business models need to be further explored.

RQ2: How to measure the disruptions of manufacturing synchroperation on supply chain? How to integrate manufacturing synchroperation with the processes of supply, warehousing and delivery to increase the agility of the supply chain?

Manufacturing synchroperation with cyber-physical synchronization promises to remove information or communications barriers cross multi-echelon and inter-organizational activities. Effective methods to measure the disruptions of manufacturing synchroperation on supply, warehousing and delivery processes, and increase the agility of the whole supply chain through the real-time cyber-physical visibility and traceability deserve further explorations.

RQ3: What is the technical requirement for transforming to Industry 4.0 manufacturing? How to design effective technical standards and architectures for real-time information exchange among "real-time things" to support manufacturing synchroperation?

The transformation of Industry 4.0 manufacturing requires technical infrastructures to support real-time visibility and information sharing. Technical standards and architectures with a high degree of connectivity, interoperability and accessibility must be designed to define the specifications for real-time information exchange among "real-time things", which is the basis for achieving manufacturing synchroperation in the era of Industry 4.0.

RQ4: What are the effects of the real-time visibility and information sharing on complexity and uncertainty nature of manufacturing? How to model and minimize the

uncertainty and complexity in real-time manufacturing environment?

Although the potential benefits of the real-time visibility and information sharing in the era of Industry 4.0 have been acknowledged in general, the theoretical foundations are rarely considered. Innovative methods to model and measure the effects of the real-time visibility and information sharing on complexity and uncertainty nature of manufacturing, and minimize the uncertainty and complexity in the Industry 4.0 manufacturing environment are crucial.

RQ5: How to realize the full potentials of historical and real-time production data? How to derive decentralized/autonomous decision-making to create data-driven value-adding services for Industry 4.0 manufacturing?

The hyper-connection, digitization and sharing in Industry 4.0 manufacturing bring new decentralized production patterns with real-time production data. Under this circumstance, decentralized elements in the production system can independently or collaboratively make decisions and even take actions. Therefore, how to derive decentralized/autonomous decision-making from the fusion of enormous production data and corresponding management strategies to create data-driven value-adding services need to be investigated.

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Reference

Akkermans, H.A., van der Horst, H., 2002. Managing IT infrastructure standardisation in the networked manufacturing firm. *International Journal of Production Economics*, 75, 213-228.

Balakrishnan, J., & Cheng, C. H., 2007. Multi-period planning and uncertainty issues in stationular manufacturing: A review and future directions. *European Journal of Operational Research*, 177(1), 281-309.

Baker, K. R., 1984. Sequencing rules and due-date assignments in a job shop. *Management Science*, 30(9), 1093-1104.

Browne, J., Dubois, D., Rathmill, K., Sethi, S.P., Stecke, K.E., 1984. Classification of flexible manufacturing systems. *The FMS magazine*, 2, 114-117.

Buzacott, J. A., & Yao, D. D., 1986. Flexible manufacturing systems: a review of analytical models. *Management Science*, 32(7), 890-905.

Chen, J., Huang, G. Q., Luo, H., & Wang, J., 2015. Synchronisation of production scheduling and shipment in an assembly flowshop. *International Journal of Production Research*, *53*(9), 2787-2802.

Chen, J., Wang, M., Kong, X. T., Huang, G. Q., Dai, Q., & Shi, G., 2019. Manufacturing synchronization in a hybrid flowshop with dynamic order arrivals. *Journal of Intelligent Manufacturing*, *30*(7), 2659-2668.

Chen, T., Chiu, M.C., 2017. Development of a cloud-based factory simulation system for enabling ubiquitous factory simulation. *Robotics and Computer-Integrated Manufacturing,* 45, 133-143.

D'Amours, S., Montreuil, B., Lefrancois, P., Soumis, F., 1999. Networked manufacturing: The impact of information sharing. *International Journal of Production Economics,* 58, 63-79.

Da Xu, L., He, W., & Li, S., 2014. Internet of things in industries: A survey. *IEEE Transactions on Industrial Informatics*, *10*(4), 2233-2243.

Fang, J., Qu, T., Li, Z., Xu, G. and Huang, G.Q., 2013. Agent-based gateway operating system for RFID-enabled ubiquitous manufacturing enterprise. *Robotics and Computer-Integrated Manufacturing*, 29(4), pp.222-231.

Fazlollahtabar, H., Saidi-Mehrabad, M., & Balakrishnan, J., 2015. Mathematical optimization for earliness/tardiness minimization in a multiple automated guided vehicle manufacturing system via integrated heuristic algorithms. *Robotics and Autonomous Systems*, *72*, 131-138.

Ganti, R.K., Ye, F. and Lei, H., 2011. Mobile crowdsensing: current state and future challenges. *IEEE communications Magazine*, 49(11), pp.32-39.

GE, 2020. Predix Platform: Connect, optimize, and scale your digital industrial applications. Available online: https://www.ge.com/digital/iiot-platform (accessed on 22 October 2020).

Gunasekaran, A., 1999. Agile manufacturing: A framework for research and development. *International Journal of Production Economics,* 62, 87-105.

Guo, D., Li, M., Zhong, R. and Huang, G.Q., 2020a. Graduation Intelligent Manufacturing System (GiMS): an Industry 4.0 paradigm for production and operations management. *Industrial Management & Data Systems*.

Guo, D., Zhong, R. Y., Rong, Y., and Huang, G. Q., 2020d. Synchronization between manufacturing and logistics under IIoT and digital twin-enabled Graduation Intelligent Manufacturing System. *IEEE Transactions on Industrial Informatics*, under review.

Guo, D., Zhong, R. Y., Lin, P., Lyu, Z., Rong, Y., & Huang, G. Q., 2020c. Digital twin-enabled Graduation Intelligent Manufacturing System for fixed-position assembly islands. *Robotics and Computer-Integrated Manufacturing*, *63*, 101917.

Guo, D., Zhong, R. Y., Ling, S., Rong, Y., & Huang, G. Q., 2020d. A roadmap for Assembly 4.0: self-configuration of fixed-position assembly islands under Graduation Intelligent Manufacturing System. *International Journal of Production Research*, 58(15), 4631-4646.

Hsu, S. Y., & Liu, C. H., 2009. Improving the delivery efficiency of the customer order scheduling problem in a job shop. *Computers & Industrial Engineering*, *57*(3), 856-866.

Huang, G.Q., Wright, P.K., Newman, S.T., 2009. Wireless manufacturing: a literature review, recent developments, and case studies. *International Journal of Computer Integrated Manufacturing*, 22, 579-594.

Huang, G.Q., Zhang, Y.F., Jiang, P.Y., 2008. RFID-based wireless manufacturing for real-time management of job shop WIP inventories. *The International Journal of Advanced Manufacturing Technology*, 36, 752-764.

Hwu, W.-r., & Patt, Y. N., 1986. Hpsm, a high performance restricted data flow architecture having minimal functionality. *ACM SIGARCH Computer Architecture News*, *14*(2), 297-306.

Ivanov, D., Tang, C. S., Dolgui, A., Battini, D., & Das, A., 2020. Researchers' perspectives on Industry 4.0: multi-disciplinary analysis and opportunities for operations management. *International Journal of Production Research*, 1-24.

Koh, L., Orzes, G., & Jia, F. J., 2019. The fourth industrial revolution (Industry 4.0): technologies disruption on operations and supply chain management. *International Journal of Operations & Production Management,* 39, 817-828.

Kong, X.T., Zhong, R.Y., Zhao, Z., Shao, S., Li, M., Lin, P., Chen, Y., Wu, W., Shen, L., Yu, Y. and Huang, G.Q., 2020. Cyber physical ecommerce logistics system: An implementation case in Hong Kong. *Computers & Industrial Engineering*, 139, p.106170.

Kortuem, G., Kawsar, F., Sundramoorthy, V., & Fitton, D., 2009. Smart objects as building blocks for the internet of things. *IEEE Internet Computing*, *14*(1), 44-51.

Kusiak, A., 2017. Smart manufacturing must embrace big data. *Nature*, *544*(7648), 23-25.

Lee, J., Bagheri, B., & Kao, H. A., 2015. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18-23.

Li, Z., Barenji, A.V. and Huang, G.Q., 2018. Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. *Robotics and Computer-Integrated Manufacturing*, 54, pp.133-144.

Lin, P., Li, M., Kong, X., Chen, J., Huang, G. Q., & Wang, M., 2018. Synchronisation for smart factory-towards IoT-enabled mechanisms. *International Journal of Computer Integrated Manufacturing*, *31*(7), 624-635.

Lin, P., Shen, L., Zhao, Z., & Huang, G. Q., 2019. Graduation manufacturing system: synchronization with IoT-enabled smart tickets. *Journal of Intelligent Manufacturing*, *30*(8), 2885-2900.

Lin, Y. C., & Chen, T., 2017. A ubiquitous manufacturing network system. *Robotics and Computer-Integrated Manufacturing*, 45, 157-167.

Luo, H., Wang, K., Kong, X. T., Lu, S., & Qu, T., 2017. Synchronized production and logistics via ubiquitous computing technology. *Robotics and Computer-Integrated Manufacturing*, *45*, 99-115.

Luo, H., Yang, X., & Wang, K., 2019. Synchronized scheduling of make to order plant and cross-docking warehouse. *Computers & Industrial Engineering*, *138*, 106108.

Martinez, M.T., Fouletier, P., Park, K.H., Favrel, J., 2001. Virtual enterprise-organisation, evolution and control. *International Journal of Production Economics,* 74, 225-238.

McFarlane, D., Sarma, S., Chirn, J.L., Wong, C.Y., Ashton, K., 2003. Auto ID systems and intelligent manufacturing control. *Engineering Applications of Artificial Intelligence*, 16, 365-376.

McGehee, J., Hebley, J., & Mahaffey, J., 1994. The MMST computer-integrated manufacturing system framework. *IEEE Transactions on Semiconductor Manufacturing*, 7(2), 107-116.

Montreuil, B., Frayret, J.M., D'Amours, S., 2000. A strategic framework for networked manufacturing. *Computers in industry*, 42, 299-317.

Mourad, M.H., Nassehi, A., Schaefer, D., Newman, S.T., 2020. Assessment of interoperability in cloud manufacturing. *Robotics and Computer-Integrated Manufacturing*, 61.

Nagalingam, S.V., Lin, G.C.I., 1999. Latest developments in CIM. *Robotics and Computer-Integrated Manufacturing*, 15, 423-430.

Newman, S.T., Nassehi, A., Xu, X.W., Rosso, R.S.U., Wang, L., Yusof, Y., Ali, L., Liu, R., Zheng, L.Y., Kumar, S., Vichare, R., Dhokia, V., 2008. Strategic advantages of interoperability for global manufacturing using CNC technology. *Robotics and Computer-Integrated Manufacturing*, 24, 699-708.

Olsen, T. L., & Tomlin, B., 2020. Industry 4.0: opportunities and challenges for operations management. *Manufacturing & Service Operations Management*, *22*(1), 113-122.

Pickardt, C. W., & Branke, J., 2012. Setup-oriented dispatching rules–a survey. *International Journal of Production Research*, 50(20), 5823-5842.

Qu, T., Lei, S.P., Wang, Z.Z., Nie, D.X., Chen, X., Huang, G.Q., 2016. IoT-based real-time production logistics synchronization system under smart cloud manufacturing. *The International Journal of Advanced Manufacturing Technology*, 84, 147-164.

SAP, 2020. SAP Cloud Platform. Available online: https://www.sap.com/hk/products/cloud-platform.html (accessed on 22 October 2020).

Schwiegelshohn, U., & Yahyapour, 1998. Analysis of first-come-first-serve parallel job scheduling. *SODA*, 98, 629-638.

Siemens, 2020. MindSphere: Connecting the things that run the world. Available online: https://siemens.mindsphere.io/en (accessed on 22 October 2020).

Stecke, K.E., 1983. Formulation and Solution of Nonlinear Integer Production Planning Problems for Flexible Manufacturing Systems. *Management Science*, 29, 273-288.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F., 2018. Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, *94*(9-12), 3563-3576.

Torkaman, S., Ghomi, S. F., & Karimi, B., 2017. Multi-stage multi-product multi-period production planning with sequence-dependent setups in closed-loop supply chain. *Computers & Industrial Engineering*, 113, 602-613.

Wang, X., Ong, S.K., Nee, A.Y.C., 2018a. A comprehensive survey of ubiquitous manufacturing research. *International Journal of Production Research,* 56, 604-628.

Wang, X.V., Wang, L.H., Gordes, R., 2018b. Interoperability in cloud manufacturing: a case study on private cloud structure for SMEs. *International Journal of Computer Integrated Manufacturing*, 31, 653-663.

Wang, X.V., Wang, L.H., Mohammed, A., Givehchi, M., 2017. Ubiquitous manufacturing system based on Cloud: A robotics application. *Robotics and Computer-Integrated Manufacturing*,

45, 116-125.
Wang, X.V., Xu, X.W., 2013. An interoperable solution for Cloud manufacturing. *Robotics and Computer-Integrated Manufacturing*, 29, 232-247.
Xu, G., Wang, J., Huang, G.Q. and Chen, C.H., 2017. Data-driven resilient fleet management for cloud asset-enabled urban flood control. *IEEE Transactions on Intelligent Transportation Systems*, 19(6), pp.1827-1838.
Xu, X., 2012. From cloud computing to cloud manufacturing. *Robotics and Computer-integrated Manufacturing*, *28*(1), 75-86.
Xu, X.W., Wang, H., Mao, J., Newman, S.T., Kramer, T.R., Proctor, F.M., Michaloski, J.L., 2005. STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM CNC integration. *International Journal of Production Research,* 43, 3703-3743.
Yin, Y., Stecke, K. E., & Li, D., 2018. The evolution of production systems from Industry 2.0 through Industry 4.0. *International Journal of Production Research, 56*(1-2), 848-861.
Yusuf, Y.Y., Sarhadi, M., Gunasekaran, A., 1999. Agile manufacturing: The drivers, concepts and attributes. *International Journal of Production Economics*, 62, 33-43.
Zhang, L., Luo, Y.L., Tao, F., Li, B.H., Ren, L., Zhang, X.S., Guo, H., Cheng, Y., Hu, A.R., Liu, Y.K., 2014. Cloud manufacturing: a new manufacturing paradigm. *Enterprise Information Systems*, 8, 167-187.
Zhang, Y., Qu, T., Ho, O.K. and Huang, G.Q., 2011. Agent-based smart gateway for RFID-enabled real-time wireless manufacturing. *International Journal of Production Research*, 49(5), pp.1337-1352.
Zhang, Y.F., Qu, T., Ho, O., Huang, G.Q., 2011. Real-time work-in-progress management for smart object-enabled ubiquitous shop-floor environment. *International Journal of Computer Integrated Manufacturing*, 24, 431-445.
Zhao, Z., Fang, J., Huang, G.Q. and Zhang, M., 2017. Location management of cloud forklifts in finished product warehouse. *International Journal of Intelligent Systems*, 32(4), pp.342-370.
Zhong, R.Y., Dai, Q.Y., Qu, T., Hu, G.J., Huang, G.Q., 2013. RFID-enabled real-time manufacturing execution system for mass-customization production. *Robotics and Computer-Integrated Manufacturing*, 29, 283-292.
Zhong, R.Y., Xu, X., Klotz, E., Newman, S.T., 2017. Intelligent Manufacturing in the Context of Industry 4.0: A Review. *Engineering*, 3, 616-630.