Robotics and Computer–Integrated Manufacturing 73 (2022) 102236

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Synchronization of production and delivery with time windows in fixed-position assembly islands under Graduation Intelligent Manufacturing System

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ARTICLE INFO

Keywords:
Fixed-position assembly islands
integration of production and delivery with time windows
production synchronization
real-time visibility and information-sharing
Graduation Intelligent Manufacturing System

ABSTRACT

The layout of fixed-position assembly islands (FPAI) offers flexibility and efficiency for the production of bulky or fragile products with medium variety and volumes. With the unique production operations and customized delivery requirements in FPAI, the manufacturing practitioners are plagued by long waiting times, frequent setups, and high finished product inventory levels, which are mainly caused by the unsynchronous organization and operations of production and delivery. For achieving synchronization of production and delivery with time windows in FPAI, this paper introduces a concept of production synchronization with three pillars of real-time visibility and information-sharing, coordination of decision-making and synchronized operations. Following the concept, a synchronization-oriented Graduation Manufacturing System (GMS) with distinct functional tickets, including job ticket (JT), setup ticket (ST), operation ticket (OT) and twined logistics ticket (LT) is designed to organize production operations in an integrated and synchronized manner in FPAI. The IIoT-enabled Graduation Intelligent Manufacturing System (GiMS) with real-time visibility and information-sharing is proposed for achieving real-time operational visibility in FPAI. Under GiMS, consider customer requirements and production constraints, a coordinated decision-making model of production and delivery with time windows for FPAI is developed. The observation and analysis of the case company show the effectiveness of the proposed concept and approach, with the highest synchronous degree between production and delivery as well as the best performance in simultaneity (lowest waiting times), punctuality (minimum number of tardy jobs) and cost-efficiency (lowest setup times).

1. Introduction

The layout of fixed-position assembly islands (FPAI) is widely used in the heavy equipment industry. It is normally adopted when products are too bulky or fragile, i.e., ships, aircraft, locomotives, rotary printing presses, and big milling machines [1-3]. In FPAI, the product remains at one assembly island for its entire assembly period, while required workers, equipment, and materials are moved to the island according to the assembly plan.

As a product fixed-oriented layout, FPAI has several advantages over the product flow-oriented layout (e.g., a flow shop), such as reduced damage or cost of product movement and more continuity of the assigned workforce [4]. But there are also some challenges when using the layout of FPAI for the production of bulky or fragile products, such as the work-in-process (WIP) and finished product holding costs are quite high, and the setup for switching from production of one product type to another is relatively time-consuming. Besides, due to the deliveries of bulky or fragile products are expensive and time-consuming, customers expect to have all the individual products belonging to the same order to be shipped in one batch within a certain time window. With the customized demand for delivery as well as the unique production operations in FPAI, the manufacturing practitioners are facing difficulties in coordinating production and delivery to meet customer demand. A laser equipment manufacturing company that faces similar dilemmas motivated this study. The company uses the layout of FPAI for producing heavy-duty laser equipment, and the required equipment in one

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https://doi.org/10.1016/j.rcim.2021.102236
Received 30 December 2020; Received in revised form 14 June 2021; Accepted 26 July 2021
Available online 6 August 2021

customer order must be shipped as a batch to the customer. Besides, to keep safety lead-time to buffer against upstream uncertainties, a time window that specifies the time interval this batch is expected to be shipped is placed by the customer. With unsynchronous organization and operations of production and delivery, the company has been plagued by long waiting times, frequent setups, and high finished product inventory levels in the production.

For achieving synchronization of production and delivery, many researchers have focused on integrated production scheduling such as due date-based scheduling [5], earliness and tardiness scheduling [6], just-in-time (JIT) scheduling [7], integrated scheduling of production and delivery [8, 9]. The integrated production scheduling offers promising insights into the coordination of production and delivery; however, several significant challenges are still existing and can be summarized as follows: (1) Most of the related work focus on flow shop or job shop environment, little attention has been paid to the layout of FPAI, in which the production operations are distinctive. (2) Most of the integrated production scheduling models mainly concern the finished time of the last job in the order not exceed the pre-specified due date or shipment date, which is reasonable when the products are easy to move or store. While for the production of bulky or fragile products that in one order need to be shipped as a batch to the customer, holding such finished product is more difficult and expensive in FPAI [10]. The coordination of the variation in completion times of all jobs within the same customer order as well as the delivery time window constraints in FPAI increase the complexity of the problem. (3) Lack of real-time feedback of accurate production information (e.g., capacity constraints), and the synchronization of production and delivery cannot be achieved at the operational level without timely and accurate data to support that decision-making.

Fortunately, with the confluence of new-generation information technologies in manufacturing, such as Industrial Internet of Things (IIoT) [11], cloud computing [12], cyber-physical systems (CPS) [13], and many other related technologies, the concept of smart or intelligent manufacturing with identification, connection and interaction among workers, machines and materials on a real-time basis becomes possible [14-16]. The power of smart manufacturing promises to capture real-time field data to support production optimization. But enabling technologies alone does not guarantee that as it also needs the understanding of specific production scenarios as well as corresponding operations management innovations. Some further research needs to be investigated to achieve synchronization of production and delivery with time windows in FPAI as follows.

Firstly, how to design a manufacturing system for the unique layout of FPAI? Due to the unique production operations, the material flow and workflow in FPAI are quite different from that in traditional flow shop and job shop [10]. A specific manufacturing system with appropriate configurations and effective operations management strategies is the basis for improving the production performance in FPAI.

Secondly, how to develop effective mechanisms for achieving synchronization of production and delivery with time windows in FPAI? With the customized requirements that the required products in one customer order must be shipped as a batch to the customer as well as the delivery time window constraints, effective mechanisms are needed to achieve synchronized production and delivery with reducing setup times and maintaining low finished product inventory levels in FPAI.

Thirdly, how to achieve real-time operational visibility with up-to-date field data to support the implementation of the proposed mechanisms at the operational level in FPAI? To realize the successful implementation of the proposed mechanisms to support decision-making and daily operations in FPAI, the real-time operational visibility from shop-floor to top-floor leveraged by enabling technologies is essential.

To address the above challenges, this paper introduces a concept of production synchronization for achieving synchronization of production and delivery with time windows in FPAI. Inspired by the graduation ceremony, a synchronization-oriented Graduation Manufacturing System (GMS) with distinct functional tickets is designed to organize production operations in an integrated and synchronized manner in FPAI. The IIoT-enabled GiMS with a coordinated decision-making model is proposed for achieving synchronization of production and delivery with time windows in FPAI. Cloud services under GiMS are developed for transforming real-time visibility in operations to support the implementation of that coordinated decision-making at the operational level. An industrial case is carried out to validate the feasibility of the proposed concept and approach.

The rest of this paper is organized as follows. Section 2 briefly reviews the key related research streams from integrated scheduling of production and delivery and IIoT-enabled smart manufacturing. Section 3 presents the concept of production synchronization with corresponding pillars and measures. In Section 4, the pillars for synchronization of production and delivery with time windows in FPAI following the concept of production synchronization are discussed. A case study is conducted to validate the performance of the proposed concept and approach in Section 5. Section 6 summarizes this paper by giving our findings, key contributions as well as future work.

2. Literature review

This section reviews the key related research streams from integrated scheduling of production and delivery and IIoT-enabled smart manufacturing.

2.1. Integration of production and delivery

The study of the integration between production and delivery has attracted considerable attention with the increasing demands for on-time delivery. In order to achieve integration of production and delivery, it is understandable that a proper production schedule is made with the consideration of the appointed shipping date [17]. To guarantee all the customer orders are finished before their due dates, a lot of contributions have been made to integrated scheduling of production and delivery. Kim et al. [5] proposed a due-date based scheduling and control strategy to meet the due dates of the orders in a semiconductor wafer fab production system. Samarghandi [18] presented a transformation approach for solving the no-wait job shop scheduling problem with due date constraints, which suggests that transformation or approximation is promising as it is difficult to find feasible solutions for problems with deadlines in real-world applications. The only emphasis on tardiness criterion in due date-based scheduling has changed with the advent of JIT production. Both tardiness and earliness are discouraged since JIT espouses that all jobs should be completed exactly on their assigned due dates in an ideal schedule [7]. Earliness, in which jobs are finished before pre-specified due dates, usually induces penalties related to holding the finished product inventory before their delivery [19]. Tardiness not only generates penalties but also affects customer satisfaction. Therefore, many researchers have adopted earliness and tardiness penalties as the objectives in the due date-related scheduling problems [20,21].

The consideration of both earliness and tardiness in the integrated production scheduling models offers promising insights into the synchronization of production and delivery. However, most of the related work focus on flow shop or job shop environment, little attention has been paid to the layout of FPAI, in which the production operations are distinctive. Besides, most of the integrated production scheduling models only follow with interest in the of the last job in the order not exceed the pre-specified due date or shipment date. But in the real-life world, customers may not stipulate a pre-specified due date for each order; instead, they desire all the products within one order to be delivered as one batch with a delivery time window [22]. For instance, when procuring the heavy-duty equipment, to keep safety lead-time to buffer against upstream uncertainties, a time window will be placed by the customer to schedule the delivery date. Mohammadi et al. [23]

proposed an integrated production scheduling model with consideration of delivery time windows constraints for a furniture manufacturing company. But in this model, it assumed that an order only contains one job, which is not applicable to the production scenarios (e.g., the mentioned case in the introduction) with multiple jobs are contained in one order. Since holding the finished bulky or fragile products is difficult and expensive in FPAI, in the case of that the required multiple products in one order need to be shipped as a batch to the customer within a delivery time window, apart from the delivery time windows constraints, the coordination of the variation in completion times of all jobs within the same customer order must be considered in FPAI.

2.2. IIoT-enabled smart manufacturing

The term of Internet of Things (IoT) was first presented by Kevin Ashton in 1999, and was popularized by the work of Auto-ID Center at the Massachusetts Institute of Technology (MIT) with initially targeting the design of the architecture of networked RFID with EPCglobal [24]. Actually, before this, similar ideas, such as RFID or Auto-ID have been explored in the field of computer integrated manufacturing (CIM) in the early 1990s [25, 26]. IoT presents a vision in which physical things are connected to the Internet, and able to sense the surroundings and transmit information to the network by themselves [27]. The application of IoT technologies in industries is referred to as IIoT, which provides a promising way for automatically capturing and collecting real-time object-level information throughout the whole production process [11]. By equipping with various IIoT devices (e.g., Auto-ID, RFID, and iBeacon), traditional manufacturing objects are becoming smart objects augmented with identification, sensing, and network capabilities, and could communicate and interact with each other [28]. Imtiaz and Jasperneite [29] investigated the Open Platform Communication Unified Architecture (OPC-UA) as a middleware solution to a chip level for the IoT devices communication. With consideration of quality monitoring of the whole system, Mocnej et al. [30] presented a decentralized IoT architecture for efficient resources utilization. Based on IIoT and cloud computing technologies, Helo et al. [31] presented a practical tool and technical solution to help manufacturers think about moving towards cloud manufacturing ecosystems. Under such a IIoT-enabled manufacturing ecosystem, production information includes order progress, material consumptions, workforce situations, vehicle locations, and machine statuses are captured and managed in an accurate and real-time way, which lays the foundation for production optimization in an integrated and synchronized manner [32]. Nikolakis et al. [33] developed an end-to-end approach for dynamic planning and control in the IIoT-enabled cyber-physical production system. Yan et al. [34] explored the flexible job shop scheduling with the consideration of actual transportation conditions in a digital twin workshop.

IIoT-enabled hyper-connection, digitization, and sharing make the conceptions of production synchronization or synchroperation possible, which is revolutionizing the way how production operations are managed and done in the era of Industry 4.0 manufacturing [35, 36]. The most relevant work related to this research stream is [10], based on IoT, digital twin, smart gateway, Web 3D and industrial wearable technologies, Guo et al. [10] proposed the Graduation Intelligent Manufacturing System (GiMS) for achieving real-time synchronization between physical and digital spaces in FPAI. The previous work mainly focused on the technical solution and architecture for the development of digital twin-enabled GiMS, which provides the technical foundations for achieving real-time visibility and information-sharing in FPAI. The main focus of this research is how to achieve synchronization of production and delivery with time windows in FPAI, through the marriage of the revolutionary power of real-time information and corresponding operations management innovations.

3. The concept and measure for production synchronization

3.1. The concept of production synchronization

Synchronization is a universal phenomenon that occurs and can be observed in nature or artificial systems, which refers to the pace of one process or act and the pace of other process or act “to happen at the same time” or “to concur or agree in time”. The analysis of synchronization phenomena in various chaotic systems of natural science, engineering, and social life has been a subject of active investigation since the earlier work of Hugenii [37]. Though there is no general agreement about a precise definition of production synchronization, some related ideas have been paid attention to the presence of synchronization in the manufacturing sector.

In production, one widely acknowledged idea closes to the concept of production synchronization is JIT presented in the Toyota production system (TPS). JIT seeks to reduce the production lead time and inventory level through synchronization of production operations, as it advocates that “all processes produce the necessary parts at the necessary time and have on hand only the minimum stock necessary to hold the processes together” [38]. JIT has played a key role in revolutionizing production and operations management for the modern manufacturing industry. Key to JIT production is the make use of physical cards carried with necessary information (referred to as Kanbans), by which pulling the production from demand to reduce inventory level and shorten lead time [39]. Deleersnyder et al. [40] pointed that one limitation of JIT is the information time lag, as information in a Kanban system needs to take some time to reach the initial work centers. To achieve the synchronization of order information between Toyota and its suppliers, Kotani [41] proposed an optimal method for controlling the number of Kanbans in an e-Kanban system powered by computers and a communications network, and it is shown that the e-Kanban system can be implemented more efficiently and effectively than the original Kanbans system. Lack of information sharing among stakeholders and decision-making delays are two major barriers hampering the implementation of successful JIT production [42, 43].

Beyond the concept of JIT that seeks to reduce production lead time and inventory level through synchronization of production operations, the value of real-time visibility and information-sharing as well as coordination of decision-making has been identified for achieving production synchronization. Qu et al. [44] presented a production and logistics synchronization system with the support of IoT-based real-time data capturing. Lin et al. [45] proposed the IoT-enabled synchronization for the smart factory by using rule-based heuristics and real-time production data with horizontal synchronization (HSync) and vertical synchronization (Vsync) dimensions. Chen et al. [46] proposed an integrated production and shipment scheduling model in a two-stage assembly flow shop system to reduce the inventory of the finished products. Considering the coordination of production decision and warehouse decision simultaneously, Luo et al. [47] presented a synchronized scheduling model for a typical MTO company manufacturing paint, and indicated that it can improve the system performance with the reduction of the order leading times.

The literature mentioned above provides some insights into production synchronization from some special cases. On the basis of the review of related ideas, and through a number of academic initiatives and industrial implementation led by the research team in the era of Industry 4.0, in this work, we extend the concept of JIT philosophy and understand production synchronization as a new production and operations management strategy for Industry 4.0 manufacturing as follows.

Production synchronization refers to the adjustment of production paces toward synchronous interactions through real-time visibility and information-sharing, coordination of decision-making and synchronization of production operations in a production system.

Three pillars, including real-time visibility and information-sharing, coordination of decision-making and synchronization of production operations, play key roles in achieving production synchronization. Real-time visibility and information-sharing focus on creating and establishing real-time information visibility and traceability with the support of data acquisition and processing technologies (e.g., IIoT and cloud computing), it lays the foundation for coordination of decision-making and synchronization of production operations. Coordination of decision-making focuses on coordinated and global optimal production decisions benefiting from the marriage of real-time visibility and information-sharing and effective production strategies. With the support of real-time visibility and information-sharing, and coordination of decision-making, synchronization of production operations focuses on the synchronous production operations through the utilization of production resources (e.g., men, machines and materials) in the right place at the right time in a synchronized manner.

3.2. Performance indicators and measures for production synchronization

From the concept, it can be seen that production synchronization aims to achieve synchronous interactions in a production system. Such synchronous interactions may involve multi-echelon and inter-organizational production activities (e.g., supply, manufacturing, logistics, and services). Three important aspects of measures for production synchronization, including simultaneity, punctuality and cost-efficiency are derived from the literature, and will be considered comprehensively in this section.

As listed in Table 1, performance indicators and measures for production synchronization are divided into three categories: simultaneity, punctuality and cost-efficiency. Simultaneity is one of the most important aspects of measures for production synchronization, and indicators for simultaneity, such as flow time [48] and waiting time [49, 50] have been adopted in specific applications. 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 [10]. Punctuality is another important aspect of measure for production synchronization that focuses on earliness and tardiness [46, 51,52]. 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 improve shipment punctuality [46]. Cost-efficiency is a common aspect of measure for production synchronization, most of the literature deals with such regular indicators as utilization [44] and makespan [47, 53]. Cost-efficiency could be used as a measure in a complicated production environment that involves 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. [47] proposed a synchronized production and warehouse decision model to minimize the overall makespan.

4. Pillars for synchronization of production and delivery with time windows in FPAI

Production synchronization aims to achieve synchronous interactions in a production system. Such synchronous interactions may involve inter-organizational production operations. The main concern of this study, the synchronization of production and delivery with time windows in FPAI, is a typical problem of production synchronization across supply, manufacturing, and logistics. This section will illustrate how to achieve synchronous interactions between production and delivery following the concept of production synchronization.

4.1. The unique production operations in FPAI

Unlike the product flow-oriented layouts (e.g., a flow shop or a job shop) in which the products generally circulate within the production facilities, the fixed-position layout belongs to the product fixed-oriented layout in which the product remains at a fixed site for its entire manufacturing period [54]. The layout of FPAI is widely used for producing bulky or fragile products as well as producing products with medium variety and volumes. Generally, a typical workshop consists of limited assembly islands, in which production tasks (e.g., setup tasks and assembly tasks) are performed on available islands.

For simplicity of discussion but without losing generality, Fig. 1 shows the diagram of the unique production operations in FPAI. As depicted in Fig. 1, setup and assembly tasks are organized at limited assembly islands to meet customer demand with various types and quantities of products. As depicted in section 1 of Fig. 1, required manufacturing resources including workers, equipment and materials are supplied at each assembly island for performing the specific task according to the assembly plan. Taking the assembly island k_1 as an example, Section 2 in Fig. 1 illustrates the typical assembly process at

Table 1
Performance indicators and measures for production synchronization

Measures	Environment	Major aims	References	Indicators
Simultaneity	Job shop	Reduce finished product inventory level through synchronous interactions of production and delivery	Hsu and Liu [48]	Flow time
	Flow shop	Improve overall performance of production and logistics through synchronous interactions of production and warehousing	Luo et al. [49]	Waiting time
	Flow shop	Improve production efficiency through synchronous interactions of demand and production	Chen et al. [50]	
	Flow shop	Improve production efficiency through synchronous interactions among production operations	Lin et al. [45]	Setup time
Punctuality	Flow shop	Improve production lead time and shipment punctuality through synchronous interactions of production and shipment	Chen et al. [46]	Earliness andtardiness
	Job shop	Improve punctuality through synchronous interactions of production and transport	Fazlollahtabar et al. [51]	
	FPAI	Improve overall performance through synchronous interactions of manufacturing and logistics	Guo et al. [52]	Number of tardy jobs
Cost-efficiency	Flow shop	Improve resources utilization through synchronous interactions of production and logistics	Qu et al. [44]	Utilization
	Flow shop	Improve overall performance through synchronous interactions of production and cross-docking	Luo et al. [47]	Makespan
	Flow shop	Improve production efficiency through synchronous interactions of production operations	Lin et al. [53]	

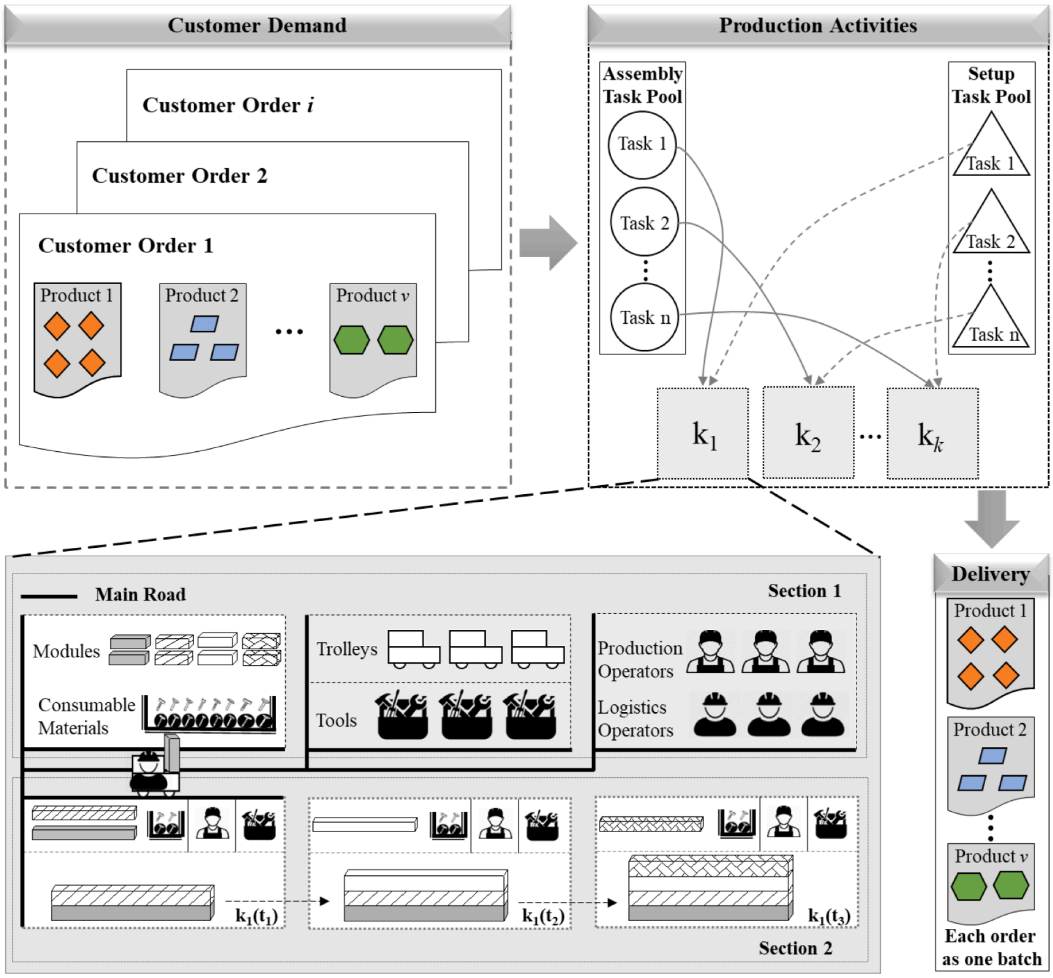


Fig. 1. The unique production operations in FPAI

the same assembly island at different time spots. With required manufacturing resources supplied at the right time, the product will remain at the island k_1 until it is fully assembled with specific sequences. Due to the customized requirement of the customer, all the required products belong to one order will be delivered to the customer as one batch within the delivery time window.

4.2. GMS with synchronization of production operations in FPAI

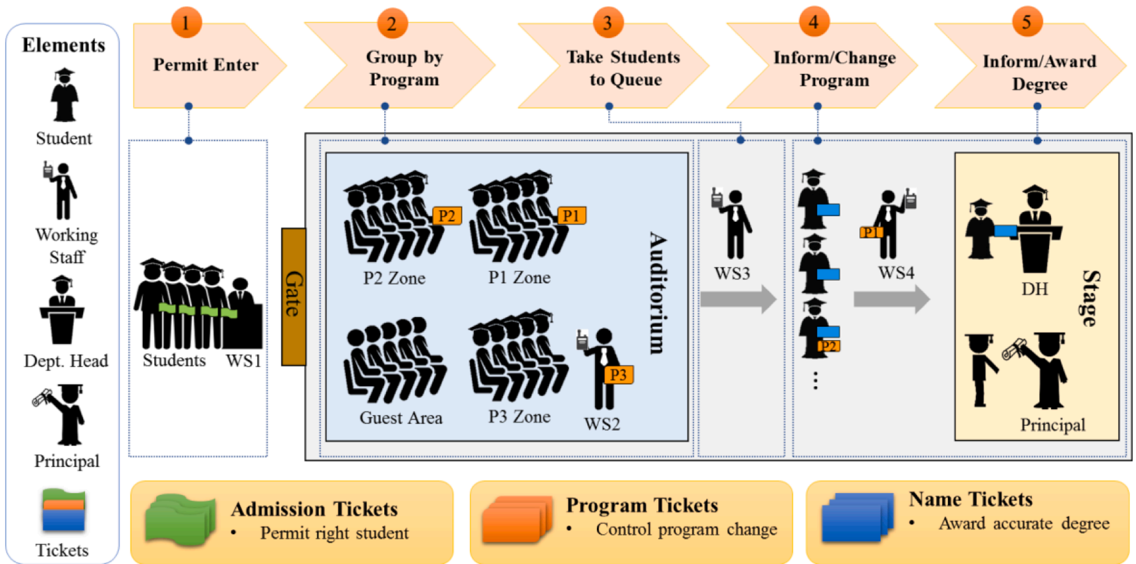
University graduation ceremony has been successfully conducted for hundreds of years, as shown in Fig. 2 (a), with real-time ticket queuing and coordinating, the ceremony is always orderly and robust to students with various degrees and certificate programs, as every stakeholder in the system knows “where, when, what and how to do” [32]. Inspired by the graduation ceremony with highly synchronized organization and operations, a synchronization-oriented novel manufacturing mode-GMS, has been proposed to organize and manage production operations in FPAI with simplicity and resilience [10, 54].

As shown in Fig. 2(b), by analogy to three kinds of tickets used in the graduation ceremony, three kinds of tickets with distinct functionalities, including job ticket (JT), setup ticket (ST), operation ticket (OT) and twined logistics ticket (LT) in GMS, are designed to achieve order-job synchronization, job-operation synchronization and operation-logistics synchronization. The power of GMS promises to organize and manage production operations in an integrated and synchronized way. Order-job synchronization refers to the synchronized organization of production jobs based on customer demand. Job-operation synchronization refers to the coordination of production operations in various job families. Operation-logistics synchronization refers to the synchronization of production resources and operations. JTs are designed for releasing/ permitting the right jobs as well as controlling variation in job completion times. STs are designed for controlling flexible setup/ reconfiguration when producing different product families or introducing new products. OTs are designed for coordinating operations through real-time queuing adjustment. Twined LTs are designed to ensure accurate materials and JIT delivery as well as control WIP/ finished product inventory level with OTs.

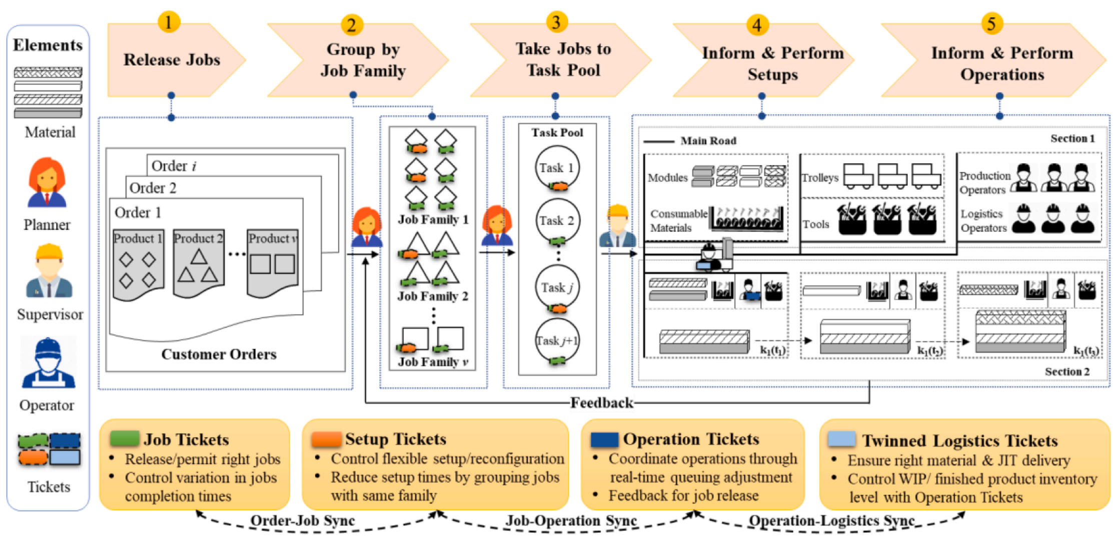
4.3. GiMS with real-time visibility and information-sharing in FPAI

GMS offers promising insights for organizing production operations in an integrated and synchronized manner in FPAI. For achieving real-time operational visibility to support the coordinated decision-making of production and delivery with time windows, an IIoT-enabled architecture for GiMS is depicted in Fig. 3, it consists of three layers: physical space layer, real-time ticket pool layer, and cyber space layer.

Physical space focuses on intelligent perception, connection, and interaction in FPAI. Due to the unique production operations, various manufacturing objects need to be frequently moved to different assembly islands. Besides, the ratio of manual operations is high as the sophisticated assembly operations heavily rely on skilled operators. In this layer, the concept of smart object is proposed for achieving intelligent perception and connection among various manufacturing objects. With the deployment of IIoT devices (e.g., RFID, iBeacon, and embedded sensors), physical manufacturing objects (e.g., material, machine, tool, and trolley) become smart objects augmented with identification,



(a) Typical ticket queuing system of a university graduation ceremony



(b) A synchronization-oriented novel manufacturing mode-GMS

Fig. 2. A graduation ceremony-inspired manufacturing mode-GMS for FPAI

sensing, and network capabilities. To assist onsite operators to dynamically interact with various manufacturing objects, the concept of the augmented operator is proposed. Equipping with IIoT-enabled industrial wearable devices (e.g., smart helmet, smart glass, smart belt, wrist computer, smart glove, and smart shoe), the augmented operator becomes smart and flexible problem-solvers with nearly error-free operations [10]. For bridging multiple heterogeneous IIoT devices with universal plug and play (UPnP) into wireless communication networks, a mobile gateway operating system that acts as a light-weighted middleware system is developed with easy definition, configuration, and execution [55]. Thus, heterogeneous production data related to materials, machines, operators, processes, etc. could be automatically captured and managed, which provides support for the production optimization in the real-time ticket pool layer.

In the middle layer, the concept of the real-time ticket pool is proposed for production and operations management in the IIoT based production environment in FPAI. Ticket pool is a representation of sequenced tasks coined by tickets with distinct functionalities, such as JTs, STs, OTs, and LTs. In this layer, the real-time ticket pool with coordinated decision-making (will be discussed in the following section) is proposed to achieve synchronized production and delivery in consideration of customer demand and production capacity constraints. With the support of real-time feedback of field data provided in the physical space layer, the real-time status of each assembly island could be easily captured, and through the real-time coordination of ticket queues at available assembly islands controlled by the coordinated decision-making model, the coordinated decision-making of production and delivery with time windows could be achieved.

Cyber space layer provides cloud-based applications to support the implementation of the coordinated decision-making proposed in the real-time ticket pool layer. Two types of applications, including desktop applications (DApps) and mobile applications (MApps), are encapsulated as services for managers and onsite operators. With real-time visibility and information-sharing, job task service, setup task service, logistics task service, and operation task service are offered to facilitate their decision-making and daily operations in production planning, scheduling, execution, and control in FPAI. Deployment in the cloud, managers and onsite operators could easily access these applications

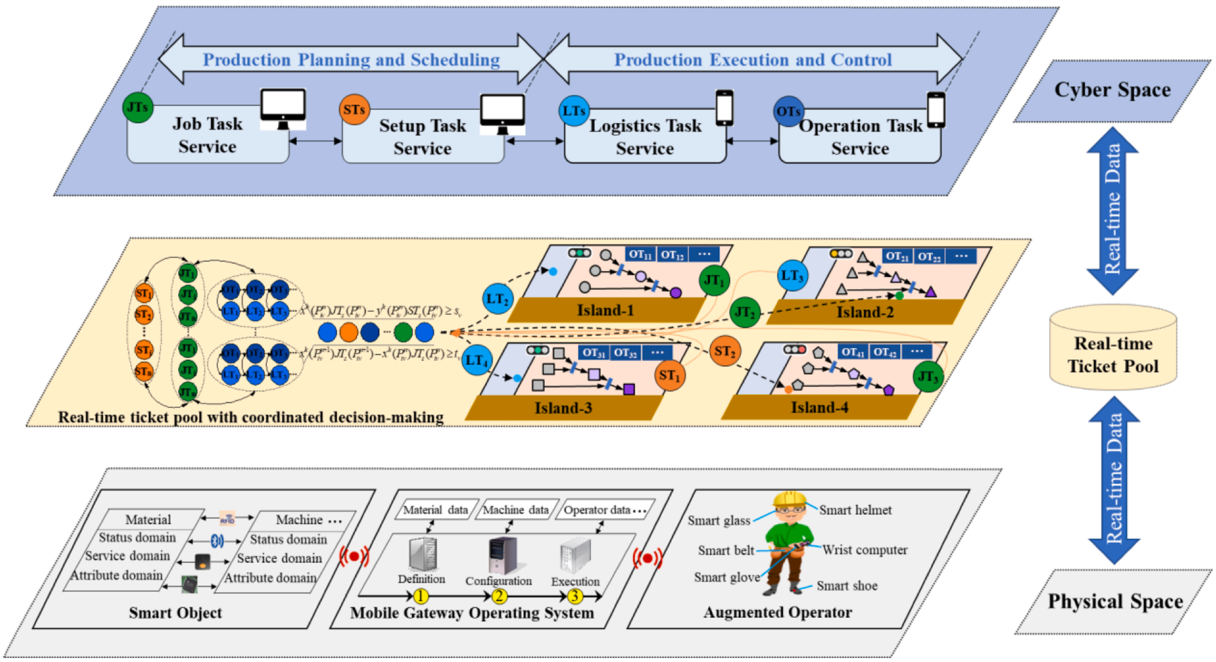


Fig. 3. Overall architecture of IIoT-enabled GiMS for FPAI

through stationary and mobile terminals, such as PC, iPad, smartphone, and wearable device.

The main characteristics of the proposed framework of the IIoT-enabled GiMS can be summarized as follows: (1) Based on IIoT technologies, the concepts of smart object and augmented operator are proposed for intelligent perception and connection among various manufacturing resources. (2) The real-time ticket pool with coordinated decision-making of production and delivery is proposed in consideration of customer demand and real-time feedback of production information. (3) Digital tickets with appropriate sets of information are encapsulated into cloud services for managers and onsite operators to facilitate their decision-making and daily operations. With real-time convergence between cyber and physical spaces, GiMS has the power to transform real-time visibility in operations to support coordinated decision-making of production and delivery with time windows.

4.4. Coordinated decision-making of production and delivery with time windows under GiMS for FPAI

The layout of FPAI is widely adopted when coping with the production of bulky or fragile products with customized services, in which a variety of products required in one customer order must be shipped as a batch to the customer within a delivery time window. Let us give a formal description of the problem, within a time horizon t, there are K_t available identical assembly islands capable of producing V different product families in the system, I_t customer orders arrival and customer order $i$contains j products from different product families with arrival date T_a^i and delivery time window $[T_{ds}^i, T_{dd}^i]$. Generally, setup time s_v is needed for starting a production lot of product family v, and each product from the product family v requires a processing time t_v at a continuously available island k. To achieve the synchronization of production and delivery with time windows in FPAI to meet customer demand, production paces need to adjust toward synchronous interactions in which the required products from the same customer order are completed simultaneously (at the same time or at least as close as possible) to reduce the inventory level of finished goods and to improve the delivery punctuality, meanwhile, the production paces of the required products from the same product family needs to concur or agree in time to reduce setup times and improve production efficiency.

Before presenting the model of coordinated decision-making of production and delivery with time windows in FPAI, we define the following notations and variables in Table 2.

For achieving synchronization of production and delivery with time

Table 2
Notations and variables used in the model

Notations	Description
K_t	The total number of available assembly islands at the time horizon t
k	The index of assembly island, $k = 1, 2, \ldots, K_t$
I_t	The total number of customer order at the time horizon t
i	The index of customer order, $i = 1, 2, \ldots, I_t$
V	The total number of product family
v	The index of product family, $v = 1, 2, \ldots, V$
n_{iv}	The number of required product from family$v$in customer order i
P_{iv}^n	The required nth product from family v in customer order i, $n = 1, 2, \ldots, n_{iv}$
s_v	The setup time for starting a production lot of product family v
t_v	The processing time of assembly a product from family v
T_a^i	The arrival date of customer order i
T_{ds}^i	The allowed start date of delivery for customer order i
T_{dd}^i	The allowed due date of delivery for customer order i
w_d	The weighting coefficient of delivery punctuality
w_p	The weighting coefficient of production efficiency
ST_a^v	The actual quantity of Setup Tickets for production of products from family v
ST^v	The ideal quantity of Setup Tickets for production of products from family v
$JT_s(P_{iv}^n)$	The start time of Job Ticket for assembling required nth product from family v in customer order i
$JT_e(P_{iv}^n)$	The end time of Job Ticket for assembling required nth product from family v in customer order i
$ST_s(P_{iv}^n)$	The start time of Setup Ticket when setup for nth product from family v in customer order i
$ST_e(P_{iv}^n)$	The end time of Setup Ticket when setup for nth product from family v in customer order i
C_i	The completion time of the last job in customer order i
$x^k(P_{iv}^n)$	1 if the job task for the P_{iv}^n is performed at island k, 0 otherwise
$y^k(P_{iv}^n)$	1 if the setup task for the $P_{iv}^n$is performed at island k, 0 otherwise

windows in FPAI, we define an indicator PS_{pd} to understand and quantify the synchronization between production efficiency and delivery punctuality in FPAI. In this scenario,PS_{pd} is the synchronization indicator for measuring the degree of the synchronous interaction between production and delivery in PFAI, and the definition of PS_{pd} is defined as Formula (1), which comprises two terms. The first term (PS_1) presents the clustering degree of the production, which is defined by the ratio of the ideal setups to the actual setups in the production. The fewer setups, the higher the clustering degree in the production with jobs from the same family are clustered. Adjustment of production pace to achieve the clustered production of jobs from the same family, which could reduce unreasonable setups and improve production efficiency. The second term (PS_2) presents the simultaneity degree of the production within the same customer order, which is defined by the ratio of the total variations in finished time of all jobs within the same order to the completion of this order. The smaller the variations in finished time of all jobs within the same order, the higher the simultaneity degree of the production within the same customer order. Adjustment of production pace to achieve the synchronous completion time of the jobs from the same customer order, which could reduce the inventory level of finished goods and improving the delivery punctuality.

$$PS_{pd} = \underbrace{w_p\left(\frac{\sum_{v=1}^{V} s_v ST^v}{\sum_{i=1}^{I_t}\sum_{k=1}^{K_t}\sum_{v=1}^{V}\sum_{n=1}^{n=n_{iv}} y^k\left(P_{iv}^n\right)s_v ST_a^v}\right)}_{PS_1} + \underbrace{w_d\left(1-\frac{1}{I}\sum_{i=1}^{I}\left(\frac{\sum_{v=1}^{V} n_{iv}C_i - \sum_{k=1}^{K_t}\sum_{v=1}^{V}\sum_{n=1}^{n=n_{iv}} x^k\left(P_{iv}^n\right)JT_e\left(P_{iv}^n\right)}{\sum_{v=1}^{V} n_{iv}C_i}\right)\right)}_{PS_2} \quad (1)$$

Some assumptions are made as follows before the mathematical formulation of the coordinated decision-making of production and delivery in FPAI:

- Assembling one product defines a job task, and a corresponding JT is needed for performing the job task.
- Performing a setup when switching from production of a distinctive product family to another defines a setup task, and a corresponding ST is needed for conducting the setup task. In an ideal scenario, only one ST is needed for one product family.
- For each assembly island, only one job task or one setup task can be processed on it at any time, and once the task starts, it must be finished at the assembly island.
- All assembly islands are alternative to each other, which means that the task can be performed at any island when it becomes available.

For improving the production efficiency and delivery punctuality simultaneously in PFAI, the objective of the mathematical model is to improve the degree of the synchronous interaction between production and delivery in PFAI, which is given by:

$$\textit{Maximize } PS_{pd} \quad (2)$$

subject to:

$$\sum_{k=1}^{K_t} x^k\left(P_{iv}^n\right) = n_{iv},\ \forall i, v \quad (3)$$

$$\sum_{v=1}^{V}\sum_{n=1}^{n=n_{iv}}\sum_{k=1}^{K_t}\left[x^k\left(P_{iv}^n\right)t_v + y^k\left(P_{iv}^n\right)s_v\right] \le T_{dd}^i - T_a^i,\ \forall i \quad (4)$$

$$JT_s\left(P_{iv}^n\right) \ge T_a^i,\ \forall i, v, n, k \quad (5)$$

$$C_i = \max_{1\le n\le n_{iv}, 1\le v\le V}\left\{x^k\left(P_{iv}^n\right)JT_e\left(P_{iv}^n\right)\right\},\ \forall i \quad (6)$$

$$T_{ds}^i \le C_i \le T_{dd}^i, \forall i, v, n, k \quad (7)$$

$$ST_s\left(P_{iv}^n\right) \ge T_a^i,\ \forall i, v, n, k \quad (8)$$

$$ST_e\left(P_{iv}^n\right) \le T_{dd}^i,\ \forall i, v, n, k \quad (9)$$

$$x^k\left(P_{iv}^{n+1}\right)JT_s\left(P_{iv}^{n+1}\right) - x^k\left(P_{iv}^n\right)JT_s\left(P_{iv}^n\right) \ge t_v,\ \forall i, v, n, k \quad (10)$$

$$y^k\left(P_{iv}^{n+1}\right)ST_s\left(P_{iv}^{n+1}\right) - y^k\left(P_{iv}^n\right)ST_s\left(P_{iv}^n\right) \ge s_v,\ \forall i, v, n, k \quad (11)$$

$$x^k\left(P_{iv}^n\right)JT_s\left(P_{iv}^n\right) - y^k\left(P_{iv}^n\right)ST_s\left(P_{iv}^n\right) \ge s_v,\ \forall i, v, n, k \quad (12)$$

$$ST^v = 1,\ \forall v \quad (13)$$

$$ST_a^v = \sum_{i=1}^{I_t}\sum_{k=1}^{K_t} y^k\left(P_{iv}^n\right),\ \forall v \quad (14)$$

$$ST_a^v \ge ST^v,\ \forall v \quad (15)$$

$$\sum_{v=1}^{V} ST_a^v \ge V \quad (16)$$

$$w_p + w_d = 1 \quad (17)$$

$$x^k\left(P_{iv}^n\right) \ge y^k\left(P_{iv}^n\right),\ \forall i, v, n, k \quad (18)$$

$$y^k\left(P_{iv}^n\right) \le \sum_{k=1}^{K_t} x^k\left(P_{iv}^n\right),\ \forall i, v, n, k \quad (19)$$

$$x^k\left(P_{iv}^n\right) \in \{0,1\},\ \forall i, v, n, k \quad (20)$$

$$y^k\left(P_{iv}^n\right) \in \{0,1\},\ \forall i, v, n, k \quad (21)$$

The objective function (2) is to maximize the PS_{pd} defined in Formula (1). Constraint (3) defines that the production quantity should meet the demand requirement. Constraint (4) guarantees that the completion of each customer order should not exceed the allowed processing time of the order. Constraint (5) guarantees that the start time of each JT for assembling the required product from the customer order should not precede the arrival date of the order. Constraint (6) and (7) guarantee that the end time of JT for assembling the last required product from the customer order should fall into the delivery time window of the order. Constraint (8) and (9) guarantee that the start time and end time of each ST when switching from production of a distinctive product type to another from the customer order should not precede the arrival date and no later than the allowed due date of delivery for the order. Constraint (10) guarantees that for each assembly island, only one job task can be processed on it at any time, and once the task starts, it must be finished at the assembly island. Constraint (11) guarantees that for each assembly island, only one setup task can be processed on it at any time, and once the task starts, it must be finished at the assembly island. Constraint (12) guarantees that for each assembly island, the job task can be started when the setup task is finished if the setup task is required for that job task. Constraint (13) defines that only one setup task is needed for one product family in the ideal scenario. Constraint (14)-(16) guarantee that at least one setup task should be carried out for one product family. Constraint (17) defines the relationship between the weighting coefficient of delivery punctuality and the weighting coefficient of production efficiency. Constraint (18) and (19) define the relationship between decision variables. Constraint (20) and (21) define the ranges of decision variables.

To improve the degree of the synchronous interaction between

Table 3
Algorithm for production and delivery synchronization in FPAI

Algorithm for production and delivery synchronization in FPAI
Input: Customer demand, product attribute, and current production capacity**Output:** Synchronization indicator, job ticket, and setup ticket queue at each available assembly island
1: Initialization with formed orders (i.e., required product type, quantity, position, receive date, delivery time windows) and product attribute (i.e., setup transition matrix, setup time, processing time)
2: Get the number of available assembly islands
3: **For** $k \leftarrow 1$ **to** the number of available assembly islands
4: Assign jobs to assembly islands with constraints satisfied
5: **If** the setup task is needed forP_{iv}^{n}
6: $JT_s(P_{iv}^{n}) \leftarrow JT_s(P_{iv}^{n}) + s_v$
7: **Else**
8: $JT_s(P_{iv}^{n}) \leftarrow JT_s(P_{iv}^{n})$
9: **End if**
10: Generate JT and ST queues at each available assembly island
11: Calculate PS_{pd} defined in Formula (1) with generated JT and ST queues
12: **For** $m \leftarrow 1$ **to** M, where M is a large positive number
13: Repeat 3-10 and get $\{PS_{pd}^{1}, PS_{pd}^{2}, \ldots, PS_{pd}^{m}, \ldots, PS_{pd}^{M}\}$
14: $PS_{pd} \leftarrow \max\{PS_{pd}^{1}, PS_{pd}^{2}, \ldots, PS_{pd}^{m}, \ldots, PS_{pd}^{M}\}$
15: Update JT and ST queues at each available assembly island
16: **End for**
17: **End for**

production and delivery in PFAI, it is sufficient to generate feasible JT and ST queues at each available assembly island to satisfy customer demand and production constraints. The production and delivery synchronization problem is similar to JIT job-shop scheduling (JIT-JSS) that is NP-hard in the strong sense [56], but it is much more complex since the completion time of the last job in each order is unknown rather than a pre-specified due date in JIT-JSS, besides, the transition between setup task and job task also increases the complexity. Heuristic algorithms are proved to be effective and efficient in solving JIT-JSS problems [57]. In this reseach, considering the accuracy requirement and solution cost, a heuristic algorithm, as depicted in Table 3, is proposed for the production and delivery synchronization problem.

5. Case study

In this section, to validate the feasibility and effectiveness of the proposed concept and approach, a near-life testbed is conducted before being implemented in a laser equipment manufacturing enterprise in China. As a leading laser equipment manufacturer in the domestic industry, the company uses the layout of FPAI for producing multiple types of heavy-duty laser equipment. The operation process of the enterprise meets the typical operation pattern of FPAI (as shown in Fig. 1). One customer order contains certain products with different product types with the demand that all products must be shipped as one batch within a given delivery time window. After receiving customer orders, the enterprise organizes production activities (e.g., setup and assembly) at available assembly islands to meet customer demand.

Currently, the enterprise has implemented enterprise resource planning (ERP), manufacturing execution systems (MES), and warehouse management systems (WMS) for business process, production activity, and resource management. However, these systems address only a limited portion of the production process from different points of view. Besides, due to a lack of unsynchronous organization between production and delivery with time windows, the company still has difficulty in achieving synchronized production and delivery. Following the proposed concept and approach, a prototype system GiMS with job task service, setup task service, logistics task service, and operation task service, is developed and integrated as complementary to the existing ERP, MES, and WMS systems.

As shown in Fig. 5, in physical space, manufacturing objects in the workshop, including modules, consumable materials, tools, and trolleys, are attached with RFID and iBeacon devices. The module is generally bulky with high value, thus it can be individually tagged with RFID depends on the cost and benefit. Consumable materials (e.g., screws and bolts) are non-critical materials, the tray-level tagging scheme is adopted. Other objects that need to be tracked, such as tools and trolleys, are individually equipped with iBeacon tags. With the support of IIoT devices, these physical objects in physical space become smart objects, which can be uniquely identified, traced, shared, and managed in the cyber space. Onsite operators, including production operators and logistics operators, become augmented operators by equipping smartphones, smart glasses, and smart gloves. Through the innovative smart gateway, which consists of a credit card-sized microcomputer chip embedded Bluetooth Low Energy (BLE) module and the wired/wireless communication module, the networked wearable devices can connect and communicate with each other, which significantly enhances the interaction between onsite operators and various manufacturing objects. In cyber space, with the support of real-time field data collected from the IIoT devices in GiMS, DApps and MApps are encapsulated as cloud services (e.g., JT, ST, OT, and LT services).

Deployed with IIoT technologies, real-time information visibility and traceability throughout the whole production processes can be achieved with the support of GiMS. Synchronized and global optimal production decisions can be made based on the real-time ticket pool with coordinated decision-making under GiMS. With the assistance of JT, ST, OT, and LT services, managers and onsite operators could utilize production resources in FPAI in the right place at the right time in a synchronized manner under GiMS. For evaluating the performance of production synchronization, a detailed experiment will be illustrated in the following section.

Before adopting the proposed production synchronization strategy, the company managed its original production operations based on the combined earliest due date (EDD) with family selection rules. The experimental test data are generated based on the historical data collected from the company with the non-dimensionalized time unit. As shown in Table 4, a total of thirty-six products from six product families are required in six customer orders, which are needed to produce at six available assembly islands at a certain time horizon. In this case, the weighting coefficient of delivery punctuality and the weighting coefficient of production efficiency are equally important with $w_p = w_d = 0.5$. The information of the product attribute (PA) involved in the computation model is defined as Formula (22). The experiment case is built upon Java Runtime Environment (JRE) following the heuristic algorithm proposed before, and running on a 64-bit machine with Intel (R) Core (TM) i7-10510U CPU at 2.30 GHz processor and 16.00 GB RAM.

$$PA = \begin{bmatrix} & A & B & C & D & E & F \\ t_v & 30 & 40 & 60 & 50 & 20 & 10 \\ s_v & 15 & 16 & 25 & 20 & 8 & 5 \end{bmatrix} \tag{22}$$

Apart from the measure of the degree of the synchronous interaction between production and delivery (PS_{pd}) defined in Formula (1), three measures presented in Table 1, including the total setup time (TS) defined in Formula (23) (cost-efficiency), and the total waiting time (TW) defined in Formula (24) (simultaneity), the number of tardy jobs (N_{tj}) defined in Formula (25) (punctuality), are calculated and compared. Apart from the original production, the two most popular rules, including EDD and shortest process time (SPT), are also used as benchmarks for those performance criteria. The reason why adopted EDD and SPT are because they are the most commonly used due-date based rules in the industry for easy implementation and practice and hence are used as common benchmarks in many studies [58, 59].

$$TS = \sum_{i=1}^{I_t} \sum_{k=1}^{K_t} \sum_{v=1}^{V} \sum_{n=1}^{n=n_{iv}} y^k\left(P_{iv}^{n}\right) s_v ST_a^v \tag{23}$$

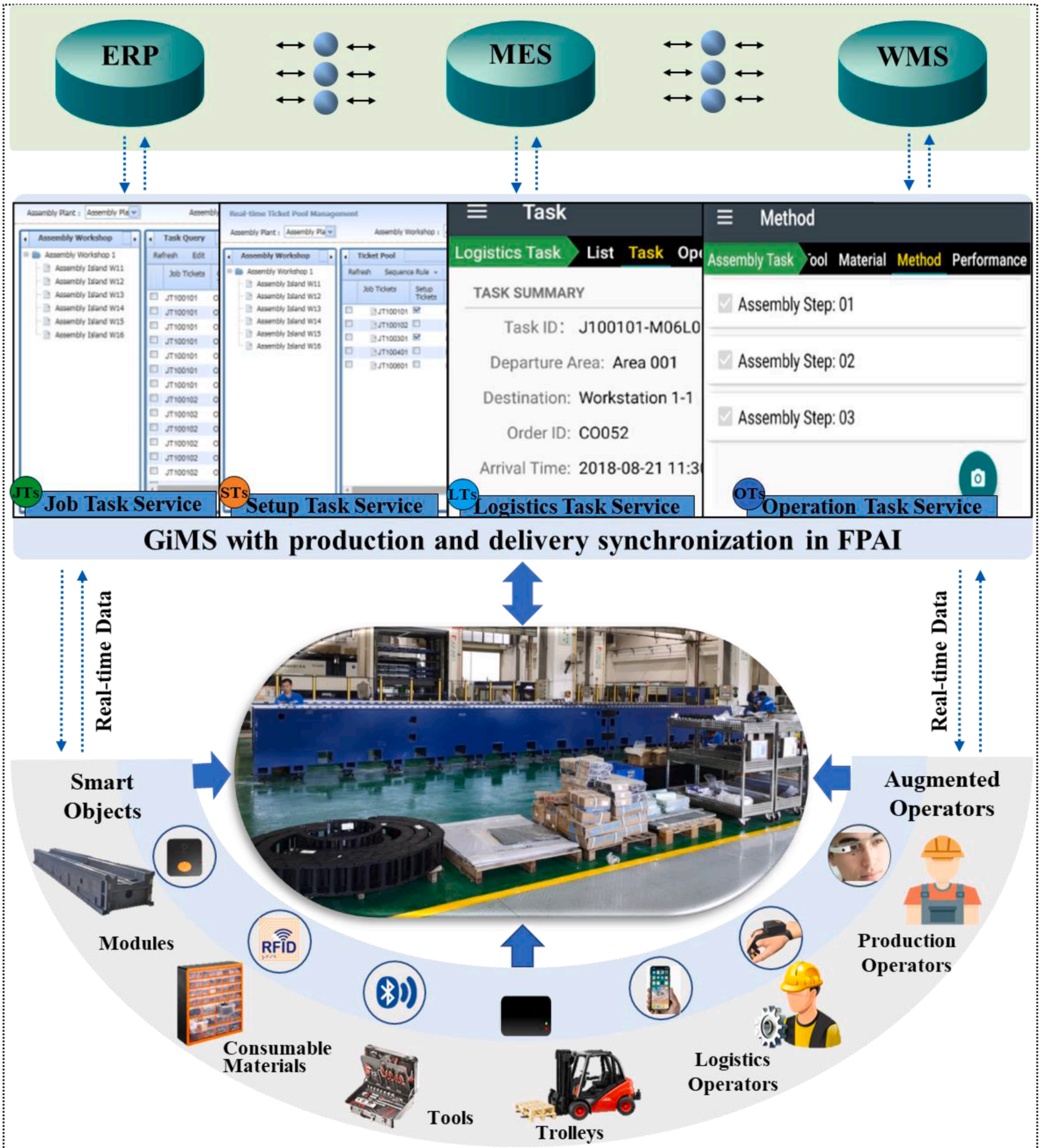


Fig. 4. Implementation of GiMS with production and delivery synchronization in an industrial company

$$TW = \sum_{i=1}^{I_t}\sum_{v=1}^{V} n_{iv}\max_{1\leq n\leq n_{iv},1\leq v\leq V}\left\{x^k\left(P^n_{iv}\right)JT_e\left(P^n_{iv}\right)\right\} - \sum_{i=1}^{I_t}\sum_{k=1}^{K_t}\sum_{v=1}^{V} \times \sum_{n=1}^{n=n_{iv}} x^k\left(P^n_{iv}\right)JT_e\left(P^n_{iv}\right) \tag{24}$$

$$N_{tj} = \sum_{i=1}^{I_t}\sum_{k=1}^{K_t}\sum_{v=1}^{V}\sum_{n=1}^{n=n_{iv}}\left\{x^k\left(P^n_{iv}\right)\middle|JT_e\left(P^n_{iv}\right) > T^i_{dd}\right\} \tag{25}$$

Table 5 shows the comparisons among the original production, synchronization-oriented production, EDD, and SPT. Although there are six assembly islands are available in this case, we also calculated the scenario with four and eight available assembly islands for comparisons. As shown in Table 5, the proposed synchronization mechanism improves the degree of the synchronous interaction between production and delivery with the highest value PS_{pd} among all the scenarios. It can be understood as the production and delivery synchronization is achieved through the adjustment of production paces with reducing setup time and waiting time, and the lowest setup time and waiting time in this table are further evidence of that.

As shown in Table 5, compared with the original production and SPT, EDD fares quite well for reducing waiting time, which is consistent with previous studies [59]. Although the original production outperforms EDD and SPT to some extent with the consideration of due date and family selection in FPAI, the degree of the synchronous interaction between production and delivery is still low than the synchronization-oriented production. The number of available assembly islands significantly affects the performance of production in FPAI; thus, the real-time accurate field data on assembly island availability is crucial for achieving the synchronization of production and delivery with time

Table 4
The relevant information involved in the experiment test

Customer order	Product type	Quantity	Arrival date	Time window of delivery
1	A	2	0	[190, 298]
	B	2		
	C	1		
	D	2		
2	A	1	5	[223, 343]
	C	2		
	D	2		
3	B	3	8	[284, 428]
	C	2		
4	A	4	14	[93, 165]
	F	2		
5	B	4	15	[133, 181]
	E	3		
6	E	3	22	[50, 122]
	F	3		

windows. It is noteworthy that there are 0, 8, and 10 tardy jobs in the scenarios of synchronization-oriented production, EDD, and SPT, respectively, with only four available assembly islands. It means that the proposed concept of production synchronization is more effective in achieving on-time delivery with limited or tight assembly islands.

Fig. 6 shows the completion time of each customer order within different scenarios. As depicted in Fig. 6, compared with the original production, EDD, and SPT, the synchronization-oriented production improves the delivery punctuality with the completion times of all six customer orders are completely fall into the given delivery time window. Apart from improving the punctuality, the synchronization-oriented production trends to reduce the inventory level of finished goods, for example, in the case of six islands, it obtains the fastest completion time of each order compared with other scenarios.

To illustrate the results of the synchronization-oriented production, we take the scenario with six available assembly islands as an example. Fig. 7 shows the real-time pool with ST and JT queues at each island. It can be seen that the production paces are adjusted through clustering production of required products from the same product family with the consideration of customer demand and production constraints, and

Table 5
The comparison of the original production, synchronization-oriented production, EDD and SPT

Scenario	PS_{pd}	Cost-efficiency *TS*	Simultaneity *TW*	Punctuality N_{tj}
Four available assembly islands (K_t = 4)				
Synchronization-oriented production	**0.7179**	**194**	**1269**	**0**
EDD	0.5995	392	1462	8
SPT	0.6007	356	2761	10
Six available assembly islands (K_t = 6)				
The original production	0.6269	301	1817	0
Synchronization-oriented production	**0.7350**	**180**	**994**	0
EDD	0.5861	445	1074	0
SPT	0.5717	464	1876	0
Eight available assembly islands (K_t = 8)				
Synchronization-oriented production	**0.7436**	**174**	**996**	0
EDD	0.5727	496	1093	0
SPT	0.5635	511	1622	0

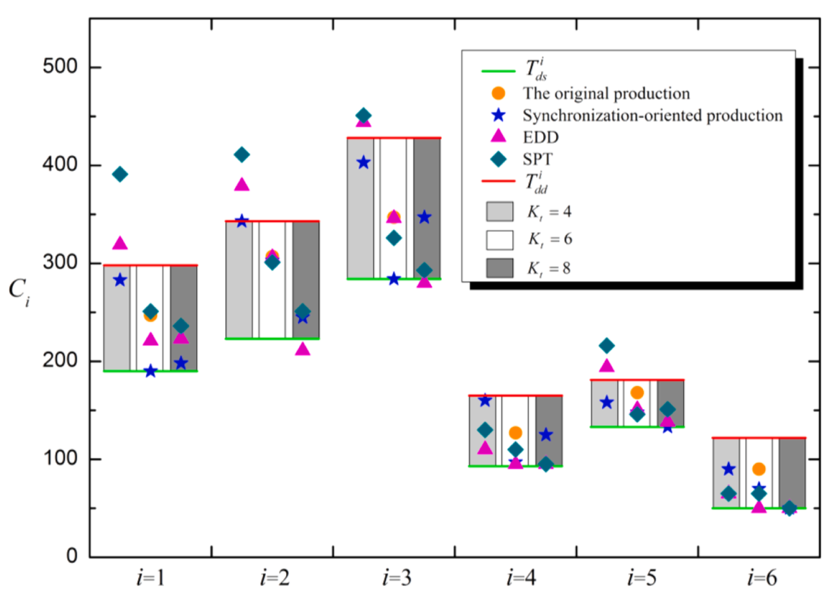


Fig. 5. The completion time of each customer order within different scenarios

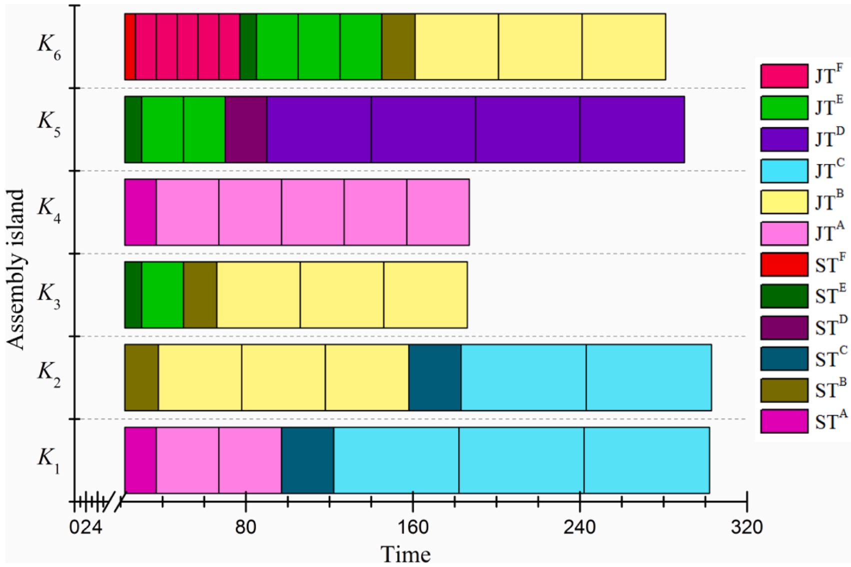


Fig. 6. The real-time pool with ST and JT queues at each island

therefore the unreasonable setups can be avoided, and the setup times are reduced.

These findings and observations from the case study could be converted into managerial implications. With the customized requirements for delivery as well as the unique production operations in FPAI, the synchronous organization and operations of production and delivery are crucial in real-life production. The proposed concept of production synchronization is quite effective for improving the production efficiency and delivery punctuality simultaneously in real-life production, with the highest synchronous degree between production and delivery as well as the best performance in simultaneity (lowest waiting time), punctuality (minimum number of tardy jobs) and cost-efficiency (lowest setup time) compared with other production strategies. Industrial Apps with cloud services act as practical tools for managers and onsite operators to facilitate synchronous operations based on coordinated decision-making with enhanced operational visibility. The proposed concept and approach are not only suitable for the layout of FPAI, but also support similar production scenarios with the customized requirements on production and delivery.

6. Conclusion

Motivated by a company that uses the layout of FPAI for producing heavy-duty laser equipment, this paper explores synchronous organization and operations of production and delivery in FPAI. The concept of production synchronization with corresponding methodologies and technologies is proposed to achieve synchronization of production and delivery with time windows in FPAI. The observation and analysis of the case company show the advantages of the proposed concept and approach. Even though the integration of production and delivery is known to yield significant cost savings [22, 23], this research shows that apart from increasing cost-efficiency, synchronous organization and operations of production and delivery can also improve simultaneity and punctuality.

The main contributions of this paper are concluded as follows. Firstly, a concept of production synchronization with corresponding pillars and measures is proposed as a new production and operations management strategy in the era of Industry 4.0 for the first time. Production synchronization refers to the adjustment of production paces toward synchronous interactions through real-time visibility and information-sharing, coordination of decision-making and synchronization of production operations in a production system. Secondly, following the concept of production synchronization, a graduation-inspired manufacturing mode-GMS with synchronization of production operations, and the IIoT-enabled GiMS with real-time visibility and information-sharing is proposed for FPAI. Thirdly, under GiMS, a coordinated decision-making model of production and delivery with time windows for FPAI is developed. The findings and observations from the case study show the potential advantages of the proposed concept and approach, with the highest synchronous degree between production and delivery as well as the best performance in simultaneity, punctuality and cost-efficiency compared with the original production, EDD, and SPT.

Although this paper put forward the concept of production synchronization with corresponding methodologies and technologies to achieve synchronous organization and operations of production and delivery in FPAI, the understanding of production synchronization is in its infancy and still needs a lot of research work. Further research on synchronization of production and delivery under uncertain environment caused, for instance, by machine breakdown or worker absenteeism, need to be investigated as the occurrence of such disturbances is inevitable in practical production. Besides, since the case analysis only involves one industrial company with limited experimental test data, more experimental tests need to be conducted to validate the performance of the proposed approach, and to provide more general managerial implications for the industry.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from gqhuang@hku.hk.

Acknowledgment

Acknowledgment to Hong Kong ITF Innovation and Technology Support Program (ITP/079/16LP), the 2019 Guangdong Special Support Talent Program-Innovation and Entrepreneurship Leading Team (China) (2019BT02S593), and the National Key Research and Development Program of China (2018YFB1702803).

Availability of data and material

The data will not be deposited.

Code availability

Custom code.

Author's contributions

Daqiang Guo: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing -original draft, Writing-review & editing.

Zhongyuan Lyu: Methodology, Visualization, Writing-review & editing

Wei Wu: Software, Writing-review & editing

Ray Y. Zhong: Conceptualization, Writing-review and editing

Yiming Rong: Supervision, Funding acquisition, Writing-review & editing.

George Q. Huang: Supervision, Funding acquisition, Writing-review & editing.

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