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ORIGINAL ARTICLE

IoT-based real-time production logistics synchronization system under smart cloud manufacturing

T. Qu[1] · S. P. Lei[1] · Z. Z. Wang[1] · D. X. Nie[1,2] · X. Chen[1] · George Q. Huang[3]

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Abstract Cloud manufacturing (CM) and Internet of things (IoT) are interlinked, yet most works only focused on one of them and take the other as a constituent technology unit. This is practically inadequate, especially for a highly service-driven manufacturing execution system which entails systematical CM supports to respond to the real-time dynamics captured from the IoT-enabled execution hierarchy. To deal with the dynamics occurring in production logistics (PL) processes, this paper investigates a dynamic PL synchronization (PLS) of a manufacturer adopting public PL services. Contemporary CM and IoT infrastructures are systematically integrated to enable a smart PLS control mechanism with multi-level dynamic adaptability. The S-CM operation framework, operation logic, and PLS infrastructure are presented with an industrial case, and the effectiveness is also demonstrated and analyzed.

Keywords Cloud manufacturing · Internet of things · Production logistic · Dynamic synchronization

✉ X. Chen
chenx@gdut.edu.cn

1 Guangdong CIMS Provincial Key Lab, Guangdong University of Technology, Guangzhou 510006, People's Republic of China

2 The College of Science, South China Agricultural University, Guangzhou 510642, People's Republic of China

3 Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, People's Republic of China

1 Introduction

The execution process of a manufacturing system, especially a discrete manufacturing system, is often disturbed by both internal dynamics, e.g., equipment failure, and external dynamics, e.g., customer order changes. Small-batch or customized production has brought much more frequent dynamics to the manufacturing systems and further increases the odds and influences of the execution dynamics [1]. Production logistics (PL) refers to the logistics activities taking place within a production process, which is responsible to the material transfer between production stages. Normally, PL processes will occupy nearly 95 % execution time of the whole production process which has significant influence to the overall production efficiency. A PL execution process, similarly, has to cope with external and internal dynamics, but the external dynamics are from the linked production stages rather than from customers. After customer requirements are converted into production tasks, the influence scope becomes wider and execution cycle becomes shorter, which bring more external dynamics to a PL process. Also, the PL equipment, e.g., forklift, is more dependent to the operator's behavior, and thus is subject to more internal dynamics. All these have raised higher challenges to the management and control of PL processes, and this is partly the reason why all the advance production management strategies, e.g., Just-in-time (JIT) production, will take the rigorous coupling of PL and production processes as a fundament. The involvement of third-party logistics (3PL) will unavoidably expand the execution scope and the resource types of a PL process. On the one hand, the unstable collaboration among frequently changed 3PL services will decrease the regularity of PL processes and further increase the execution dynamics. On the other hand, the rental-based service consumption mode has also brought higher pressure to both production and 3PL companies, pushing them to control the potential execution dynamics. So, how to effectively deal with the dynamics to maintain the performance of a PL execution process is of interest.

The execution of a plan is essentially a requirement fulfilling process by certain capabilities. The control of a dynamics normally has two possible results. For those light-weight dynamics which will be tackled in the execution level, the adjustment of execution plan, e.g., production rescheduling, is enough for the control. Yet for other heavy-weight dynamics, we have to passively accept the change of the original plan which will not only delay the current order delivery but also influence the subsequent plans. MES or RT-MES could maximize the effectiveness through plan adjustment in the execution level, yet they cannot overcome the hard constraint of physical resources' upper limit. The service-based manufacturing mode has offered another possible solution in the middle of the above two, i.e., dynamically involve external resources and services to extensively reconfigure the system to deal with heavy-weight dynamics. This mode is especially suitable for PL process which is more and more outsourced to services.

Cloud manufacturing (CM) is a newly emerging Internet manufacturing mode, which provides a service-oriented manufacturing platform to organize the manufacturing resources over the Internet and enable users to consume on-demand manufacturing services (http://finance.ifeng.com/a/20140509/12294384_0.shtml) [2, 3]. The application scope of CM mentioned in the literature covers design, manufacturing, management, trading, etc., while the current practical applications are mainly on the sharing of manufacturing software, such as design, simulation, and resource management [2, 3]. We could categorize the CM application mode into two types. The first is a task-dispatching mode, which means the service requester dispatches the task to the distributed services for execution and then gets results back. This mode normally deals with those small-scale, light-weight, or relatively independent task which does not need extensive physical moving of CM resources. The other is a service-integration mode, which means the CM resources are integrated together around the service requester for the undertaking of a set of tasks which may be large scale, heavy weight, and systematical, and then disintegrate and return. This integration could be logical but sometimes have to involve physical part, such as forklift or truck rental discussed in this paper.

To maintain feasibility, the service-integration CM mode requires the cloud resources to be geographically close and integrable. This perfectly meets the features of a recently advocated industrial development mode named industry cluster, typically including industrial park or group company [4]. The developing motivation of industry cluster is resource sharing, which could largely relieve the pressure of land using and hardware investment faced by manufacturers located in those industrially developed countries or areas. Examples include the thousands of specialized industrial townships having been established in the Pearl River Delta (PRD) and Yangtze River Delta (YRD) regions of China which are referred to as the two big factories of the world. Clustered manufacturers share the public PL resources provided by the industrial clusters, such as public warehouses or transportation vehicles and involve the public PL services in their production process due to the services' geographical approximation. This provides an important practical basis for this paper.

This paper investigates a CM-enabled dynamic PL process in which multiple manufacturers in an industrial park share public warehouses and transportation vehicles, i.e., truck and forklifts. As the workshops, warehouses, and transportation in the PL process own their respective plan and execution stages/departments, the execution dynamics have to be collaboratively tackled by them. Under the MIoT-enabled real-time PL execution environment, such collaboration will be conducted in the form of multi-level and multi-stage dynamic synchronization which results in the so-called production logistics synchronization (PLS) to be discussed in detail in the next section.

The remainder of the paper is organized as follows. The second section analyzes the typical PL process control problems and the research challenges of applying CM and IoT technologies. The third section introduces the smart CM mode which is systematically enabled by IoT and extends it to a smart cloud-based PLS (S-CPLS) mode. Based on the S-CPLS, the detailed construction of the S-CPLS system and its enabling infrastructures and technologies are discussed in the fourth section. Based on a practical large-scale production company in an industrial park which adopts public warehouses and forklifts, to participate in the PL process, the developed system's application procedures and results are demonstrated. Conclusions and future works are summarized in the last section.

2 Problem analysis for production logistics synchronization

From the production perspective, production logistics is an organic system responsible for the material's physical state-transferring process ranging from raw material purchasing, distribution among the workshops, as well as the flow along production cells, for both manufacturing and storage [5]. Researchers also extend the PL to the inter-company scope and study the production and distribution problem among suppliers, manufacturers, and retailers. But from the matching perspective of PL resources and processes, we depict the PL process in Fig. 1, which shows the six PL execution stages and the required PL resources, including the collection, warehousing, and distribution stages for both raw materials and finished products. The upper part shows the PL processes, and the lower part shows the resources.

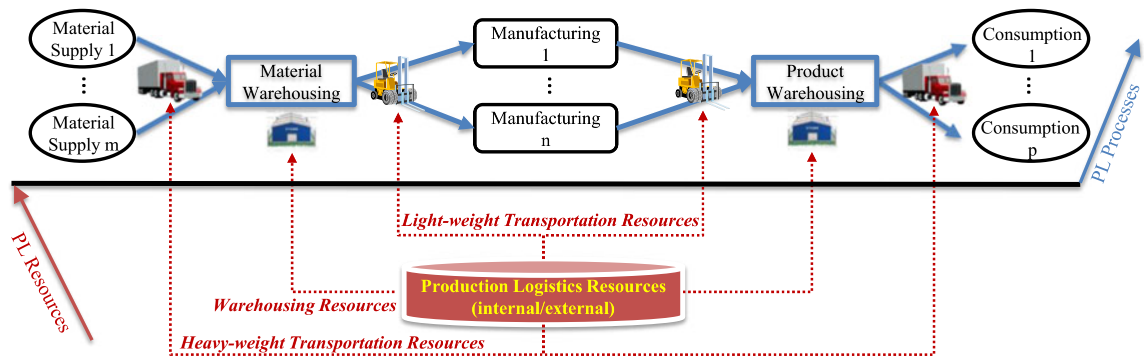

Fig. 1 Production logistics processes and resources

In recent years, extensive works have been made on the integrated optimization of PL process and resource. Most of them consider the collaboration problem among production, warehouse, and transportation in a multi-cycle environment. Under the consideration of capability constraint, Pundoor [6] establishes an integrated PL scheduling model for a PL process with multiple suppliers, single warehouse, and single customer. Bard and Nananukul [7] investigate an integrated optimization problem toward production, warehouse, distribution, and route planning and put forward an adaptive Tabu algorithm. Such integrated optimization applies well to those PL problems with unchanged customer order, stable system structure, fixed execution cycle, and safe execution environment, which ensure that the plan could be executed without a disturbance.

During the increase of the total production output of manufacturers, their original inventory levels have been relatively lowered. Due to cost control and land constraint, however, they cannot increase the inventory through continuously expanding the warehouse and therefore the dynamics buffering effect will be reduced. Manufacturers have to rely on the accurate PL execution to realize the afore-mentioned dynamic synchronization mechanism among adjacent production stages. PL synchronization means, in the presence of certain execution dynamics, some parts or the whole PL systems will be real-timely triggered to make adaptively collaborative decision which takes the dynamics into consideration and generates an updated execution plan for the next execution stage. The execution dynamics are categorized into two levels, namely light-weight and heavy-weight dynamics, which will trigger the PL process (re-)plan and PL resource (re-)configuration respectively as in accordance with Fig. 1.

Researchers have been using IoT solution to real-timely monitor the PL environment and applied adaptive control mechanism to solve the deal with the PL process (re-)plan problem. Huang et al. [8] put forward the wireless manufacturing concept, while Zhang et al. [9] present an overall architecture of multi-agent-based real-time production scheduling to achieving real-time production scheduling. Zhang et al. [10] design a dynamical optimization model for shop-floor material handling (DOM-SMH) to make a better decision based on the real-time and multi-source manufacturing data. Chow et al. [11] further employ real-time logistics data to plan the storage shelf and transportation route to minimize the total operation time. The authors' team mainly focuses on the PL fields, developing the IoT-based PL systems for both individual manufacturers [12–14] and manufacturer clusters [15].

The broad-scope manufacturing resource management based on CM mode has been gradually interesting. Li et al. (http://finance.ifeng.com/a/20140509/12294384_0.shtml) define CM as an Internet-based service platform which could organize the distributed resources to offer on-demand services to users. Xu [16] encapsulates the distributed resources into CM services under centralized management and offers CM services as product design, manufacturing, testing, and management. Wu et al. [17–19] focus on developing a strategic vision for the CM environment, considering the benefits of cloud computing to the information technology sector and propose a new concept of cloud-based design and manufacturing (CBDM). In order to realize manufacturing capability sharing and circulation, Luo et al. [20] propose a modeling and description method of multi-dimensional information for manufacturing capability in CMfg system. Zhang et al. [21] propose a service encapsulation and virtualization access method for cloud manufacturing machine. Guo and Guo [22] give a CM-based decision support framework, realizing the order plan and tracking for the distributed manufacturing environment. To solve the OACR problem, Laili et al. [23] propose a new comprehensive model for OACR in the CMfg system. Tao et al. [24, 25] not only give a new parallel intelligent algorithm to solve the service combination optimization problem but also outline a systematic service framework integrating both cloud computing and IoT to realized the effective sharing, cost calculation, and on-demand allocation of CM resources. Although CM and IoT are known to be somewhat interlinked, yet most existing works only focused on one of them and take the other as a constituent technology unit. They have not been systematically integrated toward the concrete requirements of a specific manufacturing process, especially PL process. This is practically inadequate, especially for a highly service-driven manufacturing execution system which entails systematic CM supports to respond to the real-time dynamics captured from the IoT-enabled execution hierarchy. The existing research challenges are summarized as follows.

1. How to apply IoT modeling technologies to encapsulate the various heterogeneous PL resources, such as warehouse and vehicles, in a consistent way? How to realize the real-time data collection, processing, service, and application for the PL process and construct an effective PLS information infrastructure?
2. How to establish a CM resource platform to manage both the internal PL resources and the public PL resources according to their service mode and business constraints, in order to support the dynamic PLS resource configuration?
3. How to systematically integrate the IoT-based real-time multi-level control and CM-based dynamics resource management, to realize a generic control mechanism for the PL dynamics?
4. How to integrate the newly emerged CM and IoT infrastructures to make use of their respective advantages of real-time data capturing and dynamic resource management to solve PLS problems and develop a cloud-based real-time PLS management system to cope with the various execution dynamics?

3 Smart cloud manufacturing

Smart cloud manufacturing (S-CM) is a new development stage of cloud manufacturing (CM), which is based on ubiquitous network including Internet, mobile network, IoT, telecommunication network, satellite net, etc., or their combinations and integrates various rising manufacturing technologies such as networked manufacturing, information technology (IT), and smart technology (http://finance.ifeng.com/a/20140509/12294384_0.shtml). It make comprehensive use of both manufacturing technologies and IT technologies to upgrade the traditional manufacturing resources into smart ones and adopt service-oriented concept to virtualize and servitize their capabilities, and finally construct cloud-based smart service pool. The pooled services are managed and coordinated in a smart way to enable users to get their on-demand services and fulfill the manufacturing activities along the whole lifecycle also in a smart way.

3.1 S-CM operation framework

The smart data capturing and multi-stage adaptive collaboration are two key enablements in a smart operation process. Although literature has indicated that IoT is a key for realizing CM, yet only regard it as a technology unit in the whole CM hierarchy [26–28]. In fact, however, IoT system is itself a standard industrial system which is facilitated by a complete multi-level, multi-dimensional, systematically functioned, and real-time information infrastructure [29]. As compared with CM, the mature IoT infrastructure has been established even earlier and obtained more widely applications in industry [30–32]. Reasonably, a complete and practically applicable S-CM system should be systematical with existing IoT system from the infrastructure level considering resource exchanging, logic merging, module consistency, etc. Therefore, this section will introduce the way for the infrastructure integration and then details the resulted PLS system. Two basic functions of S-CM are to realize high-level resource sharing and smart process control for manufacturing. They are enabled by the CM-based resource management infrastructure [33] and IoT-based real-time information infrastructure, respectively [29, 34]. Their integrated operation results in the S-CM operation mode are shown in the left part of Fig. 2. S-CM mode makes complementary use of the CM's advantages of managing wide-range, various-resource service capability as well as the IoT's advantages of performing real-time, accurate, adaptive process control, and thus is able to deal with the uncertain dynamics in an iterative way by their two.

3.2 S-CM operation logic

The operation logic of S-CM is shown in the right part of Fig. 2. After a service request is released, S-CM will make two initial execution plans, i.e., system configuration and execution process plan, based on the IoT-based smart cloud resources. After the initial system begins to operate, real-time dynamics will be captured and evaluated. In the presence of level-1 dynamics, i.e., light-weight ones, only the execution process plan will be made again based on the real-time environment being monitored. Yet in case of level-2 dynamics, i.e., heavy-weight ones, which cannot be addressed only through re-planning the process, a resource reconfiguration for the overall execution system will be made. The above procedure will be continued following the operation logic until the tasks are completed.

3.3 Production logistics synchronization under S-CM

Based on the above explanation, a smart cloud-based production logistics synchronization (S-CPLS) operation mode is instantiated toward the PL control requirements analyzed in the preceding section. The S-CPLS mode is centrally coordinated by the PLS control mechanism which accords with the above-mentioned S-CM operation logic.

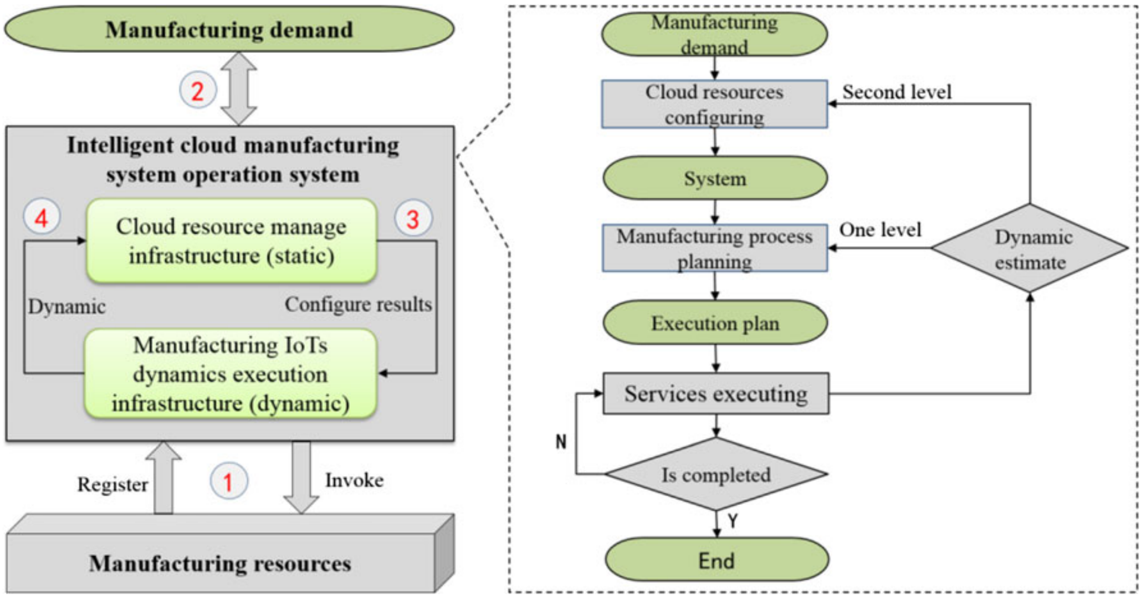

Fig. 2 S-CM operation framework

The S-CPLS infrastructure is actually an infrastructural integration of AUTOM and cloud manufacturing, as shown in Fig. 3. The right part of Fig. 3 is a typical IoT information infrastructure named AUTOM, which is put forward by the authors' research team [35]. Through encapsulating the physical PL resources into smart PL objects, the real-time execution data will be captured, processed, transferred, and turned into services and applications. The left part of Fig. 3 is CM infrastructure, which defines the management, organization, and service hierarchy of CM resources. These two infrastructures will be introduced in Sect. 4.1.

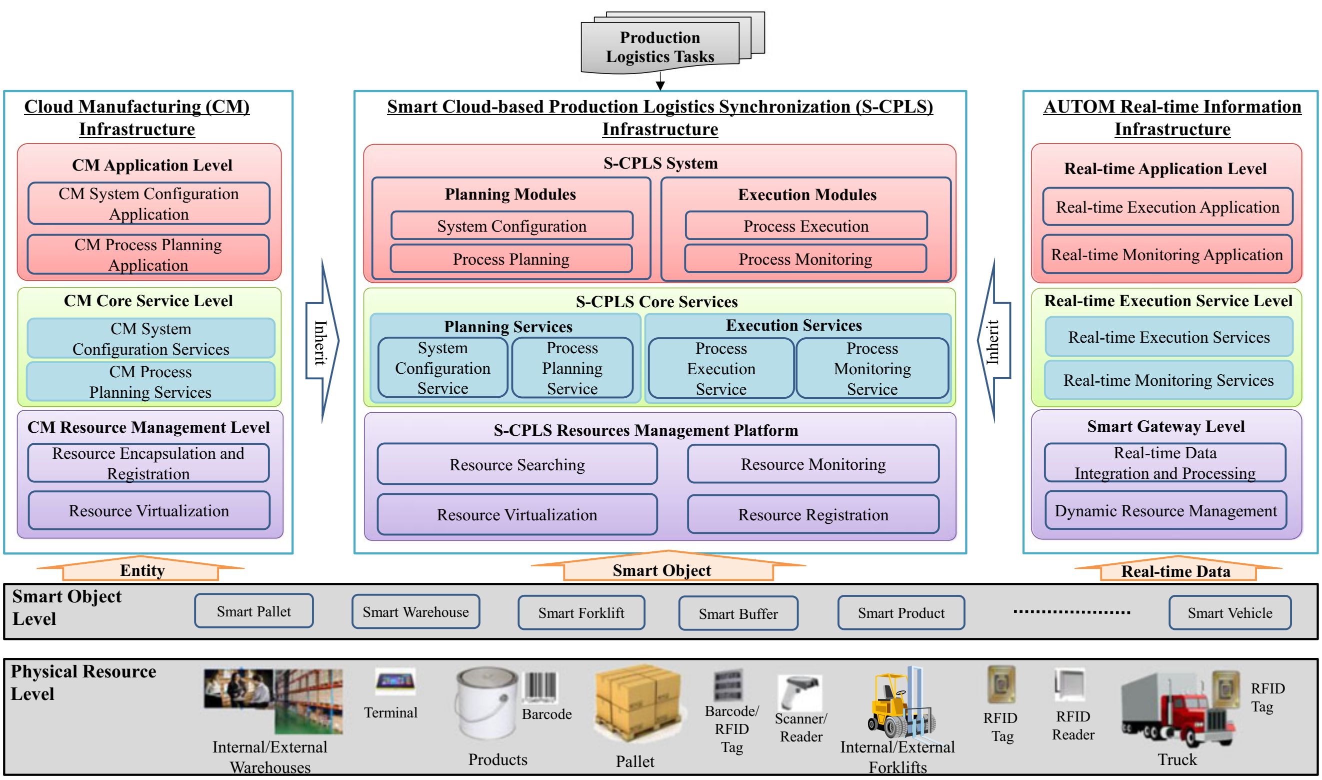

Fig. 3 Smart cloud-based production logistics synchronization infrastructure

4 S-CPLSS: S-CM-based production logistics synchronization system

4.1 Basic infrastructures

4.1.1 Cloud manufacturing infrastructure

The cloud manufacturing infrastructure proposed in [3] and [16] are followed. It includes five layers as follows.

1. Physical resource layer. All the physical resources (such as forklift, warehouse, tray, truck, human, etc. in the PL environment) which have the potential to be involved in the executive process are managed in this layer.
2. Smart object layer. All the physical resources in the S-CPLS environment will be firstly converted into smart object by IoT technologies, i.e., being equipped with the real-time information sensing capability, before they are managed by the cloud. The smart object conversion is enabled by AUTOM infrastructure, as shown by the two commonly shared layers in Fig. 3.
3. Cloud manufacturing resource management layer. Being enabled by the resource virtualization and encapsulation, the PL-SO connected to the Internet can be transformed into virtual cloud-based PL resources, which can be registered into the cloud manufacturing service registration center to provide PL services. The main functions of this layer include definition, virtualization, quality management, and the decomposition of cloud resource.
4. Cloud manufacturing core service layer. According to the service requirements generated from the PL process, this layer is designed to provide core facilitating services. The main functions of this layer include service interface management, service data management, cloud task management, service-based system configuration, process planning, etc. Among them, system configuration and process planning are normally the two core services.
5. Cloud manufacturing application layer. Two sets of application modules which are related to the system configuration and process planning are normally contained in this layer. These applications can be directly used by customers via various terminals such as mobile phone, PC, or cloud manufacturing portal.

4.1.2 Real-time production logistics information infrastructure

During production logistics synchronization, dynamically triggered PL events will lead to the continuous involvement of uncertain PL resources from the cloud. Due to the uncertain types, interfaces, capabilities, and performances of the various cloud resources, it is difficult to maintain a highly efficient PL operation, say real-time PLS, which normally relies on the familiar interactions among resources and their operators. Thus, heterogeneous PL resources must be encapsulated by IoT technologies in a standard way, based on which a set of standards and measures for real-time information collecting, processing, and transmitting could be established. Finally, the major PLS services and applications could be developed based on the standard real-time information to effectively support the dynamic PLS management. AUTOM is originally put forward as a standard manufacturing Internet of things (MIoT) infrastructure which is compliant with ISA-95 standards [36]. It defines an easy-to-deploy and simple-to-use way for the communication and interaction of real-time information. The AUTOM has obtained broad interests from academia, and been practically applied to many real-life manufacturing companies as well [12]. This paper extends AUTOM to deal with the real-time PL information from cloud-managed PL resources. A brief representation of AUTOM is shown in the right part in Fig. 3, which consists of four functional layers.

The smart object layer Through equipping the physical PL resources with a series of IoT devices (such as PDA, mobile, PAD, etc.) and IoT tags (such as RFID, sensor, barcode, etc.), with the help of communication technologies (such as the Internet, Wi-Fi, Bluetooth, etc.), the original resources can be transformed into smart objects (PL-SO) which have the ability of real-time information perception, transmission, and task processing. The smart objects could perform analysis, execution, and even decision-making based on the captured information and feedback the dynamics of the PL execution process to the higher-level management in a real time and accurate way.

Smart gateway layer Smart gateway acts as an information hub to enable the real-time connection and interaction among smart objects through caching and exchanging their real-time data and events.

Service layer Based on the requirements from the application layer, a series of standard service components will be developed to transform the real-time information into functional service, taking the form as Web services for example.

Application layer This lay contains user-oriented functional applications, such as distribution management, warehouse management, workshop management, etc. Users could employ appropriate terminals to track the real-time status of an execution process.

4.2 Key enabling technologies

Through the infrastructural succession and integration of the capabilities of both CM and AUTOM, a S-CPLS infrastructure which supports the real-time planning and execution of a cloud-based production logistics synchronization system will be constructed, as shown in the middle part of Fig. 3. It makes uses of the IoT-based smart PL objects shown in the two bottom layers, which are managed in a CM-based mode and provide real-time information to enable the smart synchronization of a production logistics execution process. In the following subsections, the three key enabling technologies forming the three main lays of the S-CPLS infrastructure will be discussed in detail, which are concerning with how the smart PL resources are managed in CM mode, how their executional information is used to construct real-time PLS planning and execution services, and how the constructed services are employed to develop the S-CPLS system, respectively.

4.2.1 Production logistics resource management

In this paper, the design of the cloud-based production logistics resource manager (CPLRM) is shown in Fig. 4, which is a more complete description of the CM infrastructure given in Fig. 3. It comprises resource encapsulation, resource virtualization, resource management, and service management.

- Encapsulation of production logistics smart object
  With the integration of cloud manufacturing and AUTOM, this procedure is exactly the same as for the afore-mentioned creation of PL smart objects, as shown on step ① of Fig. 4.
- Virtualization of production logistics smart object
  According to the rules of virtualization description of PL resource, the basic properties, function properties, and management properties of PL-SO will be modeled, abstracted, and virtualized. Then, the virtualized PL-SO will meet the interface standard of CPLRM platform, as shown on step ② of Fig. 4.
- Core middleware
  The core middleware is responsible for the information storage in the CPLRM platform. In addition, it also provides the function of service quality evaluation, as well as the query, addition, deletion, modification of PL resource, and service, as shown on step ③ of Fig. 4.
- Resource management
  This module provides the basic management functions of the virtualized PL resource in the CPLRM platform, including the registration, search, composition, scheduling, selection, and monitoring of resources, as shown on step ④ of Fig. 4. Based on the legality verification by the CPLRM platform, virtualized PL resources will be registered in the resource registration center.
- Service management
  In relation to the preceding resource management, a set of corresponding service management functions will also be developed to form a cloud-based service management, as shown on step ⑤ of Fig. 4, which is the key part of the CPLRM.

By CPLRM, a CM-based PL resources management process could be realized as shown in Fig. 5. In the S-CPLS operation system, the PL-SO is the actual provider of elementary PL service. Through function abstracting, performance mapping, and method encapsulation, the physical PL-SO can be virtualized as a standard cloud resources, which can provide certain functions for the corresponding services. Virtualized PL-SO should be registered in the CPLRM to become a legal PL service provider which can participate in the PLS operations. PL services will be described to define the service object (such as materials on pallet), service capability (such as forklift shipping), the service time windows (begin time and end time of a service), and other service attributes before they are registered into the service registration center and published for customers' searching. Each time a service searching query is obtained from the customer, the invalid information in the search query is filtered and a new semantic search query will be created, resulting in a suitable service set. Service composition management ensures multiple PL services to be linked together to form a larger PL service unit which offers richer service modes and options. On receiving a PL service demand, the PL service selection module and service scheduling module will be simultaneously triggered. The former ensures a certain set of service to be configured and locked for the contract period, while the latter employs optimization algorithms to make the execution plan with the selected service. Service monitoring module acquires the real-time execution status of the corresponding resources and feedback the information in appropriate form to the PL service management modules.

4.2.2 Typical production logistics synchronization services

According to the afore-mentioned PLS operation mechanism, a PLS process under S-CM is composed of continuously iterated PLS segments. Each segment contains an updated PL system plan followed by a consequently improved PL execution process. Both the plan and the execution are enabled by the corresponding service sets which are to be introduced in the following.

1. Cloud-based production logistics system planning services

This is one of the two core service sets in the smart PL services layer, as shown by planning services in the middle part of the S-CPLS infrastructure of Fig. 3. It includes two kinds of

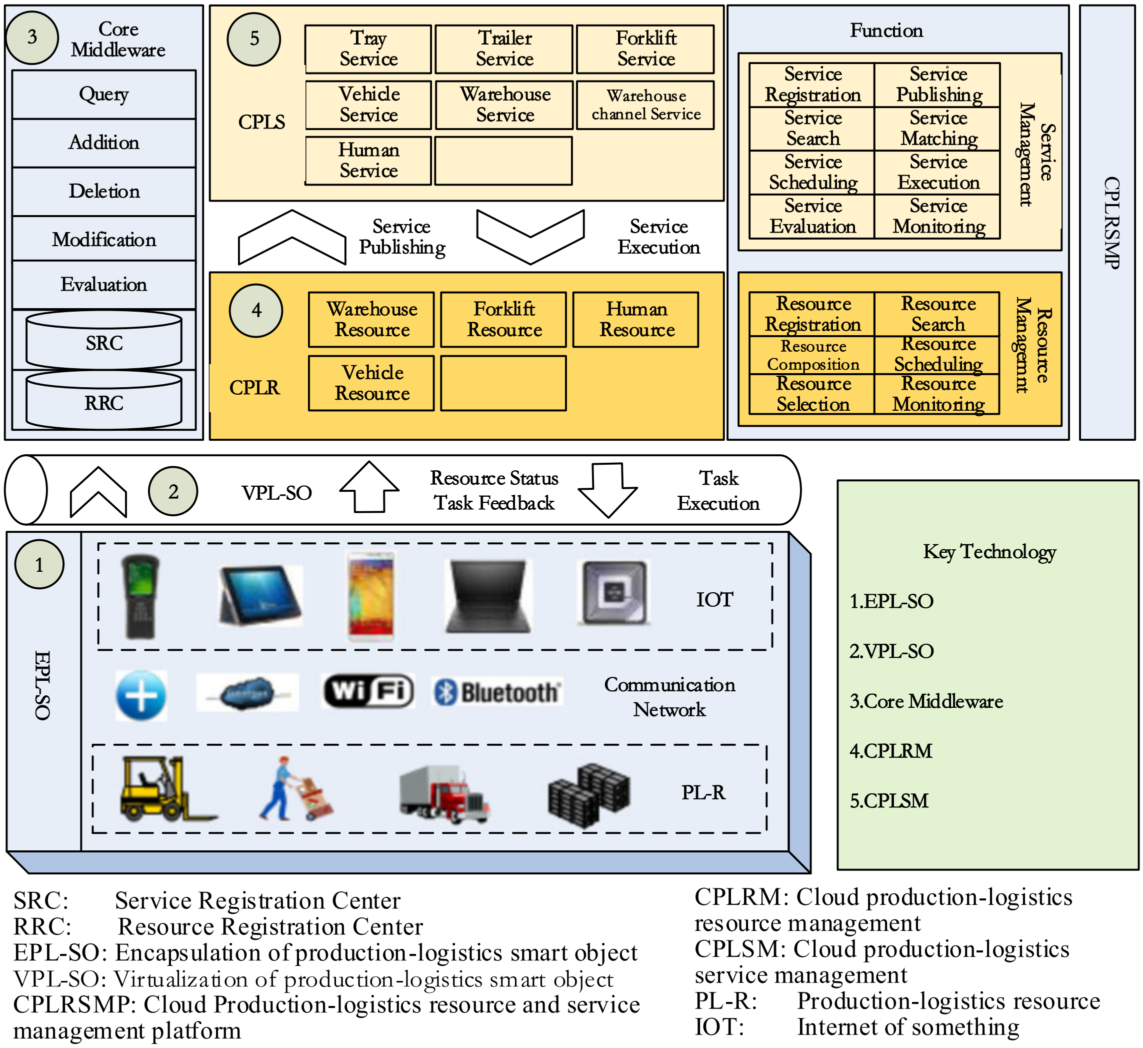

Fig. 4 Cloud manufacturing based production logistics resource manager

services as CPL system configuration service (CPLSCS) and CPL process planning service (CPLPPS). The former is responsible for the optimal configuration of PL resource services towards the continuously updated PLS requirement, while the latter conducts process planning with the optimized configuration.

In developing the optimization-oriented services, however, it is hard to use traditional All-in-One (AIO) optimization methods, e.g., genetic algorithm, which include all the resources' fixed service parameters into an individual optimization model. This is because the PL-SO resources registered in the CPLRM are from different providers and therefore probably have different service capabilities and provision modes, e.g., service charge and cycles. In addition, their configuration and actual service capabilities are changing over time along with the real-timely captured functional status by IoT. Therefore, multi-disciplinary design optimization (MDO) methods which support a collaborative decision are needed. As PL resources are organized in a way of management pyramid, a hierarchical MDO method, i.e., analytical target cascading (ATC), is adopted to coordinate and optimize resource services. ATC is a multidisciplinary hierarchical optimization methodology for translating the overall design targets of a system to the specifications of the constituent elements that are decomposed to the multi-level hierarchy [15]. The coordinating mechanism offered by ATC is responsible for assembling the local designs of these elements consistently into the final optimal system design. By ATC, both CPLSCS and CPLPPS could be realized toward the distributed heterogeneous PL resources with rapidly changed statuses.

An ATC-enabled cloud resource optimization framework is designed based on [37], as shown in the right triangle of Fig. 6. Resource services (RS) stands for the cloud-based PL resource services while resource service register center (RSRC) is the resource service registration center which has been introduced in Sect. 4.2.1. The atcGenernator module acts as an interface to communicate with the service requester, i.e., and translate their service demands into a RS-based ATC optimization model based on the contextual information. The

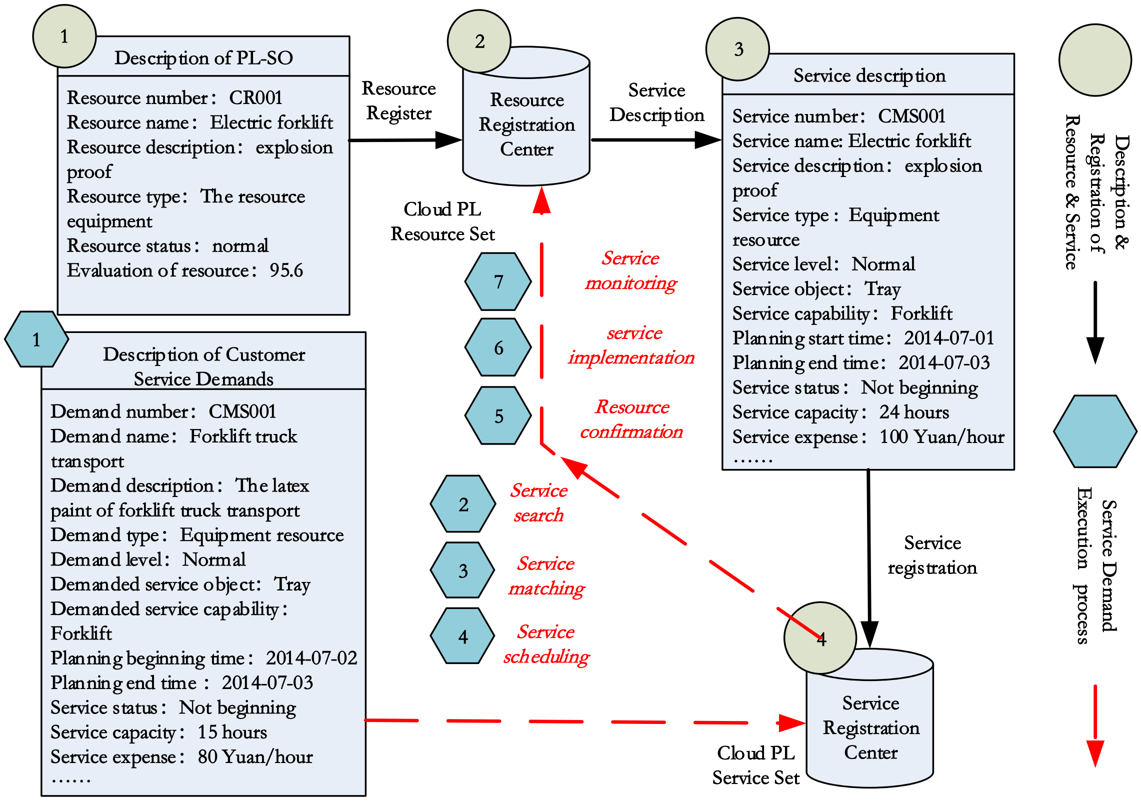

Fig. 5 Cloud manufacturing based production logistics resource management process

atcEngine module takes on collecting information in IoT and coordinating and optimizing production logistics cloud resource services. The atcGenernator and atcEngine work together to provide CPLSCS and CPLPPS which will be discussed in details in the following.

- CPL system configuration service (CPLSCS)

  When a service request is initially received from the customer, the PL manager will use atcGenernator to define a PL system which takes the registered PL-SO in CPLRM as constituent elements. In this paper, a common three-level PL execution system is chosen for discussion, as shown in Fig. 7. The first is system level which represents the whole system to respond to customers. The second level includes two kinds of PL management departments, i.e., warehouse sub-systems and transportation sub-systems. The third level is the physical resource level, which is managed by their corresponding

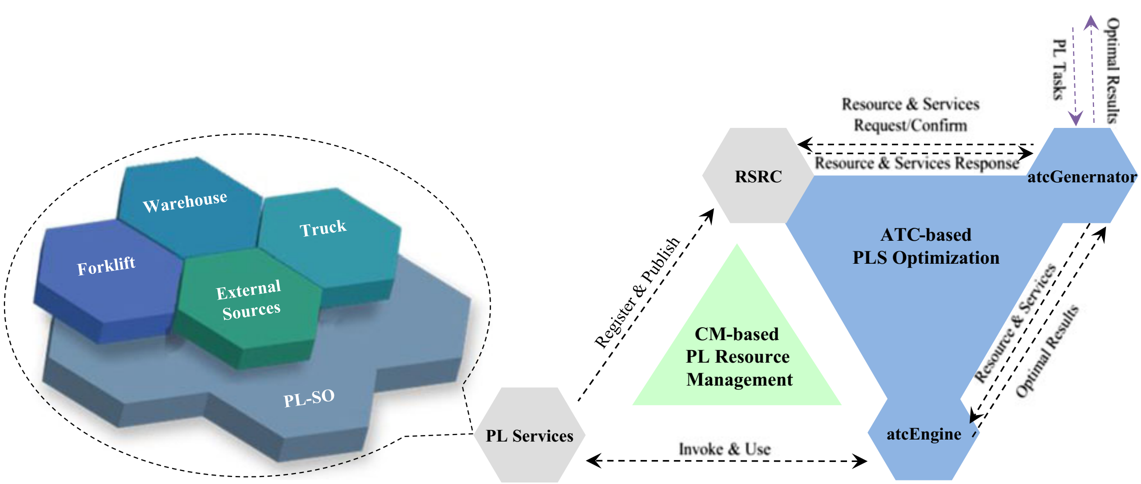

Fig. 6 ATC-based cloud resource optimization framework

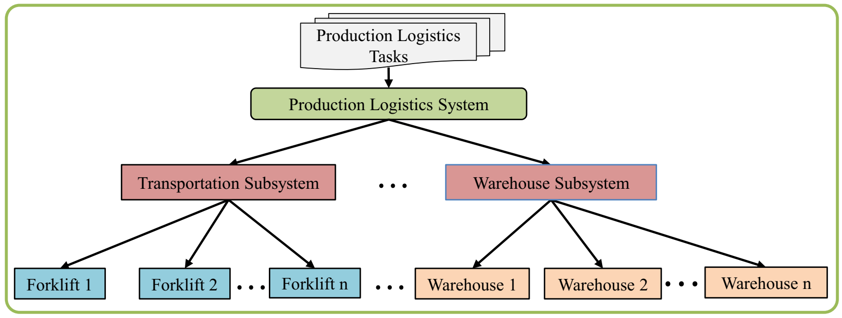

Fig. 7 A generic hierarchy of production logistics system

upper-level departments. After the system structure is defined, the supplier searching criterion for each structural element will then be set, such as the required service capacity and capability, etc. The searching criteria of each element will be sent to CPLRM to find out a suitable set of PL-SO alternatives which meet the criteria and return back to the atcGenernator module. All the searched PL-SO will be put in their corresponding elements as service alternatives to form a generic CPL system structure, which will then be sent to the atcEngine for the optimal configuration. If this is the initial stage that a CPL system is configured, atcEngine will and collect the real-time statuses of the distributed cloud-based PL-SO to form their capability model and then coordinate the models to obtain the optimal PL system configuration which could best meet the customer demand.

After the initial service configuration is put into use, with a process plan to be discussed in the next subsection, the real-time service statues as well as their execution progress will be collected from their IoT-based working environment. Executional dynamics in the process will be captured and evaluated and may trigger a system re-configuration if needed. A CPL system reconfiguration is easy to do by the system, yet to practically fulfill the reconfiguration results, i.e., add or remove a service, is normally difficult or expensive especially in case that external resources have been or are to be involved in the CPL system. Therefore, a CPL system reconfiguration will be necessary only if certain dynamics cannot be tackled by process re-plan and will cause an unacceptable consequence, i.e., serious delivery delay, and the resource changes are possible, i.e., could come to the PL execution spot in a short time.

- CPL process planning service (CPLPPS)

  After each round of CPL system configuration or re-configuration, a corresponding process plan or re-plan will be conducted to better coordinate the configured resources to fulfill the PL tasks. Literature talking about such logistics route planning problems is not few; however, the CPL process plan service will pay attention to three special characters. First, considering the cloud-based distributed and dynamical PL resources and services, the ATC-based decentralized decision-making approach is adopted as afore-mentioned. Second, similar as for the CPL system configuration, the real-time in-progress statues, e.g., location and workload, of all the constituent PL-SO will be collected through IoT system to enable an adaptive process planning. Third, for IoT-based real-time PL execution, we are concerning with the event-driven dynamic synchronization among different PL stages. The PL synchronization requirement normally exists in the following three forms. The first is the synchronization between production and transportation. This situation mainly exists in a large manufacturer where the warehouses have enough storage capacities yet the fixed production plan requires the fleet to be synchronized accordingly. The second is the synchronization between production and warehousing. This situation mainly exists in the industrial parks where the public fleet has fixed transportation schedule, which requires the manufacturer's production and warehouses to be synchronized so as to make economic use of transportation. The third is the overall synchronization among production, transportation, and warehouse. This situation accommodates most of the synchronization possibilities especially when PL resources are dynamically involved to serve the production processes.

2. Production logistics execution services

Normally, a PL execution processes could be fulfilled by different combinations of the following services. Interested readers may refer to Qu et al. [38] for details about the design and realization of these services.

- Real-time production logistics execution services

  This service set includes three kinds of execution services. The first is loading and unloading service. The purpose of this service is to assist the driver of a transportation resource, e.g., truck or forklift, to perform loading and unloading pallets. The second is transportation service.

The purpose is to assist a transportation resource driver to perform object collection and delivery processes. The third is warehousing service, which includes put-away and order-picking services. The purpose of the put-away service is to assist a driver to place the loaded object to a destination, while the purpose of the order-picking service is to assist a driver to locate an object and move it to a destination. All the concerned PL objects are IoT tagged, and therefore the execution data of the PL process will be automatically captured and recorded. The data could be used for real-time progress monitoring and be compared with the original process plan for next round PL synchronization in case certain dynamics occur, see Sect. 4.2.3.

- Real-time production logistics monitoring services

  This service is to get the execution dynamics from the captured above-mentioned execution services. Dynamics are categorized into two levels according to their influences to the PL process. For the level-1 dynamics, CPLS CS will be invoked for a re-planning of the subsequent PL execution process based on the current execution state captured by the PLS process monitoring module. Yet for the level 2, CPLSCS will be invoked in which a CPL system configuration service is functioned for the PLS reconfiguration.

4.2.3 Production logistics synchronization applications

1. Production logistics synchronization planning system (PLSPS)

   Similar as for other real-time control system, the dynamic PLS discussed in this paper is also a near real-time control scheme which monitor and control the system with enough short periods. Within each monitor period, the real-time execution dynamics are captured and quantitatively accumulated. In the end of each period, the total quantity of dynamics will be evaluated. When it is less than the threshold of level 1, or in between the thresholds of levels 1 and 2, or exceed the threshold of level 2, different actions will be taken. The details procedures are shown in Fig. 8.

   a) Initial system configuration. For a PLS plan period (T), PLSPS generates the total PL resource requirement based on the received PL tasks in T. PLSPS invokes the afore-mentioned CPLSCS to generate the initial PLS execution system with both internal and external resources. It should be noted that T is not only determined by the manufacturer's business requirement but also subject to the constraints of the resource provider, say minimum or maximum rental cycle.
   b) Initial process plan. For a PLS execution period, PLSPS invokes the afore-mentioned CPLPPS to make process plan based on the initial PLS execution system and the execution environment captured by the PLS process monitoring module, see Fig. 3. It is the manufacturer's work cycle time, and normally 1 day.
   c) Process re-plan. If the PLS process monitoring module captures level-1 dynamics, such as a forklift failure, the CPL process planning service will be invoked again based on the current execution state from RT PLS monitoring service and generate the plan for the subsequent execution processes.
   d) System re-configuration. If the PLS process monitoring module captures level-2 dynamics which cannot be addressed only by process re-plan, such as an urgent inserted order, a system re-configuration has to be conducted to involve new resources, normally external CM ones. Of course, process re-plan is also necessary after a new system is configured.

2. Production logistics synchronization execution system

   This part mainly contains two functions, namely PLS execution and PLS monitoring. With the combination of the afore-mentioned services, the former will guide the users to execute the PL operations with IoT facilities, while the latter monitors the execution process and capture the dynamics for evaluation.

5 Case study

The case company is a large-size old-brand paint-making company located in the PRD region in China, which has formed a fixed and mature PL operation flow, as shown in Fig. 9. This process contains eight workshops, ten forklifts, and two warehouses, which form the internal PL resources. The rapidly developed real estate market in China caused the increased demand of decoration materials like paint; the company has to largely increase its production output. Although the workshop capacity could be increased through working in shift round the clock, the logistics resources, especially warehouses, have become a hard constraint due to the land constraint in the old factory.

This problem mainly exists in the finished products' PL process, i.e., forklifts transport the finished products from the workshops to the warehouses, because the size or finished products are much bigger than the raw materials while the types and customers and therefore the necessitated PL processes are much more complicated. Therefore, this paper mainly discusses this portion of PL process. The company begins to involve external PL resource such as public warehouse and renting forklifts as a complement. However, as all

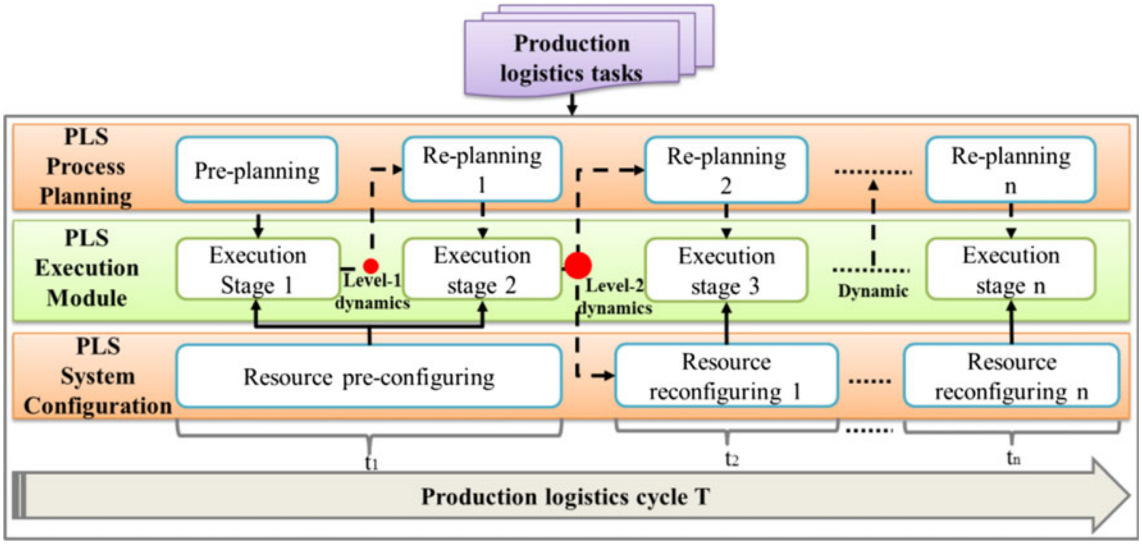

Fig. 8 PLS planning mechanism

the PL execution stages are planned and controlled in a manual way, the following problems emerge.

1. Lack a platform for dynamically managing and using PL resources. Making PL plan and execution control toward both internal and external PL resources is very difficult especially when their service states are unstable. Let us to say the possible resource reconfiguration during the execution process.
2. Lack an adaptive control mechanism to adjust execution system toward dynamics. The company adopts make-to-order production mode, and therefore the whole PL execution processes is subject to frequent changing requirement due to the rapidly changed market demand as well as the uncertain output of chemical reaction process.
3. Lack real-time execution management system. All the decision coordination and data transfer among workshops,

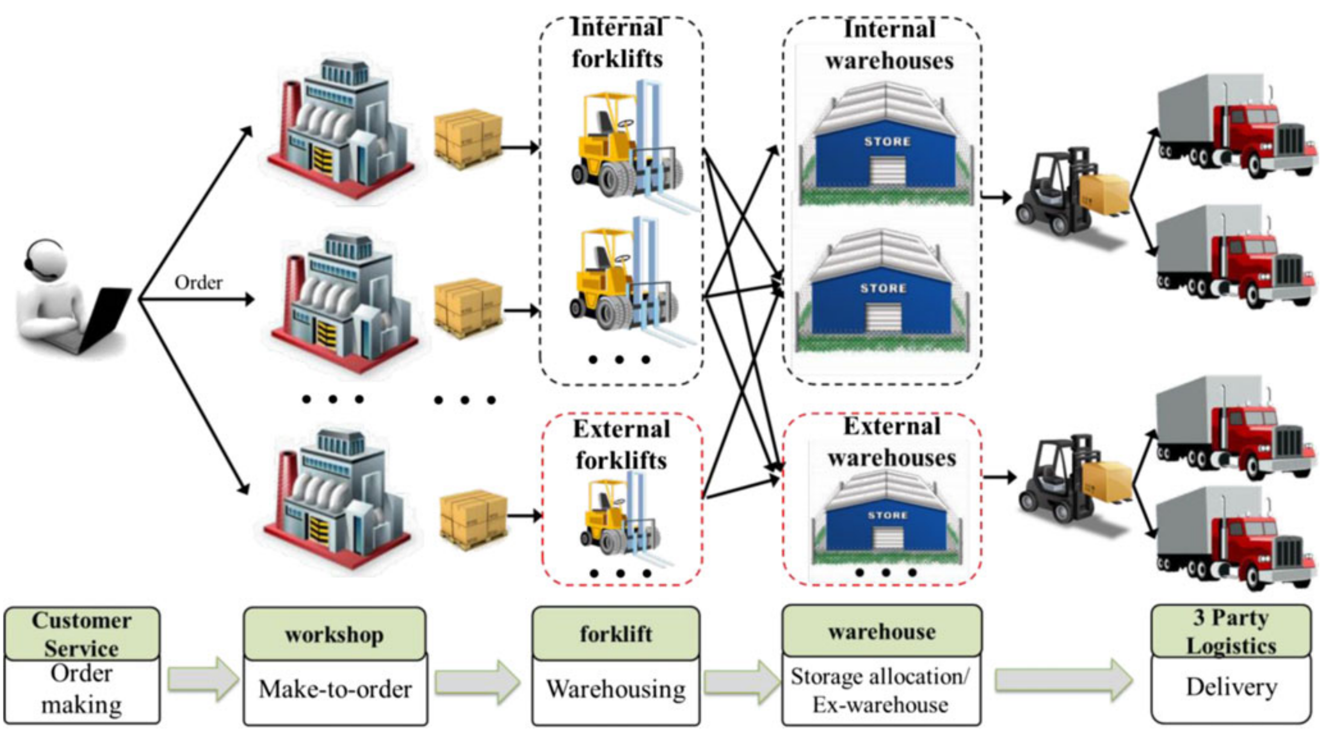

Fig. 9 Production logistics operation process

fleets, and warehouses are conducted in manual ways. The execution dynamics cannot be real-timely captured and adaptively tackled.

Seeing these challenges, the company urgently needs the implementation of the proposed C-CPLSS to realize an effective PLS management in the dynamic operation environment.

5.1 Creation of AUTOM infrastructure

In order to realize the production logistics synchronization, the acquiring, transmitting, and processing of the production logistics dynamic information must be realized firstly. Therefore, based on the AUTOM information infrastructure oriented to production logistics introduced in the fourth section, some special kinds of equipment of manufacturing IOT are deployed at the key places, such as forklifts, warehouse, the palletizing points, etc., to entirely and accurately sense dynamic information of the production logistics resource, as is shown in Fig. 10. The reactive smart object with two-in-one "RFID/2D barcode" tag is deployed on produce. The active smart object with PDA and PAD is deployed on the forklifts. Information collected at the palletizing points, forklifts, warehouse will be transmitted to service layer through Wi-Fi. Then, with Web service technology, the information will be encapsulated into standard xml files to be transmitted to the application layer to be shared among different modules or different system.

5.2 Development of cloud resource management system

According to the above analysis, there exists a large number of various resources, such as internal forklifts, internal warehouse, external forklifts, and external warehouse. The management, sharing, and service of these resources must be realized at first. Consequently, based on the cloud manufacturing architecture described in the Chap. 3, an environment of cloud production logistics resource management is constructed, as is shown in Fig. 11.

The smart warehouse and smart forklifts can be transformed into virtual resources through encapsulation according to the cloud manufacturing resource semantic description and registered in the service group shown at middle part in Fig. 11.

5.3 System demonstration

We instantiated the C-CPLSS shown in Fig. 3 to develop a finished-product-oriented C-CPLSS. The developed system has been successfully implemented in the company, and the application demo is shown by the ten steps in Fig. 12.

Step 1 Warehouse and forklift registration. All the internal and external resources are equipped with IoT devices to be virtually encapsulated as cloud resources. The registration information includes type, capability, identifier, service charge, available period, etc. Only the registered resources could be searched.

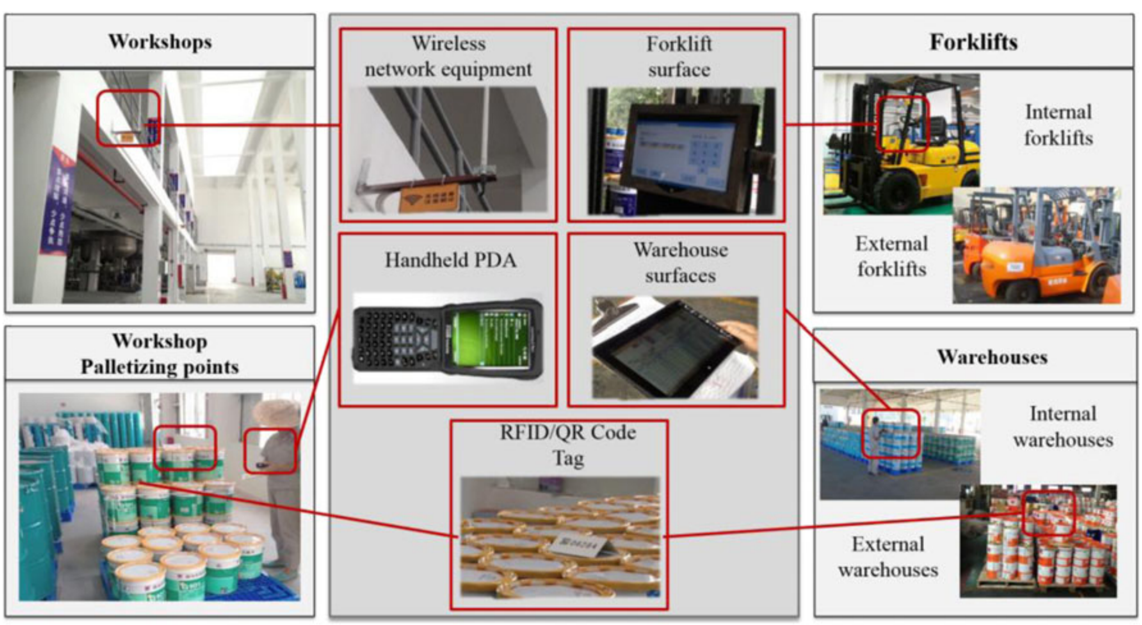

Fig. 10 AUTOM deployment environment

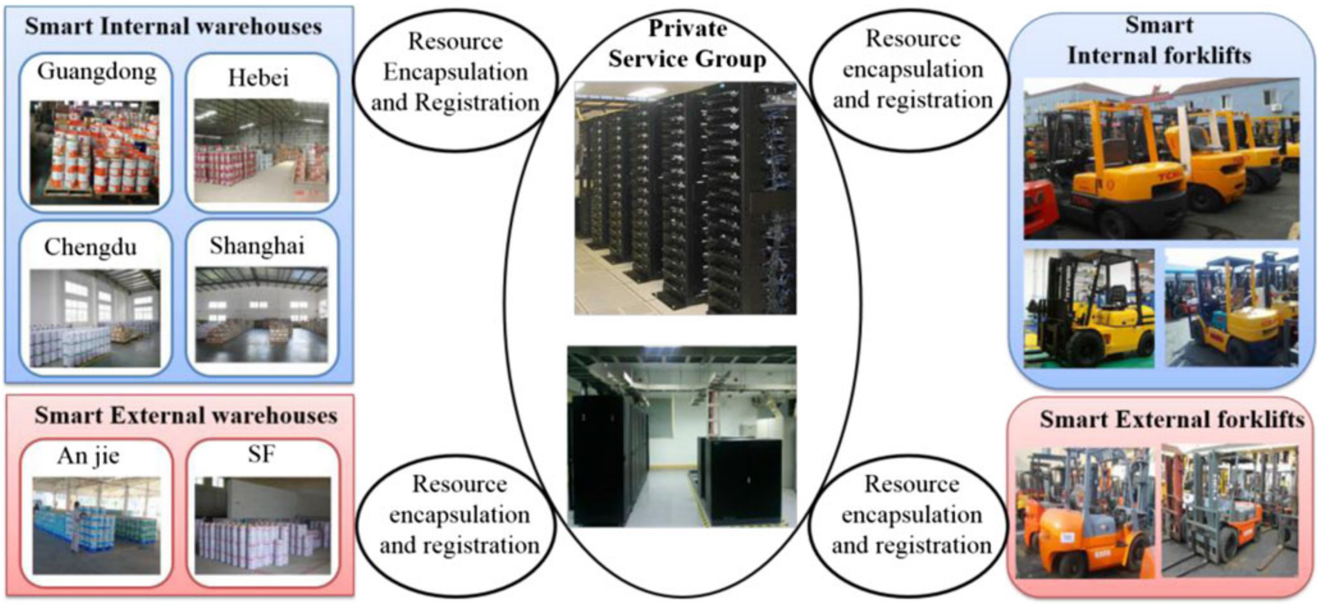

Fig. 11 Cloud-based production logistics resource management environment

Step 2 PL order. The daily PL order will be downloaded from the ERP system, which will be distributed to all the onsite resources.

Step 3 Resource configuration. Every Friday, the company will make decisions about the PL resources configuration for the next week, including what external forklifts to be rented, which public warehouse, and how much area is needed.

Steps 4 and 5 PLS planning. With all the available PL resources, the company will make a daily plan on how to make the finished products be optimally warehoused. The typical decisions in the plan include which forklift to be used, where and when to pick up the products, what is the transportation route, which warehouse, and which location to put the product?

Step 6 Finished-product recording. Although PLS plan is made, dynamics concerns force us to capture the actual time when a finish product is ready for warehousing. A handheld PDA is employed for this purpose, as shown in the middle part in Fig. 8.

Step 7 Finished-product warehousing. A mobile IoT installed on the forklift is employed for this purpose, as shown in the middle part in Fig. 8, which not only guide the driver to finish a PL execution task appropriately but also to capture the possible dynamics if the transportation is not executed as in the original PLS plan.

Step 8 Dynamics control. It may identify the dynamics to trigger PLS re-plan or system reconfiguration if the execution is not consistent with the original PLS plan.

Steps 9 and 10 PLS re-plan and PLS system re-configuration. In the presence of level-1 and level-2 dynamics, they will be triggered respectively. These two steps are similar as steps 3 and 4 and 5, and the only difference is that the real-time state of the execution environment should be considered.

5.4 Application result analysis

This section will demonstrate and analyze the application results of the proposed PLS system from both qualitative and quantitative perspectives.

1. The qualitative analysis

   - Prior to the system implementation

     In the aspect of PL process management, when making the production and logistics plans, the company can only develop the satisfactory ones for the individual stages without considering either their operational interactions or their real-time execution environments. Once the plan of any stage is affected by executional dynamics, not only the stage's original plan will fail to perform but also the plans for all its dependent stages will probably be a subject to serious

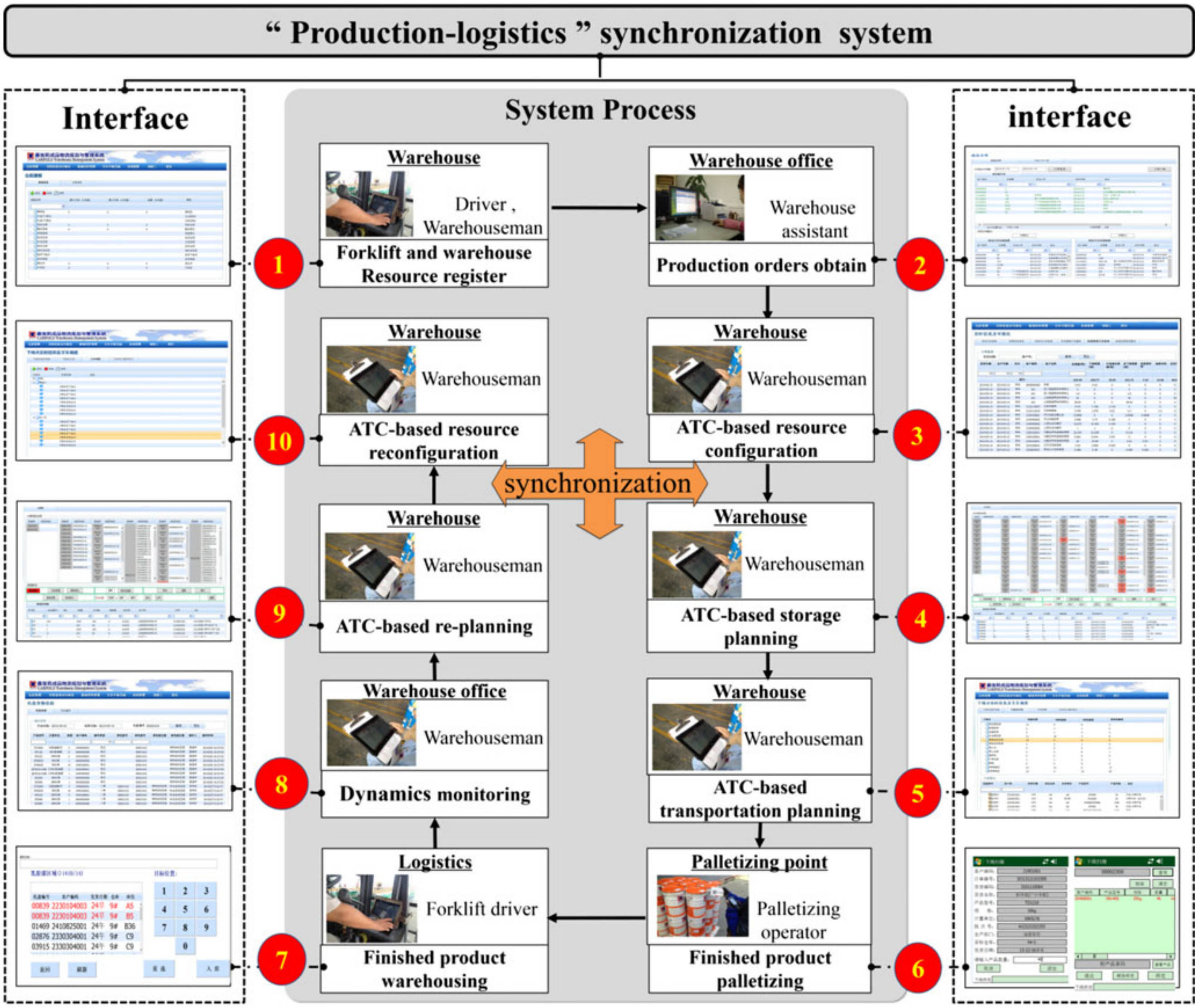

Fig. 12 System application process

process effects. Some passive dynamics-handling measurements including overtime working, logistics vehicle waiting, and excessive buffer are usual consequences in such situations, which have brought redundant costs to the company.

In the aspect of PL resource management, the company employs many PL resources in the renting mode to deal with the possible demand and thus production fluctuations. However, as it is difficult to accurately anticipate the coming times of fluctuations, fixed and normally loose renting periods are normally adopted which unavoidably cause redundant rents. In addition, based on the manual resource management, the monitor, management, and dynamic allocation of PL resources, e.g., forklifts, trucks, and warehouses are quite difficult.

- After the implementation of the system

Firstly, based on the proposed two-level PLS mechanism, the real-time feasibility of an initial plan could be continuously ensured and the system performance could be adaptively maximized in the presence of execution dynamics. After the system implementation, those passive dynamics-handling measurements including overtime working, logistics vehicle waiting, excessive buffer, warehouse idle, etc.

Secondly, the using costs of production logistics equipment have been largely reduced. Three typical improvements are as follows. First, as the renting mode of a forklift has been changed from a fixed contract-based period to a dynamic demand-driven flexible period, the overall renting economics has been improved and the redundant rents have been reduced as a result. Second, as the dynamically

Table 1 Improvement data

Statistical project analysis	Time (month)	
	September 2013	September 2014
Shipments (ton)	11,400	12,600
The punishment cost of vehicle waiting (ten thousand RMB)	10.17	5.03
Total work overtime (hours per person)	50	29
Warehouse space utilization rate (%)	76.2 %	84.5 %
Forklift utilization (%)	76.8 %	86.2 %

generated forklift requirements could be real-timely filled by the cloud-based resource management platform, the above-mentioned passive measurements caused by resource scarcity could be solved. Third, the traditional manual production-logistics resource management has been replaced by the cloud-based one, and the real-time monitoring and dynamic adjustment could therefore be easily achieved.

2. The quantitative analysis

The company began to use the proposed C-CPLSS system from 2013. With the historical data captured and stored by the IoT system, we are able to conduct a quantitative analysis. In the following, the operational data of 2 months, i.e., September 2013 and September 2014, are chosen for examination. These 2 months have two peak production volumes which are prior to and after the system application, respectively. As shown in Table 1, the total shipments and the utilizations of warehouse and forklift have been increased by nearly 10 %, while the logistics waiting cost and overtime working have been decreased by nearly 50 %.

In order to get a more direct or even visible proof of the system's effectiveness, we choose the major performance indicator, i.e., the delivery rate (total shipments/work hours), of the largest warehouses, e.g., 4th warehouse, to conduct a before–after comparison. The upper part of Fig. 13 shows the delivery rates of the last 10 days in both September 2013 and 2014 which are before and after the system application, as shown by the dotted and real lines, respectively. As can be seen, the delivery rate has obtained an overall increase after the system application, and some days, e.g. 27th, even see a 50 % improvement. In the lower part, two comparative pictures taken from the fields are given. As can be seen, because of the more efficient PL operation and the resulted faster shipment speed, the inventory level of the warehouse could be kept in a lower level after the system application.

Fig. 13 Comparison of application results

6 Conclusions

This paper investigates a manufacturer's PL process which is subject to uncertain execution-stage dynamics due to the frequently changed market demands and the newly emerged service-oriented resource acquiring mode. Although IoT technologies is able to capture the execution dynamics while cloud manufacturing (CM) is argued that can realize flexible resource management, yet how they can be integrated to systematically deal with the various dynamics of a PL process still lacks of in-depth discussion. This paper proposes an IoT-based real-time production logistics synchronization system under cloud manufacturing environment, which enables a smart PLS mechanism with two-level dynamics control. The detailed construction of the system and its enabling infrastructures and technologies are given, and the practical application to a large-scale paint making company which adopts service-oriented public PL resources is demonstrated.

The contributions of this paper are four folded. First, from management perspective, the proposed PLS mechanism provides an IoT-enabled adaptive solution to address the challenge of plan infeasibility caused by execution dynamics. Second, from the technical perspective, the newly emerged concepts of IoT and CM are systematically integrated to make use of their respective advantages of real-time data capturing and dynamic resource management, not only to support the realization of the PLS mechanism but also to provide a generic way for mixed IoT and/or CM implementation. Third, from the application perspective, the above management mechanism and technical system are practically demonstrated with a real-life project implemented by the authors' research team, which provides meaningful reference for both researchers and practitioners.

The future works of this research could be summarized as follows. First, this paper mainly focuses on the S-CPLS system implementation framework. Such qualitative solution will be extended to the quantitative stage in which the detail mathematical formulation of each PL stage will be established, and more accurate application results and value-adding sensitivity analyses could be obtained. Second, this paper only gives out an initial idea of what the PLS mechanism is like. Yet when it is put into use, many practical rules and constraints in the PL process have to be comprehensively considered, e.g., which stage has the higher priority to be re-planned if multiple stages indicate equal effects for dynamics handling, and which PL resources can or cannot be dynamically involved into the process, etc.

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