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ORIGINAL ARTICLE

Real-time data-driven monitoring in job-shop floor based on radio frequency identification

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Abstract Real-time manufacturing data plays more and more important roles in today's competitive manufacturing industry; however, many enterprises are still troubled by the lack of this timely, accurate, and consistent manufacturing data as there are no effective data collecting and process methods. The hysteretic and unmatched information flows lead to great opacity and uncertainty for production management. This paper thereby proposes a comprehensive real-time data-driven monitoring method in job-shop floor based on radio frequency identification (RFID) technology to address these issues. Firstly, a RFID configuration strategy is put forward including both RFID tag and device configuration schemas. The essence of RFID applications in job-shop floor is revealed too. Next, different levels of data collecting and monitoring models are established one by one, from single RFID reader level to process and process flow levels, wherein different types of state blocks are deployed to a decomposed process/process flow, generating a series of continuous event-driven data collecting units (EDCUs), which not only specify how to collect real-time on-site data but also point out what data should be collected. Then, three data processing methods are presented for different situations such as data preprocessing, fusion, and exception handling. Finally, a use case of a typical part is studied based on a prototype system which demonstrates how to use the proposed models and methods to monitor the production process of the part in job-shop floor and shows their feasibility simultaneously.

Keywords RFID · Real-time data · Job-shop floor monitoring · Data collecting · RFID configuration

1 Introduction

The fast-moving market full of furious competition accelerates manufacturing enterprises to be more and more agile, responsive, and transparent, especially for job-shop floor. Besides, as the popularization of service-oriented manufacturing, the amount of the MVSB (multiple-variety and small-batch) manufacturing orders increases sharply too, which are characterized by long process flows and complex machining operations. But because of the complexity and unpredictability of the practical manufacturing processes in job-shop floor, the accompanying on-site manufacturing data and information are very enormous and diverse, hence hard to be captured and uploaded, resulting in very low transparency of the workshop just like a black box [1]. The information not accurately and promptly reflecting the real-life situations and changes in job-shop floor cannot only limit the functions of the enterprise information systems (EISs), such as ERP (enterprise resource planning), SCM (supply chain management), and MES (manufacturing execution system), but also lead to wrong production decision and cause unnecessary losses. Without doubt, all these problems are due to the lack of an effective method for collecting the real-time on-site data and further monitoring the production processes in job-shop floor, so that managers cannot obtain the accurate states of the workpieces, equipment, workers, and materials and can hardly respond to any accidents very quickly. On the other hand, various products require enterprises to implement real-time monitoring of

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the status of the work-in-progress (WIP) products during their frequent delivery in the workshop and their quick response to various mutations and dynamic optimization of buffer store and capacity of storage. The conflict between the real-time requirements and the practical hysteresis is becoming more and more prominent [2]. Therefore, the real-time data collecting and job-shop monitoring based on this data are a bottleneck and key issue for the development of manufacturing enterprises.

The new emergence of RFID technology shows great opportunities in dealing with this issue in terms of its strong advantage in automatic identification and perception. RFID is a contactless automatic identification and data collection (CAI&DC) technology based on radio frequency, which can detect and identify the signals of a visualized object (VO) with a RFID tag, obtaining its dynamic or static information easily and timely [3]. It is the most important technology in IoT (Internet of Things), which has been developed and matured sharply at both software and hardware aspects recently, showing its tremendous potential in manufacturing and logistic fields. As a key advanced manufacturing technology in the next-generation manufacturing systems, RFID technology is considered to be one of the most promising technological innovations to increase visibility and improve efficiency.

Actually, RFID applications in manufacturing are typically classified into two types, that is, history-oriented tracking applications and real-time-oriented monitoring applications based on RFID’s powerful data collection capability [4, 5]. In this paper, RFID technology is applied for monitoring the production processes in job-shop floor. Specifically, a comprehensive real-time data-driven monitoring method based on RFID is proposed that comprises of three submodels, including a RFID configuration model guiding where and how to deploy RFID devices, a RFID data collecting model illustrating how to collect on-site data timely and what kinds of data should be collected, and a RFID data processing model showing how to transform the abundant, redundant, and disorganized raw RFID data into some meaningful and systematic information for monitoring. The rest of this paper is arranged as follows: after a brief review about production monitoring, RFID applications, and RFID data processing in Section 2, a RFID configuration strategy is put forward in Section 3. Section 4 builds up several data collecting and monitoring models from single RFID reader level to process and process flow levels progressively. In Section 5, three RFID data processing methods are proposed to deal with different situations such as data preprocessing, fusion, and exception handling. Then, a prototype software system is developed and a use case with a typical part is studied in detail based on it in Section 6 to illustrate the feasibility and applicability of the proposed methods and models. Finally, some conclusions are drawn in Section 7.

2 Literature review

2.1 Production monitoring

Unexpected disturbances or disruptions are likely to occur very frequently during manufacturing processes such as machine breakdown, workers failing to perform as expected, urgent order arrivals, short of materials, and sudden alteration order deadlines or quantities, especially for the MVSB production in job-shop floor characterized by high complexity with numerous interrelated jobs, processes, machines, transport equipment, cutting tools, and workers, making the production plans hard to be accurately executed and monitored [6]. But managers are compelled to respond to these disturbances in a timely manner, so as to decrease these adverse effects as much as possible. It shows the significance of a dynamic feedback element—production monitoring—that could support the formulation, execution, and modification of the production plan.

Manufacturing companies should collect and record tremendous amounts of data in order to monitor the real-time status of the target objects and shop-floor events [7]. Ge et al. believed that the key of production monitoring including on-site data acquisition, feature extraction, and decision-making is a kind of pattern recognition in some sense [8]. In most of the existing systems, the on-site data is collected by kinds of data collecting modules, such as RFID readers and digital measuring devices, embedded in or equipped around the target equipment. Then, the corresponding data can be collected by these sensors. The most important step in production monitoring is to process large volumes of on-site data and further transform it into systematic information according to complex production logic. The raw data collected by sensors is essentially useless for the purposes of higher-level applications unless it is processed. Feature extraction connects the virtual data and the practical manufacturing events, which means it requires one to understand the monitored process and the sensor signals simultaneously.

For years, many researchers have concentrated their efforts on production monitoring in order to realize its closed loop control. Senkuvienet et al. proposed a job-shop visualization method to monitor the running status of the equipment [9]. A novel monitoring framework for networked manufacturing based on role-based access control method was provided by Sun et al., wherein fine-grained access control and monitoring are accomplished by defining rules at the XPath-level of the real-time state data and control instruction documents that are represented in the XML format [10]. Because RFID enables fast, accurate data collection and needs no contact or light-of-sight requirement, it can greatly increase the performance of real-time production monitoring. Recently, its applications are gradually tending to using RFID technology. Zhong et al. developed a RFID-enabled real-time MES that can collect real-time production data and track-and-trace the shop floor VOs, wherein disturbances are identified to assist managers with the planning and scheduling decisions [11].

2.2 RFID models and applications in manufacturing

RFID adopts radio waves for identifying, tracing, and tracking VOs, such as tagged workpieces, equipment, cutting tools, and workers. Because of its outstanding performance like real time, prompt read and write, portability, good penetration, long lifetime, good environmental resistance, and high-capacity store, RFID technology has been widely used in food industry, transportation, construction, logistics, medical, and health [12–16].

RFID technology has been deployed to various manufacturing objects through different schemas [17]. Once the objects are tagged, they become VOs that can be tracked. The information or data carried by them can be collected and uploaded showing their status changing from time to time [18]. In this way, production on-site data in job-shop floor such as machine status, workforce situations, material consumptions, part locations, and order progresses are collected and managed at a level that is accurate, complete, and real-time [1]. Therefore, tracing and tracking VOs and collecting their status-related data in manufacturing and supply chain systems must be the most important applications for RFID technology. Chongwatpol et al. presented a RFID traceability approach to improve production scheduling, which established a real-time traceability system for tracking WIPs, parts and components, and raw materials [19]. Lee and Park proposed a dynamic tracing task model for tracing the end item and its subparts involved in a BOM (bill of materials) to enhance the traceability range along the supply chain beyond simple distribution channels [20]. Both items and sub-components are transformed into VOs by attaching with RFID tags, to keep track of the information on the specific location, the time spent in that location, and eventually the history of an entity throughout the manufacturing tier. DeVries dealt with RFID trace and track in the airline industry and showed some typical examples of effective baggage tracking [21]. Kim et al. evaluated the benefits derived from using real-time information acquired with RFID technology to track the movement of vehicles during the deployment and shipment in the automotive assembly plant [22]. It was found that RFID can significantly improve customer satisfaction by reducing dwell time variability and decreasing labor cost, thus leading to profit increase.

After RFID-based intelligent tracking technologies were firstly introduced by Brewer to provide real-time manufacturing information and support dynamic scheduling [23], more and more RFID-based systems driven by the captured real-time data are established. Chen et al. proposed a RFID-based integration framework for facilitating real-time management of dynamic production operations [24]. Huang et al. established a RFID-based real-time management model to control WIP inventories in a manufacturing shop floor, and they also provided a detailed discussion on RFID-based product assemble applications based on a demo system with simple assembly operations [25, 26]. Genc et al. reported an event-based supply chain early warning system that could facilitate real-time identification of critical events within the supply network by using event data, enabling the adaptive situational control of intracompany production processes [27]. The contribution of integration RFID into manufacturing and supply chains is not only in increasing the efficiency of the systems but also in supporting the reorganization of the systems that become more efficient. Researches showed that after the deployment of RFID technologies, Procter & Gamble and Wal-Mart simultaneously reduced inventory levels by 70% and improved service levels from 96 to 99% [28, 29]. Compared with the other most commonly and widely used bar code technology, it has been proved that when replacing bar code with RFID for most manufacturing application systems, they might raise the overall management efficiency [30, 31].

2.3 RFID data processing

RFID provides fast data collection with precise identification of VOs with unique IDs written in RFID tags without line of sight for real-time identifying, locating, and monitoring [32]. But meanwhile, the adoption of RFID technology poses new challenges for data processing and management and gets companies in trouble that they should be confronted with a huge amount of data generated by RFID networks [20]. At least, there are two challenges as follows:

- RFID data collected by RFID networks is always massive, disorganized, and heterogeneous and has some implicit meanings. So, how to extract useful data from this RFID data and further transform and aggregate it into semantic LBI (logical business information) linked to RFID applications of EISs [33]?
- RFID data is highly temporal, streaming, and in high volume. So, how to process it on the fly?

It is believed that RFID data processing is also crucial besides data collecting in the integration of RFID applications for improving the management performance [34]. In order to deal with RFID data and to mine the valuable information from this data effectively, many research studies have been conducted very recently. Gonzalez proposed a novel model called RFID-Cuboids for warehousing and processing RFID data, which preserves object transitions while providing significant compression and path-dependent aggregates [35]. Choi presented a RFID tag data processing and synchronization algorithm to generate initial e-pedigrees for general, tangible products during production, based on which an innovative track-and-trace anti-counterfeiting system was built up [36]. Furthermore, because the tag data of the VOs within the scopes of the RFID signal detecting spaces (SDSs) are read and uploaded periodically, massive data are produced regularly, forming a kind of big data. From this point of view, Zhong proposed a holistic big data approach to excavate frequent trajectory from massive RFID-enabled shop-floor logistic data for supporting production decision-making [7].

Actually, RFID data processing in RFID applications mainly involves two research aspects, i.e., data clean and data mining. Data clean is an essential step for RFID data processing that always uses the sliding window-based method [37]. It aims to clean the flood of data stream by providing more opportunities to interpolate missed readings and eliminate redundant and false readings. However, data-cleaning algorithm can just provide supports for limited and small-scale RFID data combination and aggregation capabilities, yet not appropriate for applications with complex setups [38]. RFID data mining is the process of extracting and analyzing data and summarizing it into more semantic LBI [39]. Another important issue in RFID data processing is about complex event processing, which addresses the task of processing multiple events with the goal of identifying the meaningful events within a high-volume data stream. It is usually used to process RFID data streams. Specifically, it can continually monitor the data stream with predefined patterns by using rule language or structure query language.

2.4 Motivations

From the aforementioned review, it can be found that:

- Monitoring in job-shop floor is very crucial for closed loop management and control.
- Real-time on-site data collecting and processing can greatly facilitate the monitoring performance, enhance the transparency of production processes, and realize visualization.
- RFID technology together with its applications is an effective tool for supporting these automatic data collecting and processing and improving the management efficiency in job-shop floor.

Although lots of methods, models, and application systems based on RFID have already been proposed in literature, almost all of them are case-specific. Specifically, RFID configuration solutions in these models are always based on human experience, considering the practical application scenarios. They are always prior to the modeling of RFID-enabled process flow, which will cause some adaptability and cost problems. But the deeper connotation why RFID technology should be used in these ways is not discussed. They mainly focus on how to use RFID data yet ignore specifying how to collect on-site data in real time and what data to collect, which are also very critical issues concerned by RFID users. And very few research contributions can be found in the literature that discuss these issues in detail.

In order to solve these problems and reveal the essence of RFID applications in job-shop floor, the authors of this paper proposed a RFID-driven graphical formalized deduction model (*rfid*-GFDM) for the time-sensitive state and position changes of WIP material flows in job-shop floor [18, 33]. This paper is the follow-up study which inherits the basic idea of *rfid*-GFDM to concentrate on the application of monitoring the discrete production process in job-shop floor. The crucial issues such as how to deploy RFID devices, how to collect real-time data, and what data to collect are fully discussed.

3 RFID configuration strategy

3.1 Visualized object

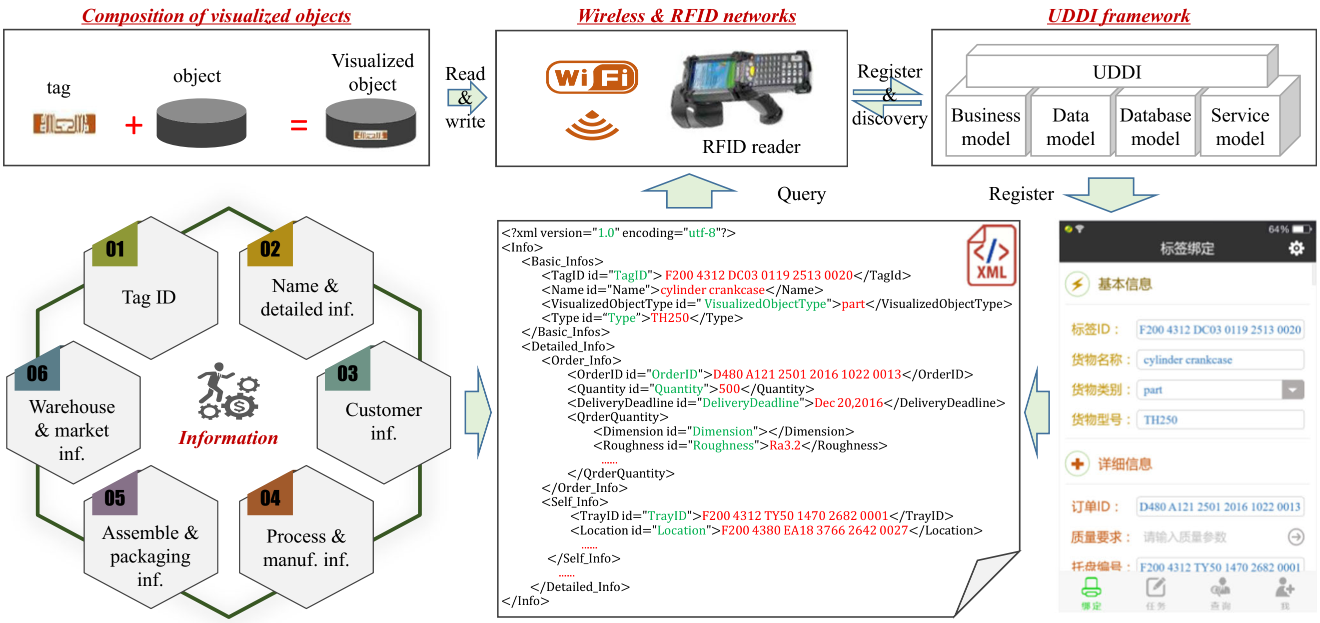
Definition 1: *VOs* are physical manufacturing resources in job-shop floor that are made "visualized" for monitoring purpose by equipping with RFID devices or sticking with RFID tags. A visualized object has a certain degree of built-in intelligence, so that the time-sensitive data can be collected and it can therefore be tracked and traced.

VOs can be classified into two types: active or passive. Active VOs mean those resources equipped with RFID readers or antennas, e.g., machines, workstations, and forklift, while passive VOs are those objects attached with RFID tags such as parts, trays, boxes, and locations. VOs can contain and process information about their history and current states, and they can also interact with each other through wireless network and be monitored with the help of RFID networks.

As shown in Fig. 1, a target resource can be defined as a VO and registered into the database through UDDI (universal description, discovery, and integration), which serves as a unified framework for describing and discovering the web service of VOs over the intranet. Moreover, detailed information of a VO can be described through XML as web services too.

3.2 Deployment of RFID tags

There are various resources involved in a specific manufacturing system in job-shop floor, such as devices (e.g., machines and measurement equipment), vehicles (e.g., forklifts, AGVs (automatic guided vehicles), and cranes), materials (e.g., raw materials, WIP materials, and finished products), tools (e.g., cutting tools, fixtures, and jigs), containers (e.g., trays, boxes, shelves, and buffers), space resources (e.g., locations, work regions, and inventories), human resources (e.g., operators, inspectors, and managers), infrastructures (e.g., passages,



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<?xml version="1.0" encoding="utf-8"?>
<Info>
    <Basic_Infos>
        <TagID id="TagID"> F200 4312 DC03 0119 2513 0020</TagId>
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        <VisualizedObjectType id=" VisualizedObjectType">part</VisualizedObjectType>
        <Type id="Type">TH250</Type>
    </Basic_Infos>
    <Detailed_Info>
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            <DeliveryDeadline id="DeliveryDeadline">Dec 20,2016</DeliveryDeadline>
            <QrderQuantity>
                <Dimension id="Dimension"></Dimension>
                <Roughness id="Roughness">Ra3.2</Roughness>
                 ......
            </QrderQuantity>
        </Order_Info>
        <Self_Info>
            <TrayID id="TrayID">F200 4312 TY50 1470 2682 0001</TrayID>
            <Location id="Location">F200 4380 EA18 3766 2642 0027</Location>
             ......
         </Self_Info>
          ......
      </Detailed_Info>
</Info>
```

基本信息

标签ID： F200 4312 DC03 0119 2513 0020
货物名称： cylinder crankcase
货物类别： part
货物型号： TH250

详细信息

订单ID： D480 A121 2501 2016 1022 0013
质量要求： 请输入质量参数
托盘编号： F200 4312 TY50 1470 2682 0001

Fig. 1 Definition and registration of a visualized object

doors, and gates), and paper documents (e.g., all kinds of reports and specification) [17].

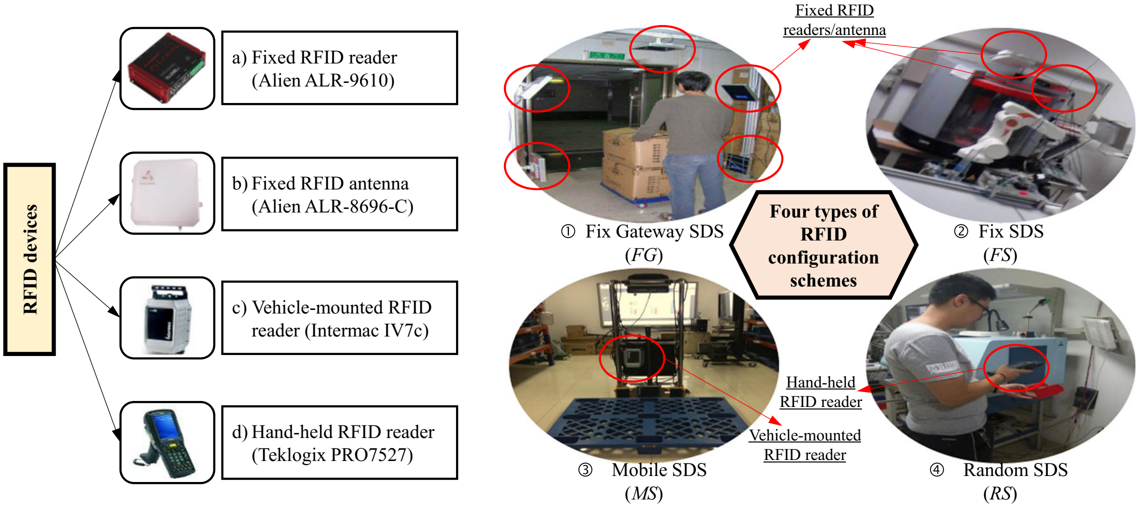
In an ideal situation, every resource in job-shop floor should be compulsively attached with a RFID tag, making it a VO in order to be tracked and traced, which is called *one-resource one-tag* (OROT) mode. But in practical situation, OROT is not preferred due to cost consideration. Therefore, different tagging schemas are applied depending on specific considerations. For critical parts (big volumes or highly customized items), devices, vehicles, tools, etc., OROT is adopted because they are one of a kind items and should be uniquely monitored. For those unimportant materials (small size) which are put on trays or in boxes, tags can be just attached to these containers. In addition, each worker should wear his unique stuff card that has a built-in RFID tag too.

3.3 RFID device configuration schemas

Definition 2: *A RFID signal detecting space (SDS)* refers to the physical space covered by the electromagnetic wave signal of a RFID reader or multiple shunt-wound RFID readers.

A SDS is an actinomorphic space like a spheroid in 3D space, and its projection in a 2D plane is rounded or elliptical depending on the relative position and included angle. Different SDSs represent different physical interpretations due to different RFID device configuration and monitoring schemas. For instance, for a typical process flow configured with RFID devices, the related SDSs could stand for the in-buffers, machines, out-buffers, forklifts, or even the entire process. Through vast amount of investigation and study, four typical RFID device configuration schemas in job-shop floor can be concluded as follows:

- *Gateway monitoring mode based on fixed RFID readers* (denoted with *FG*): it identifies whether a VO *passes-through* the gateway covered by a fixed gateway SDS of a fixed RFID reader, which is always deployed at gates, doors, conveyors, etc., to control whether materials, trays, workers, etc. enter-into or go-out of the controlled areas.
- *Fixed-space monitoring mode based on fixed RFID readers* (*FS*): it identifies whether a VO *enters-in*, *passes-through*, or *goes-out* of a fixed SDS of a fixed RFID reader, e.g., those fixed RFID readers deployed at the buffers, machines, shelves, etc.
- *Mobile-space monitoring mode based on vehicle-mounted RFID readers* (*MS*): it identifies whether a VO *enters-in*, *passes-through*, or *goes-out* of a mobile SDS of a vehicle-mounted RFID reader, e.g., those readers deployed at the AGVs, forklifts, etc.
- *Random-space monitoring mode based on hand-held RFID readers* (*RS*): it identifies whether a VO *enters-in*, *passes-through*, or *goes-out* of a random SDS of a hand-held RFID reader accompanying with the ruleless movement of an operator, e.g., a logistic worker uses a hand-held RFID reader to make an inventory and a machine operator uses it to record the starting time, the ending time, and the quality information when machining a workpiece. Common RFID devices and the four types of RFID configuration schemas in job-shop floor are shown in Fig. 2.



Legends: 1) Generally, a fixed RFID reader always works together with several antennas depending on the signal channels (SCs) the reader has, e.g., a ALR-9610 has four SCs, so it can connect four Alien ALR-8696-Cs. The difference between readers and antennas is that readers have the ability to processing RFID data, while antennas just have the ability to read and write. Besides, some readers can also read and write themselves.

2) The vehicle-mounted RFID reader listed above, which cannot read and write itself, is connected with four related types of antennas around the forklift.

Fig. 2 Four types of RFID configuration schemas

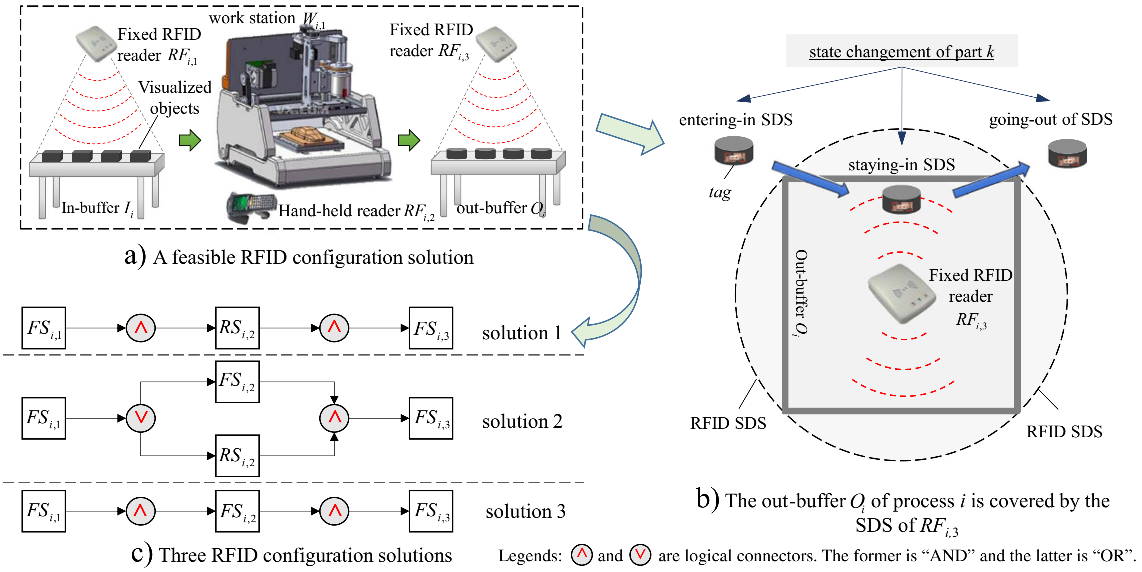
3.4 The essence of RFID applications in job-shop floor

Since RFID configuration is a hot topic in RFID applications, many researchers began to focus on the RFID layout algorithms so as to work out a RFID network that is optimal and robust, such as those algorithms that aim at using the least RFID readers to cover the entire manufacturing area in job-shop floor with the least reader signal collision [40, 41]. These fully covered methods could meet the requirements of some special conditions; however, they are not applicative for monitoring the production processes in job-shop floor. Furthermore, the mixed use of different types of RFID devices (e.g., different powers, signal frequencies, and SDS ranges) is not considered by these algorithms, leading to poor adaptability and a huge waste of the so expensive RFID resources. Another hot topic about RFID is about the localization algorithms, which aim at locating the exact position of a VO in a 2D or 3D space by using multiple RFID devices. Currently, TOA (time-of-arrival) and RSS (received-signal-strength) are the two mainstream localization algorithms [42]. TOA measures the propagation time of the received signal and determines the distance through multiplying it by its own speed, while RSS measures the power strength of the signal at the readers to calculate the distance according to the propagation loss model [43]. Although these approaches can also realize the monitoring of VOs, they are costly and unnecessary because many other sensor networks can also make it yet with much lower cost. In short, misunderstanding the essence of RFID technology results in the misuses in job-shop floor.

Actually, the essence of RFID applications in job-shop floor is monitoring the state changes of VOs and collecting the related data along with the changes and finally achieving the visualization of the entire production process and satisfying the data requirement of other EISs through data processing according to the context of the production and manufacturing constraints. Considering from this point of view, a novel RFID configuration strategy is proposed (as illustrated in Fig. 3) based on the four schemas revealed in Section 3.3. It not only can reach the aforementioned goals but also can significantly cut down the RFID cost comparing to the above two methodologies.

Figure 3(a) shows a feasible RFID configuration solution of a typical machining process. Apparently, the process is divided into three parts: in-buffer I_i, workstation W_i, and out-buffer O_i. Here, two fixed RFID readers ($RF_{i,1}$ and $RF_{i,3}$) are deployed to the in-buffer and out-buffer, respectively, to automatically identify whether a VO enters-into, stays-in, or goes-out of the buffers. A hand-held RFID reader $RF_{i,2}$ is deployed to the workstation for manually recording the starting time and ending time of the part machining, together with some other information such as machining quality. Figure 3(b) shows the sketch map of using $RF_{i,3}$ to monitor the out-buffer O_i, whose physical space is fully covered by the SDS of $RF_{i,3}$. On this occasion, the physical space of O_i and the SDS of $RF_{i,3}$ are equivalent. Once $RF_{i,3}$ detects that the VO has moved into its SDS, it means that the VO is being in the state "staying-in out-buffer O_i." The meaningful information needed by most EISs is the timestamp when the VO is entering-in and going-out of O_i and the lasting time of staying-in O_i, rather than its accurate position coordinate in O_i.

Figure 3(c) gives three feasible RFID configuration solutions. Solution 1 is the graphic schema of that illustrated in Fig. 3(a). Solution 2 applies a fixed RFID reader and a hand-held RFID reader simultaneously to monitor the workstation



a) A feasible RFID configuration solution

b) The out-buffer O_i of process i is covered by the SDS of $RF_{i,3}$

c) Three RFID configuration solutions

Legends: $\wedge$ and $\vee$ are logical connectors. The former is “AND” and the latter is “OR”.

Fig. 3 Feasible RFID configuration solutions of a typical machining process i

W_i, forming a fixed SDS ($FS_{i,2}$) and a random SDS ($RS_{i,2}$). The fixed reader identifies the starting and ending times of the machining automatically, while the hand-held reader records the other information manually. Solution 3 just deploys a fixed RFID reader to W_i, which can only collect the time-related data. Users can choose the most appropriate solution considering the needed information and the compromise between efficiency and cost.

4 RFID-based data collecting and real-time monitoring

4.1 Data collecting models

In this section, the data collecting mechanism of a single RFID reader is discussed in detail. Two different graphic data collecting models are established, namely an event-driven data collecting unit (EDCU) model and a state block model. Both of them can reveal what data need to be collected and how to collect them from different perspectives.

4.1.1 EDCU model

Before introducing the EDCU model, some important concepts are defined in Table 1 that are partly inherited from our early works [18, 33].

The event $E_{i,j}^k$ in Table 1 is a kind of logistic event. Actually, there is another kind of event called RFID event, which means the procedure that a RFID reader detects and reads the tag data of a VO when logistic event $E_{i,j}^k$ happens, then generates a piece of raw data stream at time t^r, and uploads and stores it into a RFID database. The RFID event E_t^r can be formalized as follows:

$$E_t^r ::= \left\langle ID_{\text{tag}}, RF_i, t^r \right\rangle \tag{1}$$

where E_t^r is also the collected data stream; ID_{tag} represents the unique EPC code of the RFID tag attached to a workpiece; RF_i stands for the ith RFID reader; and t^r $\left(t^r = t_{i,j}^k\right)$ means the timestamp that event E_t^r or $E_{i,j}^k$ happens at and it is also the time when the data stream generates.

There is a one-to-one relationship between RFID tag ID and workpiece ID as $ID_{\text{tag}}^k \xleftrightarrow{1:1} ID_{\text{work}}^k$, which are bound together and registered into the database. The location where a reader RF_i is deployed can be found through querying the database according to $RF_i \xleftrightarrow{1:1} L_{RF_i} \xleftrightarrow{1:1} L_{i,j}^k$. So, the location $L_{i,j}^k$ of event $E_{i,j}^k$ related to RF_i can be obtained too. Furthermore, the current state $S_{i,j}^k$ of workpiece k can be derived by predefining and reasoning the context of its machining process. Some additional on-site data can also be collected such as operator $R_{i,j}^k$ and quality set $Q_{i,j}^k$. Based on this, an EDCU model of a single RFID reader is established and shown in Fig. 4. When a logistic event $E_{i,j}^k$ happens, it will trigger the corresponding EDCU automatically for collecting the above data.

Obviously, EDCU clearly shows what on-site data should be collected and how to collect them. In fact, an EDCU is just a data collecting unit for a single RFID reader. Several EDCUs related to the RFID readers deployed to a process or even a process flow can work together to collect the related data and monitor the process or the entire process flow. The EDCU of $RF_{i,j}^k$ can be defined as follows:

Table 1 Definitions of some important concepts

Concepts	Notations	Definitions	Remarks
State	$S_{i,j}^k$	A kind of stable and unchanged situation which lasts a period of time	The starting and ending points of the period are the triggering times of two neighboring events.
Event	$E_{i,j}^k$	A kind of operation/action which happens at a special time point and causes a state change	The state change means a new state starts and the old one stops.
Triggering time	$t_{i,j}^k$	A special timestamp which lasts a period of time.	The triggering time of event $E_{i,j}^k$ is denoted with $t_{i,j}^k$.
Location	$L_{i,j}^k$	The location that an event happens	It represents the physical space that a RFID SDS covers, e.g., an in-buffer or an out-buffer.
Operator	$R_{i,j}^k$	The operator or worker who executes event $E_{i,j}^k$	$R_{i,j}^k$ represents the *j*th operator in process *i* of workpiece *k*.
Quality	$Q_{i,j}^k$	A set of quality characteristics involved in a state	$Q_{i,j}^k$ includes the dimensions, roughness, and planeness of a workpieces in state $S_{i,j}^k$.

$$cu_{i,j}^k ::= \left\langle ID_{\text{work}}^k, S_{i,j}^k, E_{i,j}^k, t_{i,j}^k, L_{i,j}^k, R_{i,j}^k, T_{i,j}^k, Q_{i,j}^k \right\rangle$$
$$s.t.\begin{cases} E_{i,j}^k = \left\{E_{i,j-1}^k, E_{i,j}^k\right\} \\ t_{i,j}^k = \left\{t_{i,j-1}^k, t_{i,j}^k\right\} \\ L_{i,j}^k = \left\{L_{i,j-1}^k, L_{i,j}^k\right\} \\ R_{i,j}^k = \left\{R_{i,j-1}^k, R_{i,j}^k\right\} \\ T_{i,j}^k = t_{i,j}^k - t_{i,j-1}^k \end{cases} \tag{2}$$

where $cu_{i,j}^k$ stands for the EDCU of $RF_{i,j}^k$ and $E_{i,j}^k$,$t_{i,j}^k$, $L_{i,j}^k$, and $R_{i,j}^k$ respectively represent the event set, triggering time set, location set, and operator set involved in an EDCU.

4.1.2 State block model

The aforementioned EDCU model is just the most acceptable and understandable data collecting model that essentially reveals how to collect data for a RFID reader; however, it does not bridge the connections between data collection and the four types of RFID configuration schemas. For this purpose, the SDSs in the four schemas are further mapped into rounded/quadrate and solid/dotted blocks as shown in Table 2, which are called state block model.

It can be found that the two state blocks *FS* and *MS* are exactly two simplified EDCUs, but the other two state blocks *FG* and *RS* are a little bit different. In short, the four state blocks clearly reveal the important data that should be collected along with a VO entering-in, staying-in, passing-through, or going-out of a SDS for different configuration schemas, respectively. Some other crucial data such as position, operator, lasting time, and quality are not displayed in these graphic blocks. For both *FG* and *RS*, actually, there are also two triggering times t_{in} and t_{out} related to two events E_{in} and E_{out}, forming a momentary state S_{stay}. But because its lasting time $T = t_{\text{out}} - t_{\text{in}} \approx 0$ and S_{stay} is meaningless, the two events E_{in}

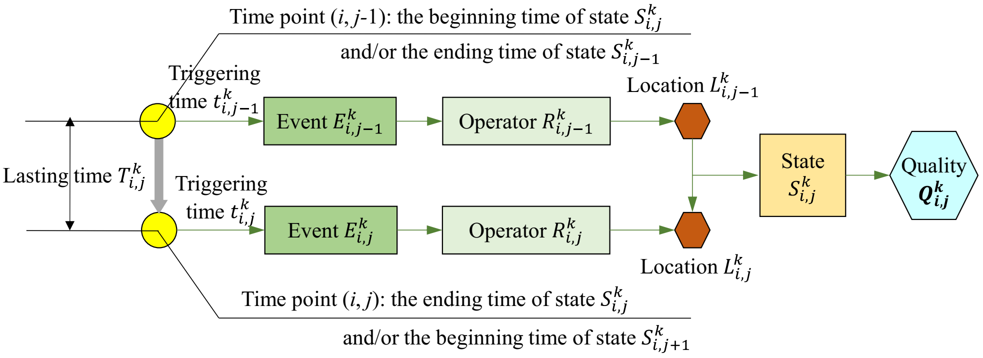


Fig. 4 The graphic schema of the EDCU model

Table 2 Four types of state blocks

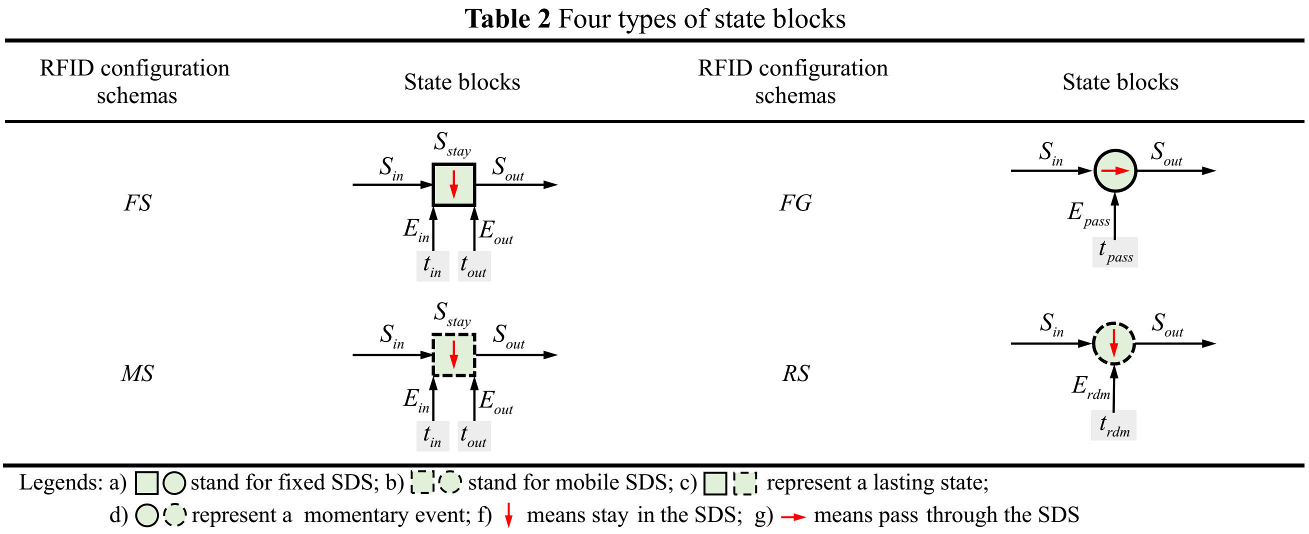


Table 2 Four types of state blocks

RFID configuration schemas	State blocks	RFID configuration schemas	State blocks
FS	S_{stay} S_{in} S_{out} E_{in} E_{out} t_{in} t_{out}	*FG*	S_{in} S_{out} E_{pass} t_{pass}
MS	S_{stay} S_{in} S_{out} E_{in} E_{out} t_{in} t_{out}	*RS*	S_{in} S_{out} E_{rdm} t_{rdm}

Legends: a) □○ stand for fixed SDS; b) ⬚◌ stand for mobile SDS; c) □⬚ represent a lasting state;
d) ○◌ represent a momentary event; f) ↓ means stay in the SDS; g) → means pass through the SDS

and E_{out} combine to one as E_{pass} or E_{rdm}. Therefore, the state blocks can be formalized as follows:

$$sb::=\langle S_{\text{stay}},E_{\text{in}},E_{\text{out}},t_{\text{in}},t_{\text{out}},T_{\text{stay}},L_{\text{in}},L_{\text{out}},R_{\text{in}},R_{\text{out}},Q\rangle$$
$$s.t.\begin{cases} sb\in[FG,MS,FG,RS] \\ \left.\begin{array}{l} T_{\text{stay}}=t_{\text{out}}-t_{\text{in}}=0,L_{\text{in}}=L_{\text{out}},R_{\text{in}}=R_{\text{out}} \\ S_{\text{stay}}=\varnothing,E_{\text{in}}=E_{\text{out}} \end{array}\right\} \forall sb\in[FG,RS] \end{cases} \tag{3}$$

4.2 Process monitoring

4.2.1 Multi-granularity process decomposition

Definition 3: *A process* is defined as a sequence of operations/actions happening at/around a machine or workstation for machining a workpiece according to its processing technology. The *i*th process of workpiece *k* is denoted as P_i^k.

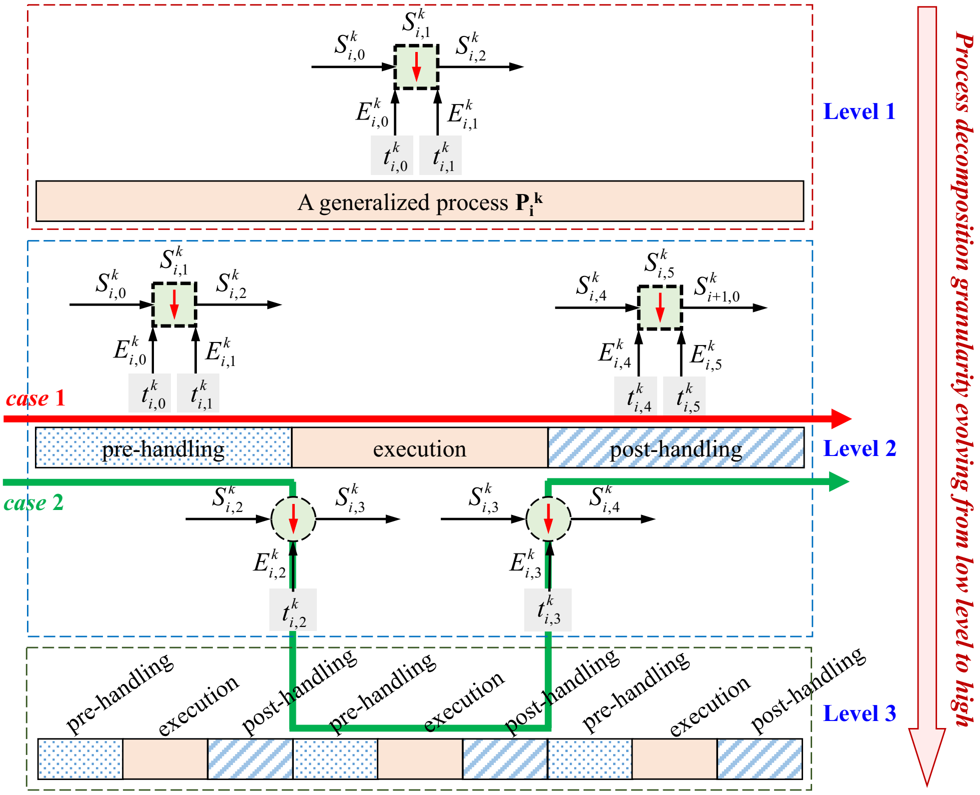


Fig. 5 Process decomposition based on requirement

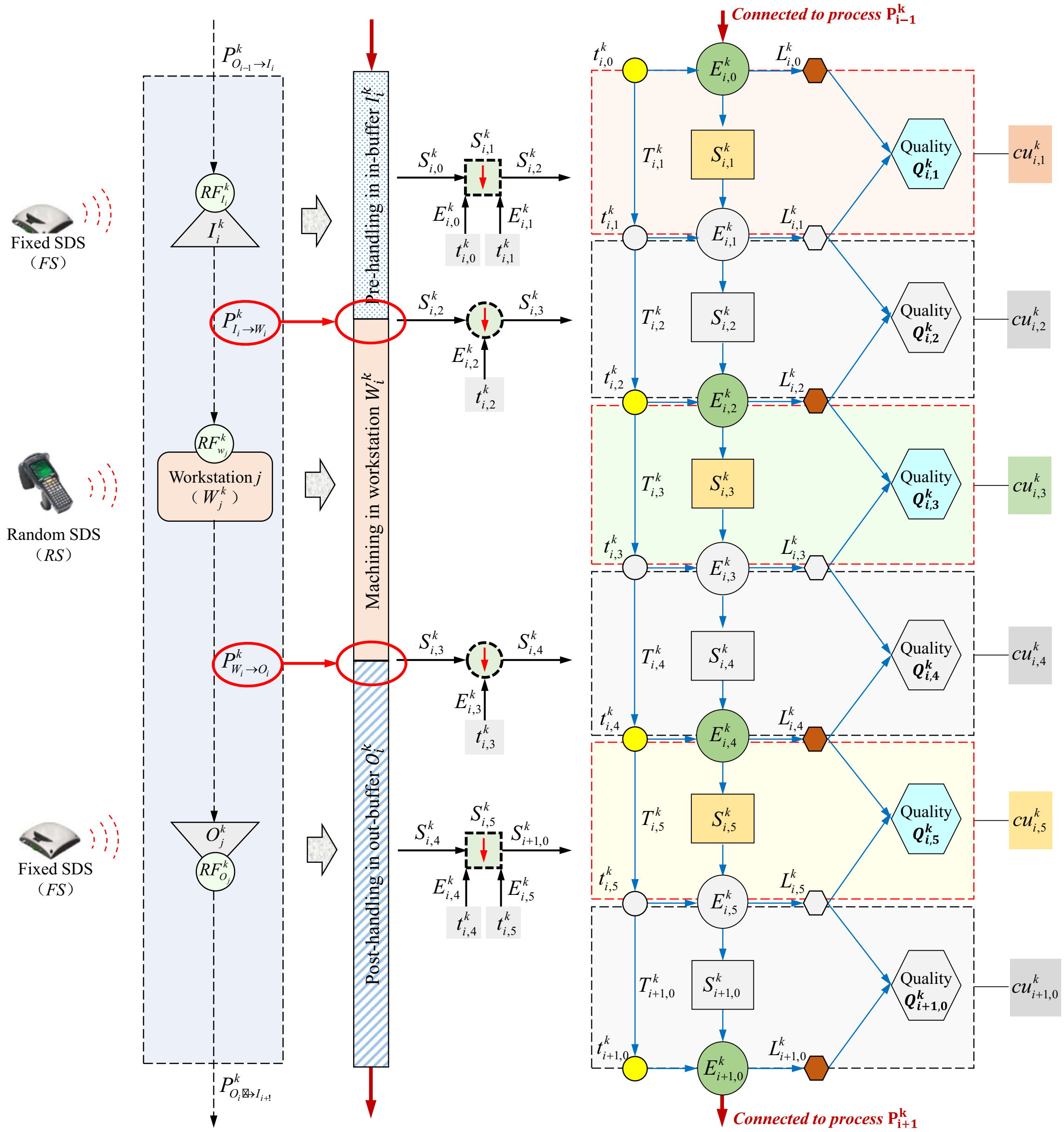


Fig. 6 The data collecting model of a machining process P_i^k

A process is always considered as the fundamental unit of a process flow, through which a workpiece can finally turn into a finished part from raw material as its features are created one by one. But actually, a process can also be decomposed into different granularities of subprocesses according to its interior operations and actions to meet monitoring requirements. As shown in Fig. 5, a process is represented as three levels of decomposition granularities. Level 1 is the lowest granularity that shows a generalized process. It means the monitoring requirement is very low too, and only one fixed RFID reader is competent to monitor the entire process. So, a state block *FS* is deployed here representing the fixed reader. By this way, only little on-site data can be collected such as the times when the process starts ($t^k_{i,0}$) and ends ($t^k_{i,1}$) and how long it lasts ($T^k_{i,1} = t^k_{i,1} - t^k_{i,0}$). If more detailed information about the process is needed, the process should be decomposed into some high granularity levels. For example, level 2 contains three subprocesses including prehandling (storing in I_i^k), execution (machining in W_i^k), and post-handling (storing in O_i^k), which could be monitored individually. Hence, at least three RFID readers (e.g., two fixed readers and a hand-held reader) are needed. And in level 3, each subprocess in level 2 is further divided into three parts in the same way. Therefore, more readers are needed yet much more information is obtained too.

Theoretically, a process can also be decomposed into some higher granularity levels if needed. But considering the RFID cost, these three levels are enough in most instances. Besides,

Table 3 The descriptions of E_i^k and S_i^k in process P_i^k

E_i^k	Descriptions	S_i^k	Descriptions
$E_{i,0}^k$	Put workpiece k into the in-buffer I_i^k of process P_i^k	$S_{i,1}^k$	Workpiece k is being at the storing state in I_i^k, weighting for machining
$E_{i,1}^k$	Move workpiece k out of the in-buffer I_i^k	$S_{i,2}^k$	Being at the transformation state from I_i^k to W_2^k
$E_{i,2}^k$	Put workpiece k into the workstation W_2^k, and start machining	$S_{i,3}^k$	Being at the machining state in W_i^k
$E_{i,3}^k$	End machining and move workpiece k out of W_i^k	$S_{i,4}^k$	Being at the transformation state from W_2^k to O_i^k
$E_{i,4}^k$	Put workpiece k into the out-buffer O_i^k	$S_{i,5}^k$	Being at the storing state in O_j^k, weighting to be moved to the next process P_{i+1}^k
$E_{i,5}^k$	Move workpiece k out of O_i^k	$S_{i+1,0}^k$	Being at the transformation state from O_i^k to I_{i+1}^k. It is considered as a connecting state to link P_i^k and P_{i+1}^k

different levels of granularity can be mixed together, e.g., case 2 mainly focus on monitoring the machining subprocess.

4.2.2 Data collecting and monitoring

Because an EDCU is just a basic data collecting unit, so several EDCUs are usually needed to monitor the entire process. Besides, an event is the only reason that makes the state of a workpiece change from one to another, which stands for the old state ends and a new state starts. Therefore, an event $E_{i,j}^k$ can be considered as the connector of two neighboring states ($S_{i,j}^k$ and $S_{i,j+1}^k$), and it can also be used to link two neighboring EDCUs ($cu_{i,j}^k$ and $cu_{i,j+1}^k$). The coupling relationship between them can be formalized as follows:

$$E_{i,j}^k \in cu_{i,j}^k \cap cu_{i,j+1}^k \tag{4}$$

When a process is decomposed into a special granularity level (e.g., level 2 in Fig. 5), the RFID configuration solution of a typical machining process can be extracted as the data collecting model revealed in Fig. 6. In the left column, three RFID readers are configured to the process, including two fixed reader ($RF_{I_i}^k$ and $RF_{O_i}^k$) and a hand-held reader ($RF_{w_i}^k$). In the middle column, four state blocks are deployed to the graphic process according to the RFID configuration, generating six EDCUs ($cu_{i,1}^k$ ~$cu_{i+1,0}^k$) that are connected by five events ($E_{i,1}^k$~$E_{i,5}^k$). Here, only three EDCUs ($cu_{i,1}^k$, $cu_{i,3}^k$, and $cu_{i,5}^k$) are veritable corresponding to the three RFID readers deployed to P_i^k, which execute the data collecting tasks practically. The other three ($cu_{i,2}^k$, $cu_{i,4}^k$, and $cu_{i+1,0}^k$) are fictional and do not collect any data. They are just applied to describe the short interval from the moment workpiece k goes out of the prior SDS until it enters into the next SDS, e.g., $cu_{i,2}^k$ means the action that taking out workpiece k from I_i^k (it is $E_{i,1}^k$ actually) and then putting it into W_i^k ($E_{i,2}^k$), forming a momentary state $S_{i,2}^k$. Besides, it can also reveal the WIP path such as $P_{I_i \to W_i}^k$. When being at these fictional states, the workpiece cannot be detected by any readers because the neighboring two SDSs cannot intersect with each other in order to avoid collision.

It can be seen from Fig. 6 that in order to monitor process P_i^k using RFID, the real-time on-site data that should be collected includes an event set E_i^k, a state set S_i^k, a quality set Q_i^k, a triggering time set t_i^k, a lasting time set T_i^k, an operator set R_i^k, a location set L_i^k, and a path set PA_i^k. Detailed descriptions about E_i^k and S_i^k are listed as an example in Table 3.

The data collecting and monitoring model of process P_i^k can be formalized as follows:

$$P_i^k ::= \left\langle S_i^k, E_i^k, t_i^k, T_i^k, L_i^k, PA_i^k, R_i^k, Q_i^k \right\rangle$$
$$s.t. \begin{cases} S_i^k = \left\{ S_{i,1}^k, S_{i,2}^k, S_{i,3}^k, S_{i,4}^k, S_{i,5}^k, S_{i+1,0}^k \right\} \\ E_i^k = \left\{ E_{i,0}^k, E_{i,1}^k, E_{i,2}^k, E_{i,3}^k, E_{i,4}^k, E_{i,5}^k \right\} \\ t_i^k = \left\{ t_{i,0}^k, t_{i,1}^k, t_{i,2}^k, t_{i,3}^k, t_{i,4}^k, t_{i,5}^k \right\} \\ T_i^k = \left\{ T_{i,1}^k, T_{i,2}^k, T_{i,3}^k, T_{i,4}^k, T_{i,5}^k \right\}, T_{i,j}^k = t_{i,j}^k - t_{i,j-1}^k \quad \forall j \in [1,5] \\ L_i^k = \left\{ E_{i,0}^k, L_{i,1}^k, L_{i,2}^k, L_{i,3}^k, L_{i,4}^k, L_{i,5}^k \right\}, L_{i,1}^k = I_i^k, L_{i,3}^k = W_i^k, L_{i,5}^k = O_i^k \\ PA_i^k = \left\{ PA_{i,1}^k, PA_{i,2}^k, PA_{i,3}^k \right\}, PA_{i,1}^k = P_{O_{i-1} \to I_i}^k, PA_{i,2}^k = P_{I_i \to W_i}^k, PA_{i,1}^k = P_{W_i \to O_i}^k \\ R_i^k = \left\{ R_{i,0}^k, R_{i,1}^k, R_{i,2}^k, R_{i,3}^k, R_{i,4}^k, R_{i,5}^k \right\} \\ Q_i^k = \left\{ Q_{i,1}^k, Q_{i,2}^k, Q_{i,3}^k, Q_{i,4}^k, Q_{i,5}^k, Q_{i+1,0}^k \right\} \end{cases} \tag{5}$$

4.3 Process flow monitoring

Definition 4: *A process flow* is defined as a sequence of operations/actions happening at/around a series of machines or workstations for machining a workpiece according to its processing technology, transforming it from the original raw material to a final finished product. The process flow of workpiece k is denoted with M^k.

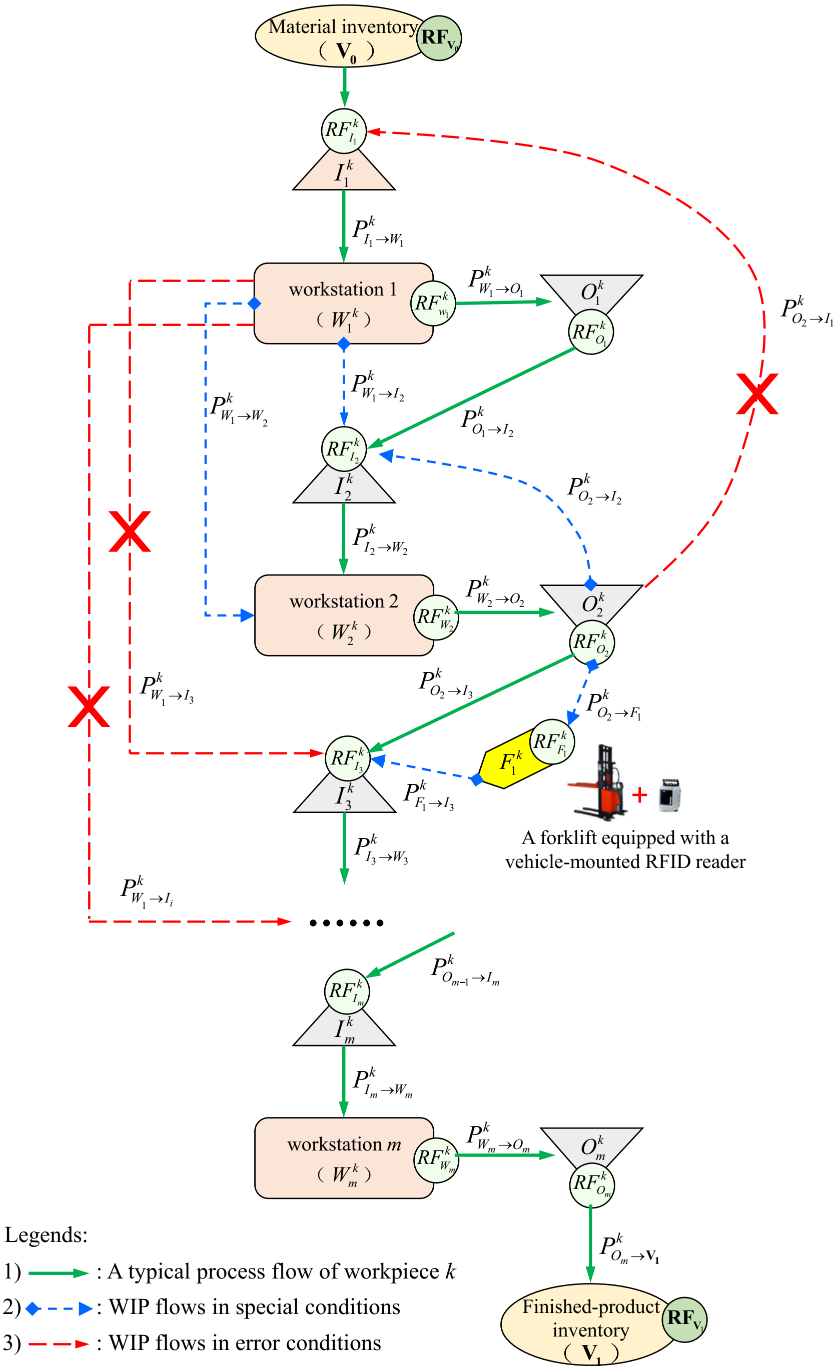


Fig. 7 A feasible RFID configuration solution of process flow M^k

The fundamental unit of a process flow is a process. Every workpiece in job-shop floor should undergo a sequence of machining process attached with other auxiliary activities, generating a specific process flow. In order to monitor the process flow, RFID devices should be deployed to all its processes to collect real-time data. According to the aforementioned RFID configuration strategy, a feasible RFID configuration solution of a typical process flow M^k with m processes is shown in Fig. 7.

In Fig. 7, each process is decomposed into three subprocesses and each subprocess is deployed with a RFID reader. Workpiece k starts from the raw material inventory V_0 and then goes to the in-buffer I^k_i, workstation W^k_i, and out-buffer O^k_i of each process P^k_i $(i\in[1,m])$ one by one, and finally to the finished-product inventory V_1 for storage. So, the WIP flow could be described by moving path PA^k as follows:

$$PA^k=\left\{P^k_{V_0\to I_1},P^k_{I_1\to W_1},P^k_{W_1\to O_1},\cdots\cdots,P^k_{I_m\to W_m},P^k_{W_m\to O_m},P^k_{O_m\to V_1}\right\} \quad (6)$$

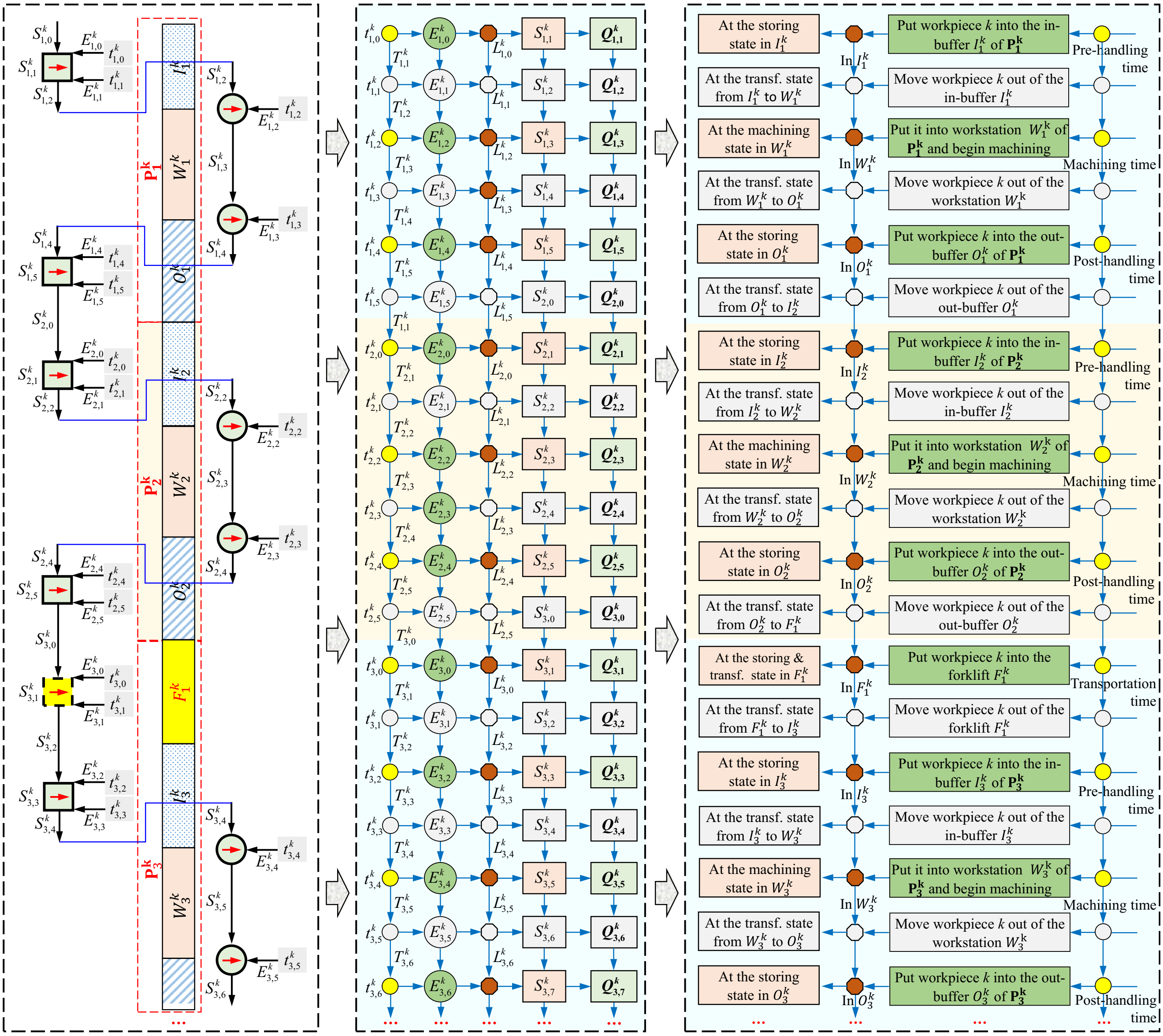


Fig. 8 The data collecting and monitoring model of M^k

Sometimes, a forklift or an AGV is also used to transport workpieces between two neighboring processes in some special conditions, e.g., when the workpiece is very large and heavy or the distance is too long. In Fig. 6, a forklift F_1^k deployed with a vehicle-mounted RFID reader $RF_{F_1}^k$ is used to transport workpieces from process P_2^k to P_3^k —specifically, from the out-buffer O_2^k of P_2^k to the in-buffer I_3^k of P_3^k. So, the WIP flow nearby is $\cdots\rightarrow O_2^k\rightarrow F_1^k\rightarrow I_3^k\rightarrow\cdots$ rather than $\cdots\rightarrow O_2^k\rightarrow I_3^k\rightarrow\cdots$. In some special conditions (e.g., P_1^k has no out-buffer) or error conditions (e.g., some processes are skipped over such as $P_{W_1\rightarrow I_3}^k$), the accompanying WIP flow changes too.

By deploying different state blocks to M^k according to its RFID configuration, Fig. 7 can also be extracted as a data collecting and monitoring model as shown in Fig. 8. Actually, the series-wound state blocks in the right column show the RFID configuration solution, while the generated EDCUs in the middle column reveal the data collecting procedure and the collected datasets such as the event set E^k, state set S^k, triggering time set t^k, location set L^k, and moving path set PA^k. Actually, for a specific process flow M^k monitored by RFID devices, some of these sets (such as E^k, S^k, and PA^k) that the workpiece will be experienced can be predicted and predefined through CAPP (computer-aided process planning) and stored in a predefined dataset database. Once workpiece k is entering-in the SDS of any RFID reader $R_{i,j}^k$, the occurrence of the related event $E_{i,j-1}^k$ can be detected, which will trigger the corresponding $cu_{i,j}^k$ to collect data. By matching the collected data with the predefined sets, the current production state of workpiece k can be reasoned out. Hence, the monitoring of M^k is achieved. The monitoring

Table 4 Definitions of the four types of TISs

TIS	Related event	Definition
Unknown	/	When a tag is out of the SDS of a RFID reader, it cannot be detected. Then, the TIS type of the tag is *unknown*.
Sensed	Entering-in	When the tag is entering-in the SDS, if the number of times n_1 that the RFID reader continuously read the tag is smaller than the set threshold N_1 ($n_1 < N_1$), then the TIS type is *sensed*.
Identified	Staying-in	When the tag is being in *sensed* state, if n_1 is equal or greater than N_1 ($n_1 \geq N_1$), then the TIS type is *identified*.
Unsensible	Going-out	When the tag is being in *identified* state, if the number of times n_2 that the RFID reader continuously cannot read the tag is smaller than the set threshold N_2 ($n_2 < N_2$), then the TIS type is *unsensible*.

model of M^k with m processes can be formalized as follows:

$$M^k = \left\{P_1^k, P_2^k, \cdots, P_i^k, \cdots, P_m^k\right\} \tag{7}$$

4.4 Batch and division monitoring

Definition 5: *A batch* is the total workpiece amount of a production order constrained by delivery deadline in job-shop floor. The rth batch is denoted with B^r.

Definition 6: *A division* means to divide a batch of workpieces into some small divisions according to production scheduling and planning, so that each division can be machined and transported individually. The mth division in B^r is denoted with D_m^r.

They can be respectively formalized as follows:

$$B^r ::= \left\langle T^r, P^r, N^r, D^r \right\rangle \tag{8}$$

$$D_m^r ::= \left\langle T^r, P^r, n^r, W_m^r \right\rangle \tag{9}$$

where T^r, P^r, and N^r respectively stand for the delivery deadline, workpiece type, and amount in the batch order; D^r is the division set divided from B^r, where $D^r = \left\{D_1^r, \cdots, D_m^r, \cdots, D_{s^r}^r\right\}$ and s^r is the division number in B^r; n^r means the volume of workpieces in each division, and $n^r = {}^{N^r}\!/_{s^r}$; and W_m^r stands for the workpiece set and $W_m^r = \left\{W_{m,1}^r, \cdots, W_{m,k}^r, \cdots, W_{m,n^r}^r\right\}$. According to formula (6), each workpiece $W_{m,k}^r$ (k∈$[1, n^r]$) can be described as a process flow M^k. So, W_m^r can also be formalized as follows:

$$W_m^r ::= \left\{\cdots, M^k, M^{k+1}, \cdots\right\} \tag{10}$$

5 RFID data processing

5.1 Preprocessing

Once a VO enters the SDS of a RFID reader, the tag information will be collected repeatedly until it moves out, leading to large amount of redundant data. Under the circumstance, one of the key issues is to eliminate the unwanted data. So, the raw data should be preprocessed firstly to decide which data is useful. In order to solve this problem, the lifecycle of a RFID reader identifying a tag should be subdivided and studied in detail. Four types of tag identifying states (TISs) are extracted to describe the changes of the procedures that the tag is entering-in, staying-in, and going-out of the SDS of the RFID reader, namely *unknown*, *sensed*, *identified*, and *unsensible*. Detailed information about them is listed in Table 4.

TIS is different from the logistic state (defined in Table 1). Different TISs will convert from one to another when the relative

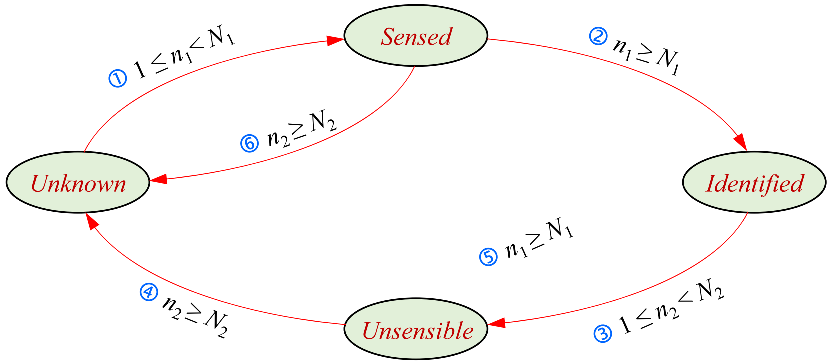


Fig. 9 The mutual transformation among different TISs

Legends: ①→② : Tag is entering-in the SDS; ③→④ : Tag is going-out of the SDS;
③→⑤ : The reader signal is not stable or there are some other faults;
①→⑥ : Tag enters in the SDS in sudden and go out of it immediately.

Fig. 10 The pseudo code of the preprocessing rules

```
$n_1$=0; $n_2$=0                                          // initialize $n_1$ and $n_2$
for (int i=0; i<+∞; i++)                                  // make a cycle for every RFID read event
    if ($Rd_i$ = true)  $n_1$++;  $n_2$=0                  // When the result of RFID read event is empty, $Rd_i$ = false; or $Rd_i$ = true
    else   $n_2$++;  $n_1$=0                               // $n_1$ and $n_2$ cannot greater than 0 at the same time
    if ($1 \le n_1 < N_1$)   TIS = Sensed                  // tag is entering-in the SDS
    else if ($n_1 \ge N_1$)   TIS = Identified             // tag is staying-in the SDS
        if ($n_1 = N_1$)                                  // record the time $t$ when tag enters the SDS
            collect and upload the triple <$ID_{tag}$, $R_i$ , $t^r$>
        else if ($n_1 > N_1$)                             // delete all the redundant data when $n_1 > N_1$
            delete all the collected data
    else if ($1 \le n_2 < N_2$)   TIS = Unsensible         // tag is going-out of the SDS
    else if ($n_2 \ge N_2$)   TIS = Unknown                // tag has left the SDS
        if ($n_2 = N_2$)                                  // record the time $t$ when tag leaves the SDS
            collect and upload the triple <$ID_{tag}$, $R_i$ , $t^r$>
        else if ($n_2 > N_2$)                             // cannot read any data when $n_2 > N_2$
            no data
end for
```

position between the RFID reader and the VO changes, as shown in Fig. 9. When and only when the tag undergoes "*unknown→sensed→identified*" or "*identified→unsensible→unknown*" means it has already entered-in or gone-out of the SDS. At this time, the related logistic event is happening that immediately triggers the corresponding EDCU for collecting and uploading real-time data. When the TIS is *identified*, the collected data are redundant that should be removed directly. Therefore, several rules can be concluded for preprocessing; the pseudo code of which is shown in Fig. 10.

5.2 Data fusion

As mentioned in Section 4.1, the raw data streams that collected and uploaded by RFID readers are a sequence of simple triple $\langle ID_{\text{tag}}, R_i, t^r \rangle$, which can be translated into some semantic information such as a state set and event set automatically through the aforementioned models to achieve real-time monitoring. Actually, those models mainly take charge of rule-based reasoning of state, event, location, etc., while the primary task of the data fusion model is to deal with the time-related data, such as triggering time and lasting time as shown in Fig. 11.

The lasting time set T^k of process flow M^k can be figured out through the lasting time of each $S^k_{i,j}$ in terms of the formula $T^k_{i,j} = t^k_{i,j} - t^k_{i,j-1}$. Furthermore, the lasting times of all the processes (T^k_i) and the entire process flow (T^k) can also be calculated, which are critical not only for real-time monitoring but also for production scheduling, control, and optimization. The calculating methods are shown as follows:

$$T^k_i = \sum_{j=1}^{n_i - 1} T^k_{i,j} + T_{i+1,0} = t^k_{i+1,0} - t^k_{i,0} \tag{11}$$

$$T^k = \sum_{i=1}^{m} T^k_i = t^k_{m,n_m} - t^k_{1,0} \tag{12}$$

where n_i stands for the number of states in process i.

As the real-time data is stored in the RFID database after collection, the time-related data fusion is also a database-based process. Figure 12 shows a simple example about a data fusion process of a workpiece whose ID is F00120020. All the semantic

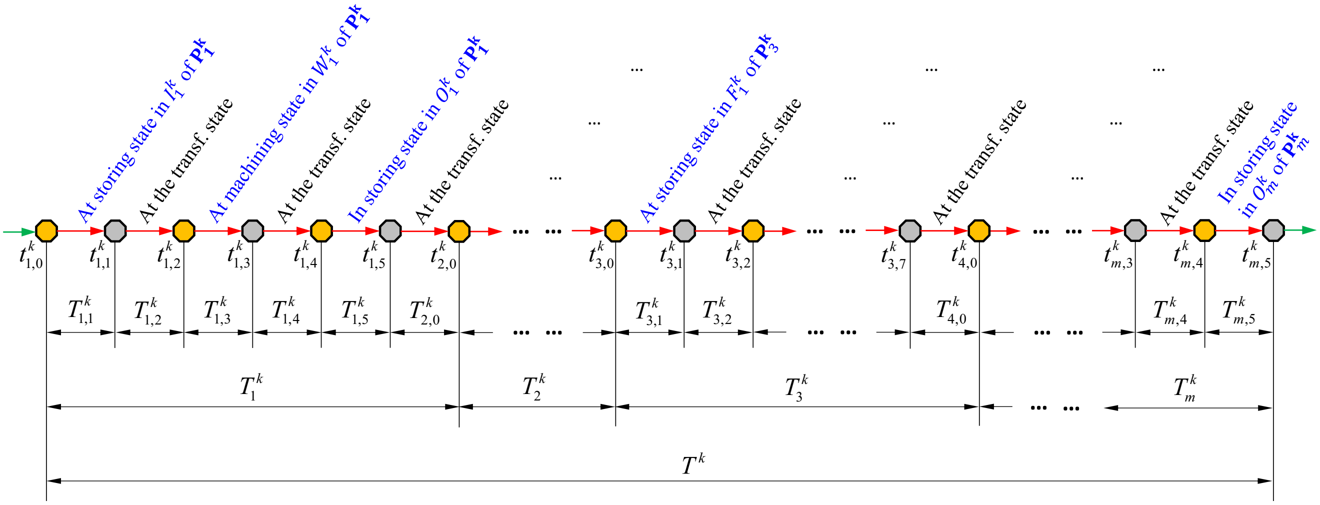
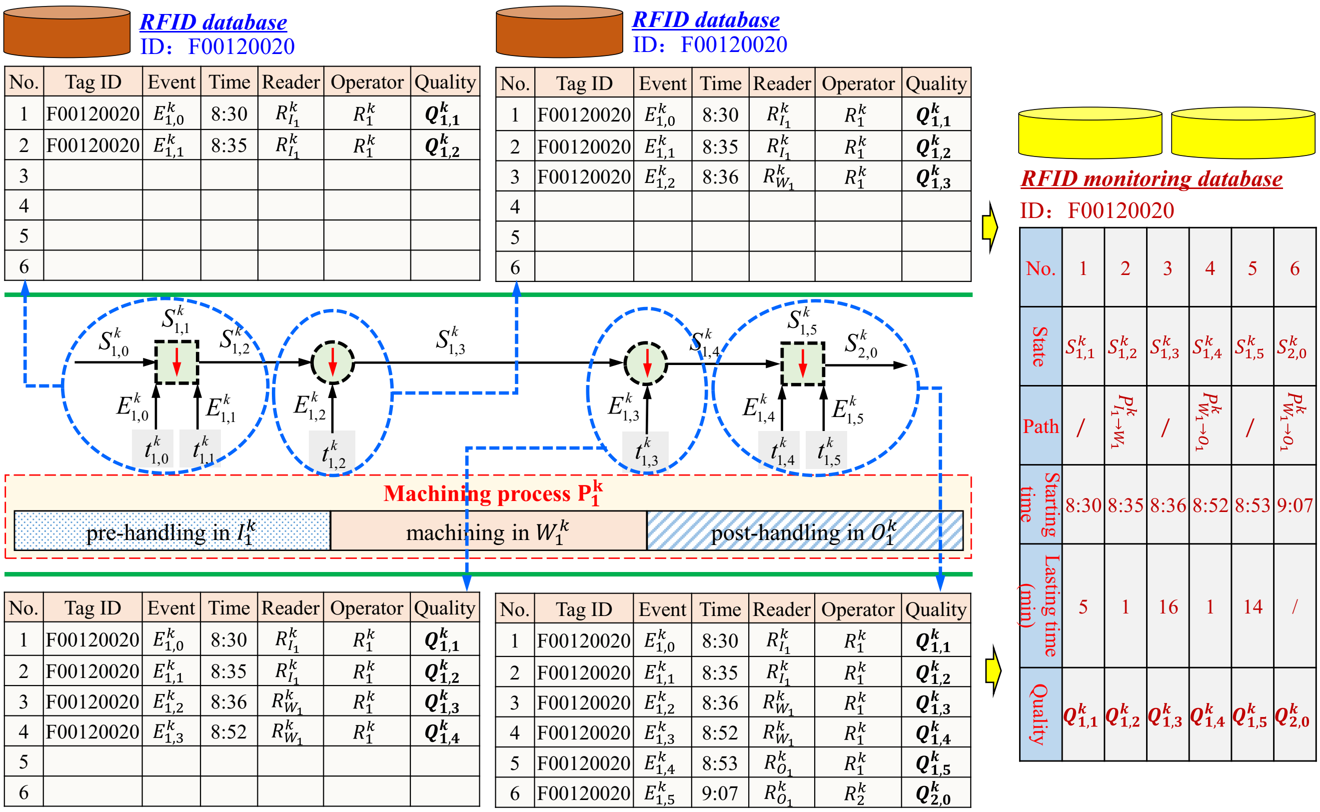


Fig. 11 Data fusion model of the time-related RFID data



RFID database
ID： F00120020

No.	Tag ID	Event	Time	Reader	Operator	Quality
1	F00120020	$E^k_{1,0}$	8:30	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,1}}$
2	F00120020	$E^k_{1,1}$	8:35	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,2}}$
3						
4						
5						
6						

RFID database
ID： F00120020

No.	Tag ID	Event	Time	Reader	Operator	Quality
1	F00120020	$E^k_{1,0}$	8:30	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,1}}$
2	F00120020	$E^k_{1,1}$	8:35	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,2}}$
3	F00120020	$E^k_{1,2}$	8:36	$R^k_{W_1}$	R^k_1	$\boldsymbol{Q^k_{1,3}}$
4						
5						
6						

No.	Tag ID	Event	Time	Reader	Operator	Quality
1	F00120020	$E^k_{1,0}$	8:30	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,1}}$
2	F00120020	$E^k_{1,1}$	8:35	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,2}}$
3	F00120020	$E^k_{1,2}$	8:36	$R^k_{W_1}$	R^k_1	$\boldsymbol{Q^k_{1,3}}$
4	F00120020	$E^k_{1,3}$	8:52	$R^k_{W_1}$	R^k_1	$\boldsymbol{Q^k_{1,4}}$
5						
6						

No.	Tag ID	Event	Time	Reader	Operator	Quality
1	F00120020	$E^k_{1,0}$	8:30	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,1}}$
2	F00120020	$E^k_{1,1}$	8:35	$R^k_{I_1}$	R^k_1	$\boldsymbol{Q^k_{1,2}}$
3	F00120020	$E^k_{1,2}$	8:36	$R^k_{W_1}$	R^k_1	$\boldsymbol{Q^k_{1,3}}$
4	F00120020	$E^k_{1,3}$	8:52	$R^k_{W_1}$	R^k_1	$\boldsymbol{Q^k_{1,4}}$
5	F00120020	$E^k_{1,4}$	8:53	$R^k_{O_1}$	R^k_1	$\boldsymbol{Q^k_{1,5}}$
6	F00120020	$E^k_{1,5}$	9:07	$R^k_{O_1}$	R^k_2	$\boldsymbol{Q^k_{2,0}}$

RFID monitoring database
ID： F00120020

No.	1	2	3	4	5	6
State	$S^k_{1,1}$	$S^k_{1,2}$	$S^k_{1,3}$	$S^k_{1,4}$	$S^k_{1,5}$	$S^k_{2,0}$
Path	/	$P^k_{I_1\to W_1}$	/	$P^k_{W_1\to O_1}$	/	$P^k_{W_1\to O_1}$
Starting time	8:30	8:35	8:36	8:52	8:53	9:07
Lasting time (min)	5	1	16	1	14	/
Quality	$\boldsymbol{Q^k_{1,1}}$	$\boldsymbol{Q^k_{1,2}}$	$\boldsymbol{Q^k_{1,3}}$	$\boldsymbol{Q^k_{1,4}}$	$\boldsymbol{Q^k_{1,5}}$	$\boldsymbol{Q^k_{2,0}}$

Fig. 12 An example of the database-based fusion

information is recorded in the database including triggering times, the predefined events, and reader IDs. When the workpiece is flowing on different processes within M^k, this data will be collected successively and further fused and stored in a RFID monitoring database, generating a sequence of semantic data to satisfy the real-time monitoring.

5.3 Exception handling

Some exceptions might be inevitable when using RFID in job-shop floor, which are classified as follows:

(a) The workpiece does not flow according to the arranged processing route (as shown in Fig. 7). That one or more processes are skipped over, the sequence of the process flow is wrong, or even the workpiece bursts into an unauthorized process can all lead to this exception.

(b) The collecting, uploading, and storing of the wrong data will happen in terms of the invasion of illegal VOs, which can also cause confusion to RFID databases.

(c) Unqualified workpieces in a process flow to the next process.

In order to handle the first two types of exceptions, the correct state set, event set, location set, etc. should be predefined and stored in the predefined dataset database for reasoning. Once a VO is detected, the collected data will be matched with the predefined datasets. If they are not matchable, it means some exceptions are happening. Then, the back end system will automatically identify the exception types, trigger alerts, and guide operators to revise the exceptions immediately. Furthermore, the important data related to the exceptions such as the times, locations, states, and operators will also be recorded that can benefit the traceability in the future.

6 Case study

Following the concepts and methods described in the preceding sections, a demonstration RFID-based job-shop monitoring system (*rfid*-JSMS) is developed for monitoring the production processes in job-shop floor driven by the collected real-time on-site data. Based on the *rfid*-JSMS, a use case with a typical box-type part (a cylinder crankcase of a TH250-type compressor) with nine machining processes and two inventory processes is studied (it is a simulative experiment in the laboratory). According to the aforementioned models and methods, the case study is divided into three steps as follows:

Step 1: *RFID configuration solution and its state block model.* In this step, all the processes in the process flow of box-type part

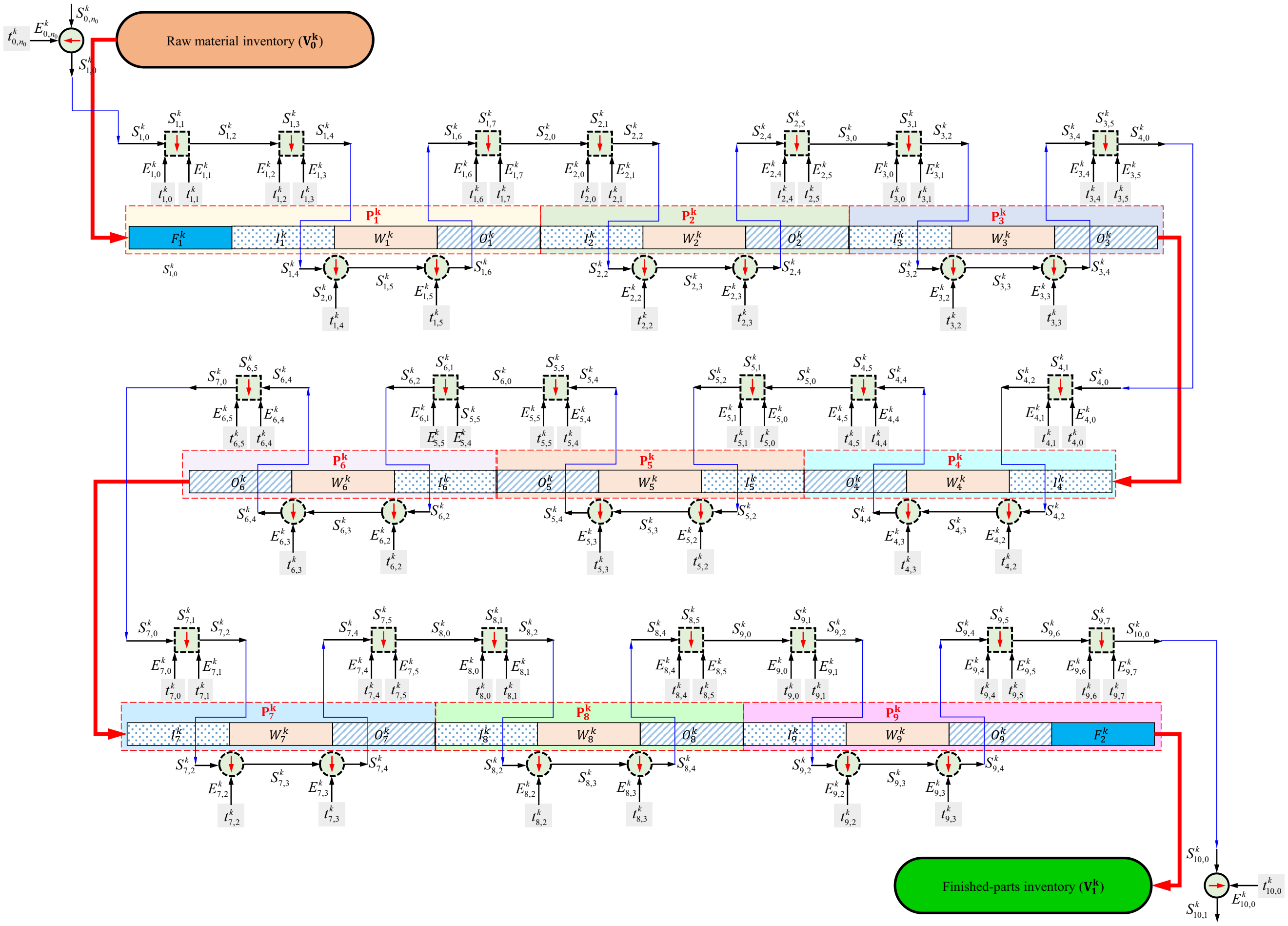


Fig. 13 The state block model of the process flow

should be decomposed into appropriate granularity levels so as to deploy state blocks on them and realize RFID configuration. As shown in Fig. 13, all the nine machining processes are divided into three parts (granularity level 2) including prehandling (in I_i^k), execution (in W_i^k), and post-handling (in O_i^k) considering the compromise between the RFID device cost and monitoring requirements. Besides, there is a transportation subprocess in both processes P_1^k and P_9^k, because two forklifts F_1^k and F_2^k are respectively used to move the raw material from inventory V_0^k to process P_1^k and transport the finished parts from process P_9^k to inventory V_1^k. Furthermore, the retrieving process (P_0^k) and storing process (P_{10}^k) in the inventories are just partly monitored in this case study.

According to the granularity decomposition, different types of state blocks can be deployed to the graphic process flow, as shown in Fig. 13. Apparently, fixed state blocks (*FS*) are deployed to all the prehandling and post-handling subprocesses, while random state blocks (*RS*) are deployed to all the execution subprocesses. In addition, two mobile state blocks are deployed to the two transportation subprocesses. When replacing the state blocks by the related RFID devices, the RFID configuration of the process flow is realized too. Specifically, 18 fixed readers are used to monitor the in-buffers and out-buffers of the nine machining processes; nine hand-held readers are used for recoding the starting/ending times and the quality information when machining, and each workstation equips one; two vehicle-mounted RFID readers are deployed to the two forklifts, respectively; for the doors of both the raw material inventory and finished-part inventory, each of them is equipped with one fixed RFID reader.

In the case study, four types of RFID devices are used as shown in Fig. 2, including Alien ALR-9610 (fixed RFID reader), Alien ALR-8696-C (fixed RFID antenna), Intermac IV7c (vehicle-mounted RFID reader), and Teklogix PRO7527 (hand-held RFID reader). All these RFID readers are UHF (ultra high frequency) readers whose frequency is 915 MHz. Because an ALR-9610 reader cannot work by itself, and it should work together at least one ALR-8696-C antenna (four antennas at most), so the practical RFID configuration solution is a little bit different from that described above. In order to enhance the accuracy, each door of V_0^k and V_1^k is configured with one fixed RFID and four shunt-wound antennas, generating a unified fixed gateway SDS. But beyond that, the other antennas are series-wound, and each one generates a separate fixed SDS. Table 5 reveals the details of the RFID devices and state blocks deployed to each process of the process flow. It can be seen that 7 fixed readers, 26 antennas, 2 vehicle-mounted readers, and 9 hand-held readers are used in the case study, whose total cost is ¥254,000. About 40 different state blocks are applied too. All these readers and antenna deployed in the process level, the process flow level, and the entire workshop level generate a unified RFID data collecting network.

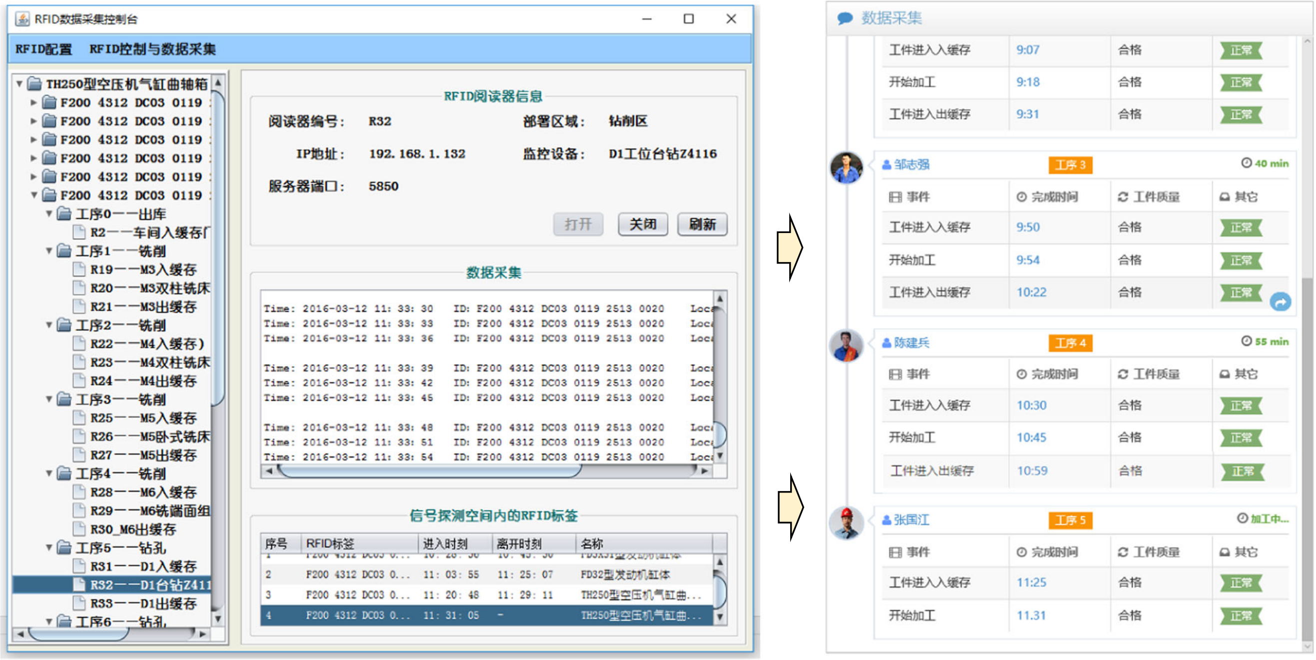
Table 5 Details of the RFID devices and state blocks deployed to the process flow

RFID description					RFID devices deployed to the process flow											Total	
	RFID	Type	Unit cost (¥)	SDS	V_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	V_1	Amount	Cost (¥)
RFID device	Alien ALR-9610	Fixed reader	13,000	*FS/FG*	1	1	0	1	0	1	0	1	0	1	1	7	91,000
	Alien ALR-8696-C	Fixed antenna	1500	*FS/FG*	4	2	2	2	2	2	2	2	2	2	4	26	39,000
	Intermac IV7c	Vehicle-mounted reader	26,000	*MS*	0	1	0	0	0	0	0	0	0	1	0	2	52,000
	Teklogix PRO7527	Hand-held reader	8000	*RS*	0	1	1	1	1	1	1	1	1	1	0	9	72,000
	Sum	/	/	/	5	5	3	4	3	4	3	4	3	5	5	44	254,000
State block description					State blocks deployed to the process flow											Total amount	
	State blocks	RFID	SDS type		V_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	V_1		
State blocks	*FS*	Alien ALR-9610 and Alien ALR-8696-C	Fixed space		0	2	2	2	2	2	2	2	2	2	0	18	
	FG	Alien ALR-9610 and Alien ALR-8696-C	Fixed gateway		1	0	0	0	0	0	0	0	0	0	1	2	
	MS	Intermac IV7c	Mobile space		0	1	0	0	0	0	0	0	0	1	0	2	
	RS	Teklogix PRO7527	Random space		0	2	2	2	2	2	2	2	2	2	0	18	
	Sum	/			1	5	4	4	4	4	4	4	4	5	1	40	

Step 2: *Data collecting and processing*. Actually, the state block model shown in Fig. 13 not only directly instructs managers about the RFID configuration solution but also clearly shows what data needs to be collected. Furthermore, these state blocks can be transformed into a series of consecutive EDCUs too, which can collect the corresponding data, such as events, triggering times, states, locations, and quality sets based on the physical RFID data collecting network.

In *rfid*-JSMS, two different data collecting soft modules are developed as shown in Fig. 14. One (Fig. 14(a)) is developed in C/S (client/server) architecture for real time, which is directly responsible for the data collecting functions of all the readers. It is the software format of the fictitious EDCU model. Besides, it also controls the turning-on, turning-off, and restart of every reader individually. So, the time-related data of all the VOs covered by the SDS of the RFID reader (R32) are collected repeatedly. This collected data should be preprocessed firstly to get rid of the redundant data, and then, the remaining useful data is uploaded and stored in the RFID database, as shown in Fig. 14(b). Through data fusion, it can be transformed into a series of semantic LBI, which is displayed by another data collecting soft module (Fig. 14(a)). It is developed in B/S (browser/server) architecture for better interactivity and takes charge of displaying the real-time data collected by the first module. The LBI can be used for the monitoring functions too. Furthermore, the predefined datasets of the part are stored in another database before machining. Through comparing the collected data with the predefined datasets, *rfid*-JSMS can reason out whether there are some exceptions or not and further provide proposals for correction automatically.

Step 3: *Real-time job-shop monitoring*. In this step, the prototype system *rfid*-JSMS is developed based on Java language and SSH (Spring-Struts-Hibernate) framework. MySQL database is used to provide data storage service. Figure 15(a) clearly shows the real-time monitoring of the process flow of the cylinder crankcase whose tag ID is F2004312DC03011925130020 in a very acceptable and comprehensible way based on the job-shop floor plan. Different colors are used for marking the processes that have been finished, are being executed, and will be fulfilled, respectively, generating a colored complete WIP path. It can be seen that the cylinder crankcase is now being machined in the workstation W_5^k of process P_5^k. In Fig. 15(b), the detailed information of the current process is shown, e.g., the complete



RFID数据采集控制台

TH250型空压机气缸曲轴箱
- F200 4312 DC03 0119
- F200 4312 DC03 0119
- F200 4312 DC03 0119
- F200 4312 DC03 0119
- F200 4312 DC03 0119
- F200 4312 DC03 0119
  - 工序0——出库
    - R2——车间入缓存
  - 工序1——铣削
    - R19——M3入缓存
    - R20——M3双柱铣床
    - R21——M3出缓存
  - 工序2——铣削
    - R22——M4入缓存）
    - R23——M4双柱铣床
    - R24——M4出缓存
  - 工序3——铣削
    - R25——M5入缓存
    - R26——M5卧式铣床
    - R27——M5出缓存
  - 工序4——铣削
    - R28——M6入缓存
    - R29——M6铣端面组
    - R30_M6出缓存
  - 工序5——钻孔
    - R31——D1入缓存
    - R32——D1台钻Z411
    - R33——D1出缓存
  - 工序6——钻孔

RFID阅读器信息

阅读器编号： R32
部署区域： 钻削区
IP地址： 192. 168. 1. 132
监控设备： D1工位台钻Z4116
服务器端口： 5850

数据采集

```
Time: 2016-03-12 11: 33: 30   ID: F200 4312 DC03 0119 2513 0020   Loc
Time: 2016-03-12 11: 33: 33   ID: F200 4312 DC03 0119 2513 0020   Loc
Time: 2016-03-12 11: 33: 36   ID: F200 4312 DC03 0119 2513 0020   Loc

Time: 2016-03-12 11: 33: 39   ID: F200 4312 DC03 0119 2513 0020   Loc
Time: 2016-03-12 11: 33: 42   ID: F200 4312 DC03 0119 2513 0020   Loc
Time: 2016-03-12 11: 33: 45   ID: F200 4312 DC03 0119 2513 0020   Loc

Time: 2016-03-12 11: 33: 48   ID: F200 4312 DC03 0119 2513 0020   Loc
Time: 2016-03-12 11: 33: 51   ID: F200 4312 DC03 0119 2513 0020   Loc
Time: 2016-03-12 11: 33: 54   ID: F200 4312 DC03 0119 2513 0020   Loc
```

信号探测空间内的RFID标签

序号	RFID标签	进入时刻	离开时刻	名称
2	F200 4312 DC03 0...	11: 03: 55	11: 25: 07	FD32型发动机缸体
3	F200 4312 DC03 0...	11: 20: 48	11: 29: 11	TH250型空压机气缸曲...
4	F200 4312 DC03 0...	11: 31: 05	-	TH250型空压机气缸曲...

数据采集

事件	完成时间	工件质量	其它
工件进入入缓存	9:07	合格	正常
开始加工	9:18	合格	正常
工件进入出缓存	9:31	合格	正常

邹志强 工序 3 40 min

事件	完成时间	工件质量	其它
工件进入入缓存	9:50	合格	正常
开始加工	9:54	合格	正常
工件进入出缓存	10:22	合格	正常

陈建兵 工序 4 55 min

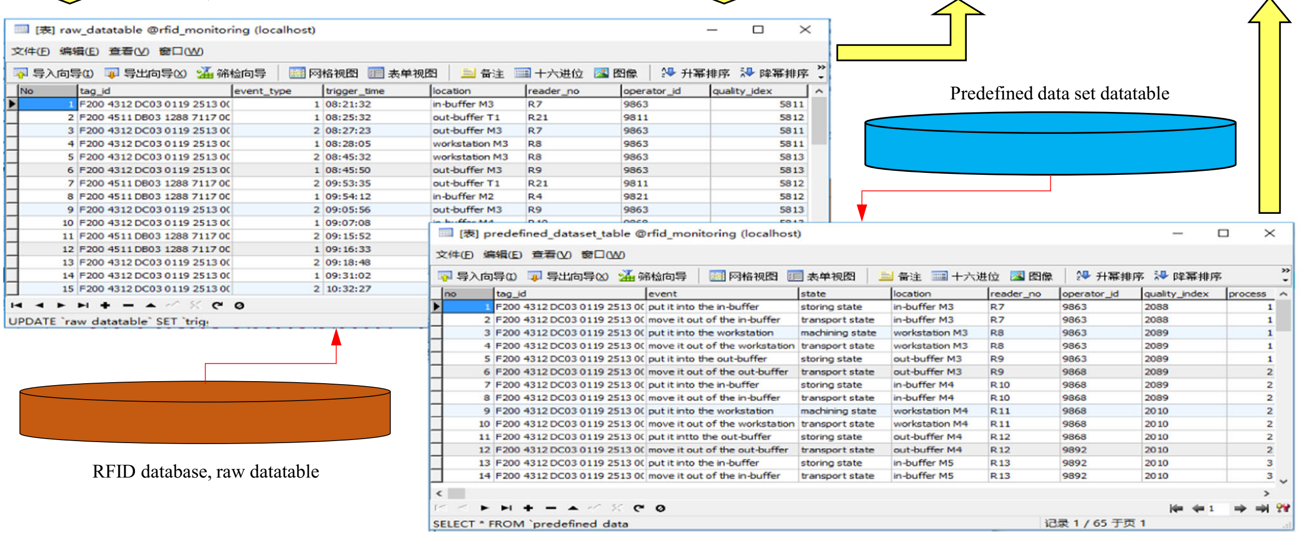
事件	完成时间	工件质量	其它
工件进入入缓存	10:30	合格	正常
开始加工	10:45	合格	正常
工件进入出缓存	10:59	合格	正常

张国江 工序 5 加工中...

事件	完成时间	工件质量	其它
工件进入入缓存	11:25	合格	正常
开始加工	11.31	合格	正常

a) Data collecting module in C/S architecture

c) Data collecting module in B/S architecture



[表] raw_datatable @rfid_monitoring (localhost)

No	tag_id	event_type	trigger_time	location	reader_no	operator_id	quality_idex
1	F200 4312 DC03 0119 2513 0(	1	08:21:32	in-buffer M3	R7	9863	5811
2	F200 4511 DB03 1288 7117 0C	1	08:25:32	out-buffer T1	R21	9811	5812
3	F200 4312 DC03 0119 2513 0(	2	08:27:23	out-buffer M3	R7	9863	5811
4	F200 4312 DC03 0119 2513 0(	1	08:28:05	workstation M3	R8	9863	5811
5	F200 4312 DC03 0119 2513 0(	2	08:45:32	workstation M3	R8	9863	5813
6	F200 4312 DC03 0119 2513 0(	1	08:45:50	out-buffer M3	R9	9863	5813
7	F200 4511 DB03 1288 7117 0C	2	09:53:35	out-buffer T1	R21	9811	5812
8	F200 4511 DB03 1288 7117 0C	1	09:54:12	in-buffer M2	R4	9821	5812
9	F200 4312 DC03 0119 2513 0(	2	09:05:56	out-buffer M3	R9	9863	5813
10	F200 4312 DC03 0119 2513 0(	1	09:07:08				
11	F200 4511 DB03 1288 7117 0C	2	09:15:52				
12	F200 4511 DB03 1288 7117 0C	1	09:16:33				
13	F200 4312 DC03 0119 2513 0(	2	09:18:48				
14	F200 4312 DC03 0119 2513 0(	1	09:31:02				
15	F200 4312 DC03 0119 2513 0(	2	10:32:27				

```
UPDATE `raw datatable` SET `trig
```

[表] predefined_dataset_table @rfid_monitoring (localhost)

no	tag_id	event	state	location	reader_no	operator_id	quality_index	process
1	F200 4312 DC03 0119 2513 0(	put it into the in-buffer	storing state	in-buffer M3	R7	9863	2088	1
2	F200 4312 DC03 0119 2513 0(	move it out of the in-buffer	transport state	in-buffer M3	R7	9863	2088	1
3	F200 4312 DC03 0119 2513 0(	put it into the workstation	machining state	workstation M3	R8	9863	2089	1
4	F200 4312 DC03 0119 2513 0(	move it out of the workstation	transport state	workstation M3	R8	9863	2089	1
5	F200 4312 DC03 0119 2513 0(	put it into the out-buffer	storing state	out-buffer M3	R9	9863	2089	1
6	F200 4312 DC03 0119 2513 0(	move it out of the out-buffer	transport state	out-buffer M3	R9	9868	2089	2
7	F200 4312 DC03 0119 2513 0(	put it into the in-buffer	storing state	in-buffer M4	R10	9868	2089	2
8	F200 4312 DC03 0119 2513 0(	move it out of the in-buffer	transport state	in-buffer M4	R10	9868	2089	2
9	F200 4312 DC03 0119 2513 0(	put it into the workstation	machining state	workstation M4	R11	9868	2010	2
10	F200 4312 DC03 0119 2513 0(	move it out of the workstation	transport state	workstation M4	R11	9868	2010	2
11	F200 4312 DC03 0119 2513 0(	put it intto the out-buffer	storing state	out-buffer M4	R12	9868	2010	2
12	F200 4312 DC03 0119 2513 0(	move it out of the out-buffer	transport state	out-buffer M4	R12	9892	2010	2
13	F200 4312 DC03 0119 2513 0(	put it into the in-buffer	storing state	in-buffer M5	R13	9892	2010	3
14	F200 4312 DC03 0119 2513 0(	move it out of the in-buffer	transport state	in-buffer M5	R13	9892	2010	3

```
SELECT * FROM `predefined data
```

记录 1 / 65 于页 1

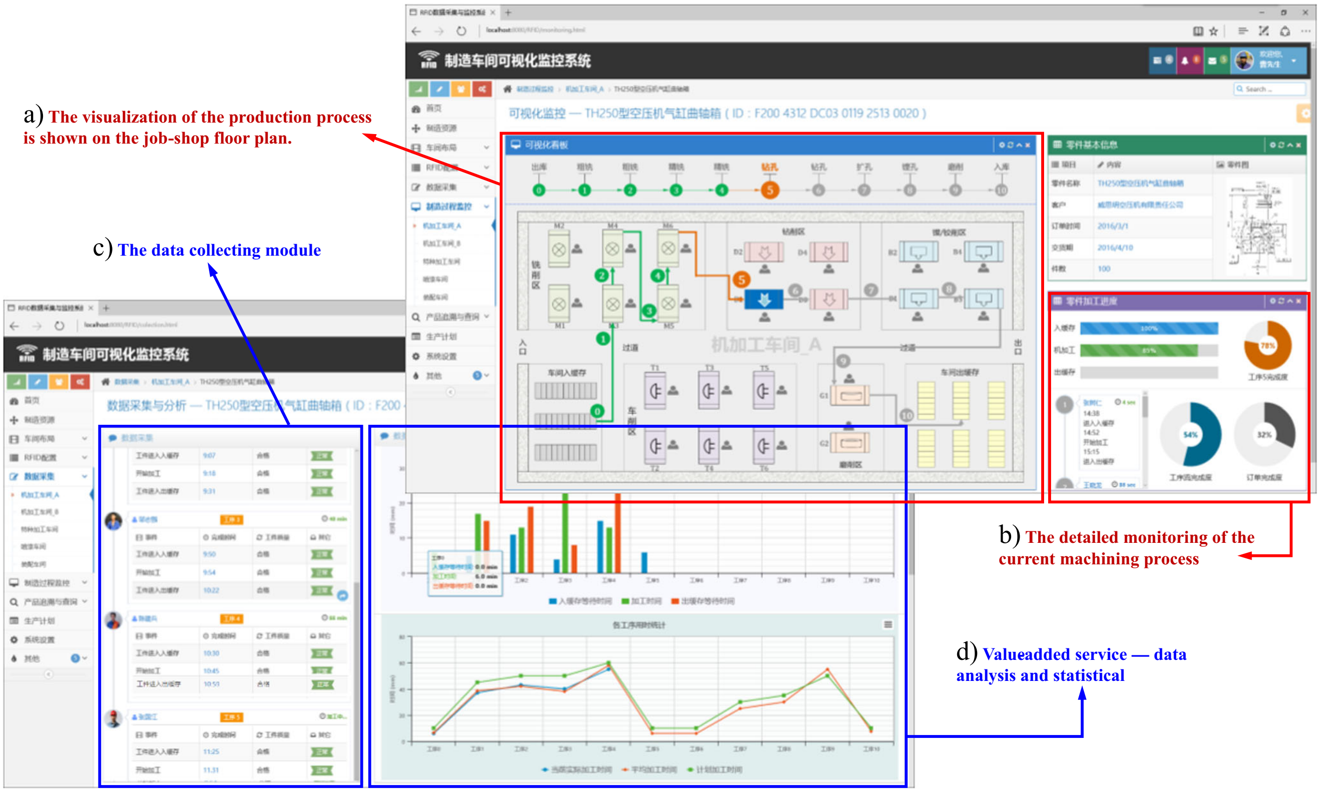
b) The collected raw data and the predefined data set are stored in databases

Fig. 14 Data collecting and processing modules in *rfid*-JSMS

progresses of the prehandling/execution/post-handling subprocess, the current process, and even the entire process flow. Figure 15(c) is the data collecting module mentioned above. Besides, some value-added data services are also provided by *rfid*-JSMS through further data statistics and analysis, as shown in Fig. 15(d). Specifically, the upper histogram dynamically shows the statistical data including the lasting times of each storage state in I_i^k ($i\in[1,4]$) and O_i^k and machining state in W_i^k of the finished process. The below line chart shows the comparison result of three different types of lasting times for every process, including the actual machining times of part *k*, the planning machining times of part *k*, and the statistic average machining times all the finished parts (form part 1 to part *k*) in the same division D_m^r. If the errors between the actual time and the other two are bigger than a set threshold, some exceptions happen undoubtedly.

7 Conclusion

The production process of MVSB manufacturing is very complex; along with which, there is a huge amount of on-site data. Although this data is significant for production monitoring and control, yet it is hard to be collected and uploaded in real time,



a) The visualization of the production process is shown on the job-shop floor plan.

b) The detailed monitoring of the current machining process

c) The data collecting module

d) Valueadded service — data analysis and statistical

Fig. 15 Real-time data-driven monitoring in job-shop floor based on *rfid*-JSMS

making the production processes non-transparent and uncontrollable. This paper proposed a real-time data-driven monitoring method based on RFID technology for collecting the job-floor data and monitoring the production process. This method can be divided into three parts, including RFID configuration, data collecting and real-time monitoring, and data processing.

Firstly, the configuration strategies of both RFID tags and devices are put forward. Four typical RFID device configuration schemas are concluded and extracted. Moreover, the essence of RFID applications in job-shop floor is revealed, which is to monitor the state change of VOs and collect the related data for making the production process transparent.

Secondly, an EDCU model is established to describe how a single RFID reader collects data, and it is further transformed into four types of state blocks according to different types of RFID configuration schemas, showing what data needs to be collected in different situations. Both the EDCU model and state block model can complement one another. Based on them, a data collecting and monitoring model of a typical process is established through a proposed multi-granularity process decomposition method, which reveals the connection between RFID configuration and monitoring requirements. Similarly, the monitoring models of a typical process flow, batch, and division are further established one by one.

Then, several RFID data processing methods are proposed to deal with different situations after the data is collected by the above models. A data preprocessing method is used to filter out the redundant data from the raw data firstly, while a data fusion method is applied to transform this data into some meaningful LBI for job-shop floor monitoring function. An exception handling method is discussed too.

Finally, a use case of a typical part is studied based on a prototype system called *rfid*-JSMS, which demonstrates the feasibility and applicability of the proposed models and methods. Future work about this area will include the modification and popularization of this monitoring method. Besides, the construction and complexity analysis of the RFID monitoring network should also be studied in detail.

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