# RFID-Enabled Physical Object Tracking in Process Flow Based on an Enhanced Graphical Deduction Modeling Method

Kai Ding, Pingyu Jiang, Peilu Sun, and Chuang Wang

***Abstract*—The purpose of this paper is to develop an enhanced radio frequency identification (RFID)-enabled graphical deduction model (rfid-GDM) for tracking the time-sensitive state, position, and other attributes of RFID-tagged objects in process flow. Concepts and definitions related to processes and RFID applications are first clarified, and enhanced state blocks are proposed to depict four kinds of RFID application scenarios. The implementation framework of rfid-GDM and its five steps are further addressed. Both mathematical formalization and graphical description of each step are involved. Finally, a case is studied to verify the feasibility of rfid-GDM. It is expected that rfid-GDM will provide instructions for modeling and tracking RFID-enabled process flows in diverse fields.**

***Index Terms*—Configuration, graphical deduction modeling, process flow, radio frequency identification (RFID), tracking.**

## I. Introduction

The emergence of radio frequency identification (RFID) technology raises great opportunities for tracking physical objects efficiently, especially in manufacturing, inventory, and logistics [1]–[4]. RFID tags are attached to physical objects, forming RFID-tagged objects. Meanwhile, RFID readers/antennas are deployed onto process flows, forming RFID-enabled process flows. Through wireless communication with RFID readers/antennas, RFID-tagged objects can be automatically identified in the RFID-enabled process flow with high efficiency and low labor cost, compared with the manual or barcode methods [5]. In fact, the nature of RFID applications, which is summarized from the broad application spectrums, is to track the time-varying state, position, and other attributes of RFID-tagged objects consecutively [6]. The objective of RFID applications is to ensure that right objects perform right things under right states at right times and in right locations during the process flow. The deviations or disturbances occurred are captured and fed back timely by RFID readers/antennas for dynamic control and decision-making.

Manuscript received December 13, 2015; accepted March 1, 2016. This work was supported by the National Natural Science Foundation of China under Grant 71571142 and Grant 51275396. This paper was recommended by Associate Editor D. Akopian.

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Digital Object Identifier 10.1109/TSMC.2016.2558104

It is essential for industrial practitioners to model the RFID-enabled process flows when applying RFID technology. Building the mapping relationship between RFID-enabled process flow and configuration of RFID devices would provide instructions for them to deploy on-demand RFID devices efficiently. Numerous RFID models and relevant control methods have been investigated in both academic research and practical applications [6]–[25]. However, most of the current RFID models are case-specific. RFID devices configuration in these models is always based on human's judgment on the application scenarios, and is prior to the modeling of RFID-enabled process flow, which causes the adaptability and cost problems.

To solve the problems mentioned above, an enhanced RFID-enabled graphical deduction model (rfid-GDM) is proposed for modeling and configuring RFID-enabled process flow rapidly. First, process-related and RFID-related concepts are clarified. Four kinds of RFID application scenarios are summarized from industrial practice, based on which four kinds of enhanced state blocks are defined to describe the changes of object attributes (e.g., state, position, operator, etc.) and the triggering events graphically. Second, modeling methodology of rfid-GDM, which includes five steps, is addressed. The first step is to decompose processes into multigranularity subprocesses according to the tracking requirements. The second step is to extract events from the processes and subprocesses and build the event sequence units (ESUs) automatically. The third step is to generate an RFID-enabled process flow by connecting processes and subprocesses with two kinds of connectors. The fourth one is to deploy enhanced state blocks onto the RFID-enabled process flow to form the final rfid-GDM, which builds the mapping relationship between the process flow and the corresponding RFID devices configuration. In the last step, RFID devices are deployed onto the process flow cost-effectively based on the rfid-GDM. It should be pointed out that events in the RFID-enabled process flow trigger the changes of object attributes. Such triggering events are monitored by RFID devices. Thus, rfid-GDM is an event-driven model.

The rest is arranged as follows. Related work about RFID applications is given in Section II. Section III clarifies the relevant concepts and definitions. Section IV addresses the modeling methodology of rfid-GDM. A case is studied in Section V to verify the feasibility of rfid-GDM. Finally, discussion and the conclusion are given in Sections VI and VII.

## II. Related Work

RFID technology has shown big potentials in diverse fields, such as material flow tracking [6], [7], quality assurance [8], [9], production control [1], [10]–[13], cold chain logistics tracking [14], [15], on-site objects locating [16], supply chain and warehouse management [17]–[19], and access control [20]. In general, the RFID applications mentioned above can be classified into two categories: 1) object identifying and locating and 2) process flow tracking. Moreover, the corresponding RFID application sites can be classified into two levels: 1) within-a-place and 2) cross-places, where a place can stand for an enterprise, job-shop, store, warehouse, or others.

Specifically, referring to the process-flow-tracking category, researchers mainly focused on manufacturing, production logistics, inventory, and supply chains. At the within-a-place level, RFID enhances real-time data capturing and fusing for process visibility. Jiang and Cao [6] proposed an RFID-driven graphical formalized deduction model for monitoring the time-sensitive state changes of material flow in a job-shop. Qu *et al.* [7] discussed a real-life case of applying RFID for managing material distribution in a complex assembly shop floor, where the entrance/exit of RFID-tagged objects were monitored by RFID-Gateways. Wang *et al.* [13] discussed an RFID-enabled manufacturing execution system to achieve real-time control for one-of-a-kind production. Nevertheless, monitoring the staying state of objects at a certain place was not involved in [6] and [7]. Zhang *et al.* [10] proposed a multiagent-based real-time production scheduling method for RFID enabled ubiquitous shop floors. This method did not discuss how to model the RFID-enabled process flow from the view of objects. At the cross-places level, RFID technology helps to close the loop of supply chain control. Sari [18] investigated the benefits of using RFID in a four-stage supply chain under different environmental and operational conditions via a simulation model. Chow *et al.* [3] discussed an information system integrated with RFID and IT technologies for logistics service companies and supply chain parties to manage and visualize the logistics processes. Kang and Lee [21] developed a set of RFID traceability services for supply chains, through which aggregation and disaggregation relationships among items and logistics units were easily queried to acquire the dynamic lifecycle information of product flows. Huang *et al.* [22] discussed an RFID-enabled gateway product service system for collaborative manufacturing. RFID-gateways, which can monitor the workflow of product manufacturing, were provided in the form of product services. Qu *et al.* [23] integrated cloud manufacturing with Internet of Things infrastructures to enable smart production logistics control with multilevel dynamic adaptability.

The models and methods mentioned above play an important role in facilitating the application of RFID technology. However, most of them are case-specific. The uniform event-driven modeling method is not involved for modeling RFID-enabled process flow and tracking physical objects. Besides, there is little theoretical basis to configure RFID devices for the process flow due to the lack of mapping relationship between them.

## III. Concepts and Definitions

### A. Process-Related Concepts

*Definition 1:* A process is defined as a set of consecutive triple operations executed at a certain working position within a time interval, such as machining, transportation, and quality inspection. Each operation can be viewed as a subprocess, and it is classified into three kinds: 1) prehandling (or preparation); 2) execution; and 3) post-handling (or completion). In fact, a subprocess can be decomposed further. Process and subprocess change the shape, size, position, and other attributes of physical objects consecutively

$$P(P_T, P_{\text{name}}, R, L, LT, \text{St}, \text{Dt}) \tag{1}$$

$$P ::= \{P_1, P_2, P_3\} \tag{2}$$

where $P_T$ is the process type, $P_T \in [BX, EX, AX]$. $BX$, $EX$, and $AX$ represent the process type of prehandling, execution, and post-handling, respectively. $P_1$, $P_2$, and $P_3$ are the three subprocesses. $P_{\text{name}}$ is the process name, $R$ is the process operator, $L$ represents the working position where process is executed, $LT$ is the type of $L$ (fixed place or movable place), and St and Dt are the start time and duration time of the process. The formalization of subprocess is the same as that of process.

*Definition 2:* An event is defined as the action that happens on a process at a specific timestamp. Four kinds of events are summarized, i.e., start event, finish event, pass-through event, and random event. Start event and finish event compose an event pair to indicate the start and finish of a process. Pass-through event indicates that physical objects pass through a gateway or other fixed positions. Random event is plugged into a process for occasional control. All events are transient and have no duration time

$$E(E_T, E_{\text{Info}}, R, L, LT, t) \tag{3}$$

$$E\_\text{LD} = \prod_{R,L,LT} (E) = \prod_{R,L,LT} (P) \tag{4}$$

where $E_T$ is the event type, $E_T \in \{E_{\text{in}}, E_{\text{out}}, E_{\text{pass}}, E_{\text{rnd}}\}$, which represents the set of start event, finish event, pass-through event, and random event; $E_{\text{Info}}$ is the relevant information; $t$ is the event occur time; and $E\_\text{LD}$ is the location domain of event inherited from the location domain of process.

*Definition 3:* A state is defined as the temporarily unchanged situation of physical objects, e.g., before-start, under-execution, and after-completion states. The changes of object state are triggered by events, as described in (5). For a certain physical object, the after-completion state of its prior process is the same as the before-start state of its next process

$$E = f(S_1, S_2) \tag{5}$$

where $f(x, y)$ stands for the mapping function of event and its adjacent states $S_1$ and $S_2$.

*Definition 4:* A process flow is defined as a series of logical-connected processes/subprocesses, which indicates the consecutive shift of object's state, position, and other attributes.

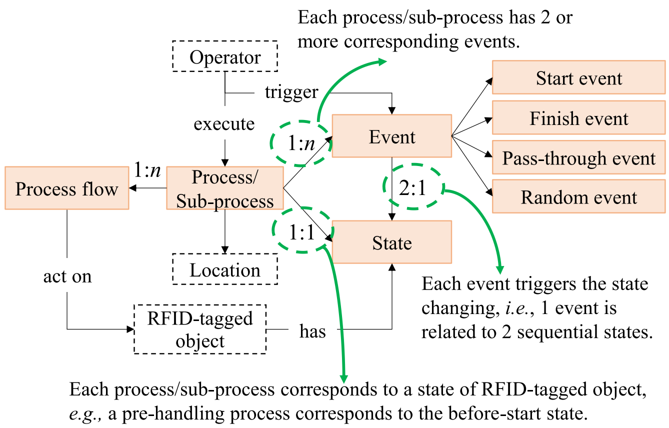



Fig. 1. Relationships among the process-related concepts.

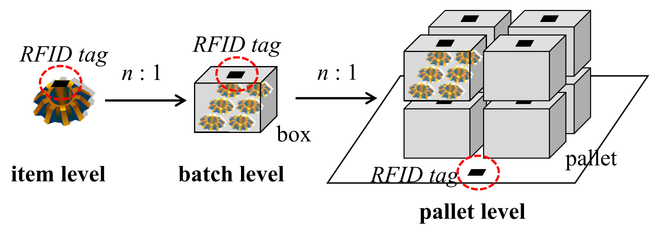



Fig. 2. Relationships among different kinds of delivery units.

Fig. 1 describes the relationships among these process-related concepts.

## B. RFID-Related Concepts

*Definition 5:* An RFID-tagged object is defined as a physical object attached with an RFID tag. It can interact with RFID readers/antennas through wireless communication. The unique RFID tag code ensures the RFID-tagged object is exclusively identified. The one-to-one binding of RFID tag and physical object facilitates the real-time data collecting and indexing to generate the semantic information. An RFID-tagged object is formalized as

$$T\left(T_{\mathrm{id}}, T_{\mathrm{name}}, T_{\mathrm{size}}, T_L, T_{\mathrm{UL}}, T_{\mathrm{Pr}}, T_{\mathrm{Qlt}}, T_{info}\right) \qquad (6)$$

where $T$ is the RFID-tagged object, $T_{\mathrm{id}}$ is the unique tag code, and $T_{\mathrm{name}}$ and $T_{\mathrm{size}}$ represent the object name and size. $T_L$ stands for the level of object in the bill of material (BOM) tree, $T_{\mathrm{UL}}$ stands for the up level item that the object belongs to. $T_{\mathrm{Pr}}$ and $T_{\mathrm{Qlt}}$ represent the provider and the quality requirements of the object. Other attributes are denoted as $T_{info}$.

In general, objects of the same kind are always packaged in batches, thus, delivery units (e.g., boxes, trays, and pallets), which package objects for delivery, are also bundled with RFID tags, forming RFID-tagged delivery units. The formalization of a delivery unit is described as

$$TT(TT_{\mathrm{id}}, \mathbf{TT}_{\mathbf{TS}}) \qquad (7)$$

where $TT_{\mathrm{id}}$ is the unique tag code and $\mathbf{TT}_{\mathbf{TS}}$ represents the set of RFID tags that indicate the packaged objects. For example, Fig. 2 shows that an RFID-tagged pallet packages RFID-tagged boxes, and a box packages a batch of RFID-tagged parts.

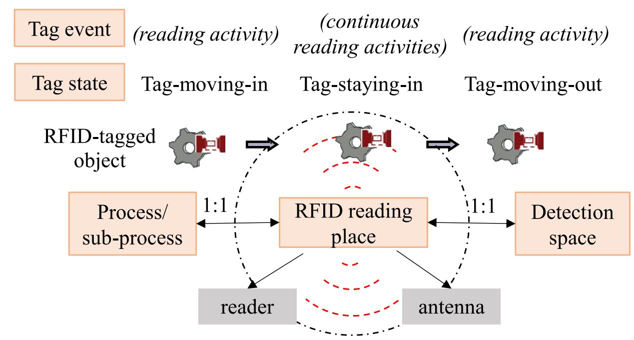



Fig. 3. Relationships among the RFID-related concepts.

Based on the definitions of the two kinds of RFID tags, physical objects are identified at different package levels throughout the process flow, and the comprehensive product states could be achieved by synthesizing the states of all the parts and components in the product BOM tree.

*Definition 6:* An RFID reading place is defined as the working position where RFID readers are installed and relevant processes are monitored. It can be fixed (e.g., machine tool's place, inspection workbench, etc.) or movable (e.g., vehicle, forklift, automatic guided vehicle, etc.).

*Definition 7:* A detection space is defined as the physical coverage of radio frequency signals where RFID readers can identify RFID tags and collect real-time data. Each detection space is related to an RFID reading place. Thus, it can be fixed or movable too.

*Definition 8:* A tag event represents the reading activity of RFID readers when RFID tags move in, move out, or pass through the detection space. The tag events are in accordance with the start event, finish event, pass-through event, and random event of RFID-tagged objects.

*Definition 9:* A tag state represents the state of an RFID tag when it enters the detection space, such as tag-moving-in, tag-staying-in, and tag-moving-out states. These tag states reflect object's states of before-start, under-execution, and after-completion during a process.

Fig. 3 describes the relationships among these RFID-related concepts.

## C. Four Kinds of RFID Application Scenarios in Industries

Most RFID applications can be summarized into four kinds based on the types of RFID reading places and RFID devices [6], [26]. Fig. 4 gives the examples in manufacturing field.

*Scenario 1 (Fixed-Reader/Antenna-Based Fixed Detection Space Control Mode):* In a fixed detection space, fixed RFID reader/antenna monitors the entrance and exit of objects (indicating the start and finish events of a common process).

*Scenario 2 (Fixed-Reader/Antenna-Based Movable Detection Space Control Mode):* In a movable detection space, vehicle-mounted RFID reader/antenna, which is fixed in the vehicles, monitor the entrance, and exit of objects (indicating the start and finish events of a transportation process).

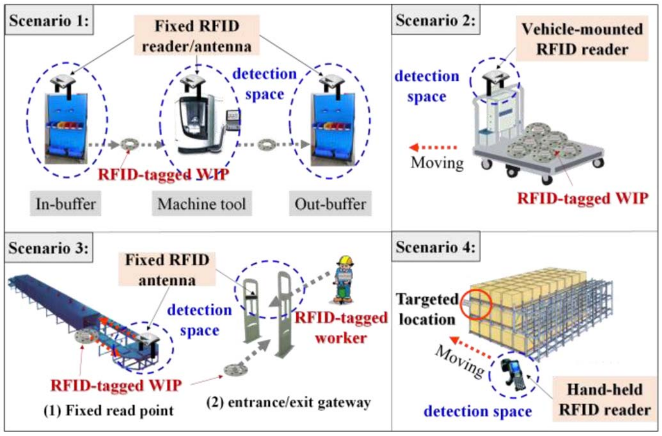



Fig. 4. Four kinds of RFID application scenarios in manufacturing field.

*Scenario 3 (Fixed-Reader/Antenna-Based Gateway Access Control Mode):* In a gateway or other fixed points, fixed RFID reader/antenna monitors the pass-through events of objects.

*Scenario 4 (Movable-Reader/Antenna-Based Random Detection Space Control Mode):* The random events executed on objects are monitored by hand-held RFID reader/antenna, whose detection space could be fixed or movable.

### D. Enhanced State Blocks

Some information should be clarified for an RFID-tagged object, such as which job is executed by which operator in which place, together with the start and finish timestamps. A state block model is defined in our prior work to solve this problem [6]. However, the prior model is a bit unreasonable because the events, which trigger the changes of object state, position, and other attributes, are not involved. Besides, the location-relevant information is limited. In this paper, an enhanced state block model is built. The definition of enhanced state blocks is given as follows.

*Definition 10:* An enhanced state block is defined as a graphical unit that illustrates the state, position, triggering event and its triggered time, and other attributes of RFID-tagged objects.

As depicted in Fig. 5, four kinds of enhanced state blocks are generated, which corresponds to the four kinds of RFID application scenarios. The rectangles indicate the fixed RFID reader/antenna, while the circles indicate the movable RFID reader/antenna. Meantime, the rectangles and circles in solid line represent fixed RFID reading places, while the rectangles and circles in dashed line represent movable RFID reading places. Besides, the down arrows in the rectangles indicate that RFID-tagged objects are staying in the RFID reading places within a time interval, while the right arrows in the circles indicate that RFID-tagged objects directly pass through the RFID reading places. These enhanced state blocks are the basic elements of the final rfid-GDM.

Adapted from our prior work, the enhanced state blocks are formulated as

$$\mathrm{SB} ::= \{FS, MS, FG, MG\} \tag{8}$$

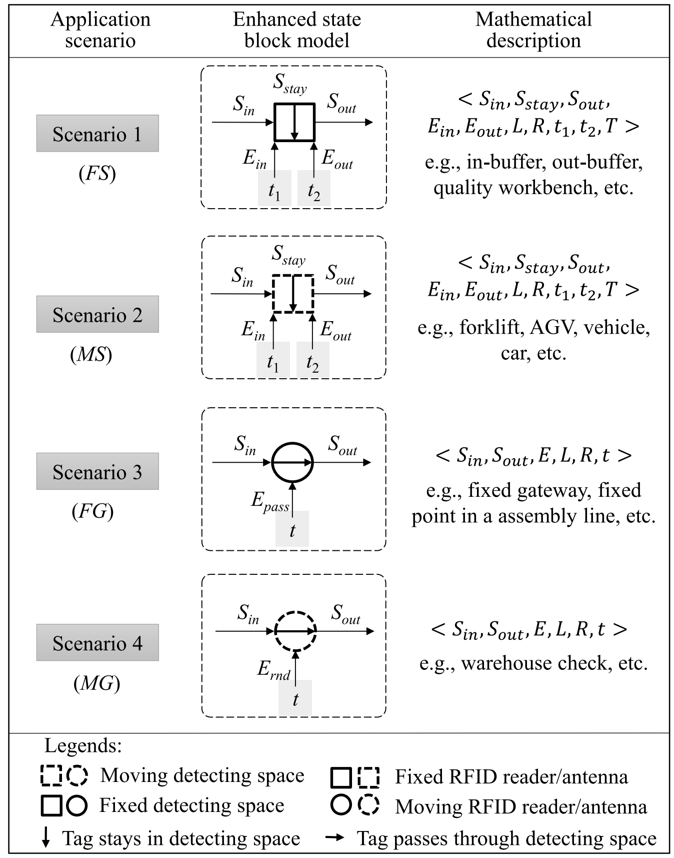



Fig. 5. Four kinds of state blocks.

$$\begin{cases} \mathrm{SB}\big(S_{\mathrm{in}}, S_{\mathrm{stay}}, S_{\mathrm{out}}, E_{\mathrm{in}}, E_{\mathrm{out}}, \\ \qquad L, \mathrm{Fr}, \mathrm{To}, R, t_1, t_2\big), & \mathrm{SB} \in \{FS, MS\} \\ \mathrm{SB}(S_{\mathrm{in}}, S_{\mathrm{out}}, E, L, \mathrm{Fr}, \mathrm{To}, R, t), & \mathrm{SB} \in \{FG, MG\} \end{cases} \tag{9}$$

$$S_{\mathrm{stay}} = \emptyset,\ \ t_2 = t_1, \quad \forall \mathrm{SB} = FG, MG \tag{10}$$

$$\begin{cases} \mathrm{SB\_}SD = \prod_{S_{\mathrm{in}}, S_{\mathrm{stay}}, S_{\mathrm{out}}} (\mathrm{SB}) \\ \mathrm{SB\_}ED = \prod_{E_{\mathrm{in}}, E_{\mathrm{out}}, t_1, t_2} (\mathrm{SB}) \\ \mathrm{SB\_}RD = \prod_{L, \mathrm{Fr}, \mathrm{To}, R} (\mathrm{SB}) \end{cases} \tag{11}$$

where SB is the enhanced state block, $FS$, $MS$, $FG$, and $MG$ represent four kinds of RFID application scenarios. $S_{\mathrm{in}}$, $S_{\mathrm{stay}}$, and $S_{\mathrm{out}}$ stand for the tag-moving-in, tag-staying-in, and tag-moving-out states, respectively. $E_{\mathrm{in}}$ and $E_{\mathrm{out}}$ represent the start event and finish event of a process, respectively. $E$ stands for the pass-through event $E_{\mathrm{pass}}$ or random event $E_{\mathrm{rnd}}$. In all, $E_{\mathrm{in}}$, $E_{\mathrm{out}}$, and $E$ trigger the changes of object's state, such as $S_{\mathrm{in}} \rightarrow S_{\mathrm{stay}}$, $S_{\mathrm{stay}} \rightarrow S_{\mathrm{out}}$, and $S_{\mathrm{in}} \rightarrow S_{\mathrm{out}}$. $L$ stands for the RFID reading place and Fr and To stand for the location where objects come from and where objects finally go. $R$ is the relevant operator, $t_1$, $t_2$, and $t$ are the triggering time of $E_{\mathrm{in}}$, $E_{\mathrm{out}}$, and $E$, respectively. The duration time of tag-staying-in state in state block $FS$ and $MS$ is $T = t_2 - t_1$. There is no tag-staying-in state in state block $FG$ and $MG$. Finally, SB_$SD$, SB_$ED$, and SB_$RD$ stand for the state domain, event domain, and RFID-related domain of the enhanced state blocks.

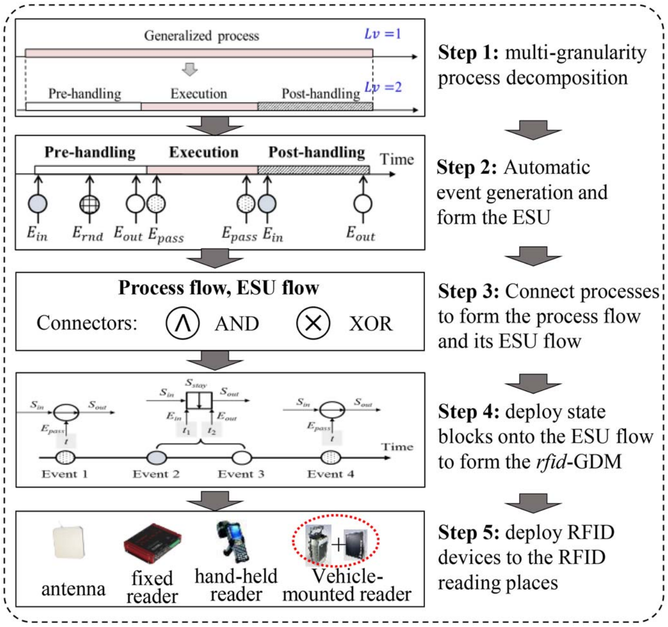



Fig. 6. Implementation framework of rfid-GDM.

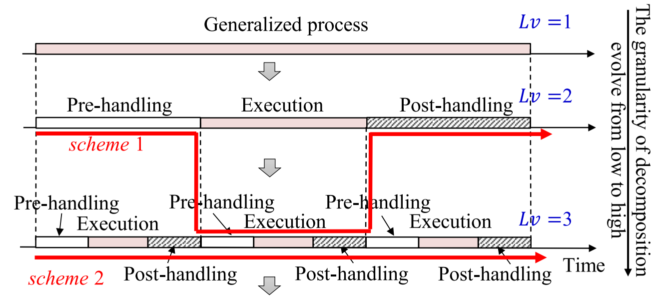



Fig. 7. Process decomposition at different granularities.

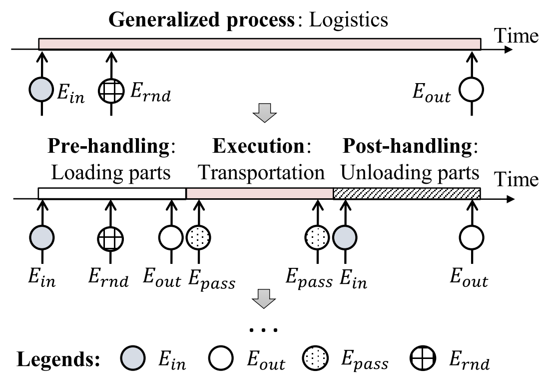



Fig. 8. Automatic events generation mechanism.

## IV. Modeling Methodology of rfid-GDM

### *A. Implementation Framework*

As shown in Fig. 6, the implementation framework includes five steps, which are listed as follows.

*Step 1:* Each process is decomposed into three subprocesses, i.e., prehandling, execution, and post-handling. Each subprocess is further decomposed into three fine-grained subprocesses until satisfying the tracking requirements. The certain decomposition granularity of each process is selected.

*Step 2:* The automatic events generation mechanism is addressed, which extracts events from processes and subprocesses to generate ESUs. The rule is to extract event pairs (start event and finish event, or two contiguous pass-through events) of each process and subprocess. Besides, random events are inserted into the ESUs for random monitoring activities.

*Step 3:* Connect the processes and subprocesses with two kinds of logical connectors to form an RFID-enabled process flow, and connect the ESUs with the connectors to form the corresponding ESU flow.

*Step 4:* Different state blocks are deployed onto the ESU flow to generate the final rfid-GDM, which builds the relationship between the RFID-enabled process flow and the following RFID devices configuration.

*Step 5:* Different kinds of RFID devices are configured and deployed onto the required RFID reading places based on rfid-GDM, forming a tracking scheme for the RFID-enabled process flow.

The rest of Section IV details each step sequentially.

### *B. Multigranularity Process Decomposition*

Processes can be decomposed into different granularities of subprocesses to satisfy the tracking requirements. As shown in Fig. 7, the decomposition rule is that each process is divided into three subprocesses, i.e., prehandling, execution, and post-handling. Each subprocess can be further divided into three fine-grained subprocesses.

The decomposition rule is a reflection of fractal theory. We use set $F$ to represent the decomposition results. The basic subset of $F$ contains three subprocesses and the length of each basic subset is 1/3. Thus, it is a special example of uniform Cantor set, $F = \bigcup_{Lv=1}^{\infty} P^{Lv}$, where $P^{Lv}$ is the set of subprocesses at the $Lv$th decomposition granularity.

A process decomposition solution is achieved by linking the required subprocesses, which is formalized as

$$P_i ::= \left\{P_{i,1}, P_{i,2}, \ldots, P_{i,A_i}\right\} \tag{12}$$

where $P_i$ represents the $i$th process and $P_{i,j}$ is the $j$th subprocess of $P_i$. $A_i$ is the amount of subprocesses, $A_i \leq 3^{Lvm}$ and $Lvm$ is the maximum decomposition granularity, $Lvm \in \mathbf{R}^+$. Two exemplary process decomposition solutions are marked with red lines in Fig. 7.

### *C. Automatic Events Generation Mechanism*

Events trigger the changes of state, position, and other attributes of RFID-tagged objects. As clarified in Definition 2, events can be classified into four kinds, i.e., start event $E_{\text{in}}$, finish event $E_{\text{out}}$, pass-through event $E_{\text{pass}}$, and random event $E_{\text{rnd}}$. Fig. 8 illustrates the automatically generated events of a process at two granularities. A common process is monitored by an event pair $E_{\text{in}}$ and $E_{\text{out}}$, and object entering and leaving the gateways are monitored by two $E_{\text{pass}}$ events. Besides, if a random action happens on the object at a certain time, a random event $E_{\text{rnd}}$ is manually inserted into the process.

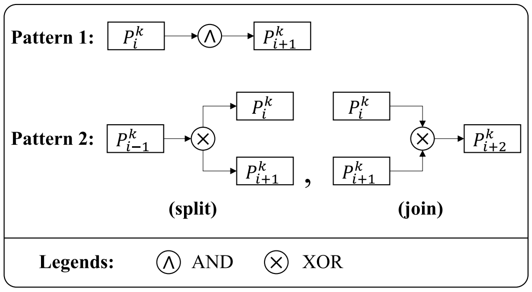



Fig. 9. Two connection patterns.

For example, an object-checking event $E_{\mathrm{rnd}}$ is added into the loading-parts subprocess for random control.

After the automatic events generation, events of each process are further connected sequentially, forming an ESU. An ESU can be formalized as

$$\mathrm{ESU}_i ::= \{E_{i,1}, E_{i,2}, \ldots, E_{i,n_i}\} \tag{13}$$

where $\mathrm{ESU}_i$ represents the $i$th ESU and $E_{i,j}$ represents the $j$th event of $\mathrm{ESU}_i$; $n_i$ is the total amount of events, $n_i = 2A_i + N(E_{\mathrm{rnd}})$, where $N(E_{\mathrm{rnd}})$ is the amount of manually-inserted random events.

*D. Modeling the RFID-Enabled Process Flow*

A process flow is generated by connecting processes and subprocess with two kinds of logical connectors—AND ($\wedge$) and XOR ($\times$). An ESU flow is also generated by connecting ESUs with the connectors. The connectors, which are the basic elements of rfid-GDM, are introduced from event-driven process chain (EPC) method [27]. Note that XOR ($\times$) connector may have one incoming and multiple outgoing directions (split) or multiple incoming and one outgoing direction (join) [28]. Thus, two connection patterns are achieved, as shown in Fig. 9.

*Pattern 1 [Sequence Connection (AND)]:* In this pattern, process $P_{i+1}$ is executed after $P_i$ sequentially.

*Pattern 2 [Exclusive Connection (XOR)]:* In this pattern, process $P_{i+1}$ is a standby choice of the target process $P_i$. If $P_i$ cancels or cannot satisfy the requirements, $P_{i+1}$ will take place.

Thus, RFID-enabled process flow can be formalized as

$$\mathbf{P} ::= \{P_1, P_2, \ldots, P_N\} \bowtie \mathbf{PRT} \tag{14}$$

$$\mathbf{PRT} = \begin{bmatrix} PRT_{1,1} & \cdots & PRT_{1,N} \\ \vdots & \ddots & \vdots \\ PRT_{N,1} & \cdots & PRT_{N,N} \end{bmatrix} \tag{15}$$

where $\mathbf{PRT}$ is the connector matrix and $PRT_{i,j}$ represents the connector between $P_i$ and $P_j$, $PRT_{i,j} \in \{\wedge, \times, 0, 1\}$. If $i = j$, $PRT_{i,j} = 1$, and if there is no relationship between $P_i$ and $P_j$, $PRT_{i,j} = 0$. $\bowtie$ is a natural connector in relational algebra.

As described in (16), there is a one-to-one mapping relationship between process and ESU. Thus, an ESU flow can be achieved by substituting $P_i$ with $\mathrm{ESU}_i$, as formalized

$$P_i \overset{1:1}{\leftrightarrow} \mathrm{ESU}_i \tag{16}$$

$$\mathbf{ESU} = \{\mathrm{ESU}_1, \mathrm{ESU}_2, \ldots, \mathrm{ESU}_N\} \bowtie \mathbf{PRT}. \tag{17}$$

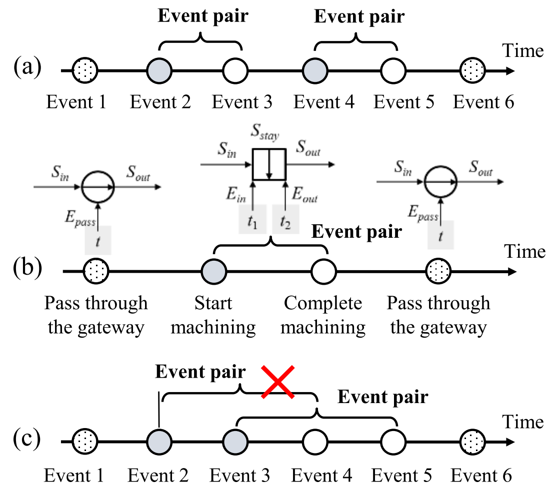



Fig. 10. Deploying state blocks onto the ESUs. (a) Correct event pair generation. (b) Corresponding state block deployment. (c) Error event pair generation.

Specially, when processes are decomposed into fine-grained subprocesses, there are still two connection patterns to connect subprocesses. The fine-grained process flow is formalized as

$$P ::= \{P_{1,1}, P_{1,2}, \ldots, P_{1,A_1}, \ldots, P_{N,1}, P_{N,2}, \ldots, P_{N,A_N}\} \bowtie \mathbf{SRT} \tag{18}$$

$$\mathbf{SRT} = \begin{bmatrix} \mathrm{SRT}_{1,1} & \cdots & \mathrm{SRT}_{1,A_1} \\ \vdots & \ddots & \vdots \\ \mathrm{SRT}_{N,1} & \cdots & \mathrm{SRT}_{N,A_N} \end{bmatrix} \tag{19}$$

where $\mathbf{SRT}$ is the relationship matrix of subprocesses, $\mathrm{SRT}_{i,j} \in \{\wedge, \times, 0, 1\}$. Obviously, $\mathbf{PRT}$ is a submatrix of $\mathbf{SRT}$. Because processes are executed on physical objects, the process flow is a reflection of the physical flow.

*E. Building the Final rfid-GDM*

As shown in Fig. 10(a) and (b), enhanced state blocks are deployed onto the ESU flow according to the types of events and event occurrence places, which bridges the gap between process flow and RFID devices configuration. Of notable, overlap of two event pairs (i.e., two processes) is not allowed because, for the same RFID-tagged object, they cannot be concurrently executed at two RFID reading places, as shown in Fig. 10(c). Thus, stack structure algorithm (first in and last out) is used to automatically deploy enhanced state blocks onto the ESU flow. Fig. 11 describes the pseudocode of the algorithm.

Fig. 12(a) illustrates a simple example to use the algorithm. A batch of RFID-tagged workpieces is transported through the entrance-gateway of a job-shop, and then the workpieces are processed in machines 1 or 2. Their machining quality is further checked at the quality inspection workbench. Finally, they are transported through the exit-gateway of the job-shop to warehouse. The final rfid-GDM is automatically built by connecting the enhanced state blocks logically, as shown in Fig. 12(b). Because the enhanced state blocks contain information about RFID reading places and RFID devices, rfid-GDM helps instruct the configuration of RFID devices for a process flow

$$\mathbf{GDM} ::= \{\mathrm{SB}_1, \mathrm{SB}_2, \ldots, \mathrm{SB}_3, \ldots, \mathrm{SB}_M\} \bowtie \mathbf{BRT} \tag{20}$$

```
Stack<Integer> stack = new Stack<Integer>();  // define a new stack
for (int i=0; i<N; i++)
  for(int j = 0; j < n; j++)
    if (E_{i,j}.E_T = E_in)  stack.push (j);      // E_{i,j} is a start (entrance) event
    else if (E_{i,j}.E_T = E_out)                 // E_{i,j} is an finish (exit) event
        stack.pop ();
        if (E_{i,j}.LT = fixed)                   // fixed event occurrence place
            deploy a state block FS between E_{i,j-1} and E_{i,j};
        else if (E_{i,j}.LT = movable)            // movable event occurrence place
            deploy a state block MS between E_{i,j-1} and E_{i,j} ;
    else if (E_{i,j}.E_T = E_pass)                // E_{i,j} is a pass-through event
        deploy a state block FG onto E_{i,j};
    else                                          // E_{i,j} is a random event
        deploy a state block MG onto E_{i,j};
  end for
end for
```

Fig. 11. Pseudocode of the stack structure algorithm.

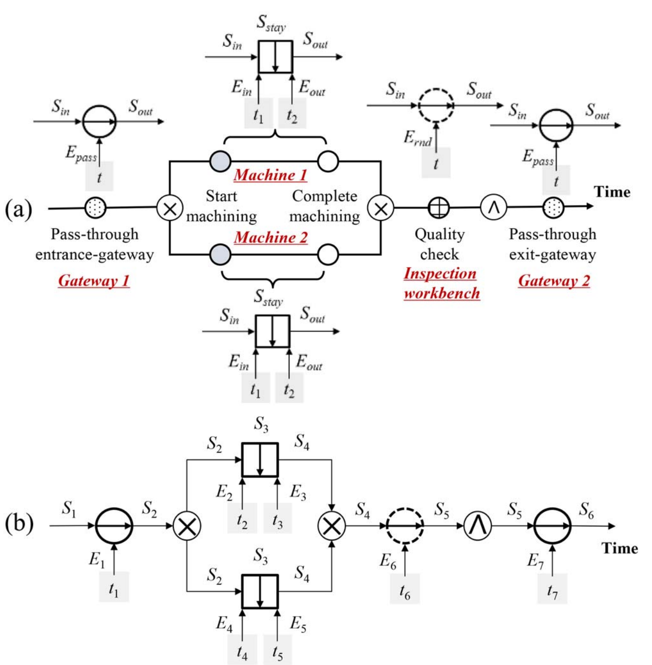


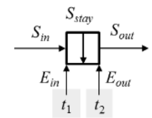
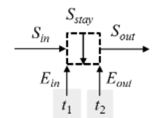
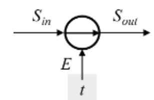
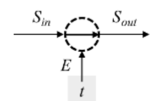

Fig. 12. Example of rfid-GDM. (a) State block deployment. (b) rfid-GDM generation.

where **GDM** represents the rfid-GDM, $\mathrm{SB}_i$ stands for $i$th enhanced state blocks, and **BRT** is the matrix of their relationships. $M$ is the amount of enhanced state blocks derived from the model.

### *F. RFID Devices Configuration Based on rfid-GDM*

Based on rfid-GDM, it can be easily resolved that which kind of RFID device should be deployed in which places. RFID devices include readers and antennas, which are always combined as a suit to realize identification. RFID readers can be classified into three kinds: 1) fixed; 2) hand-held; and 3) vehicle-mounted readers. The fixed reader can connect multiple antennas in a cost-effective way. The amount of antennas the fixed RFID reader can connect depends on its accessible channels. While a vehicle-mounted reader must bundle with a vehicle-mounted antenna, and a hand-held reader is

TABLE I
FOUR KINDS OF RFID DEVICES CONFIGURATION MODES

| Type | State block | Reader | | Antenna | |
|---|---|---|---|---|---|
| | | Type | Num | Type | Num |
| *FS* |  | Fixed | 1, or shared | Fixed | 1 |
| *MS* |  | Vehicle-mounted | 1 | Vehicle-mounted | 1 |
| *FG* |  | Fixed | 1, or shared | Fixed | 1 |
| *MG* |  | Hand-held | 1 | Integrated | – |

internally integrated with an antenna. The RFID antenna identifies RFID-tagged objects through wireless communication with RFID tags. It receives real-time data and transfers them to RFID reader and RFID middleware for data processing. In accordance with the four kinds of enhanced state blocks, four RFID devices configuration modes are achieved, as listed in Table I. Each RFID reading place is equipped with RFID readers and antennas in a certain configuration mode.

The RFID devices configuration mode can be defined as

$$Rc_i(\mathrm{id, name, CM, Pos, WS, MA, MR, RF}) \qquad (21)$$

where id and name represent the configuration id and configuration name, CM is the configuration mode, Pos is the working position where RFID devices are placed, WS is the working state of RFID devices, MA and MR represent the identification accuracy and range of RFID devices, and RF is the shared radio frequency. The solution space of RFID devices configuration for an RFID-enabled process flow is described as

$$\mathbf{Rc} ::= Rc_1 \times Rc_2 \times \ldots \times Rc_M. \qquad (22)$$

When estimating the configuration cost of **Rc**, two aspects should be considered.

1) Each enhanced state block must be configured with an antenna to identify objects. For state block *FS* and *FG*, the position-adjacent fixed antennas can be connected to the same fixed reader to reduce cost. While for state block *MS*, a vehicle-mounted antenna must be connected to a separate vehicle-mounted reader. For state block *MG*, antenna is embedded in the hand-held reader.
2) For the same type of enhanced state blocks in an RFID-enabled process flow, the configuration duplication must be eliminated. For example, two transportation processes (back and forth) in a process flow are deployed with two state blocks *MS* according to the rfid-GDM. However, only one set of vehicle-mounted reader and antenna is

needed, because they correspond to the same RFID reading place. The way to solve this problem is to compare the location of enhanced state blocks.

The total configuration cost of **Rc** is calculated in (23) when considering the above two aspects

$$\begin{cases} C_{\min} = C_{\mathrm{fa}} \cdot M_1 + C_{\mathrm{fr}} \cdot M_1' + (C_{\mathrm{va}} + C_{\mathrm{vr}}) \cdot M_2 + C_{\mathrm{ir}} \cdot M_3 \\ C_{\max} = (C_{at} + C_{rd}) \cdot M_1 + (C_{\mathrm{va}} + C_{\mathrm{vr}}) \cdot M_2 + C_{\mathrm{ir}} \cdot M_3 \end{cases} \quad (23)$$

where $C_{\min}$ and $C_{\max}$ represent the minimum and maximum configuration cost; $C_{\mathrm{fa}}$, $C_{\mathrm{fr}}$, $C_{\mathrm{va}}$, $C_{\mathrm{vr}}$, and $C_{\mathrm{ir}}$ represent the cost of fixed antenna, fixed reader, vehicle-mounted antenna, vehicle-mounted reader, and hand-held reader, respectively; $M_1$, $M_1'$, $M_2$, and $M_3$ stand for the total amount of fixed antennas, fixed readers, vehicle-mounted readers/antennas, and hand-held readers. Obviously, $M_1 \geq M_1'$.

Take the case described in Fig. 12 as an example. Two state blocks *FS* are configured with two fixed antennas and one shared fixed reader, two state blocks *FG* are configured with two fixed antennas and one shared fixed reader, and one state block *MG* is configured with a hand-held reader. Thus, the total configuration cost is $C = 4C_{\mathrm{fa}} + 2C_{\mathrm{fr}} + C_{\mathrm{ir}}$.

### G. Tracking Scheme Based on the rfid-GDM

By integrating the RFID-tagged objects and delivery units, process flow, rfid-GDM, and RFID devices configuration solution, the object-tracking scheme is formalized as

$$\mathrm{TTS} ::= T \bowtie TT \bowtie \mathbf{P} \bowtie \mathbf{GDM} \bowtie \mathbf{Rc} \quad (24)$$

where TTS represents the tracking scheme.

From the product point of view, TTS of a product (termed as $\mathrm{TTS}_P$) can be achieved by synthesizing TTS of all the parts and components, which is formalized as

$$\mathrm{TTS}_P ::= \cup_{i=1}^{i \leq n} \mathrm{TTS}_i \quad (25)$$

where $\mathrm{TTS}_i$ represents the $i$th tracking scheme.

Based on TTS and $\mathrm{TTS}_P$, RFID-tagged parts, components, and products are tracked in their process flows. Besides, the comprehensive state, position, and other attributes of them are monitored. Real-time data from RFID devices are captured and filtered as the input to model to generate semantic information for process control.

## V. Case Study

### A. Case Description

We take the part production in a factory as an example to verify the rfid-GDM. Our two laboratories (Industrial Logistics Laboratory and Micro Manufacturing System Laboratory) are regarded as the warehouse and the job-shop, respectively. Raw materials are stored on the right shelf and finished parts are stored on the left shelf in the warehouse. In the job-shop, two machine tools (no. 1: EMCO Concept Mill 55 and no. 2: MANIX CNC MM-250S3) are applied for milling process, and a quality inspection workbench is used for quality inspection processes. Meantime, there is a gateway in the warehouse and the job-shop, respectively. These fixed places act as the RFID reading places when RFID devices are deployed there. Fig. 13 shows the logic flow of the overall part production processes. After a production order is assigned, raw materials are first checked and prepared in the warehouse, and then they are transported through two gateways to the machine tool's working positions. Then, the machine tools undertake the milling process. After that, finished parts are transported to the quality inspection workbench for quality inspection. The qualified parts are further transported to the warehouse as inventory and the unqualified parts are transported to the scrap area. Finally, qualified parts are checked regularly of their positions on the shelf, total amount, current state, and other attributes in the inventory phase.

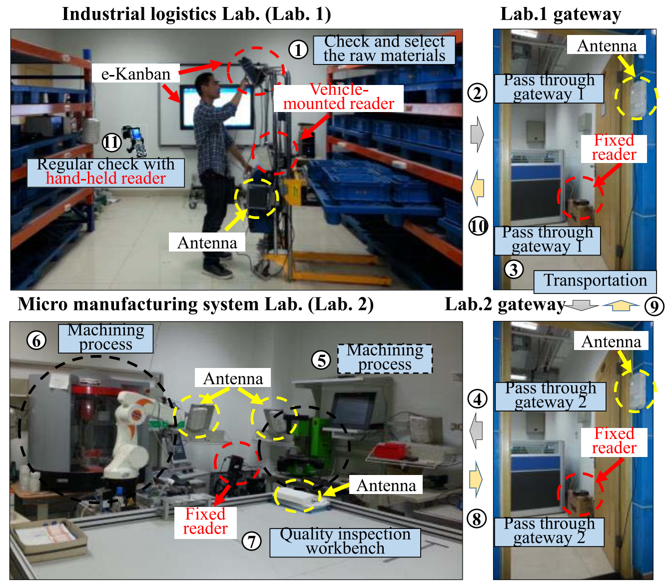



Fig. 13. Illustration of the RFID-enabled process flow.

Tracking the parts and components during their process flows facilitates the real-time process control, such as rapid response to disturbances and dynamic adjustments.

### B. Building the rfid-GDM for RFID-Enabled Process Flow

*Step 1:* Proper decomposition granularity of each process is selected according to the tracking requirements. There are seven up-level processes in this case, including a raw material check process, two transportation processes, two machining processes, a quality inspection process, and an inventory check process. The transportation process is decomposed into three subprocesses: 1) loading goods; 2) transportation execution; and 3) unloading goods. The machining process is decomposed into three subprocesses too: 1) prehandling in the in-buffer; 2) machining execution; and 3) post-handling in the out-buffer.

*Step 2:* Events of each process and subprocess are generated to form an ESU according to the automatic events generation mechanism. For the up-level raw-material-check, quality-check, and inventory-check processes, a random event is extracted from each of them. For the low-level loading-goods, uploading-goods, prehandling, machining-execution, and post-handling subprocesses, start events and finish events

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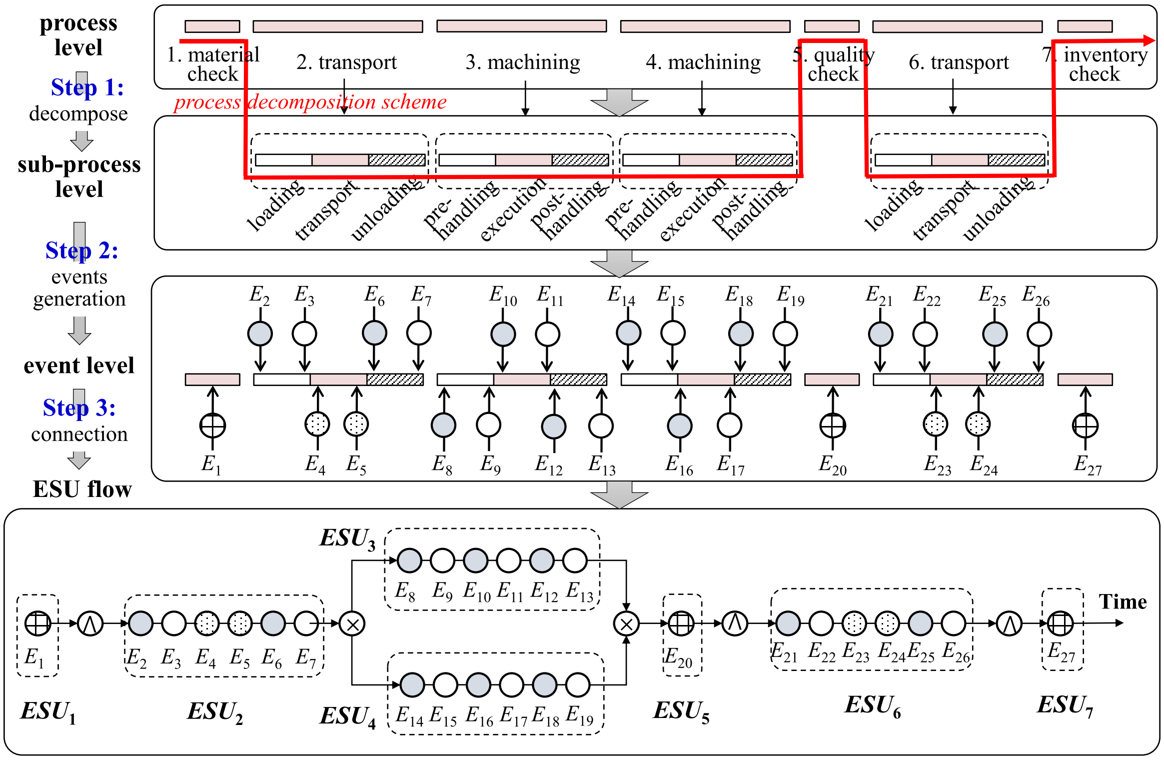


Fig. 14. Illustration from steps 1–3.

are extracted as event pairs from each of them. For the low-level transportation-execution subprocess, two pass-through-gateway events are extracted from it. On this basis, seven ESUs and 27 relevant events are generated. The attributes of processes/subprocesses and events are formalized.

*Step 3:* After the process decomposition and the events generation, two kinds of connectors are applied to connect multiple processes/subprocesses into a process flow. Besides, an ESU flow is generated by connecting the ESUs with the connectors. The graphical deduction procedures from steps 1–3 are illustrated in Fig. 14, and the mathematical descriptions of the process flow and the ESU flow are presented as

$$\mathbf{P} ::= \{P_1, P_2, \ldots, P_7\} \bowtie \mathbf{PRT} \tag{26}$$

$$\mathbf{ESU} ::= \{\mathrm{ESU}_1, \mathrm{ESU}_2, \ldots, \mathrm{ESU}_7\} \bowtie \mathbf{PRT} \tag{27}$$

$$\mathbf{PRT} ::= \begin{bmatrix} 1 & \wedge & 0 & 0 & 0 & 0 & 0 \\ \wedge & 1 & \times & 0 & 0 & 0 & 0 \\ 0 & \times & 1 & 0 & \times & 0 & 0 \\ 0 & 0 & 0 & 1 & \times & 0 & 0 \\ 0 & 0 & \times & \times & 1 & \wedge & 0 \\ 0 & 0 & 0 & 0 & \wedge & 1 & \wedge \\ 0 & 0 & 0 & 0 & 0 & \wedge & 1 \end{bmatrix}. \tag{28}$$

*Step 4:* Four kinds of enhanced state blocks are automatically deployed onto the ESU flow, as shown in Fig. 15(a). By connecting the enhanced state blocks logically, the final rfid-GDM is built, as shown in Fig. 15(b).

*Step 5:* According to the rfid-GDM, RFID devices are deployed in our laboratories to collect real-time data. The fixed reader (Alien ALR-9900+) and antenna (Alien ALR-8696C) are deployed in the fixed RFID reading places, such as gateways, in-buffers and out-buffers of the machine tools, and inspection workbench, forming eight fixed detection spaces to monitor the entrance and exit of RFID-tagged parts. The maximum number of accessible channels of the fixed readers is 4.

Considering the configuration cost and the position closeness, eight fixed detection spaces are configured with eight antennas and four readers according to the rfid-GDM. A suit of vehicle-mounted reader (Intermec IV7) and antenna (Intermec IA33E) are installed on the forklift, forming a movable detection space. Three hand-held readers (Teklogix Pro7527) are equipped in the warehouse and quality inspection workbench for inventory check and quality inspection. The actual RFID devices configuration is shown in Fig. 13. All the deployed RFID devices share the same radio frequency (915 MHz). The configuration solution of RFID devices is formalized as $\mathbf{Rc} = Rc_1 \times Rc_2 \times \ldots \times Rc_{17}$, where, for instance, the configuration of no. 1 machine tool's RFID reading place is formalized as

$$Rc_7 = \{3, \mathrm{manu.1}, \mathrm{Mode1}, \mathrm{EMCOMill55}, \\ \mathrm{atwork}, \mathrm{accurate}, 20\ \mathrm{mm}, 915\ \mathrm{MHz}\}.$$

The minimum total cost of this configuration solution is $C = 8C_{\mathrm{fa}} + 4C_{\mathrm{fr}} + C_{\mathrm{va}} + C_{\mathrm{vr}} + 3C_{\mathrm{ir}} = 8 \times 1000 + 4 \times 8500 + 18200 + 3800 + 2 \times 12000 = 300000\mathrm{RMB}$.

After the above five steps, tracking scheme based on the rfid-GDM can be generated and the overall RFID-enabled process flow starts being tracked. Furthermore, process-related real-time data are collected, and auto-ID computing technology is applied for fusing data into real-time semantic information. Production plans and directives are judged whether they are executed as expected. Thus, the tracking scheme closes the loop of production planning and production execution. Once

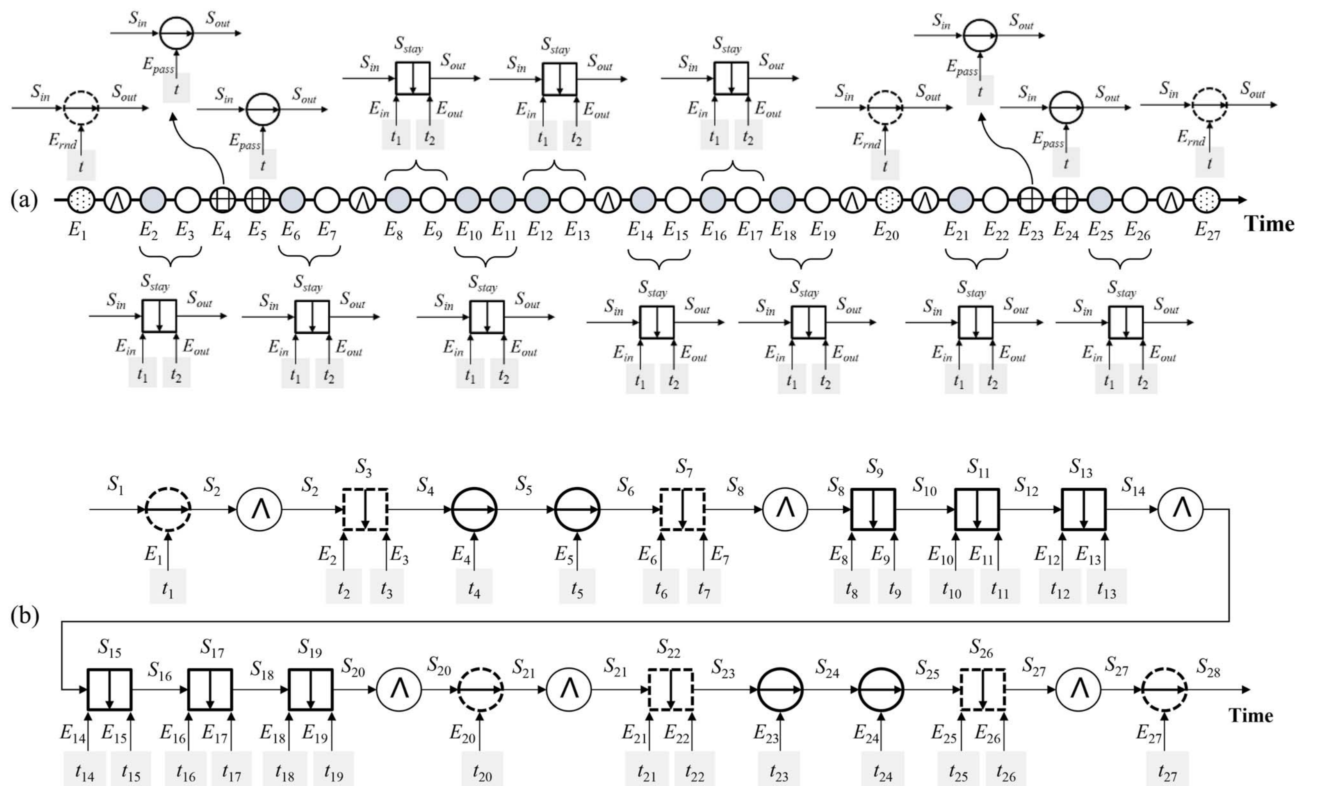


Fig. 15. (a) State block deployment and (b) rfid-GDM generation.

an unexpected event or deviation happens, it can be detected in real-time, which will avoid negative influence on the following processes. Besides, workload of operators and machine tools can be achieved to indicate the resource efficiency, and instruct the production planning and resource allocation in turn.

## VI. Discussion

### A. Model Assessment

The actual process flow is graphically mapped into the rfid-GDM, which has the following three functions.

1) rfid-GDM provides four kinds of enhanced state blocks and two kinds of connectors to illustrate and visualize an RFID-enabled process flow. According to the specific tracking requirements, the RFID-enabled process flow can be built at different granularities, which allows to configure RFID devices at different levels.
2) rfid-GDM establishes the inherent relationship between the RFID-enabled process flow and the RFID devices configuration by applying the enhanced state blocks. Based on that, industrial practitioners can deploy on-demand RFID devices with the minimal cost.
3) rfid-GDM builds the theoretical basis for the development of RFID-enabled tracking systems, which would provide a graphic interface for users to build RFID-enabled process flows in diverse industrial fields, and associate real-time data with the flows for object tracking dynamically.

Furthermore, complex network analytics is applied to assess the utility of rfid-GDM. A similar case of tracking network for job-shop-type material flow has been studied in [29], and the evaluation metrics are proposed to analyze the performance of the tracking network. This paper extends it and develops new metrics to evaluate rfid-GDM.

As shown in Fig. 16, rfid-GDM is mapped into a tracking network. The mapping rules are listed as follows.

1) Four kinds of enhanced state blocks are mapped into the top-level network nodes $P_i$.
2) The attributes (e.g., state, event, location, operator, start/finish time, reader, and antenna) of each top-level node are mapped into the bottom-level network nodes $S_{\text{in}}$, $S_{\text{stay}}$, $S_{\text{out}}$, $E_{\text{in}}$, $E_{\text{out}}$, $R$, $L$, $t_1$, and $t_2$.
3) The logic relationships among the top-level network nodes (i.e., two kinds of connectors) are mapped into the top-level network edges, while the logic relationships among different kinds of bottom-level network nodes are also mapped into the top-level network edges.
4) The time-sequential relationships among the same kind of bottom-level network nodes are mapped into the bottom-level network edges.

Thus, the tracking network is formulated as $G = (V, E)$, where $V$ and $E$ represent the nodes set and edges set, respectively. As shown in Fig. 17, the rfid-GDM is mapped into a tracking network by implementing the above mapping rules on the demonstrative case. It can be seen that the network is heterogeneous. Table II lists the metrics to assess the performance of rfid-GDM. Further information about the mapping procedures and the detailed metric parameters can be referred in [29]. From the results, it can be seen that $RE2$, $RE6$, and $RE9$ have larger degrees ($k_{RE2} = 13$, $k_{RE6} = 10$, $k_{RE9} = 10$),

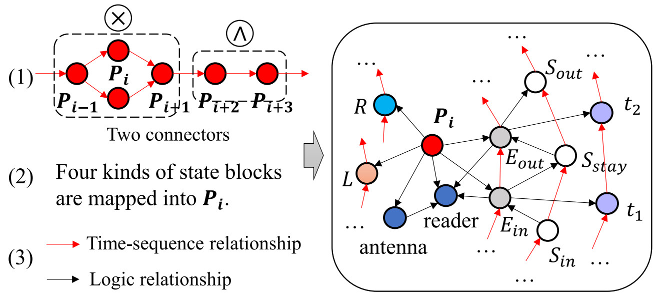


Fig. 16. Mapping procedures.

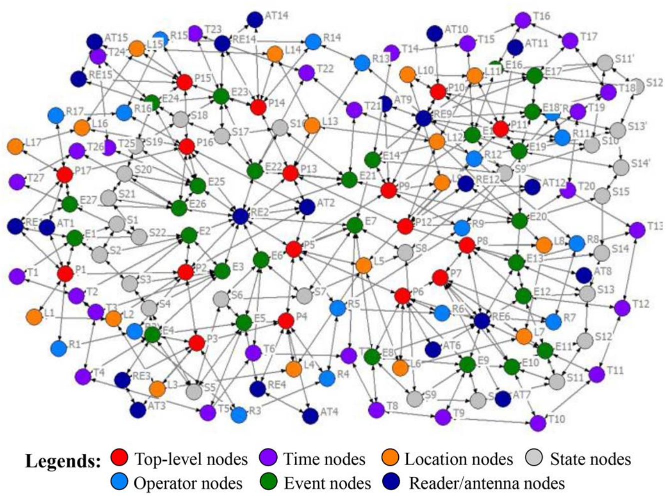


Fig. 17. Tracking network derived from rfid-GDM.

which means that the RFID readers deployed onto the vehicle and the two machine tools are relative more important than others. The capability of these RFID readers determines the overall tracking efficiency. The average clustering coefficient of the tracking network is 0.215 and it indicates that the network nodes are relatively loose-linked. *RE*2 and *P*5 (the fifth enhanced state block) have larger betweenness, which means that they act as the important bridges to connect other nodes. The break-down of *RE*2 and *P*5 will cause disruptions to the network. The minimal network reliability is $\theta = 0.989$, and it means that the tracking network derived from rfid-GDM has high invulnerability. In all, these metrics demonstrate that rfid-GDM is efficient for tracking the RFID-enabled process flow. More metrics will be developed to evaluate rfid-GDM in our future work.

### *B. Model Comparison*

*1) Comparison With Our Prior Model:* Compared with our prior model [6], three advantages of rfid-GDM are declared.

1) rfid-GDM emphasizes that events trigger the changes of object's state, position, and other attributes. Enhanced state blocks, which integrate the triggering events, are proposed to handle this situation. They are deployed onto the process flow reasonably based on the ESUs. While in the prior model, state blocks are sometimes vaguely deployed onto the process flow.
2) rfid-GDM discusses two connectors (AND and XOR) to model a generalized process flow. While the prior model only discusses the AND connector for the material flows in the job-shop.
3) In the prior model, process decomposition is with heavy human intervention, and the process is irregularly divided into subprocesses, which increases the difficulty of events generation. While in the rfid-GDM, a process is divided into three subprocesses by standard.

TABLE II
PERFORMANCE EVALUATION METRICS

| Metric | Formula | Description |
|---|---|---|
| Node degree $k_i$ | $k_i = k_i^{in} + k_i^{out}$ [29] | It measures how many edges are connected with the node. |
| Clustering coefficient $c_i$ | $c_i = \frac{2e_i}{k_i(k_i-1)} = \frac{\sum_{j,m\in N} a_{ij}a_{jm}a_{mi}}{k_i(k_i-1)}$ [29] | It indicates how many adjacent nodes surround the node. |
| Average clustering coefficient $C$ | $C = \frac{1}{N}\sum_{i=1}^{N} c_i$ [29] | It describes the overall linkage density of the network. |
| Node betweenness $b_i$ | $b_i = \sum_{m,n}\frac{g_{mn}(i)}{g_{mn}}$, $m \neq n, m, n \neq i$ | $g_{mn}(i)$ represents the number of the shortest paths connecting node $m$, $n$ and passing through $i$. It measures the node importance. |
| Network reliability $\theta$ | $\theta = R_1/R_0, R = \frac{1}{N(N-1)}\sum_{i,j\in G, i\neq j}\frac{1}{\tau_{ij}}$, ($\tau_{ij}$=1, if node $i$ and $j$ connect) | It describes the anti-attack capability of network. $R_0$ and $R_1$ are the original value and the value when moving one node. The bigger the value of $\theta$ ($0 \leq \theta \leq 1$), the more invulnerable the network is. |

TABLE III
COMPARISONS OF RFID-GDM AND OTHER MODELS

| Comparison | rfid-GDM | EPC | Petri net | BPMN |
|---|---|---|---|---|
| Event-driven | Yes | Yes | No | No |
| Tracking the real-time progress | Yes | Yes | No | No |
| Application domain | process flow | workflow | workflow | workflow |
| Assisting the RFID device configuration | Yes | No | No | No |
| Usability | Easy | Relatively easy | A little hard | A little hard |

*2) Comparison With Other Models:* Similar to the business process modeling methods, such as EPC [27], Petri net [30], and business process modeling and notations (BPMNs) [31], rfid-GDM deals with process flow modeling and analyzing. The idea of graphical deduction modeling for RFID-enabled process flow is inspired by these business process modeling methods. However, there are three differences between the rfid-GDM and other business process modeling methods.

1) Concerning RFID-enabled process flow modeling and tracking, it is difficult for EPC, Petri net, and BPMN to describe explicitly the event-triggered changes of state, position, and other attributes of RFID-tagged objects.
2) The relationship between the process flow and the RFID devices configuration is not involved in EPC, Petri net, and BPMN, while rfid-GDM articulates the inherent mapping relationship.

3) Processes defined in EPC, Petri net, and BPMN are often logical business processes, while processes defined in rfid-GDM can be the operations executed on the objects. In some sense, the process flow in rfid-GDM is like an RFID-enabled process plan.

Table III describes the detailed comparisons of rfid-GDM and other models.

### C. Model Improvement

Although rfid-GDM has been proved feasible to model and configure the RFID-enabled process flow for physical objects tracking, there are still some limitations.

1) Auto-ID computing technology and the dynamic manufacturing database for real-time data processing are not detailed in the rfid-GDM. Besides, real-time process control and unexpected events handling are not specified, which are the goals of process flow modeling and physical objects tracking.
2) When applied in other industrial fields, such as process industries and supply chains, the process decomposition method of rfid-GDM may be different, but the nature that events trigger the changes of object's state, position, and other attributes is the same. The elements in the rfid-GDM, i.e., enhanced state blocks and connectors, are generic. The applications of rfid-GDM in other industrial fields should be discussed in our future work.
3) An RFID-enabled tracking system should be developed for modeling the real process flows and tracking the RFID-tagged objects. Enhanced state blocks and connectors will function as the graphical units in the system. By dragging these units into a canvas, and linking and defining them, rfid-GDM can be generated.

## VII. Conclusion

This paper proposes an enhanced rfid-GDM to describe the RFID-enabled process flow, which is helpful for physical object tracking. Four kinds of RFID application scenarios and the corresponding enhanced state blocks are addressed. The modeling methodology of rfid-GDM, which includes five steps, is introduced. First, process is decomposed into three subprocesses to satisfy the tracking requirements. Second, events of the process to be monitored are extracted to form an ESU. Third, an ESU flow is formed by connecting ESUs with two kinds of connectors. Then, enhanced state blocks are deployed onto the ESUs to generate the final rfid-GDM. Finally, RFID devices are configured to realize real-time data capturing. After that, tracking scheme based on rfid-GDM is generated for real-time tracking. rfid-GDM provides an explicit way to build the RFID-enabled process flow, and further bridges the gap between the process flow and the RFID devices configuration. It is expected that the proposed model can be applied in diverse fields where objects are tracked throughout the process flow.

## Acknowledgment

The authors would like to thank the anonymous referees for their helpful comments and suggestions.

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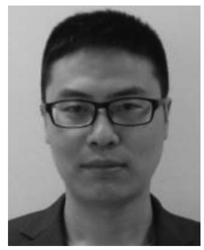

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