Int J Adv Manuf Technol (2012) 60:225–236
DOI 10.1007/s00170-011-3568-z

ORIGINAL ARTICLE

RFID-based colored Petri net applied for quality monitoring in manufacturing system

Yaqiong Lv · C. K. M. Lee · H. K. Chan · W. H. Ip

Received: 13 April 2011 / Accepted: 3 August 2011 / Published online: 8 September 2011

Abstract Product quality is difficult to be traced and monitored in the distributed manufacturing network. This paper proposes and develops a new RFID-based CPN modeling method where the colored tokens are evolved to color-tagged tokens carrying the product information of real-time status. With this new real-time modeling method, the performance of manufacturing systems such as yield rate and throughput can be realized. In this paper, a case study has been conducted to examine the feasibility and effectiveness of the proposed method. The simulation results show that the new modeling method is able to complete the preliminary real-time quality status analysis of a manufacturing system so as to handle dynamic and stochastic manufacturing network effectively and enable decision making for process improvement.

Y. Q. Lv (✉) · C. K. M. Lee
Mechanical and Aerospace Engineering,
Nanyang Technological University,
50 Nanyang Avenue, Singapore 639798, Singapore
e-mail: lvya0001@e.ntu.edu.sg

C. K. M. Lee
e-mail: CKMLee@ntu.edu.sg

H. K. Chan
Norwich Business School,
University of East Anglia, Norwich, Norfolk, UK
e-mail: h.chan@uea.ac.uk

W. H. Ip
Department of Industrial and Systems Engineering,
The Hong Kong Polytechnic University,
Hung Hom, Kowloon, Hong Kong
e-mail: mfwhip@inet.polyu.edu.hk

Keywords RFID · Colored Petri net modeling · Manufacturing process · Product quality monitoring · Process quality control · Real-time analysis

1 Introduction

Radio-frequency identification (RFID) is a form of automatic identification and data capture (AIDC) technology that has been developed since more than half a century ago. In the last few years, RFID shows its tremendous potential which has begun to be used to deliver new century solutions to the way manufacturers and retailers do business in the food and consumer packaged goods industry. Like Wal-Mart, Albertsons, Metro, and Target, four largest retailers in the USA, require their top 100 suppliers to deliver all pallets and cases with RFID tags, starting in 2005. Hence, to comply with these requirements, many suppliers find that they need to make broad investments in RFID techniques. In the manufacturing area, more and more implementation on RFID for products' quality tracking has been introduced.

In general, when the quality tracking or monitoring is undergone, the corresponding data collection and analysis is obtained so as to have continuous improvement. Before the system is implemented, the system architecture should be set up and an efficient modeling method should be selected for detailed analysis. Petri net formalism for modeling was one of the comprehensive approaches to deal with concurrency and synchronization. The doctoral dissertation of Carl Adam Petri discussed the basis for a theory of communication between synchronous components of a computer system [1]. Petri was particularly concerned with describing the causal relationships between events [2]. The basis of Petri nets is to model graphically and test analytically the discrete events of concurrent operations within a system. Recently, Petri net has extended to include different features and functions for specific modeling purposes, among which colored Petri net (CPN), combining ordinary Petri net with a high-level programming language, has been proven with promised result for complex system modeling and analysis.

This study explores the possibility to combine CPN and RFID for real-time data analysis. During production process, the warning signal for abnormality should be triggered to make production engineers alert about the quality problems. This research will focus on modeling the system dynamics with CPN and implementing the system by capturing real-time data and product status with RFID. The synergy of combining two technologies is realized through the seamless link between both technology and its application on real-time quality monitoring in the manufacturing system [3].

This paper is organized as follows: Section 2 describes literature review on both RFID and CPN technology and together with the research gap implied from the literature review. Section 3 depicts the methodology for the new RFID-based CPN network. Section 4 is a practical case study with the introduced modeling method. And the conclusion part is the last section.

2 Literature review

2.1 Latest applications of RFID technology

RFID use radio wave for identifying and tracing a person, an animal, or a product. RFID shows its huge advantage and breakthrough in information tracking applications [4–6]. RFID technology has the important features such as real time, prompt read/write, portability, good penetration, long life time, good environmental resistance, and high-capacity store, and thus it may be applied in both automatic production and business management [7].

Tracking goods in the supply chain and manufacturing system is the most important application for RFID technology [8]. Regattieri [9] mentioned that the RFID technology is currently introduced to improve information accuracy and data transmission speed throughout the business flow, including shop floors management system and marketing system and management processes system. RFID also can find its application in controlling the access to buildings and networks. Companies all over the world implement RFID technology to improve production efficiency and security features. Meanwhile, RFID applications are used to be integrated in some intelligent software to help fulfill the automatic routine decision making. Compared with the other most commonly used AIDC technology—bar code, Keskilammi [10] has proven that for some application systems which could replace bar code with RFID, they might raise the overall management efficiency.

Based on the various industry areas that are featured in the related literature of [11], the RFID applications appear outstanding in aviation, building management, library, service, construction, health and logistics, and supply chain management. Lee [12] proposed a genetic algorithm to determine the location of collection point, and RFID is used so as to count the quantity of collected items in collection point and it can send the signal to central return center so as to arrange the vehicle or resource to ship back from collection point to return center. With the high accuracy on product track and tracing, more and more manufacturing system implements RFID technology so as to monitor the quality of products. Lyu and Chang [13] has given out a framework of quality assurance system integrating RFID technology that allows on-site staff to monitor complicated variations in production process by handling numerous possible abnormalities simultaneously. As RFID can capture enormous amount of data, researchers work on data framework and architecture to achieve data aggregation and optimization [14–17].

2.2 Recent research of colored Petri net

CPN is a graphical modeling language with a well-defined semantics, which has been proven to be a suitable approach to model manufacturing system. CPN as a natural extension of the classic Petri net has been developed for supporting hierarchical construction of the large models representing real systems [18, 19]. Two reasons of using CPN for manufacturing system modeling [20–22] are that (1) CPN can reduce the size of a net. (2) CPN [23] can model similar components/subsystems and avoid having a separate net representing each part. Distribution system is complex and difficult to model, and research used colored Petri net to model the system with inference mechanism. Chen [24] applied Petri net with best first-search techniques to design the optimal switching operation which helps solve feeder overload problem. Mujica [25] explored the revisiting state space with time-colored Petri net to improve the performance of the manufacturing system. As manufacturing system needs to adapt to the latest business environment, Petri net is proposed as a systematic approach to analyze the synthesis of flexible cell in manufacturing [26]. Reconfigurability is one of the main recent characteristics of production system, and [27] defines CPN with changeable structure is important for firms and the easy modification of the current structure of the CPN model are realized in the case study. Due to the dynamic of manufacturing system, Lin and Lee [28] have proposed to have a scheduling and control level with CPN as well as a suitable dispatching rule; their proposed approach can identify the pallet flow within the flexible manufacturing cell.

2.3 Research gap

Researchers have conducted comprehensive research about the application of RFID in different domain. However, there's less research about modeling the dynamic status of the objects in the workflow with RFID for quality improvement. It is expected to have the synergy of combining RFID together with color token for manufacturing system by improving the yield rate and throughput simultaneously. It is realized that enterprises find difficulty to improve yield rate and throughput at the same time with the same amount of resource. In addition, there is a lack of methodology to analyze the system through exchanging the real-time information with ubiquitous technology so as to enable system analysis by CPN.

3 Methodology

This paper proposed RFID-based CPN to improve the quality of the system without scarifying any one of the performance (either throughput or yield rate). Figure 1 shows the structure of RFID system and colored Petri net, respectively. RFID system elements, which are connected bidirectional with CPN, can update information promptly with real-time action. The traditional colored Petri net, which acts as a modeling and simulation method, is a single direction flow analysis and decision can only be obtained after running out the simulation. Figure 1 shows the roles of the elements in both RFID and CPN. RFID tag and color token stored the information of the product in manufacturing system, and both of them can update the status of the product simultaneously. The proposed approach is to combine RFID for CPN so RFID tag can easily realize the accurate real-time data collection, and color token is effectively implemented for simulation analysis such that the synergy of combining both technologies can be obtained.

Under this situation, simulation results from CPN can help update the RFID database in a more precise way, and both databases can be synchronized. This research develops the RFID-based colored Petri net to finish the accurate real-time analysis for manufacturing system so as to realize automatic abnormity handling and enhance decision making.

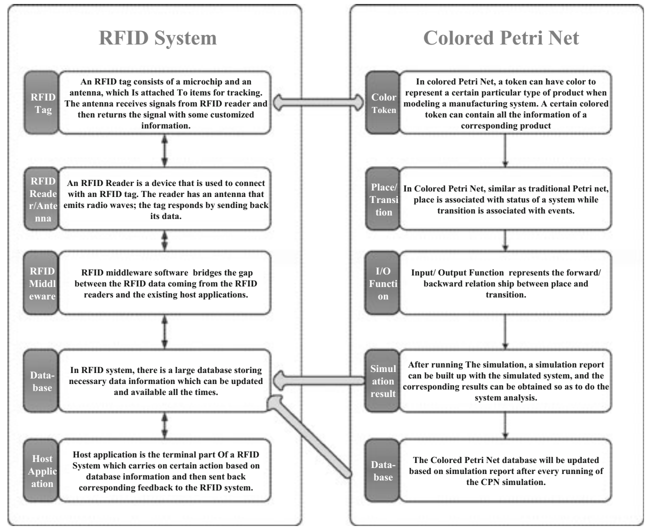


Fig. 1 Information representation and exchange between RFID and CPN

3.1 Color token—product status

In colored Petri net [29], a token can have a color to represent a certain particular type of product when modeling a manufacturing system. A certain colored token can contain all the information of a corresponding product. Figure 2a shows a simple manufacturing process which illustrates the manufacturing process of a part. Even though it is a simple process shown below, engineers need at least three nets to describe it

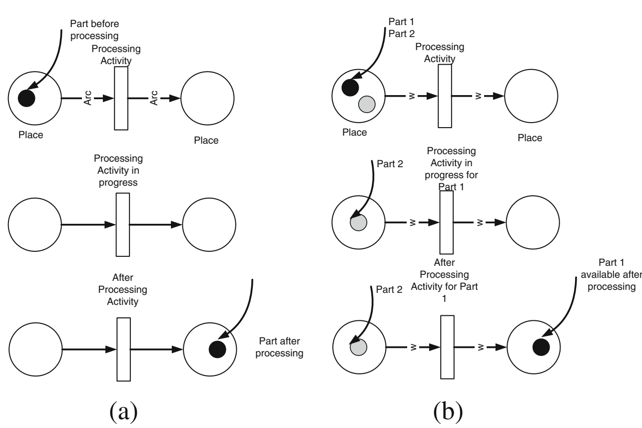


Fig. 2 **a** A simple Petri net for a manufacturing process; **b** a simple CPN example for a manufacturing process

clearly. If there is more than one part for processing, the nets have to be replicated according to the number of parts. Under this condition, even such simple process will lead to a considerable large net. Figure 2b shows the advantages of using CPN for size reduction. When modeling similar parts in a system, there is no need to build many separate nets as original Petri net, and CPN can integrate all in one.

A formal definition of CPN is as follows [30]:

A colored Petri net $R = P, T, C, I^+, I^-, M$ is defined by:

- P is a finite set of places;
- T is a finite set of transitions with $P \bigcup T \neq \emptyset$ and $P \bigcap T = \emptyset$;
- C is the color function from $P \bigcup T$ to W, where W is some finite set of finite and not empty sets. An item of $C(s)$ is called a color of s and $C(s)$ is called the color set of s;
- $I^+(I^-)$ is the forward (backward) incidence matrix of $P \times T$, where $I^+(p,t)$ is a function from $C(p) \times C(t)$ to N. N is the set of non-negative integers;
- M is the initial marking of the net and is a vector of P, where $M(p)$ is a function from $C(p)$ to N.

Similar as the original Petri net, each place in CPN is associated with a local state or condition of the system while each transition is associated with an event of the system. The set of place markings is the marking of the CPN. Unlike the original Petri net, the connections between places and transitions are labeled by a function of color. Each place can contain a set of tokens with colors. The place's marking is the number of each color in that place [20].

Figure 3 shows a simple process on how the colored token represents the status of the product. In initial marking M0, there are three colored tokens—two units of part 1 (blue) and one unit of part 2 (green) in the start place. One part 1 goes into the processing activity first, and there are two left in the start place. If the processing activity goes smoothly, the M1 shows there will be one part 1 available after processing. However, if something wrong will happen during the processing activity, the output token color will change as shown in M2, which means there is one part 1 failure after processing. In summary, within the colored token running process, the color will stay the same if the processing activity goes smoothly while color changing indicates failure modes' happening in the last transition activity.

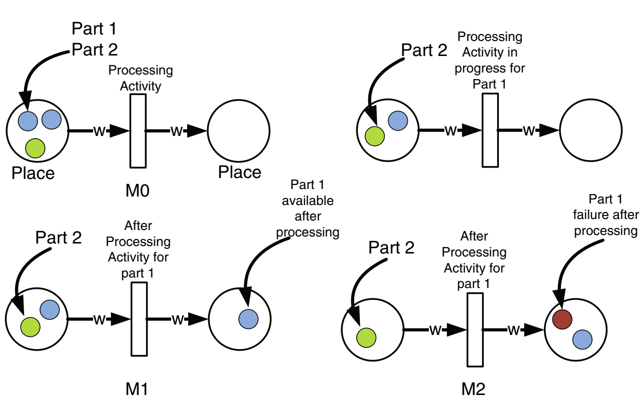


Fig. 3 Color token represent product status

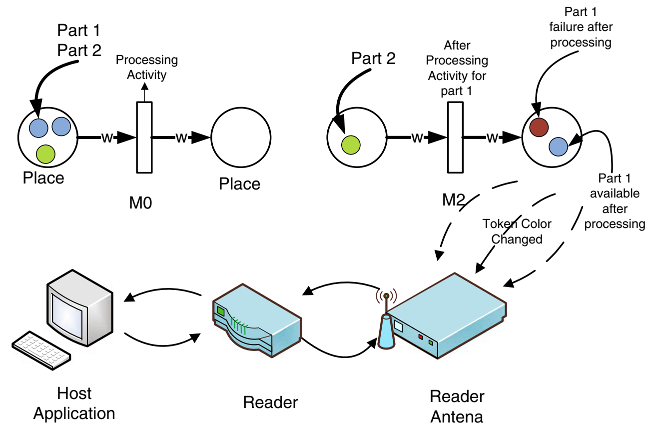


Fig. 4 The linkage between CPN and RFID

3.2 RFID-tagged token link with RFID system

In RFID-based colored Petri net, the colored token needs to be tagged so as to bridge with the RFID system. Figure 4 shows the linkage between them. The tokens color information inside this system are stored and synchronized with the RFID tag, once the color of the token changes, the reader antenna sensor receives a signal that the status of the product changed. Then the reader will rewrite the stored information and sent the new data to host application. Host application will feedback a corresponding processing activity on the colored changed token (for example, the failure part needs rework by reentrant).

3.3 RFID-based colored Petri net architecture

To integrate the two technologies, the synchronization needs to be considerate; the RFID-based colored Petri net architecture is shown in Fig. 5:

Color-tagged token Color-tagged token is the first time introduced concept. Token with various colors in manufacturing system can represent different job type

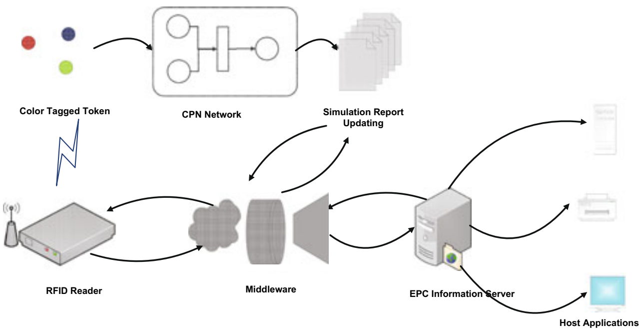


Fig. 5 RFID-based colored Petri net architecture

and store the job information including customer data, job processing routine, or any related information. Color-tagged token actually means all the colored tokens' information will undergo real-time synchronization with the RFID tag. Hence, the color-tagged token can get the real-time information from the RFID system so as to update the information promptly.

CPN network and color token As shown in Fig. 6, color-tagged token will go through the CPN network, after a certain processing activity, a necessary quality rule will be checked so as to guarantee that the products are qualified, among which the color respects the status of the product. And then the RFID reader will read the color change signal and decoding. In Fig. 6, the first figure shows the structure of an example CPN net-

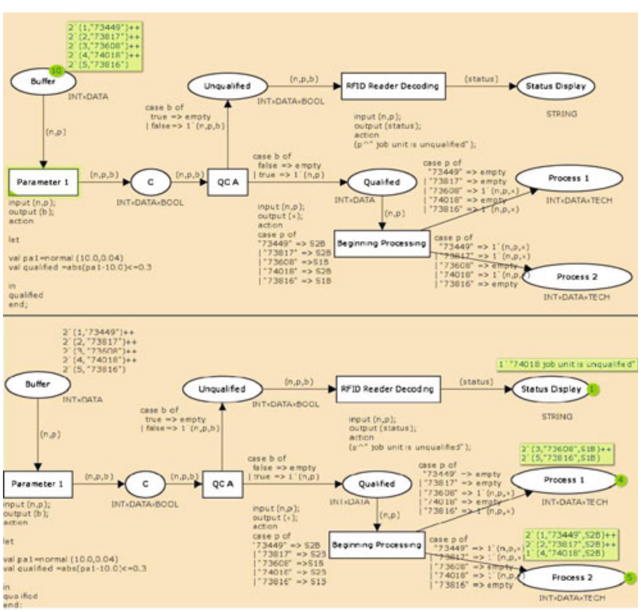


Fig. 6 The CPN network application

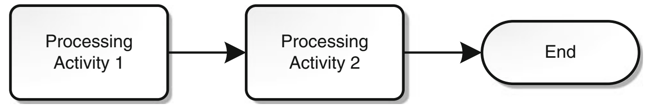


Fig. 7 Simple process example

work, with the color-tagged tokens in the input place. In the output place, the connected RFID display part will show the visualized results "one '74018' job is unqualified".

Simulation report The value after symbol "@" shows the time stamp. When the model starts running, tokens will be transferred from one place to another, and at each place a certain time stamp for each token is recorded. Under this condition, a simulation report on the processing time and throughput can be obtained when corresponding time function and time delay was preloaded. When connected with the RFID system, the time function and time delay can be obtained promptly. In addition, the simulation report can export a real-time analysis or decision making. Simultaneously, the simulation report will directly be imported to the RFID middleware so as to give a signal to host application; when host application gets the analysis results, a corresponding feedback will be sent to RFID reader so as to confirm the status updating. Meanwhile, the simulation report will be updated again.

RFID tag [31] All the items will be tagged after the first quality check in manufacturing system by the QC team, the initial information are updated in database. An RFID tag consists of a microchip, which is connected to an antenna and contains a certain amount of data. In this system, the RFID tag contains all the information from color tokens. Once the color tokens' color changed, the stored information in color tokens will update again. Meanwhile, the corresponding RFID tag will get the information so as to update the linked data table in database. After that, the host application

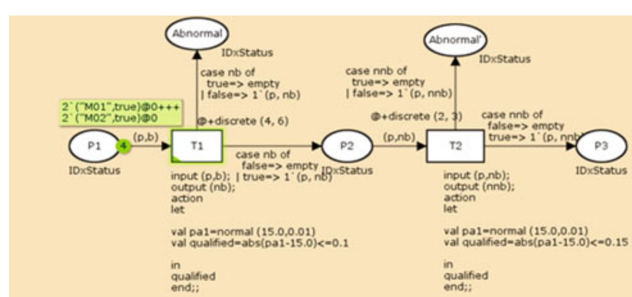


Fig. 8 CPN network for simple example

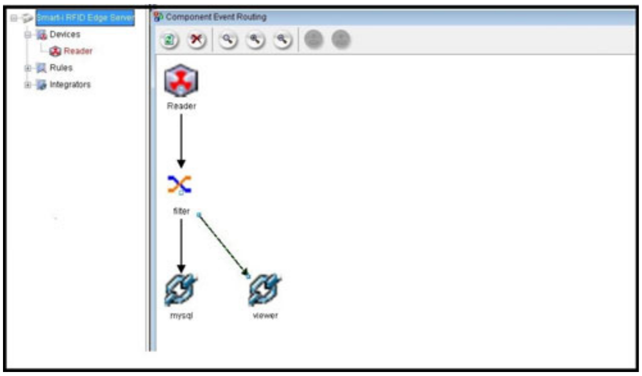


Fig. 9 Middleware setting interface

will feedback a necessary activity to deal with the abnormality which induce the color changing.

RFID antenna/reader [32] The antenna broadcasts the RF signals generated inside the reader's transmitter into the immediate environment. It also receives responses from tags within a defined range. The RFID reader sends and receives RF data to and from the tag via antennas, containing a transmitter, a receiver, and a microprocessor.

EPC information sever [33] EPC network is the gateway between any requester of information and the database. The EPC information server receives and sends messages with any requester of information [34]. It plays the role as "interpreter" between databases and applications in RFID system (detailed application found in Section 3.4).

RFID middleware/host application Every RFID system consists of an enterprise subsystem that is composed of a middleware and enterprise applications, which are critical components to the RFID system. The data information collected by the RFID readers need to create value, such as more supply chain visibility or better planning, hence, the important role of the RFID middleware software to bridge the gap between the RFID data coming from the RFID readers and the existing host applications. In this new RFID-based

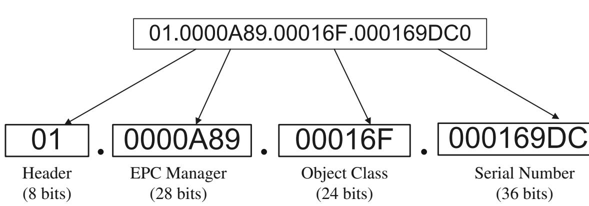


Fig. 10 EPC type I

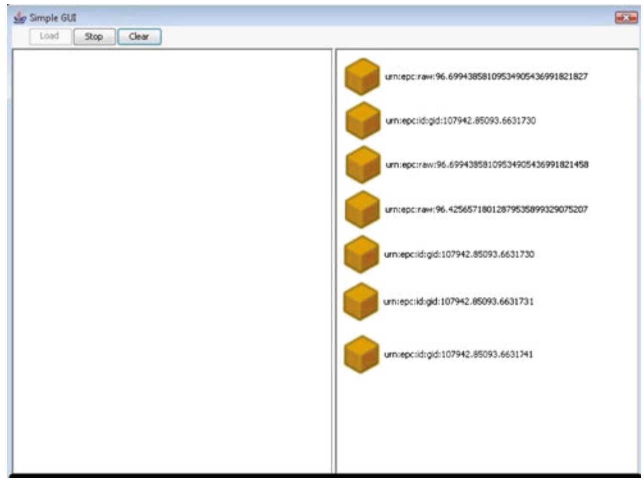


Fig. 11 EPC tags viewer

CPN network, the CPN simulation report will be real-time updated and connected with the middleware part bidirectional.

3.4 Theoretical example

In this part, a simple theoretical example will be given to explain the proposed system. Figure 7 shows a flowchart for a very simple process flow. There are two types of products "M01" and "M02" with each type of two units are ready to go through this flow. It is assumed that any processing activity with the capacity larger than 4, all the product units can enter at the same time in this example.

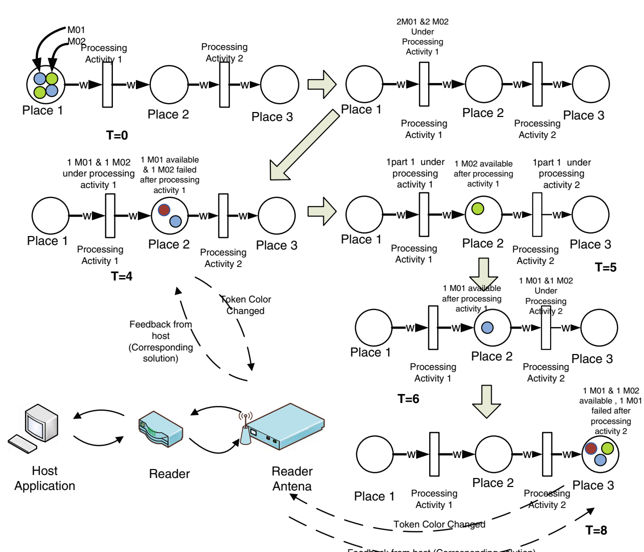


Fig. 12 RFID-based CPN for whole process flow of the simple example

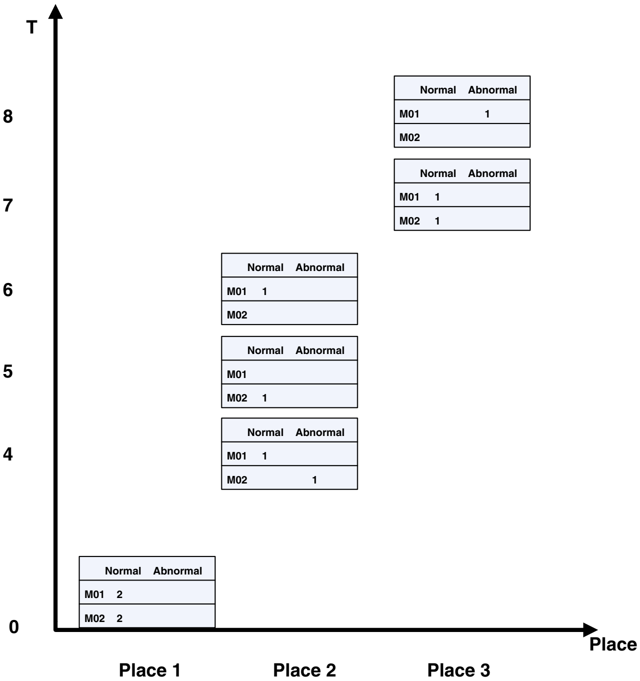


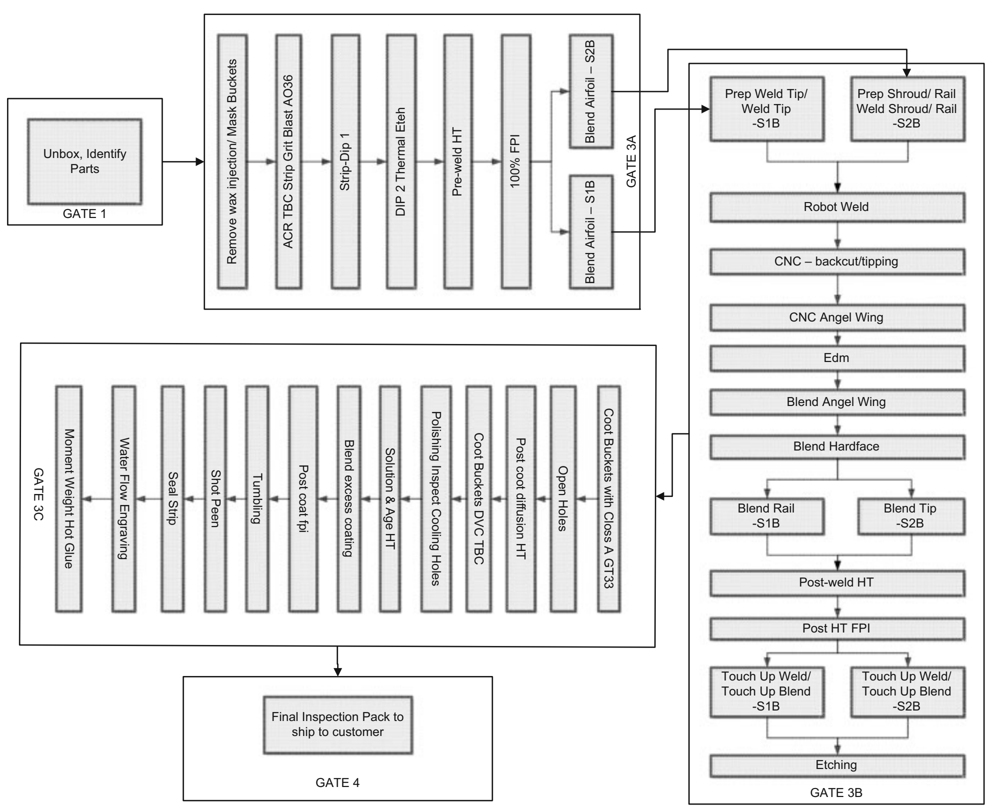
Fig. 13 Timestamp for tokens in each place

Once the process has been given, the model can be developed with CPN network as shown in Fig. 8. As mentioned, there are four product units with two different type, so the tokens in place 1 are two "M0", true) and two ("M0", true). In this example, "M01" and "M02" are the ID for products and true shows the normal status of the product. As for processing activity 1 T1 will last a time as firing function discrete (4, 6) for each token while T2's firing function is discrete (2, 3). All the tokens in CPN are tagged which can be detected by RFID reader antenna.

After development for CPN network, it is necessary to set up the RFID middle ware so as to bridge the received simulation process information to host application. Figure 9 is the interface for middleware setting for different devices (reader, rules, and integrator).

In the proposed RFID-based CPN network, the tagged tokens are encoded with EPC [35]. This is an object identification scheme which is use to uniquely identify objects and facilitates for tracking throughout the product lifecycle. The most commonly used scheme is a 96-bit code with a fixed, 8-bit header. This header defines the number, type, and length of all subsequent data partitions. Thus, a single byte provides 256 ways to partition the remaining bits. In this proposed system, the first EPC configuration, EPC type I, is employed to work as a public object identifying number. The EPC type I has three data partitions, EPC manager, object class, and serial number which are shown in Fig. 10. The first data partition identifies the EPC manager,

Fig. 14 The process flow for repairing coated buckets



that is the manufacturer, company or entity, responsible for maintaining the subsequent codes. The next partition, object class, indicates the product type. The final partition encodes a unique object identification number for each product. Together with the product code, this provides each manufacturer with 1.1×10^{18} unique item numbers—currently beyond the range of all identified products [36]. Figure 11 shows EPC tags detected by the middleware and they are the recorded tags after the configuration for RFID middleware is finished.

After running this experiment once, the whole process flow with different markings can be obtained as shown in Fig. 12. At the beginning, there are four tokens in place 1, two M01 and two M02, respectively, and then all the tokens are entering transition processing activity 1. One M01 and one M02 are firstly finishing this part while the M01 color token stays the same and the M02 color token changed which means that this unit failed. As mentioned in Section 3.2, the reader will receive the signal tagged. The token's color changes and then the signal goes through the RFID system. After that, the host application will provide a feed back to the failed token. For the next processing activity 2, it is similar as activity 1 with the three color-unchanged token going inside. Finally, the output place 3 got another one tagged token "M01" unit's color changed.

The simulation results from the RFID-based CPN are shown in Fig. 13. At time 0, there are two normal M01 tokens and two normal M02 tokens in place 1; at time 4, one normal M01 token and one abnormal M02 token arrived in place 2; at time 5, there is another one normal M02 token arriving in place 2; at time 6, the last one normal M01 token arrived in place 2; at time 7, there are one normal M01 token and one normal M02 token arriving in the output place 3; at time 8, one abnormal M01 token arrived in the output place 3.

4 Case study

4.1 Case description

In this section, a case company located in Singapore with alias name as GG will be discussed and studied. GG company repairs, modifies, and upgrades a wide range of machinery, such as buckets, nozzles, and turbines. GG Company has its own certified total quality management system of highly skilled personnel to ensure products and service meet or exceed specified quality standards and engineering requirements. In this case, the coated bucket repairing process is selected as study object, which is geographically distributed in five different locations. Due to the complex repairing process and its largely distributed machinery network which accords with the characteristic of distributed manufacturing network, this repairing flow can be regarded as a typical case study for our research. Figure 14 shows the large flowchart for repairing coated

Table 1 Current job information

Job ID	Customer	Tech	Shop want date
73449	ABC	S2B	2/10/2010
73608	CDE	S1B	10/10/2011
73817	FGH	S2B	22/10/2010
74018	IJK	S2B	1/11/2010
73816	XYZ	S1B	30/9/2010

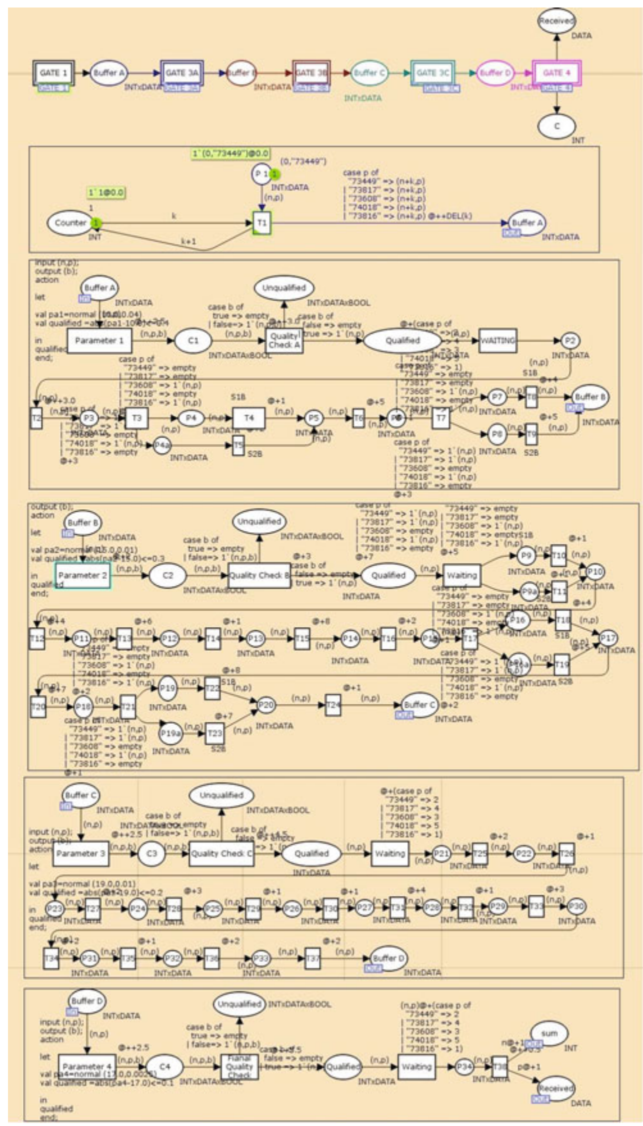


Fig. 15 CPN network model for coated bucket repairing process

Table 2 Global color set declarations

```
Colset INT = int; Colset DATA = string;
  Colset BOOL = bool;
Colset TECH = S1B|S2B  Colset INTxDATA
  = product INT*DATA
Colset TECHxINT = product TECH*INT;
Colset INTxDATAxBOOL = product INT*DATA
  *BOOL timed;
Colset INTxDATAxTECH = product INT*DATA
  *TECH timed;
Colset E = with e;
var n,k:INT, var b: BOOL; var n: INT;
var p, str:DATA; var x: TECH
fun DEL(k:int) = let
val realk = Real.fromInt k
val del = realk/2.0
in del
```

buckets. There are five different jobs under processing as shown in Table 1: (Note: to simplify the case study, the complex flow has been selected while the author only chose five simple jobs as example.)

4.2 Case modeling and simulation

Referring to Fig. 14 the repairing process for coated buckets, the CPN network model is built up in Fig. 15. There are totally five substitution transitions which are linked to five sub-CPN models. The five sub-net models represent five production processes distributed in five different locations—Gate1, Gate 3A, Gate3B, Gate3C, and Gate 4, respectively. The global color set declarations are also given in Table 2.

The interpretation of the places and transitions for the CPN network are given in Tables 3 and 4, and the firing time and functions are given in the model of Fig. 15 referring to the collected data from case company. Figure 15 is the CPN network model for coated bucket repairing process according to the process flow as shown in Fig. 14. There is one overall model layout for the whole manufacturing system and then each subnet is given to show the detail for the model structure of each gate.

4.3 Simulation results

4.3.1 Throughput

After the simulation finishes, it is found to be the total process time and final throughput as shown in Table 5 and Fig. 16. With RFID-based CPN, it enables engineers to trace which job has the shortest total processing or highest throughput. Engineers can estimate the expected delivery date based on the total processing time in the complex manufacturing system. On the other hand, the throughput can be the indicator of the manufacturing system performance and the complexity

Table 3 Interpretation of the place in the CPN for coated bucket repairing process

P1	Parts in workstation 1	P2	Parts in workstation 2
P3	Parts in workstation 4	P4	Parts in workstation 5
P5	Parts in workstation 8	P6	Parts in workstation 9
P7	Parts in workstation 10	P8	Parts in workstation 11
P9	Parts in workstation 12 waiting For preparing welding	P10	Parts in workstation 12 waiting For welding
P11	Parts in workstation 13B Waiting for CNC-backcut	P12	Parts in workstation 13B Waiting for CNC-angel wing
P13	Parts in workstation 14	P14	Parts in workstation 13A Waiting for blend angel wing
P15	Parts in workstation 13A Waiting for blend hardface	P16	Parts in Workstation 13A Waiting for blend rail/tip
P17	Parts in workstation 15	P18	Parts in workstation 16
P19	Parts in workstation 13A Waiting for touch up	P20	Parts in workstation 20
P21	Parts in workstation 21	P22	Parts in workstation 13A Waiting for open holes
P23	Parts in workstation 23	P24	Parts in workstation 24
P25	Parts in workstation 13A Waiting for polishing	P26	Parts in workstation 26
P27	Parts in workstation 27	P28	Parts in workstation 28
P29	Parts in workstation 25	P30	Parts in workstation 29
P31	Parts in workstation 29A	P32	Parts in workstation 30
P33	Parts in workstation 31	P34	Parts in workstation 32

Table 4 Interpretation of the transition in the CPN for coated bucket repairing process

T1	Unbox, identify parts in workstation 1	T2	Parts in remove wax injection/ mask buckets in workstation 2
T3	ACR TBC strip grit blast AO36 in workstation 4	T4	Strip-dip 1 in workstation 5
T5	DIP 2 thermal Eteh in workstation 5	T6	Pre-weld HT in workstation 8
T7	100% FPI in workstation 9	T8	Blend airfoil—S1B in work station 10
T9	Blend airfoil—S2B in workstation 11	T10	Prep weld tip/weld tip-S1B in workstation 12
T11	Prep shroud/rail weld shroud/Rail-S2B in workstation 12	T12	Robot weld in workstation 12
T13	CNC backcut/tipping in workstation 13B	T14	CNC angel wing workstation 13B
T15	Edm in workstation 14	T16	Blend angel wing in workstation 13A
T17	Blend hardface in workstation 13A	T18	Blend rail-S1B in workstation 13A
T19	Blend tip-S2B in workstation 13A	T20	Post-weld HT in workstation 15
T21	Post HT FPI in workstation 16	T22	Touch up weld/touch up blend-S1B in workstation 13A
T23	Touch up weld/touch up blend-S2B in workstation 13A	T24	Etching in workstation 20
T25	Coot buckets with Closs A GT33 in workstation 21	T26	Open holes in workstation 13A
T27	Post coot diffusion HT in workstation 23	T28	Coot buckets DVC TBC in workstation 24
T29	Polishing inspect cooling holes in workstation 13A	T30	Solution & age HT in workstation 26
T31	Blend excess coating in workstation 27	T32	Post coat fpi in workstation 28
T33	Tumbling in workstation 25	T34	Shot peen in workstation 29
T35	Seal strip in workstation 29A	T36	Water flow engraving in workstation 30
T37	Moment weight hot glue in workstation 31	T38	Final inspection pack to ship to customer in workstation 32

of the job and skills of mastering technology can be realized with processing time and throughput.

4.3.2 Cumulative yield detected from RFID system

In this manufacturing network, components are repaired in different workshop including GATE 1, GATE 3A, GATE 3B, GATE 3C, and GATE 4. Each of these workshops process one special repairing work for crack repairing, corrosion repairing, etc. When the repairing work has been finished, the component needs to go to the next workshop. Before repairing work begins, the products are taken for quality check, as a last step, in the buffer area for each workshop, and the unqualified components will be excluded. In the case company studied, they have their own quality standards to guarantee that the products meet the quality requirements. To simplify the model, for each workshop's processing, there is only one major parameter that needs to be taken into consideration. And together with the confidential factors, the major parameters as parameters 1–4 are set in the model.

Based on the predefined quality standard as well as the setting rules, the simulation results on cumulative yield is obtained in Table 6. Quality check is processed

Table 5 Simulation results for five jobs

Job ID	Technology	Total processing time (H)	Throughput (unit/shift, 1 shift = 12 H)
73449	S2B	131.5	5.43
73608	S1B	127.5	6.03
73817	S2B	137.5	5.96
74018	S2B	140.5	5.62
73816	S1B	121.5	6.59

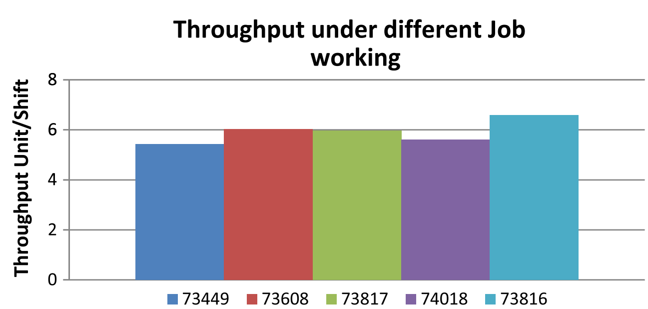


Fig. 16 Throughput under different jobs working

Table 6 Simulation cumulative yield for five main workshops

	Yield loss (unit)	Cumulative yield (unit)	Step loss rate (%)	Total yield rate (%)
GATE 1	NA	100	4.8	NA
GATE 3A	8,2,6,4,2,5,5,4,8,4 Ave. = 4.8	95.2	1.0	95.2
GATE 3B	0,1,0,1,1,3,1,1,0,1 Ave. = 0.9	94.3	4.2	94.3
GATE 3C	4,3,2,3,4,4,7,4,5,3 Ave. = 3.9	90.4	5.1	90.4
GATE 4	5,4,3,5,3,7,3,3,6,7 Ave. = 4.6	85.8	NA	85.8

at the beginning of the workshop, at the last repairing step, and in GATE 4 after final inspection. There are only packing and shipment. Therefore, it is assumed that there is no loss in this final workshop. From Table 6, it can be concluded the that GATE 3A has the highest quality in repairing coated buckets while GATE 3C with relative high yield loss needs to be improved in the future. The total yield rate for coated buckets is 85.8% which meets the company's quality standard. Meanwhile, the concluded decision results can return to processing activity by RFID reader, so that the corresponding working area can be improved and the unqualified job can be delivered to accordant workstation for necessary rework.

5 Conclusions

In this paper, a RFID-based CPN network which can monitor the quality of work in progress in manufacturing system is developed. Among different types of data capture methods and modeling methods, RFID and CPN are chosen because of the synergy of combing the RFID tag and color token can enhance the distributed manufacturing system by improving both throughputs without scarifying the quality. The complexity of the distributed manufacturing environment has been modeled by CPN, and a systematic RFID-based CPN architecture and methodology were designed and developed. Different from the typical CPN, this system can update the new color-tagged tokens at any time, and RFID can capture real-time data so as to update the latest status of the product and embed those information in the CPN. To validate the propose system, a real case for a GG company—the coated bucket repairing process is studied. Repairing and maintenance may sometimes go through hundreds of tasks and activity, and it is difficult to track and trace which activities lead to non-conformance items. The simulation results show that the proposed method is able to examine the real-time quality status of the repair components so as to diagnosis the weak point of the repairing system. Under this circumstance, the corresponding signal of abnormity will be sent back from the host application and decision maker can diagnosis the fault and plan for further improvement. RFID-CPN allows engineers to estimate the throughput and the cumulative yield so as to have efficient and accurate production planning. The significance of this research is to incorporate system modeling method, CPN with the latest ubiquitous technology, RFID to track and trace the product status and evaluate the manufacturing system performance.

The current work is mainly at the theoretical level, and only small samples are selected for illustration in the case study. Future work will be focused on further validation and improvement in detecting the bottleneck with RFID-CPN. And as the interface for automatic update, the status between RFID and CPN color token should be continued. Once a comprehensive RFID-based CPN network is totally built up with the visualized human interface, the application of this proposed method can be extended into a large complex distributed system.

Acknowledgements The authors would like to thank the anonymous reviewers for providing a number of important comments and suggestions.

References

1. Petri CA (1962) Kommunikation mit automaten. Technische Hochschule
2. Peterson JL (1981) Petri net theory and the modeling of systems. Prentice-Hall, Upper Saddle River
3. Chen CS, Lin CH (2002) A rule-based expert system with colored Petri net models for distribution system service restoration. IEEE Trans Power Syst 17(4):1073–1080
4. Kleist RA, Chapman TA (2004) RFID labeling. Printronix
5. Weinstein R (2005) RFID: a technical overview and its application to the enterprise. IT professional, pp 27–33
6. Want R (2004) RFID: a key to automating everything. Sci Am 290(1):56
7. Curty JP, Joehl N, Dehollain C, Declerq MJ (2005) Remotely powered addressable UHF RFID integrated system. IEEE J Solid-State Circuits 40(11):2193–2202
8. Wamba SF, Boeck H (2008) Enhancing information flow in a retail supply chain using RFID and the EPC network. Journal of Theoretical and Applied Electronic Commerce Research 3(1):92–105
9. Regattieri A, Gamberi M (2007) Traceability of food products: general framework and experimental evidence. J Food Eng 81(2):347–356

10. Keskilammi M, Sydnheimo L (2003) Radio frequency technology for automated manufacturing and logistics control. Part 1: passive RFID systems and the effects of antenna parameters on operational distance. Int J Adv Manuf Technol 21(10):769–774
11. Ngai EWT, Cheng TCE (2007) Mobile commerce integrated with RFID technology in a container depot. Decis Support Syst 43(1):62–76
12. Lee CKM, Chan TM (2009) Development of RFID-based reverse logistics system. Expert Syst Appl 36(5):9299–9307
13. Lyu J Jr, Chang S-Y, Chen TL (2009) Integrating RFID with quality assurance system-framework and applications. Expert Syst Appl 36(8):10877–10882
14. Traub K (2005) The EPC global architecture framework. EPC global document. Available online at http://www.epcglobalinc.org/standards/Final-epcglobal-arch-20050701.pdf
15. Huang GQ, Zhang YF et al (2008) RFID-based wireless manufacturing for real-time management of job shop WIP inventories. Int J Adv Manuf Technol 36(7):752–764
16. Wang F, Liu P (2005) Temporal management of RFID data. In: Proc. 31st VLDB conf., Trondheim, Norway, pp 1128–1139
17. Chalasani S, Boppana RV (2007) Data architectures for RFID transactions. IEEE Transactions on Industrial Informatics 3(3):246–257
18. Al-Jaar RY, Desrochers AA (1990) Petri nets in automation and manufacturing. Advances in Automation and Robotics 2:153
19. Gomes L, Barros JP (2005) Structuring and composability issues in Petri nets modeling. IEEE Transactions on Industrial Informatics 1(2):112–123
20. Desrochers AA, Al-Jaar RY (1995) Applications of Petri nets in manufacturing systems: modeling, control, and performance analysis. IEEE Press, Piscataway
21. Uzam M (2002) An optimal deadlock prevention policy for flexible manufacturing systems using Petri net models with resources and the theory of regions. Int J Adv Manuf Technol 19(3):192–208
22. Aized T (2009) Modelling and performance maximization of anintegrated automated guided vehicle system using coloured Petri netand response surface methods. Comput Ind Eng 57(3):822–831
23. Wu N (1999) Necessary and sufficient conditions for deadlock-free operation in flexible manufacturing systems using a colored Petri net model. IEEE Trans Syst Man Cybern, Part C Appl Rev 29(2):192–204
24. Chen CS, Ke YL, Wu JS (2001) Coloured adaptive structured petri-net a tool for the automatic synthesis of hierarchical control of flexible manufacturing systems. IEE Proc, Gener Transm Distrib 148(5):463–470
25. Mujica M, Piera MA, Narciso M (2010) Revisiting state space exploration of timed coloured petri net models to optimize manufacturing system's performance. Simulation Modelling Practice and Theory 18(9):1225–1241
26. Gentina JC, Bourey JP, Kapusta M (1988) Coloured adaptive structured petri-net a tool for the automatic synthesis of hierarchical control of flexible manufacturing systems. Comput Integr Manuf Syst 1(1):39–47
27. Jiang Z, Zuo MJ, Fung RYK, Tu PYL (2001) A colored Petri nets with changeable structures (CPN-CS) and their applications in modeling one-of-a-kind production (OKP) systems. Comput Ind Eng 41(3):279–308
28. Lin JT, Lee C-C (1997) A Petri net-based integrated control and scheduling scheme for flexible manufacturing cells. Comput Integr Manuf Syst 10(2):109–122
29. Feldmann K, Colombo AW (1999) Specification, design, and implementation of logic controllers based on colored Petri net models and the standard IEC 1131. I. IEEE Transactions on Specification and Design, Control Systems Technology 7(6):657–665
30. Haddad S (1990) A reduction theory for coloured nets. Adv Petri Nets 1989:209–235
31. Rao KVS, Nikitin PV (2005) Antenna design for UHF RFID tags: a review and a practical application. IEEE Trans Antennas Propag 53(12):3870–3876
32. Ngai E, Moon KKL (2008) RFID research: an academic literature review (1995–2005) and future research directions. Int J Prod Econ 112(2):510–520
33. Chien HY, Chen CH (2007) Mutual authentication protocol for RFID conforming to EPC class 1 generation 2 standards. Comput Stand Interfaces 29(2):254–259
34. Leong KS, Ng ML (2004) EPC network architecture. Auto-ID labs research workshop
35. Sarma S, Brock D (2001) Radio frequency identification and the electronic product code. IEEE Micro 21(6):50–54
36. Brock DL (2001) The electronic product code (EPC)—a naming scheme. Technical Report MIT-AUTOIDWH-002, MIT Auto-Id Center, Massachusetts Institute of Technology, Cambridge