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RFID-BASED REAL-TIME SHOP-FLOOR MATERIAL MANAGEMENT: AN AUTOM SOLUTION AND A CASE STUDY

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ABSTRACT

Radio Frequency Identification (RFID) technologies provide automatic and accurate object data capturing capability and enable real-time object visibility and traceability. Potential benefits have been widely reported for improving manufacturing shop-floor management. However, reports on how such potentials come true in real-life shop-floor daily operations are very limited. As a result, skeptics overwhelm enthusiasm. This paper introduces an AUTOM solution which provides an easy-to-use and simple-to-deploy framework for manufacturers to implement RFID/Auto-ID enabled smart shop-floor manufacturing process. A real-life case of adopting AUTOM to realize RFID-enabled material distribution in a large air conditioner manufacturer is introduced, aiming to re-vitalize the RFID efforts in manufacturing industries. It is hoped that insights and lessons gained could be generalized for future efforts across household electrical appliance manufacturers in specific and for other types of manufactures in general.

KEYWORDS

Radio Frequency Identification (RFID), air conditioner, manufacturing execution, production management, material distribution.

1. INTRODUCTION

Radio Frequency Identification (RFID) technologies offer the capability of automatic and accurate object data capturing and enable real-time traceability and visibility (Chalasani and Boppana, 2007). While supply chain logistics industries have mandated the adoption of the technologies and initiated substantial research and development activities (Williams, 2004), manufacturing industries have also made practical progress (Huang et al., 2007). Manufacturers deploy RFID devices to shop-floor objects such as men, machines and materials to capture data associated with their statuses (Brintrup et al., 2009; Ren et al., 2010). Such RFID-enabled real-time visibility and traceability substantially improve shop-floor management in general and Work-In-Progress (WIP) materials management in particular (Huang et al., 2008).

Despite widespread enthusiasm, reports on real-life industrial practices, either successful experiences or painful lessons, are very limited. Majority of the reports have been based on preliminary industrial experiments rather than implementations for everyday operations. Skeptics increasingly shadows potential benefits claimed. In order to re-vitalize the effort, this paper will introduce an AUTOM solution which means using Auto-ID technologies to enable a ubiquitous and smart manufacturing process. It is put forward by the authors' research team and has been successfully applied in several real manufacturing companies to achieve various real-time shop-floor management purposes. In the later part of this paper, we will also present one of these real-life case studies implemented in an air conditioner manufacturer.

The major purpose of this paper is multi-folded. Firstly, the paper shows how RFID-enabled potential benefits come true in a real-life company in terms of improved visibility and traceability, information accuracy, operation efficiency, reduced costs, increased speed and responsiveness, and better product quality control (Clarke et al., 2006; Henseler et al., 2008). Secondly, the paper demonstrates how a company deal with technical, social and organizational challenges in adopting the RFID solutions for shop-floor management. Finally, the paper generalizes a procedure on how RFID solutions can be applied in manufacturing shop-floors for household electrical appliance products with similar characteristics.

The remainder of the paper is arranged following a general implementation procedure (Ngai et al., 2010): (1) Analysis of existing business processes, (2) Creation of RFID-Enabled Manufacturing Shop-Floor, (3) Implementation of reengineered business process, (4) Champion of good practices, and (5) Reflection for the future. Section 2 discusses how AUTOM solution is used for creating a RFID-enabled smart and ubiquitous shop floor. Section 3 introduces a real-life case study to exemplify how the shop-floor operational problems could be solved by AUTOM (RFID) applications. Conclusions are given in Section 4.

2. CREATING RFID-ENABLED SHOP FLOOR WITH AUTOM SOLUTION

The implementation of a shop-floor RFID system is far from simply placing readers everywhere. It is a systematic process involving appropriate tagging scheme, reasonable reader arrangement, standard information communication and synchronized process integration etc. In fact, a series of implementation questions normally perplex a company during its initial investigation: What shop-floor objects should be tagged and equipped with RFID readers? Where to place RFID readers and in which form and frequency? How to convert the basic real-time data into useful visibility and traceability supports to facilitate the daily shop-floor operations? Although partial solutions could be found for each single question, integrated frameworks for practical shop-floor implementation are few.

AUTOM solution has been put forward as a holistic framework for implementing shop-floor RFID applications. AUTOM is an umbrella technology for manufacturing solutions enabled by Auto-ID devices such as RFID, barcode and other types of wireless devices such as Bluetooth, Wi-Fi, GSM and infrared. It not only defines the overall information infrastructure within a standard shop-floor resource model, but also provides facilities to enable the real-time data processing in the model. This section will introduce the AUTOM solution and how it can be customized to create a typical RFID-enabled shop floor. It should be mentioned that, AUTOM indeed provides an effective and efficient way for RFID implementation, but is not the unique solution. However, all the implementation principles and procedures introduced below are general enough to be followed if other solution is used.

2.1 REAL-TIME SHOP-FLOOR INFORMATION INFRASTRUCTURE

The role of AUTOM infrastructure is shown in Figure 1. It is designed to be consistent with the standard enterprise hierarchy defined by ISA-95 enterprise-control system integration standard (http://www.isa.org). An enterprise hosts one or more manufacturing sites or areas (e.g. factories or workshops), each of which consists of several production lines/cells or storages zones (e.g. assembly lines or warehouses). The operation of a production line involves a variety of production units, whose operations are concerning with both manufacturing resources (e.g. materials, equipments and operators) and their logical combinations (e.g. product assembling).

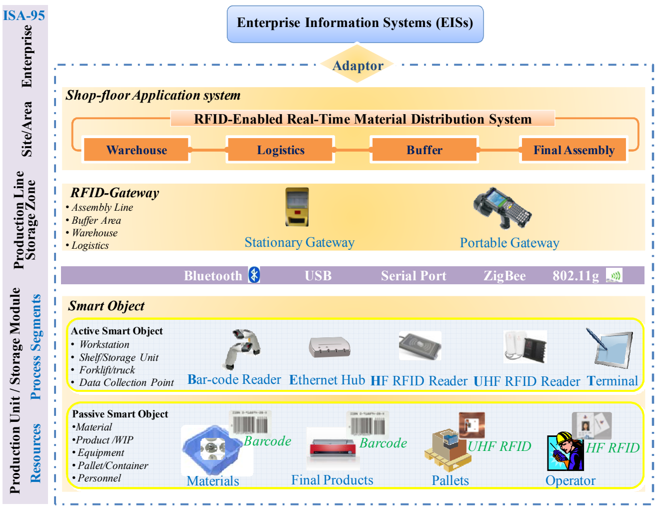

Figure 1 - AUTOM Infrastructure

Corresponding to the four-level ISA-95 enterprise hierarchy shown in the left part of Fig. 2, the AUTOM information infrastructure is also developed to comprise four technical levels, as shown in the right part. The highest level includes those conventional enterprise information systems (EISs), such as ERP, MRP etc, used by enterprise management for making production plans. The three lower levels are RFID-enabled AUTOM facilities, including two hardware facilities named smart objects and RFID-Gateway, and a shop-floor application system. Direct instantiation of these AUTOM facilities provides an effective and efficient way for creating a RFID-enabled shop floor suitable for real-time plan execution. The following subsections will details such instantiation process.

2.2 RFID-ENABLED SHOP-FLOOR HARDWARE FACILITIES

Smart Object

A smart object (SO) is a physical manufacturing resource that is made "smart" by equipping it with certain degree of intelligence: Auto-ID, memory, communicating ability etc. Normally, two typical Auto-ID techniques, namely RFID and barcode, are used in combination. SOs could be categorized into passive and active SOs. Those attached with Auto-ID tags and readers are called passive SOs and active SOs respectively.

The creation of passive smart object has two steps. The first is to scope the objects to be tracked and the second it to determine which kind of tag will be used. This case focuses on the material distribution process which concerns about delivering the right item by the right operator with the right tools in the right quantity at the right time from the right source to the right destination. Therefore, the objects need to be tracked include raw materials, final products, storage locations, circulating boxes, pallets and operators. The tagging of these objects follows the close-loop RFID system application principle advocated in Schmitt et al. (2007): RFID transponders should be attached to those objects which are shipped or moved within a cycle and eventually returns to its point of origin. Therefore, internally used or circulated resources are attached with RFID tags, such as operators, storage locations, shipping pallets and circulating boxes. Since the raw materials and final products in the case company have already used barcode labelling in agreement with other supply chain partners, they are kept unchanged. The WIP in the distribution process will be traced with their containers.

Active SOs are manufacturing resources equipped with RFID readers. They are normally installed at value-adding points of a process where passive SO are to be tracked. Normally, the influential range of an active SO is limited, e.g. around a workstation or a storage rack. In this case, active SOs are all integrated in RFID-Gateways (see next section) as built-in active SOs and only control the entrance points of line-level areas. This is due to two reasons. First, all the assembly lines operate in a continuous production mode. One reader put at the end of the production line could help derive the statuses of all the comprised workstations. Second, for a logistics process combined with storing, loading, transporting and buffering, stochastic mobile data reading and processing may happen anywhere. Portable RFID-Gateway is needed for this case.

RFID-Gateway

Instead of exposing RFID devices directly to application systems, AUTOM solution puts forward an intermediate level called RFID-Gateway to form loosely-coupled system architecture (Zhang et al., 2010). RFID-Gateway has a hardware hub and a suite of management software which acts as a server to host all the (active) SOs within a certain working area. Through incorporating various drivers of SOs to form a driver library, RFID-Gateway is enabled to work in a "Plug and Play" fashion to newly plugged SO. Heterogeneous SO drivers are wrapped into standard web service interfaces, enabling upper-level applications to use all the devices in a uniform way. The influential range of RFID-Gateway is the union of ranges of all the hosted active SOs, normally a work cell or a production line. Despite the key word "RFID", RFID-Gateway is substantially supported by other technologies, e.g. barcodes, Wi-Fi, PC, PDA etc.

There are stationary, mobile and portable RFID-Gateways. Stationary RFID-Gateway is placed at a fixed location, such as the gate of a warehouse. Items are moved to the stationary RFID-Gateway to be tracked. A mobile RFID-Gateway is installed to a moveable manufacturing resource, such as a forklift truck. Tagged items are not only carried but also traced by the movable recourses during long distance of transportation. A portable RFID-Gateway is a handheld device responsible for distributed item identification within a certain area or along a certain process. Unlike the previous two types, a portable RFID-Gateway is always moved close to the objects by an operator for tag reading.


(a) Lab Version Stationary RFID-Gateway (b) Onsite Version Stationary RFID-Gateway (c) Portable RFID-Gateway

Figure 2 - Implementation of RFID-Gateway

The case company which will be introduced in next section mainly uses stationary and portable RFID-Gateways. Figure 2(a) and 2(b) show the lab version and onsite version stationary gateways. The former exposes some of the integrated Auto-ID devices (i.e. active smart objects), including *Alien ALR-9800 UHF RFID readers*, *ACS 120 HF RFID readers*, and *Metrologic MS9535 Bluetooth barcode readers*. Figure 2(c) shows the portable gateway which is implemented based on *Motorola MC9090-G RFID handheld reader*.

2.3 RFID-ENABLED APPLICATION SYSTEMS

Shop-floor application system is a RFID-enabled real-time information system providing a two-way information channel between shop-floor execution and decision (Zhang et al., 2010). From execution to decision, the system collects real-time information of the smart objects involved in a manufacturing process via RFID-Gateways for adaptive decision or process control. From decision to execution, the system can transfer and interpret shop-floor decisions into executive work orders that should be followed by smart objects.

Such application system normally includes visibility and traceability modules. A visibility module shows the real-time operation status of a specific manufacturing site with graphical user interfaces to facilitate the easy operation of operators. The principle followed is what you see is what you do and what you do is what you see. Traceability is a backend control mechanism which integrates the real-time information captured from different manufacturing stages. Typically, information from different RFID-Gateways could be synchronized to enable coordinated operations, while history information of a manufacturing object or process could be retrieved in a later time for failure investigation. Normally, application system is very process-specific, and thus hardly any off-the-shelf system on the market is directly ready for using.

3. A CASE STUDY OF RFID-ENABLED SHOP-FLOOR MATERIAL DISTRIBUTION SYSTEM

3.1 ABOUT THE CASE COMPANY

The case company is a large air conditioner manufacturer which has a huge annual output over 4 million sets. Therefore, it pays much attention on improving the quality of its material distribution to secure an efficient and stable production process. In the air-conditioner's whole production process, the case company only undertakes the last two assembly stages, i.e. preassembly and final assembly. Over 90% of the parts and accessories manufacturing are outsourced to suppliers and shareholding subsidiaries. Currently, the case company has three assembly workshops responsible for three different product lines, but uses over 5000 types of materials purchased from nearly 80 suppliers. All the materials are stored in 49 separate warehouses and are distributed to workshops by more than 100 logistics staffs. At current stage, we choose one workshop and one warehouse to implement a small-scale pilot project. Then, the pilot achievements will be extended to other workshops and warehouses.

The typical shop-floor material distribution process is cooperated by four major functional departments: Production Plan Department for making both production and material requirement orders; Warehouses for storing both materials and final products; Logistics Department for distributing materials to Production Department, and taking the finished products back to warehouses. As can be seen in Fig. 1, production and logistics departments are located inside a workshop, while the other two departments are outside. The production department has two preassembly lines and ten final assembly lines positioned in two parallel production areas, with two corresponding buffers located to the left. Buffers and all the logistics operations are managed by the logistics department.

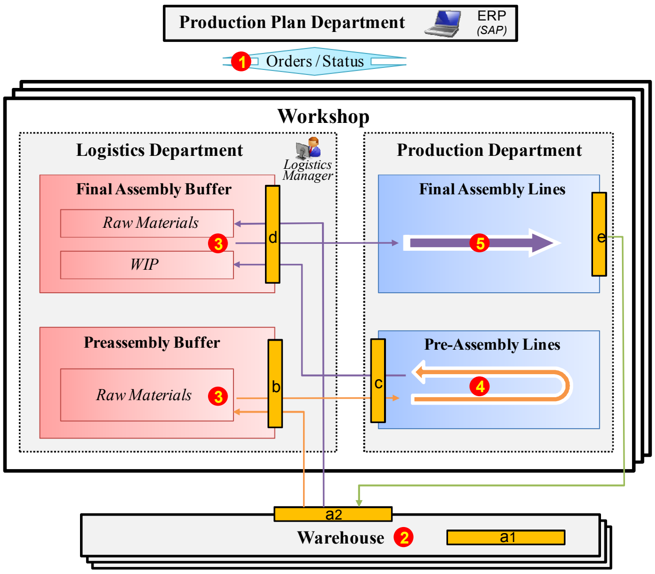

Figure 3 – Maximum dimensions for figures in single column

3.3 OPERATIONAL PROBLEMS IN SHOP FLOOR PRIOR TO RFID IMPLEMENTATION

A typical shop-floor material distribution process contains five stages as shown in Figure 1. This section will conduct confirmatory cause and effect analyses will be conducted to find out whether and how the RFID facilities are required in the material distribution process.

Stage 1 – Production and Material Requirement Plan

Production plan department makes and releases order in paper-based "multi-copy form" to shop floors. A production order is made either for final assembly line or preassembly line, while the associated material orders for both are released to logistics department and warehouse. Several order copies will also be circulated to document office for recording.

Three problems currently exist: (1) paper-based order is wasteful, time-consuming, error-prone, and subject to reprinting when order changes; (2) planned orders are always unachievable due to the various operational dynamics, e.g. machine breakdown or defective material/product; (3) out-of-stock material in warehouse cannot be timely identified and replenished, leading to frequent production delay or order changes.

The causes of the above problems are: lack of appropriate visibility and traceability functions at key working areas, e.g. order visibility; lack of data synchronization between ERP system and shop floor's key value-adding points (locations labeled from "a" to "e").

Stage 2 – Material Preparation and Delivery

Material operators at warehouses pick up all the materials based on the received material orders and load to pallets in the afternoon. Logistics workers collect all the loaded pallets from warehouses and deliver to workshops in the next morning. All the finished material orders are manually updated to ERP system by warehouse manager when they are free, normally with a one-day delay.

Three problems currently exist: (1) material locating and distinguishing in manual ways is time-consuming, especially for the same type of materials purchased from multiple suppliers; (2) logistics jam at a warehouse gate happens frequently because the logistics works happen in a relatively fixed period; (3) delayed materials consumption information normally leads to untimely replenishment and thus stock-out situations.

The causes of the above problems are: lack of Auto-ID tags on material packages, circulating boxes and pallets; lack of data capturing devices at warehouse ("a2"); lack of real-time data synchronization between warehouses ("a1") and ERP system. These causes are suffered in common in the follow stages.

Stage 3 – Material Buffering

Materials delivered to workshops will be stored in preassembly or final assembly buffers first before being replenished to the corresponding lines. Components (WIP) made by preassembly lines will also be stored in final assembly buffer.

Two problems currently exist: (1) materials checking in and out buffer involves complex manual data transaction works; (2) real-time buffer information is not real-time available. In case of order changing, buffered materials cannot get efficient handing, e.g. order transfer or re-warehoused.

The causes of the above problems are similar as those for warehouses discussed in stage 2, except the data capturing synchronization point will be "b".

Stage 4 – Preassembly

Logistics workers make their rounds along the preassembly lines periodically, and replenish materials from buffers to lines when the line-side material inventory is below a safety level. The finished WIP will be sent to final assembly buffer.

Two problems currently exist: (1) a lot of unnecessary labor costs are wasted on line-side inventory checking; (2) without real-time WIP information, final assembly may start earlier or later, resulting in either production delay or redundant WIP.

Besides the basic cause of the lacks of Auto-ID tags on materials and devices at preassembly line ("d"), lacking of synchronization between preassembly line ("c") and final assembly line ("d") is the main cause for the above two problems.

Stage 5 – Final Assembly

The way of line-side inventory replenishing is similar as that for preassembly line, while the finished final products will be sent back to warehouses instead.

Two problems currently exist: (1) the wastes of unnecessary labour costs on line-side inventory checking still exist; (2) logistics manager cannot arrange timely warehousing for final products without real-time output information, resulting in high product inventory at the line's end.

Besides the basic cause of the lacks of Auto-ID tags on materials and devices at final assembly line, lacking of synchronization between final assembly ("e") line and logistics department is the main cause for the above two problems.

3.4 APPLICATION OF AUTOM SOLUTION

3.4.1 AUTOM HARDWARE DEPLOYMENT

All the numbered locations in Figure 3 have been identified as value-adding points and will be equipped with suitable RFID-Gateways. The detailed configurations of these RFID-Gateways are listed in Table 1 for better comparison.

Table 1 - Configuration and Deployment of RFID-Gateway

No.	Location	User	Major Functions	Gateway Hardware	Active Smart Object
a1	Warehouse Storage Area	Material Operators	(1) View the pallet loading scheme; (2) Bind materials (barcode) with circulating box (UHF); (3) Bind circulating boxes (UHF) with pallet (UHF); (4) Bind pallets (UHF) with location (UHF).		• Barcode • UHF RFID
a2	Warehouse Gate	Logistics Operator	(1) Read staff card (HF) and get associated delivery tasks; (2) Locate the pallet to be delivered; (3) Check out the pallet.		• HF RFID • UHF RFID
		Warehouse Keeper	(1) Check the status of logistics operators; (2) Check the validity of materials and pallet to be checked out.		
b	Preassembly Buffer Gate	Logistics Operator	(1) Check in materials (on pallet) delivered from warehouses; (2) Check out buffered materials and send to preassembly lines.		• HF RFID • UHF RFID
c	End of Preassembly Line	Loading Operator	(1) Report finished preassembly tasks; (2) Bind finished WIP with pallet.		• UHF RFID
d	Final Assembly Buffer Gate	Logistics Operator	(1) Check in materials (on pallets) delivered from warehouses; (2) Check in WIP (on pallets) delivered from preassembly lines; (3) Check out buffered materials and send to preassembly lines.		• HF RFID • UHF RFID
e	End of Final Assembly Line	Packing Operators	(1) Report finished final assembly tasks; (2) Bind finished products with pallet being loaded;		• Barcode • UHF RFID

3.4.2 AUTOM APLLICATIONS DEVELOPMENT

The project team customized a RFID-enabled real-time shop-floor material distribution system (RT-SMDS) for the case company. The system is implemented based on service-oriented architecture (SOA) architecture, shown in Figure 4.

Visibility modules are implemented in the form of a set of web explorers to be flexible downloaded and used in RFID-Gateways. Both the traceability modules and a data services are implemented in web services. Data services not only enable standard XML-based data exchanging between application system and its own database, but also implement an *ERP Adaptor* integrating the RT-SMDS with the case company's SAP system. The adaptor has four pairs of SAP RFC (Remote Function Call). They are *Production Order RFC*, *Material Order RFC*, *BOM RFC*, and *Order Change RFC*. The former two are used to get newly made production and material orders from ERP. The latter two are used to modify the released orders if a production order is changed by production plan department. Details of the individual visibility modules and traceability services will be given in Section V with a scenario description.

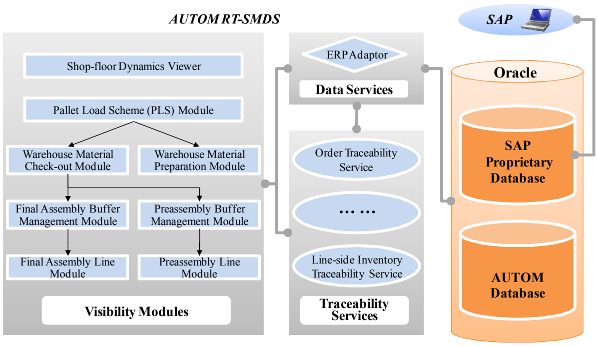

Figure 4 - System Architecture

3.5 OPERATION PROCESS AFTER RFID IMPLEMENTATION

3.5.1 SCENARIO DESCRIPTION

A complete material distribution process of using RT-SMDS to accomplish one single production order will be illustrated in this section. All steps are arranged according to the logical sequence of the involved operators and activities, see Fig 6. This process is common for other workshops and warehouses because the material distribution processes are very similar.

There are ten operational steps in this process. Each step is directly enabled by one of the visibility modules downloaded to the corresponding RFID-Gateway or PC while supported by the traceability services running at the back end. The central part in Figure 4 illustrates the operation details of each step including the venue, while the surrounding part shows the visibility interfaces. The five steps to the right are more logistics related, aiming at delivering materials from warehouse to workshops based on planned material requirements; the five steps to the left are more production related, responsible for replenishing materials to assembly lines following actual production tempo. The process can also be divided into plan and execution steps in the upper and lower parts respectively. The road signs in the central part show the above conceptual division.

The operation process is directly supported by a series of visibility modules installed at the onsite RFID-Gateways. But the information interrelationships among different operation steps are maintained through two major traceability modules. The usages of these modules will be illustrated in this section with the scenario.

3.5.2 VISIBILITY ENABLED OPERATION PROCESS

Step 1 – Production Manager: Make Production and Material Requirement Plans

With "*Real-time Shop Floor Visibility Explorer*", the manager reviews the real-time shop-floor status including progresses current orders, status of production lines, and material availability. Such information enables an adaptive planning mode and makes the orders more feasible for execution. Generated orders are then released to shop floors.

Step 2 – Logistics Manager: Make Pallet Loading Scheme

When a new material order is released, the logistics manager opens "*Pallet Loading Scheme Editor*" to make the so-called pallet loading scheme (PLS). A PLS indicates which and how many materials of which material orders should be loaded on the same pallet and delivered to which workshop and on what time. Based on PLS, the subsequent material distribution process could be conducted in batches (based on PLS instead of individual materials) to enhance the handling efficiency.

Step 3 – Material Operator: Material Preparation in Warehouse

All PLS are sequenced by the designated finish times and shown in "*Warehouse Material Preparation Explorer*" on the material operator's portable RFID-Gateway at the warehouse. The material operator selects the most urgent PLS to prepare. Materials are put into circulating boxes first and then load to pallets. Barcodes of materials will be bound to the RFID tags of circulating boxes and pallet barcodes by the portable RFID-Gateway according to their inclusion relationships. Finished pallets will be placed to the warehouse's shipping dock. Tags of the pallet and specific storage cell will also be bound to record a pallet's current position.

Step 4 – Logistics Manager: Assign Material Picking Task

Finished PLSs will be highlighted in the "*Pallet Loading Scheme Editor*". The logistics manager will then select a specific logistics operator to get the loaded pallet back from the warehouse, namely assigning a material picking task. Tasks containing final assembly and preassembly materials are shown the RFID-Gateways at the corresponding buffer gates. The logistics operator being assigned a task will then set off to the warehouse for material picking.

Step 5 – Logistics Operator: Material Picking

Through patting staff card on the RFID-Gateway at the warehouse gate, a logistics operator may view the assigned material picking tasks from "*Shipping Dock*

Visibility Explorer". With the specific pallet position of each PLS, the logistics may easily find the pallet to be picked. When checking out the pallet from warehouse, the "*Warehouse Material Check-out Explorer*" at the same RFID-Gateway will catch the pallet tag and check whether the PLS associated with this pallet is belonging to the operator's logistics tasks.

Step 6 – Warehouse Keeper: Materials Check-out Validating

When a logistics operator tries to check out a pallet out of the warehouse, the materials actually loaded on the pallet will be automatically retrieved through the binding relationships created during material preparation process and shown on "*Warehouse Material Check-out Explorer*". These materials are contrasted against the original PLS. If they are matching, the logistics operator is allowed to proceed. Otherwise, the warehouse keeper will request the logistics operator either to reload the materials or modify the PLS. All the materials being checked out are deducted from the warehouse inventory and updated to the ERP system through the ERP adaptor.

Step 7 – Logistics Operator: Preassembly Material Buffering

If the picked pallet from warehouse contains preassembly materials, it will be delivered to the preassembly buffer. When the logistics operator checks in the pallet, the RFID pallet tag is captured by the RFID-Gateway at the buffer gate. All the contained materials will be automatically shown on the "*Preassembly Buffer Visibility Explorer*" and recorded through retrieving relative PLS and marked as "in-buffer", indicating they are ready for replenishing to lines. When a preassembly line is about to finish a production order, the explorer will inform the relative logistics operators to replenish materials for the next production order.

Step 8 – Preassembly Operator: Preassembly and WIP Loading

Components made by preassembly lines are loaded on pallet by preassembly operators. Since such WIP are not tagged, the load (quantity) and affiliated production order are manually bound with the pallet tag. As the type of WIP from a preassembly line is normally fixed, they are normally loaded with default capacity. Hence, the manual binding operation is not time-consuming. Production order, default loading capacity and pallet tag will be automatically bound together by the "*Preassembly Line Visibility Explorer*". Only when the actual load is not the default value, manual intervention is required. A loaded pallet will be delivered to final assembly buffer.

Step 9 – Logistics Operator: Final Assembly Line Replenishing

Final assembly buffer receives both materials from warehouses and WIP components from preassembly lines. Their check-in processes are all the same (see *step 7*), enabled by "*Final Assembly Buffer Visibility Explorer*". Buffered materials will be replenished to final assembly lines by logistics operators based on the real-time status of line-side inventory shown on the explorer. When materials are checked out from buffer, either in circulating box or pallet, their information will be automatically captured by the RFID-Gateway through retrieving the tag's current binding relationship. Quantity of each material will be added to the corresponding line-side inventory.

Step 10 – Final Product Assembling, Packaging and warehousing

All the final products made by final assembly lines will be packaged and tagged by barcodes based on customer's requirement. Every tagging operation will trigger the "*Line-side Inventory Traceability Service*" once and the consumed materials will be deducted from current line-side inventory. Packaged products will be loaded on pallets for warehousing. Similar as material preparation in warehouse, the product barcodes will be bound with the pallet RFID tag by the "*Final Assembly Line Visibility Explorer*" on portable RFID-Gateway. Information of all the loaded pallets will be sent to both logistics manager's PC. The logistics manager will create logistics tasks accordingly by assigning logistics operator to deliver them to warehouses. This process is very similar to *Step 4*.

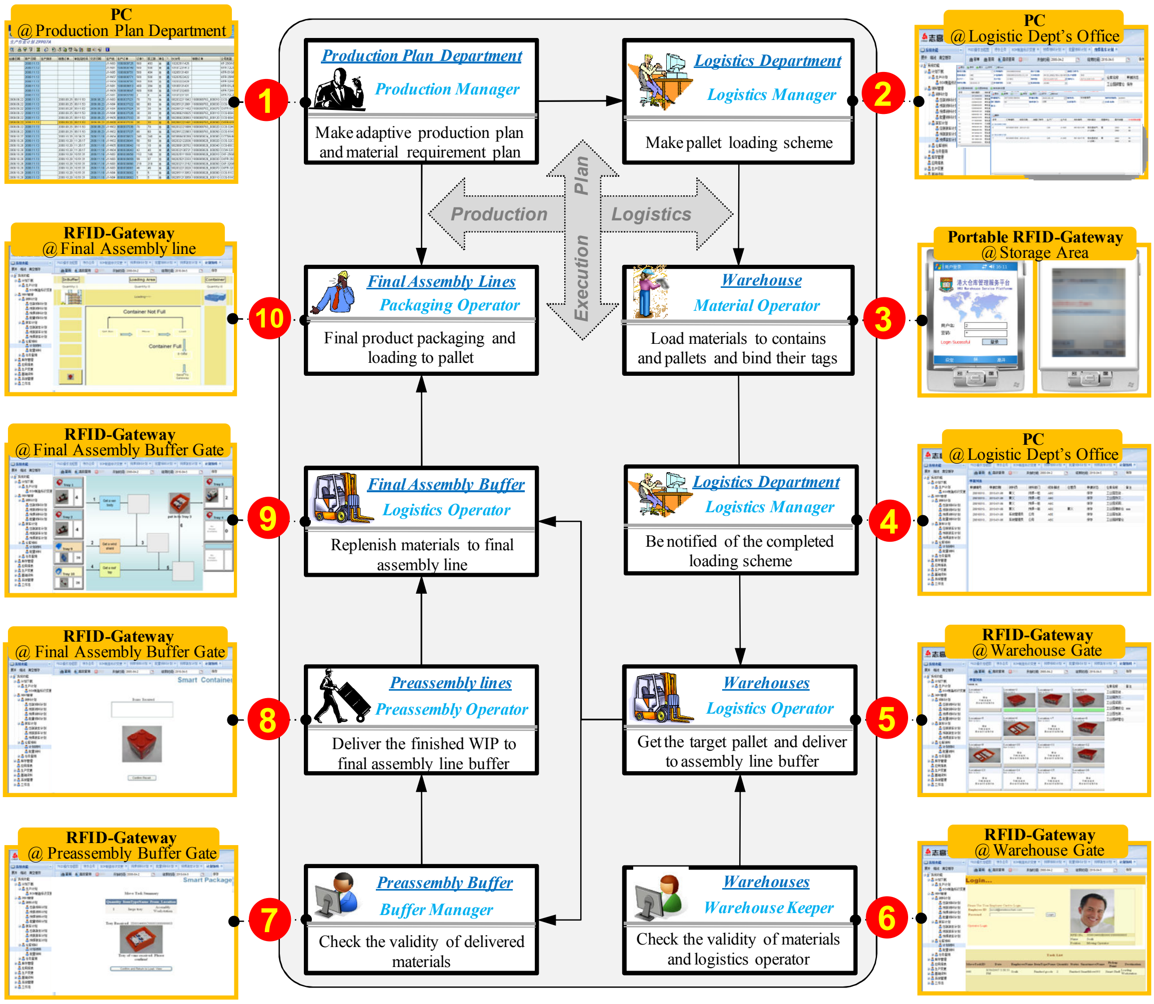

Fig 1. A Representative Operational Scenari

3.5.3 TYPICAL TRACEABILITY SERVICES

Traceability services in this system mainly serve for two purposes, tracing the information of another RFID-Gateway or tracing the history information of an operation process. The former is required in the normal operation of a material distribution process, such as the "*Line-side Inventory Traceability Service"* used in *Step 10*. However, when an order change happens in a production process, another traceability service called "*Order Traceability Service*" will be needed.

Line-side Inventory Traceability Service

Current system implementation only installs RFID-Gateways at the end of assembly lines instead of equipping every station with active smart objects (e.g. RFID readers). However, the line-side material stocks need to be monitored to enable timely replenishing. This service fulfils this need. Product outputs captured at the end of assembly line are used in connection with the product's BOM structure to calculate the line's real-time material consumption. Quantities of materials having been replenished to line are captured by the RFID-Gateway at the buffer gate. By subtracting the accumulative material consumption from the accumulative material replenishment, the real-time line-side stocks could be easily traced.

Order Traceability Service

Specifically, inserted production orders may result in new material orders and logistics tasks, while cut or cancelled production orders may result in reversed logistics tasks, i.e. material return tasks. In either case, the task's execution process is very similar to the normal material distribution process.

Exceptional processes are possibly needed if the released production orders are changed by production plan department. This service generates a remedy material distribution process for order changes. In case a new production orders is inserted, a new material order will be generated through tracing the product's BOM structure via SAP Adaptor (i.e. BOM RFC). Processing of this new material order will follow *Step 2 to 10* of the normal scenario. In case a released production order is reduced of its quantity or completely cancelled, on the other hand, this service will trace its corresponding material order and all the related logistics tasks. Those logistics tasks having not been started will be directly cancelled, while those in processing or being processed will be assigned a reversed logistics tasks. For example, a pallet of materials in preassembly buffer will be assigned a material return task requiring it to be sent back to the warehouse from where it is delivered.

4. CONCLUSION

This paper has presented an innovative shop-floor RFID implementation framework called AUTOM which has facilitated the project team to realize several successful RFID applications in a systematical way. Typical shop-floor requirements have been concluded and generalized into technical and management needs for RFID technologies. Both technical and managerial issues concerning with the RFID project implementation have been discussed in depth for manufacturing companies.

A case of applying RFID for managing material distribution in the complex assembly shop floor of a large air conditioner company is chosen in this paper to demonstrate the usage and effectiveness of AUTOM. The system has been continuously tested in the pilot workshop for a month. Several rounds of feedback collection from users have largely improved the usability and efficiency of the system on the one hand, helped all the operators familiar with the system on the other. Although positive ratings have been generally reported from both management and frontline operators, the evaluation process also revealed some challenges that deserve more attention in the future implementation.

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REFERENCES

1. Chryssolouris, G., et al., Digital manufacturing: history, perspectives, and outlook. Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, 2009. 223(5): p. 451-462.
2. Williams, D., The strategic implications of Wal-Mart's RFID mandate. Directions Magazine, 2004(Available on the Internet at http://www.directionsmag.com/article.php?article_id=629&trv=1&PHPSESSID=a942fc54a33502601eb2cbbec3fced74.).
3. Huang, G.Q., P.K. Wright, and S.T. Newman, Wireless manufacturing: a literature review, recent developments, and case studies. International Journal of Computer Integrated Manufacturing, 2009. 22(7): p. 579-594.
4. Mo, J.P.T., et al., Directional discrimination in radio frequency identification system for materials flow control in manufacturing and supply chain. Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, 2009. 223(7): p. 875-883.
5. Brintrup, A., D. Ranasinghe, and D. McFarlane, RFID opportunity analysis for leaner manufacturing. International Journal of Production Research, 2010. 48(9): p. 2745-2764.
6. Ren, Z., C.J. Anumba, and J. Tah, RFID-facilitated Construction Materials Management (RFID-CMM)-A Case Study of Water-Supply Project. Advanced Engineering Informatics, 2010. doi:10.1016/j.aei.2010.02.002.
7. Huang, G.Q., et al., RFID-enabled real-time Wireless Manufacturing for adaptive assembly planning and control. Journal of Intelligent Manufacturing, 2008. 19(6): p. 701-713.
8. De Toni, A.F. and E. Zamolo, From a traditional replenishment system to vendor-managed inventory: A case study from the household electrical appliances sector. International Journal of Production Economics, 2005. 96(1): p. 63-79.
9. Perona, M. and N. Saccani, Integration techniques in customer-supplier relationships: An empirical research in the Italian industry of household appliances. International Journal of Production Economics, 2004. 89(2): p. 189-205.
10. Clarke, R.H., et al., Four steps to making RFID work for you. Harvard Business Review Supply Chain Strategy Newsletter, 2006(P0602D).
11. Henseler, M., M. Rossberg, and G. Schaefer, Credential Management for Automatic Identification Solutions in Supply Chain Management. Ieee Transactions on Industrial Informatics, 2008. 4(4): p. 303-314.
12. Ngai, E.W.T., et al., RFID systems implementation: a comprehensive framework and a case study. International Journal of Production Research, 2010. 48(9): p. 2583-2612.
13. Huang, G.Q., Y.F. Zhang, and P.Y. Jiang, RFID-based wireless manufacturing for real-time management of job shop WIP inventories. International Journal of Advanced Manufacturing Technology, 2008. 36(7-8): p. 752-764.
14. Zhang, Y.F., et al., Agent-based Smart Gateway for RFID-enabled Real-time Wireless Manufacturing. International Journal of Production Research, 2010(Accepted).
15. Schmitt, P., F. Thiesse, and E. Fleisch, Adoption and Diffusion of RFID Technology in the Automotive Industry. Proceedings of the ECIS – European

Conference on Information Systems, St. Gallen, Switzerland, 2007.
16. Langer, N., et al., Assessing the impact of RFID on return center logistics. Interfaces, 2007. 37(6): p. 501-514.
17. Huang, G.Q., et al., RFID-Enabled Real-Time Services for Automotive Part and Accessory Manufacturing Alliances. International Journal of Production Research, 2010. Under Review.