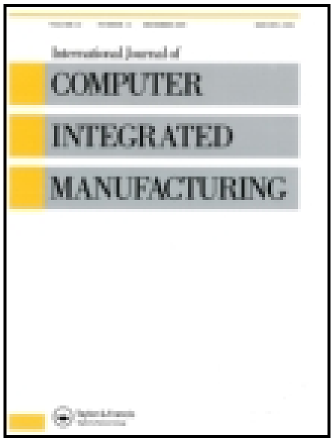

International Journal of Computer Integrated Manufacturing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tcim20

Radio frequency identification-enabled real-time manufacturing execution system: a case study in an automotive part manufacturer

Qingyun Dai [a] , Runyang Zhong [b] , George Q. Huang [b] , Ting Qu [b c] , T. Zhang [d] & T. Y. Luo [d]
[a] Faculty of Information Engineering , Guangdong University of Technology , Guangzhou, China
[b] Department of Industrial and Manufacturing Systems Engineering , The University of Hong Kong, Pokfulam Road , Hong Kong, China
[c] Faculty of Mechatronics Engineering , Guangdong University of Technology , Guangzhou, China
[d] Huaiji Dengyun Auto Parts (Holding) Co., Ltd. , Zhaoqing, China
Published online: 28 Jul 2011.

International Journal of Computer Integrated Manufacturing
Vol. 25, No. 1, January 2012, 51–65

Radio frequency identification-enabled real-time manufacturing execution system: a case study in an automotive part manufacturer

Qingyun Dai[a], Runyang Zhong[b]*, George Q. Huang[b], Ting Qu[b,c], T. Zhang[d] and T.Y. Luo[d]

[a]*Faculty of Information Engineering, Guangdong University of Technology, Guangzhou, China;* [b]*Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China;* [c]*Faculty of Mechatronics Engineering, Guangdong University of Technology, Guangzhou, China;* [d]*Huaiji Dengyun Auto Parts (Holding) Co., Ltd. Zhaoqing, China*

(*Received 13 October 2010; final version received 7 February 2011*)

Automotive vehicle manufacturers have been at the forefront of employing radio frequency identification (RFID) technology for their manufacturing logistics management. They have benefited from RFID-enabled shop-floor visibility and traceability, which have in turn facilitated the implementation of advanced manufacturing strategies such as just-in-time lean manufacturing and mass customisation. Initial successes have attracted attention and interests from small- and medium-sized enterprises (SMEs) involved in automotive part and component manufacturers down the automotive vertical. However, high levels of capital investments and technical skills have created practical hurdles for automotive SMEs to gain RFID benefits. This article reports on an industrial case study about the RFID implementation project at a typical SME engine valve manufacturer. This company manufactures a large variety of engine valves with a mixture of large and small orders. Work-in-progress items across the company have accumulated to an extreme level for human operations and decisions. The company adopted RFID-enabled shop-floor manufacturing solutions across the whole operations with little experience in the use of information systems/technology. Based on RFID-enabled real-time shop-floor data, the company has extended the efforts in setting up and integrating manufacturing execution system and enterprise resource planning system. The success of this case company demonstrates that RFID is not just for automotive giants but also practically useful to SME suppliers. The article presents a framework that has been followed by this case company with a hope that experiences and insights are useful to other automotive SMEs.

Keywords: RFID; manufacturing execution system (MES); real-time manufacturing; automotive; case study; small- and medium-sized enterprise (SME)

1. Introduction

Automotive industry has continued its role in world economy with 61.7 million vehicles produced and sold worldwide in 2009 (http://www.oica.net). Fierce global competition has also continued since motor vehicle price and time-to-market have been continuously cut down (Nag *et al*. 2007). Vehicle manufacturers have to simplify the supply chain so as to become more efficient and responsive (Huang and Qu 2008, Liu *et al*. 2008). Automotive industry has been leading the implementation of just-in-time (JIT) and flexible production systems as well (Amasaka 2007, Cao *et al*. 2009). Despite all the efforts, great challenges exist. For example, highly dynamic global automotive market has created highly stochastic customer orders and uncertain disturbances in production plans and schedules (Qu *et al*. 2010). Visibility and traceability of man, machines and materials are key to the reduction of such uncertainties for better planning and scheduling.

In recent years, a number of leading vehicle manufacturers employed radio frequency identification (RFID) to facilitate manufacturing shop-floor management. As early as 2000, Volvo Trucks had established an RFID system on the detail racks in its paint shops so as to achieve continuous production notwithstanding communication loss (Cao *et al*. 2009, Dai *et al*. 2010). BMW, since 2003, has set up four RFID-based real-time location systems within four German plants, where active tags are deployed on finished vehicles. Toyota has implemented information systems based on RFID to track auto parts production in French and South African facilities (Banks *et al*. 2007, Ilie-Zudor *et al*. 2010).

*Corresponding author. Email: zhongzry@hku.hk

ISSN 0951-192X print/ISSN 1362-3052 online

http://dx.doi.org/10.1080/0951192X.2011.562546
http://www.tandfonline.com

Automotive part and accessory manufacturers are usually small- and medium-sized enterprises (SMEs), and thus face financial and technological challenges when they initiate and implement advanced RFID technologies. Currently, most of the RFID systems are tailored by specialised information technology (IT) providers, such as IBM, Ubisense, etc, to suit the leading vehicle giants (Hur *et al.* 2009, Bendavid and Cassivi 2010). Hence, the cost and technical requirements of adopting their RFID solutions are too high for small- and medium-sized automotive part and accessory manufacturing (APAMs). Further considering the potential application risks of such a newly emerged technology, APAMs halt their steps and adopt a 'wait and see' strategy.

This article presents a real-life industrial case study and discusses how a small APAM has adopted RFID to realise real-time management and control to its shop-floor production processes. The purpose of this case study is three folded. Firstly, it aims at introducing an affordable RFID-enabled real-time manufacturing execution system (RT-MES) for small- and medium-sized APAMs. Secondly, a relatively generic and systematic framework to implement RT-MES is established for guiding SMEs to carry out RFID solutions. Thirdly, the benefits of RFID applications are to be demonstrated, to clear the shadow of sceptics on RFID usefulness on the one hand and to revitalise the enthusiasm of RFID application in manufacturing industry on the other hand.

This article focuses on several questions that a company may confront when it considers applying RFID on the shop floor. The first question is how to deploy RFID devices to collect real-time data on the manufacturing shop floors in a cost-effective way. The second is how to translate the real-time data into meaningful information to enable both the field operator's convenient operations (e.g. work-in-progress (WIP) visibility and traceability) and shop-floor supervisor's efficient decision making (e.g. workshop scheduling). The third is how to integrate RFID system into the company's current production processes so as to facilitate and rationalise shop-floor management.

The rest of this article is organised as follows. Section 2 gives some background of this case study and outlines the adopted implementation framework. From Section 3 to Section 7, the major steps comprised in the implementation framework are elaborated, respectively, including project management, business process analysis (BPA), design and configuration of RT-MES, reengineering of shop-floor operations and decisions as well as evaluation and reflection. Section 8 summarises this case study by highlighting the findings and generalising its implementation framework.

2. The case study

2.1. *About the case company*

The case company is Huaiji Dengyun Auto Parts (Holding) Co., Ltd. (Huaiji in short). Founded in 1971, Huaiji may be one of the most successful automotive part manufacturers in China's Pearl River Delta region. It mainly makes auto engine valves in original equipment manufacturer (OEM) mode. Currently, Huaiji employs more than 1600 workers, including approximate 200 plus engineers and technicians. Huaiji owns seven production lines and more than 800 machines. In the last two decades, its annual production increased from 4.5 million (1989) to 31.5 million (2010).

Huaiji's production and the related shop-floor logistics management are complex mainly due to two reasons. First, Huaiji manufactures as many as 8000 types of auto valves. They are made for not only domestic market but also overseas including USA, UK, Japan, etc. In technical terms, products are categorised according to stem diameter (Φ4.5–Φ16 mm), head diameter (Φ20–Φ70 mm), overall length (60–320 mm) and groove patterns. Second, the sizes of customer orders are much diversified. Small orders have only a few hundreds, while large orders have hundreds of thousands. These two features have results in over 20,000 kinds of materials and WIP items to be managed in the production processes. Such a huge and complex work has been considered the most direct initiative of Huaiji for starting this RFID-enabled RT-MES project.

2.2. *Success factors*

Huaiji's rapid development in the past two decades mainly results from two success factors. First, the automotive industry in the world has grown very fast in this period while China has achieved the greatest development. It was reported that the global demands for motor vehicles have increased from about 35 million in 1997 to around 80 million in 2008, while China's domestic vehicle production increased from 1.58 million in 1997 to 13.79 million in 2009 (http://oica.net/). These booming automotive markets have contributed a lot to the great development of Huaiji.

Second, despite the diversified customer orders and product types as mentioned above, Huaiji has adopted a relatively flexible production mode. The facilities have been organised into two general kinds of production lines. One is for large size orders. It works in a way that is similar to a hybrid flow shop. The other is for small and middle size orders. It follows a traditional workshop layout with machines of similar functions grouped together. Orders are categorised first and allocated to respective lines. By devoting more labour cost and sacrificing certain efficiency, Huaiji has maintained its production management at an acceptable level.

2.3. Current challenges

Although adopting a mixed production mode to deal with the wide product variety, Huaiji's potentials are still confined by various challenges related to production plan, material distribution and shop-floor production management. They are listed as follows.

2.3.1. Production plan

Prior to the system implementation, customer orders are processed manually by planners with an assumption of unlimited resources/capacities. Planners have inadequate information about job statuses at the manufacturing sites, leading to very high level of WIP inventories. Orders are released by a paper-based mechanism, which is time consuming and tedious. Significant times are spent on waiting for material arrival or completion of preceding operations (Engin *et al.* 2008, Zhu *et al.* 2010). In addition, disturbances such as frequent engineering and customer changes bring great myriad of emergency orders, which cannot be managed by the manual production planning system (Huang *et al.* 2010).

2.3.2. Material distribution

Prior to the system implementation, Huaiji only uses Excel and Word documents to manage the warehouse inventory data and adopts paper cards to identify materials. Such a mode is time consuming and error prone. Plus, the operators' personal factors involve data record and identification lacks standard and automatic data transaction rules, materials picking, sorting and counting operations are extremely difficult (Zhong *et al.* 2008, Zhang *et al.* 2010).

2.3.3. Shop-floor production management

The previous two challenges collectively lead to the third challenge of shop-floor scheduling and control. Prior to the system implementation, manufacturing schedules are made by planners and sent by shop-floor supervisors to workers in the form of paper-based task cards while reports are periodically sent back. On the one hand, task cards are prepared by planners based on their past experiences instead of standardised rules and are thus not practically appropriate. On the other hand, report sent back from shop-floor supervisors are often lagged and inaccurate, resulting in unavoidable fire-fighting situation that shop-floor supervisors blame planners for making unachievable plans, while planners complain that the plans have not been executed and reported appropriately. Therefore, snow-ball effects are triggered such as high WIP inventory level.

From the above introduction, the production characteristics of Huaiji could be summarised in five aspects. First, Huaiji belongs to small and medium-sized auto part manufacturer with a very wide product variety of variable batches serving both domestic and overseas customers. Second, Huaiji utilises hybrid flow shop production mode to organise its production facilities. The production cycle time is long, which has 40–60 operations on an average. Third, the production planning and scheduling is usually conducted in manual ways and released via paper-based sheets. The transaction data records are therefore inaccurate, inconsistent and lagged. Fourth, the information systems used in Huaiji are very rudimentary, only including word processing and spreadsheets. Fifth, Huaiji cannot perform effective track and trace to its materials and orders, resulting in high level of WIP inventory.

Although enterprise resource planning (ERP) could help managing production resources and making production plans and therefore provide a potential way for addressing the above problems, Huaiji has not applied it due to three major reasons. First, there are hardly any successful implementation cases of ERP in the same region. Comments from peer companies are most negative. Second, the investment of purchasing popular commercial ERP is too high to be afforded by the company. Finally, Huaiji believes that the bottleneck existed in the shop-floor operations given its products have a relatively simple structure (most valves are single-piece metal item).

After a few years of problem investigation and analysis with the aids from a collaborative university, Huaiji decides to develop a RFID-enabled MES, named RT-MES. With this system, production plans could be made under the consideration of the real-time statues of shop floors and be adaptively changed with shop-floor dynamics. This system coincided well with the R&D strategy of the provincial government in promoting the applications of RFID technologies in manufacturing and logistics industries. As a result, it was selected for government funding as a pilot project.

RT-MES is enabled in two levels. At the data capturing level, RFID tags are attached to key production objects, such as materials, locations and operators, while RFID readers are installed at each single machine to bind the production information of these tagged objects. At the decision level, the captured real-time data will be translated into meaningful information such as WIP, which may be used for making more appropriate decision. Decisions like production orders are released to machines to trigger next round of data capturing.

2.4. *Implementation framework*

The RT-MES project generally follows the 'idealise-design-test-improve' cycle. Specifically, a five-step framework shown in Figure 1 is adopted for the implementation. Key steps include project management, BPA, design and configuration of RT-MES, reengineering shop-floor operations and decisions with RT-MES and evaluation and reflection. These steps will be discussed in the following sections, respectively.

3. Step 1: project management

3.1. *Establishment of project team structure*

The RT-MES project team is led by 'first fiddle project' Steering Committee, which means the Chief Executive Officer (CEO) and department managers lead this project directly. They work out strategic guidance and critical decision making such as establishment of project objectives, selection of vendors and evaluation of milestones. The Steering Committee is also responsible for liaising and negotiating with government, promoting and monitoring the project progress, coping with project risks and changes, as well as arranging required resources.

The implementation of RT-MES project involves almost all the functional departments in the case company, including IT department, production department, warehouse, quality department and so on. Therefore, an interdepartmental project team has been setup. IT department serves as the internal technology provider who is responsible for designing and developing the system. All other execution departments are end users, which are responsible for user requirement collection and implementation plans.

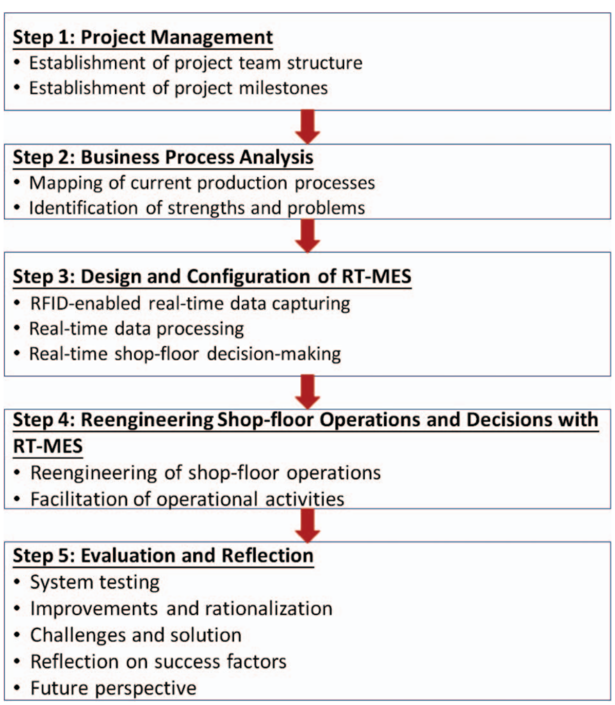

Figure 1. Implementation framework.

Huaiji has limited knowledge of RFID technology. Thus, RT-MES project invites some experts and specialists from a collaborating university as consultants and technical advisers. Consultants cooperate with the Steering Committee to figure out RFID-enabled solutions. Technical advisers act as 3rd-party technology providers, providing core technology in terms of RFID hardware and software.

RT-MES project adopts regular meeting and periodical reporting system as main working mechanisms. The aim of regular meeting is to increase people's understanding of this project through debating and exchanging ideas (Leung *et al.* 2008). Members of Steering Committee meet monthly to discuss project barriers and make related decisionssolutions. Steering Committee, together with other project parties, participates in critical meetings such as project kickoff meeting, online mobilisation meeting and project closing meeting. Project team leader gather project members for a 2-hour meeting weekly to review works of the previous week and arrange works for the next week. The aim of periodical reporting system is to strengthen communication, to reduce project risk and to review the project progress and quality. Project members report to project team leader weekly about the work progress, challenges and solutions. Project team leader reports to Steering Committee monthly about the project barriers, implementation challenges and project progress fulfilment. Steering Committee reported to the government quarterly in terms of project progress and objective fulfilment.

3.2. *Establishment of project milestones*

One key task in project management is to establish a feasible project plan so as to ensure the project progress. The project plan is labelled by milestones, which represent the end of steps within the implementation framework.

Five milestones have been established in this RT-MES project. The first is the assessment on status quo, which was identified by a deliverable so-called system requirement specification. The second is the design of blueprint that highlights the 'to-be' process that is determined by a deliverable so-called blueprint for future business operation. The third is realisation of system technology named detailed design report. The fourth is system deployment that is marked by online mobilisation meeting. The fifth is document finalisation identified by project closing meeting.

4. Step 2: business process analysis

The aim of BPA is to identify the problems in the current production process. It has been divided into three phases in this case.

4.1. Information gathering and data collection

Huaiji has a few reference documents for BPA. Therefore, RT-MES project team adopts face-to-face interview and group discussion in gathering information and collecting data. The interviewees include both frontline workers and department managers due to their well awareness of current manufacturing situations. Others are invited to participate in different discussion groups.

The project team visits the manufacturing sites to observe actual operations and activities as well. They investigate the business process through studying the physical flow of materials and flow of data. In addition, they distribute 100 copies of questionnaire to different operators to collect anonymous feedbacks.

4.2. Modelling processes by flow diagrams

After the collection of information, flow diagrams are used to model current production processes. Figure 2 illustrates a flow diagram forward directed from customer order process to finished products receiving. The flow diagram reports an order process with full batch quantity (180 items) in an 8-day manufacturing cycle. The processes consist of 10 work functions that are distributed in three key production units: production department, warehouse and manufacturing shop floors. In these units, work functions performed in a working day are streamlined from left to right, respectively.

Several key points should be highlighted. Firstly, project team have to review work functions in cross-functional processes instead of individual tasks that helps to establish a clear and holistic visioning of the company. Secondly, critical points and analysis results must be documented clearly and precisely that helps to identify final business needs or opportunities. Thirdly, the documents must be confirmed and signed by the top management that helps to avoid repeated works and maintain function/process uniqueness during system design and process reengineering.

4.3. Identification of gaps

From the above figure, the gaps in Huaiji are identified from three major departments: production department, warehouse and manufacturing shop floor.

For production department, manual-based planning strategy separates them from true shop-floor status and normally leads to inappropriate decision. For example, according to plan, there are 20% of

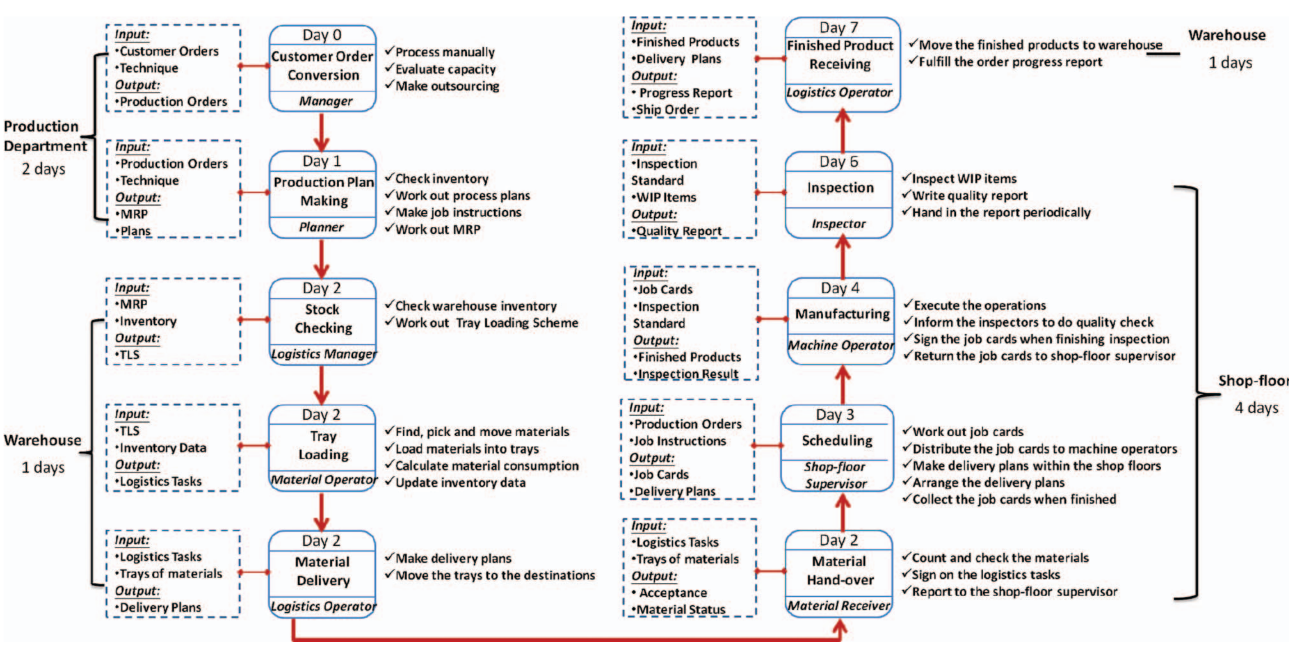

Figure 2. Flow diagram of current production process.

orders that should be outsourced. Some days, however, Huaiji actually has the capacity for fulfilling these orders by its own. A planner said 'if real-time manufacturing data can be captured on shop-floors, we can dynamically adjust our production plan and secure more profits.'

For warehouses, workers have to spend lots of time on locating, querying and counting materials every day, but still cannot avoid loss or inaccuracy. Once, around 1000 pieces of raw material were missed due to worker's carelessness. That resulted serious delay on an important customer delivery order. Huaiji had to pay high penal sum. A warehouse worker stated: 'We suffer a lot from paper-based operations and identifications. We want a more accurate and precise way to manage our inventory.'

For manufacturing shop floors, production plans are made in an arbitrary way instead of considering the real situation. Machine operators complain that supervisors often allocate 'nice jobs' (e.g. easy processing and well paid) to their familiar operators, while logistics operators grumble that supervisors usually arrange logistics tasks in an unreasonable way. A logistics operator cited: 'Shop-floor supervisors do not group the logistics tasks but arrange them arbitrarily. I have to walk frequently between shop floors and warehouse to deliver materials, even if someone nearby can do that instead.'

The main causes of the above weaknesses are the lacking of auto-Identity (ID) technologies to manage inventory and WIP items, real-time data collecting facilities on manufacturing shop floors, an adaptive planning and scheduling strategy and a tool to visualise WIP traceability.

5. Step 3: design and configuration of RT-MES

To fill the above gaps, project team design and develop the RT-MES for Huaiji's shop-floor management. The overview of RT-MES is shown in Figure 3. RT-MES includes three layers: real-time shop-floor decision-making layer, real-time data processing layer and RFID-enabled real-time data capturing layer.

Real-time shop-floor decision-making layer includes scheduling program as well as visibility and traceability program. Scheduling program facilitates planners and shop-floor supervisors making real-time plans and schedules. Visibility and traceability program includes a set of explorers showing the respective meaningful information interested by different users. For example, logistics operators will be instructed of their moving tasks and detailed requirements, while shop-floor supervisors could monitor the material delivery process and real-time WIP inventory level.

Real-time data processing layer is a RFID middleware program. It is intended to control data transfer among tags, readers and databases. This program is installed in a shop-floor computer, enabling shop-floor supervisors and hardware maintainers to real-time monitor equipment's working status and information exchanges.

RFID-enabled real-time data capturing layer includes RFID devices and communication networks. They are responsible for collecting real-time data from shop floor and transfer to the upper data processing layer through RS485 standards. Through attaching RFID readers to individual machines, an RFID-based distributed or ubiquitous shop-floor real-time manufacturing environment could be created.

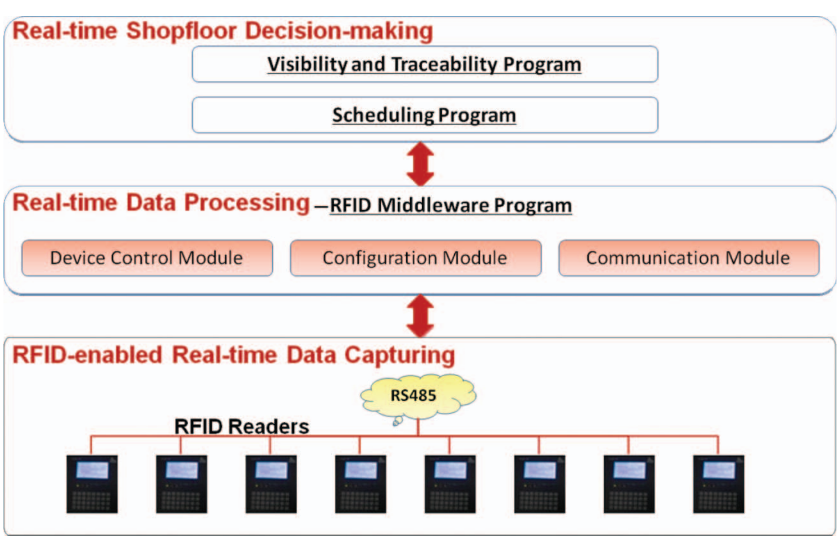

Figure 3. Overview of RT-MES.

5.1. RFID-enabled real-time data capturing

This section addresses the question on how to deploy RFID devices on the manufacturing shop floors so as to capture real-time data. The deployment is implemented in three procedures.

The first procedure is RFID selection. Huaiji employs low-frequency (LF) RFID instead of high-frequency (HF) or ultra high-frequency (UHF) due to the following considerations. HF device is the cheapest, but it is not suitable for application in the manufacturing environments with metals and liquids. Although UHF is applicable to the environment, it is too expensive. LF is less subjected to environmental interference and relative cheap and is thus selected by Huaiji.

The second procedure is to identify the manufacturing objects to be RFID tracked. It depends on whether the information of these objects should be concerned by the production management and whether their movements add values to the process. Typical objects in warehouses include material operators, raw materials and finished products, while the manufacturing shop floors contain machines, machine and logistics operators, buffers, WIP and their handling equipments (e.g. forklifts, trolleys, etc).

The third procedure is the physical deployment of RFID devices. Figure 4 demonstrates the actual RFID deployment in Huaiji. It is realised in three sub-procedures.

5.1.1. Deployment of RFID readers

RFID readers are deployed in warehouses and manufacturing shop floors. In a warehouse, two RFID readers are deployed. One is in raw material loading area, used for executing loading scheme and initiating the trays, which should be tagged. The other is in finished products receiving area, used for recycling tags. On a manufacturing shop floor, RFID readers are deployed to each machine. A machine is a value-adding point, where data processing could be conducted simultaneously with working process. This not only simplifies the data capturing, but also makes real-time adaptive instruction possible for machine operations.

5.1.2. Deployment of RFID tags

For the manufacturing objects to be tracked, Huaiji adopts a mixed tagging scheme. For materials, it adopts a tray-based scheme. That means, instead of attaching each individual material with a separate RFID tag, only the trays for containing material are tagged. This not only cuts down the RFID tag costs, but also simplifies the tagging-related labour costs. The information in tray tag contains job instructions, quality inspection standards, etc. The information will be updated along with the internal operation and logistics process. Workers, equipments and locations are tagged individually with staff cards, equipment

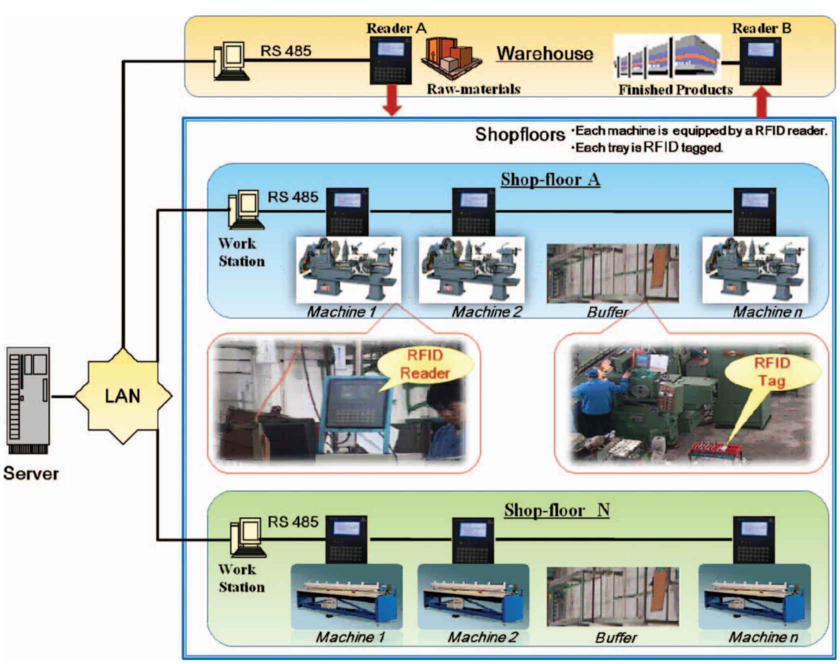

Figure 4. RFID-enabled real-time shop-floor data capture approach.

labels and location ID, respectively. Their tag information is only the object IDs, which will remain the same constantly.

5.1.3. Deployment of communication network

RS485 network devices are deployed due to three considerations. First, it suits metal machinery manufacturing fields with reasonable data transmission speed of 35 Mbit/s up to 10 m and 100 kbit/s at 1200 m (Zhou *et al.* 2007). Second, it achieves data communication effectiveness over long distance within electrically noisy environment in Huaiji. Third, data can be captured effortlessly by computers through an adapter connected with cables.

5.2. Real-time data processing

Three data structures have been defined for tag, reader and middleware, respectively. Tag data structure includes start and end flag, index, reader address, step ID, data contents and check code. Reader data structure is similar to tag except for several additional control flags including CID, STEP, LIMIT, MIN, MAX and VALUE. These additional flags are utilised for controlling data transmission reliability. Middleware data structure utilises tag index to relate with data in database, where the index serves as primary key to link to more information.

A RFID middleware program is designed to process real-time RFID data. There are three key modules. Device control module controls RFID devices in terms of switching readers, writing data into tags and updating these data. Configuration module manages the configurations of database linkage, communication channel and visualisation style. Communication module supervises real-time communication with respect to speed, transmission delay and communication port.

5.3. Real-time shop-floor decision making

This section is going to answer the question on how to utilise real-time data to support shop-floor decision making. Figure 5 depicts an RFID-enabled real-time scheduling approach in RT-MES. It can be divided into two levels: production planning and real-time scheduling.

The case company converts customer orders into production orders manually, and then put them into a

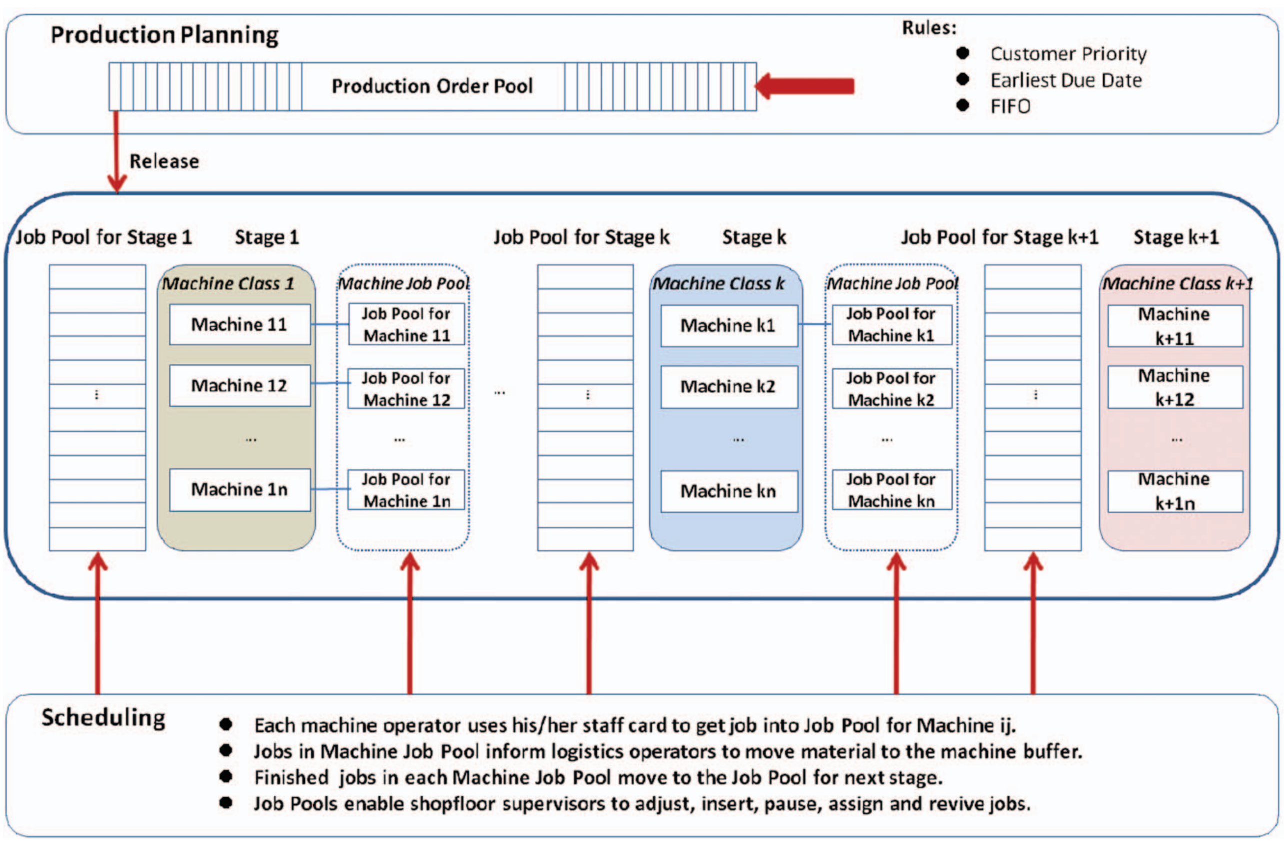

Figure 5. RFID-enabled real-time job pool scheduling.

production order pool. Three rules will be applied regarding the production order releasing, including customer priority, earliest due date and first-in-first-out. Production orders are released to the first stage of a manufacturing process according to the working shifts.

Real-time scheduling in RT-MES is based on two key concepts. The first is hybrid flow shop scheduling. That means a job is divided into several stages, each of which could be undertaken by several machines with similar functionality. Machines process jobs in parallel in the same stage. Some machines can only process one job at a time, e.g. lathe, drill machines, while some can process multiple jobs together, e.g. heat treating furnace. The buffer of each machine is unlimited since the manufacturing items can be packed into trays that are easily folded up.

The second key concept is real-time job pools (Huang *et al*. 2009). Job pools have two levels, stage job pools and machine job pools. The former stores jobs that are to be processed in a stage. These jobs are sequenced according to priority determined by rules. The latter stores jobs that a specific machine will process. For those machines with multi-job processing capability or designated job types, machine job pool is significant.

Using real-time job pools, two criteria have to be taken into account in the last stage $k + 1$. First, jobs in the pool must be finished on time. This aims at minimizing target due time for all jobs in the pool. Second, jobs in the last stage must be fulfilled as fast as possible. This aims at minimising the makespan and maximising machine utilisation. From the last stage with relative independence, sequencing decisions have to be made stage by stage of backward 'pull' sequencing method.

6. Step 4: reengineering shop-floor operations and decisions with RT-MES

The RT-MES has been deployed to the case company's shop floors and put into practical daily operations. This section will answer the question on how to integrate RFID system into the company's current production process. Figure 6 describes a representative production process enabled by RT-MES. The eight steps are arranged according to the logical sequence of the involved operators and activities.

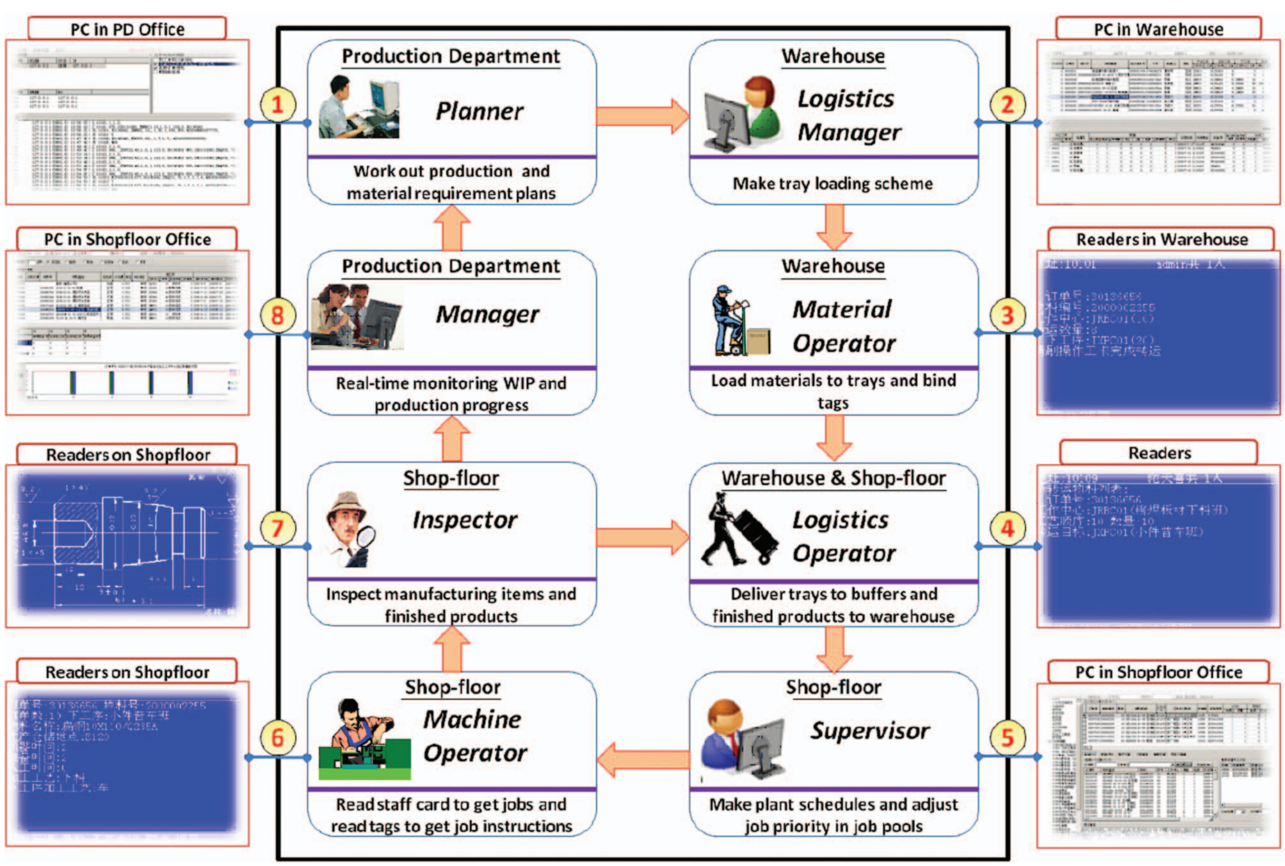

Figure 6. Representative operational process in Huaiji.

6.1. Production department: planner works out production and material requirement plans

Planners in the production department use 'production plan explore' to work out production and material requirement plans (MRPs) on a personal computer (PC). Firstly, planner opens 'stock checking explorer' on the PC to review raw materials. Secondly, he/she uses 'production plan explore' to initiate the priorities of production orders and puts them into production order pool. Thirdly, he/she releases orders according to the shifts. Finally, he/she will open 'real-time production visibility explorer' to supervise real-time status of order progress, machine capacity and material availability.

6.2. Warehouse: logistics manager makes tray loading scheme

Once production orders are released, the MRP will be available in the warehouse. The logistics manager will be alerted to make tray loading scheme through 'material loading explorer' on a PC. He/she determines how many batches have to be conducted, how many trays have to be prepared and at what time the trays should be delivered to their destinations.

6.3. Warehouse: material operator loads materials to trays and binds tags

The finished tray loading scheme will be sequenced by their priorities and shown on a RFID reader screen deployed in the raw-material loading area. Material operator pats his/her card to load materials to trays and bind tags. Once the tags attached to the trays, the information such as production order contents, job instructions, quality inspection standards, etc., will be stored in the tags. The material operator has to read his/her staff card to verify and finish this operation. Otherwise, the system will give warnings.

6.4. Logistics department: operator delivers trays to shop-floor buffers and picks the finished products to warehouse

Logistics operator will get his/her logistics tasks when patting his/her staff card through a RFID reader or checking 'logistics tracing and tracking explore' on a PC. The tasks indicate the specific tray's positions in the shipping dock and the destination of each tray. After delivery, logistics operator and the material receiver must pat their staff cards to confirm the handover. Logistics operator also picks finished products and moves them back to warehouse. In the warehouse, he/she will recycle the tags through the RFID reader deployed in finished products receiving area.

6.5. Shop floor: shop-floor supervisor makes schedules and adjusts job priority in job pools

After material handover, shop-floor supervisor will get the message immediately. He/she opens 'shop-floor scheduling editor' to make schedules. He/she intervenes in shop-floor schedules through modifying job priorities in the job pools. In addition, he/she designates jobs to dedicated workers by pulling them into the machine job pool directly. He/she will open 'shop-floor real-time manufacturing visibility explorer' to monitor the real-time status of jobs arrangement, machine status and WIP inventory level.

6.6. Shop floor: machine operator reads staff card to get jobs and then reads tags to get job instructions

Firstly, machine operator reads his/her staff card to get jobs from machine job pool. If the machine job pool is vacant, the higher priority job in the job pool for this stage will be released to this machine. Secondly, he/she takes a tag and reads it before the starting of operations to get job instructions. Thirdly, when finishing the processing, machine operator has to pat his/her staff card to verify the completion. Next job will be released to the machine immediately.

If the job cannot be accomplished during the working time, machine operator may either: (1) freeze the job and then resume it in next working time or (2) pass it to another machine operator through binding a new tag to the unprocessed items. The aim is to differentiate processing and get clear traceability.

6.7. Shop floor: inspector inspects manufacturing items and finished products

After getting job completion message from machine operator, shop-floor inspector inspects the processed items. He/she reads his/her staff card to get quality inspection standards through RFID reader. Then he/she inputs quality data and read the staff card again to verify the inspection. Meanwhile, the verification informs logistics operator to move the items to next stage or to warehouse, if this is the last stage.

6.8. Production department: manager monitors real-time WIP inventory, machine status and production progress

Production department manager uses 'real-time shop-floor production visibility and traceability explorer' to monitor shop-floor production in terms of manufacturing progress, machine status, WIP inventory and material consumption. The information enables managers to make precise and adaptive decisions in terms of machine utilisation optimisation, JIT production, WIP inventory minimisation and internal logistics optimisation.

7. Step 5: evaluation and reflection

The RT-MES has been put into practical daily shop-floor operations in the case company since 2004. This section reports the evaluation of this project in terms of system testing, tangible and intangible benefits, and then devotes a reflection on implementation challenges and solutions. Opportunities for future exploration are also highlighted.

7.1. System testing

System testing has been carried out at three levels, including module testing, integration testing and on-line testing.

Module testing has been executed by programmers or testers. They adopt white box testing strategy that concentrates on individual parts of source code. The aim is to ensure the availability and compatibility of individual function modules early in development cycle.

Integration testing has been carried out by technical team leader. Black box testing and bottom-up strategy are followed that focus on integrating RFID hardware with software. The aim is to evaluate the system fitness for processes and to verify functional, performance and reliability requirements. At this level, team leader has to finish a system testing report. The report will be referred to input and output, fluctuation and responsiveness so as to finalise the user manual.

Online testing aims to detect this system in real-life manufacturing environment by end users. They utilise testing cases such as typical production orders, error scenarios and stressful cases, etc. The purpose is to evaluate the system's compliance with its specified requirements and to support the reengineered production processes. At this level, project team summarises the feedbacks from end users and then report to Steering Committee to make further improvements.

7.2. Improvements and rationalisation

The use of the RT-MES has rationalised both the business processes and operations in the case company in several aspects.

Firstly, real-time data collection improves the quality and efficiency of business processes and operations. This strategy eliminates the time-consuming manual data collection and reduces the wasteful paper-based data sheets. The business processes and operations are therefore upgraded from man-based management style to a truly computer-based style, which is much more efficient.

Secondly, the whole production plan and execution process has been simplified and integrated. Most of the previous tedious or non-value-adding activities are eliminated. In production department, for example, production order sequencing, printing and distributing have been integrated into one process – production order release. Previously, three workers had to fulfil an order due to the lacking of up-to-date information. But now, only one is required since the RFID technology provides frontline data that is real time, accurate, complete and consistent. The integration not only freed extra workers for more productive and innovative jobs, but also enhanced processing efficiency through digitalised operations.

Thirdly, operation errors have been largely reduced. For instance, material distribution in warehouse was previously prone to errors because of manual calculation, statistics and checking. Through reading tags attached to the materials, RT-MES could calculate real-time material consumption automatically. Furthermore, the automation enables auto-alarm when some critical materials are below the safety level. Therefore, WIP inventory has been controlled in a low level.

Fourthly, real-time scheduling system largely improves the fairness and feasibility of production plans. With job pools and rules, task generation and release will be conducted by computers based on the real-time dynamics collected from manufacturing shop floors. Human factors are eliminated to avoid managerial partiality and operational inaccuracy.

Fifthly, production records will be created and synchronised along with the physical production process in a real-time fashion. Such 'what you see is what you do and what you do is what you see' style enables both managers and operators to ensure the correctness of their decision making and operation.

The benefits obtained from RT-MES not only come from macro-aspect but also come from micro-aspect in this company. Table 1 reports several

Table 1. Benefits from statistical analysis.

Item	Achievement
Improve production efficiency	12%
Reduce WIP inventory	34%
Improve product quality	40%
Eliminate paperwork	88%
Information on time	96%
Annual added output	2.2 million pieces
Save facility investment	1 million RMB

statistical analyses, showing the benefits from micro-aspects. First of all, RT-MES improves the production efficiency by 12%. That means the annual production of Huaiji increases 2.2 million pieces without adding any extra facilities. The net sales of Huaiji grew 28.6 million Renminbi (RMB) in the first year after RT-MES implementation. Secondly, RT-MES is beneficial to Huaiji in terms of WIP inventory, product quality and information transferring. Thirty-four percent of WIP inventory is reduced, and product quality was improved by 40%. On time information increased by 96% and paper work is cut down by 88%. Thirdly, the RT-MES further saved the investment on adding manufacturing facilities over 1 million RMB in one side. In the other side, it cut down the waste including cost, resources and reworking approximately over 1 million RMB within the 2nd year after RT-MES implementation.

Due to its success, this pioneer RFID project largely boosts Huaiji's Hi-Tech reputation in the region, even in the nation. It has been selected to be the China's information demonstration point in 2005. RT-MES has therefore been further extended to heavy-duty machinery assembly industry, semi-process industry and pharmaceutical industry.

7.3. Implementation challenges and solutions

During the project implementation, various challenges have been confronted that come from both people and technology adoption. It is the solving of these challenges that leads to the final success of this project. In this section, these challenges and solutions will be elaborated so that insights and lessons obtained from this case company could be referred in the future, providing a visual guide for practitioners.

7.3.1. Challenges by people

There are two challenges brought by people during the project implementation. The first is workers' resistance against standardisation. Workshop operators insisted upon their individual habits and ways of doing their jobs because they have been accustomed to them. They were not willing to follow the project's required standard operations. After a few rounds of debates and struggles, this problem was finally transferred to the Steering Committee. Steering Committee developed some incentives such as financial awards to encourage the standardisation and finally succeed.

The second lies in the workers' training process. Similar as most of the manufacturing companies in China, the majority of Huaiji workers is not well-educated and their awareness of IT was poor. It is therefore hard to put the system into usage directly. Therefore, a two-phase training process was launched. In the first phase, consultants trained Steering Committee and technical team members who are related well-educated about the basic concepts, system benefits, RT-MES working principle and representative operations. In the second phase, department managers who were familiar with the production process details in turn trained employees for their respective department through employee's understandable manners. In this way, the system is gradually accepted and mastered by managers and penetrated to the operator's everyday works.

7.3.2. Challenges by technology

There are three challenges in technology aspect. The first challenge is the limited memory of RFID tags. In case of long processes, the overflow of tag memory occurs very often. This problem cannot be simply addressed by using large memory chips due to the high cost and the uncertainties of specific future demands. After referring to the project's consultants, a solution that uses tag's ID only as index while stores the related content in database has been adopted. During operation, data is uploaded to or downloaded from database to readers by tag's index. In this way, readers and tags could carry much more information.

The second technology challenge is the slow responsiveness of RFID readers when reading multiple tags. This situation is common at the beginning of each shift when multiple operators report on their duties through patting their staff cards at each workstation. In such situation, signals will be jammed in the readers, and the signal transmission will be slow. This problem has been addressed through adding a random parameter into each reader signal. The parameter acts as a transmission delay so as to stagger signals and avoid possible collisions.

The third challenge is actually an upgraded one of the above second challenge. When a large number of data are transmitted among tags, readers and database, the communication module cannot ensure a reasonable responsive time with the limited network bandwidth. This problem was finally solved through developing a multi-threaded program in Server to dynamically create a thread for each communication. A thread from a communication requirement is a sequence of instructions that ran independently of any other threads. In this way, a server could accept multiple real-time data transferring among tags, readers and database.

7.4. Reflection on project success factors

Although suffered from poor IT infrastructures and confronted by the above-mentioned various challenges, the project has finally succeeded. The developed RT-MES has been melted into the everyday operations in Huaiji for 5 years and obtained wide recognition from both managements and field operators. After careful reflection, several factors contributing to this success have been summarised as follows.

7.4.1. *Top management support*

This RT-MES project is the so-called 'first fiddle project', an indeed CEO's project. The CEO initiates a roadmap for the whole company's informationalisation. This RT-MES project has been regarded as the critical starting point along this road from the manufacturing sites. With the must-win determination, all the managements have taken full responsibilities to ensure the smooth advances of this project. Apart from adequate financial and technical supports, human obstructs from any aspects have been overcome efficiently, paving a smooth road for driving the project.

7.4.2. *Business process reengineering (BPR)*

Before implementation, the project team carefully examined the 'as-is' processes and worked out the 'to-be' processes most suitable for application of RFID-enabled MES. Huaiji's top management devoted a lot to remove the barriers and encourage innovative processes in BPR. Such strong support ensures that the case company finally accomplish the changeover of its old business processes to the new one.

7.4.3. *Bottom-up informationalisation strategy*

Huaiji believes that the top-level enterprise decision-making systems (e.g. ERP) cannot work properly without accurate and timely data from manufacturing shop floors. Considering the limited budgets of implementing information systems, Huaiji initiated the informationalisation construction from bottom (e.g. manufacturing shop floors). The bottom-up strategy builds up an enterprise informationalisation pyramid (from RT-MES to ERP) through 'building block principle' to form a solid information system construction. In fact, ERP has been successfully implemented in the recent 2 years with the RT-MES facilities.

7.4.4. *Collaborative teamwork*

The success of this project is also attributed to the collaborative teamwork among industries, universities and government. Firstly, they are summoned to work collaboratively in a same physical working environment. The common working environment enables them to share knowledge, exchange new ideas and enhance communication among all parties. Secondly, the involved parties regularly organise seminars, workshop and meetings. The activities raise positive human interaction. Finally, government's periodic review of work ensures the project progress and elevates the team spirits. Working relationship and association after this project are strengthened within these three parties.

7.5. ***Future perspectives***

After the successful implementation of the RT-MES project, the case company has been continuously launching several enterprise informationalisation projects. These projects are regarded as extensions of RT-MES in horizontal and vertical dimensions.

In horizontal dimension, the case company initiates an ERP project. This project aims at utilizing the real-time information of RT-MES to support the enterprise-level decision making such as real-time sourcing decision, material requirement decisions, etc. In addition, the company uses the hand-held RFID devices in warehouse to integrate mobile logistics management into RT-MES. With the RT-MES and these subsequent extensions, it has been able to form a closed-loop adaptive decision-making mechanism within the company.

In vertical dimension, the case company initiates a project named manufacturing intelligence system platform (MISP). MISP integrates service-oriented manufacturing (SOM) and data mining technology to further elevate the execution-oriented decision-making capabilities in this company. MISP focuses on answering some research questions. The first is how to set up an RFID-enabled real-time planning and scheduling model to minimise the production makespan and overall machine utilisation. The second question is how to mine RT-MES historic data to facilitate setting more accurate variables such as setup time, processing time, waiting time and delivery time. The third question is how to integrate the current systems with SOM architecture to develop a platform serving for other automotive parts manufacturers.

8. Summary

This article has presented a case study of developing a RFID-enabled RT-MES to realise real time and accurate control to the dynamic shop-floor production process of a SME (APAM) company. Unlike the leading automotive makers who can afford large IT investments and the large APAMs who have already adopted enterprise-level information systems like ERP, such as SME APAM owns limited IT foundation to grow RFID and has to formulate a company-level systematic approach to develop the RFID-enabled MES totally from scratch. The adopted implementation procedure together with the rich experiences and findings from the implementation practices enable to generalise a theoretical framework called 'PADRE':

(1) 'P'-People: establish a decent project team structure;
(2) 'A'-Analyse: measure current business process;
(3) 'D'-Design: work out a suitable RFID-enabled solution/system;
(4) 'R'-Reengineering: redesign operations based on RFID-enabled solution/system;
(5) 'E'-Evaluation: assess the fit and make improvement after extensive use.

With 'PADRE', technical, institutional and procedural issues concerning with the project implementation have been discussed for the case in specific, for SME APAMs with similar RFID and MES application requirements in general. 'PADRE' can be shared among metal part manufacturers for implementing RFID-enabled solutions for solving their shop-floor problems that have been caused by a wide product variety, a mixture of both low and high production volumes, long sequence of operations and traditional functionally oriented workshop layouts.

This project is significant in three aspects. First, a set of hardware and software technologies as well as a shop-floor RFID system structure that are key to the implementation of RFID-enabled MES have been developed. These technologies are applicable and extensible to other manufacturers, while this case gives an illustrative APAM solution. Second, most of the APAM share similar production characteristics and shop-floor control problems, such as a wide variety of products, a mixture of both low and high production volumes, long sequence of operations and traditional functionally oriented shop-floor layouts. Therefore, the insights and lessons obtained from the case study could be easily generalised to other APAMs. Third, the success of this project proves the potential benefits of RFID and demonstrates its potential usage in production when integrated with production control systems. This will encourage more and more APAMs to adopt RFID technologies in their manufacturing control instead of maintaining a 'wait and see' manner.

Acknowledgements

The authors would like to acknowledge financial supports from the following institutions: HKSAR ITF (GHP/042/07LP), Guangdong Modern Information Service Fund 2009 (06120940B0260124), 2010 Guangdong Department of Science and Technology Funding (2010B050100023), HKU Research Committee, Hong Kong SAR RGC, National Natural Science Foundation of China (61074146), International Collaborative Project of Guangdong High Education Institution (gjhz1005) and HKU Teaching Development Grants (TGD). Special acknowledgements are given to Huaiji Dengyun Auto Parts (Holding) Co. Ltd. and the project team for the technical supports.

References

Amasaka, K., 2007. Applying new JIT – Toyota's global production strategy: epoch-making innovation of the work environment. *Robotics and Computer-Integrated Manufacturing*, 23 (3), 285–293.

Banks, J., *et al.*, 2007. *RFID Applied*. Hoboken, NJ: John Wiley & Sons.

Bendavid, Y. and Cassivi, L., 2010. Bridging the gap between RFID/EPC concepts, technological requirements and supply chain e-business processes. *Journal of Theoretical and Applied Electronic Commerce Research*, 5, 1–16.

Cao, H., *et al.*, 2009. RFID in product lifecycle management: a case in the automotive industry. *International Journal of Computer Integrated Manufacturing*, 22 (7), 616–637.

Dai, Q.Y., *et al.*, 2010. A RFID-enabled real-time manufacturing hardware platform for discrete industry. *In*: *Proceeding of the 6th CIRP-sponsored International Conference on Digital Enterprise Technology*, 14–16 December 2010, Hong Kong. Vol. 66. Berlin, Heidelberg: Springer-Verlag, 1743–1750.

Engin, O., Ahmet, Ç., and İhsan, K., 2008. A fuzzy approach to define sample size for attributes control chart in multistage processes: an application in engine valve manufacturing process. *Applied Soft Computing*, 8 (4), 1654–1663.

Huang, G.Q., *et al.*, 2009. RFID-enabled real-time mass-customized production planning and scheduling. *In*: *Proceeding of 19th international conference on flexible automation and intelligent manufacturing (FAIM)*, 6–8 July 2009, Teesside, UK.

Huang, G.Q., *et al.*, 2010. RFID-enabled pharmaceutical regulatory traceability system. *In*: *Proceeding of 2010 IEEE International Conference on RFID-Technology and Applications (RFID-TA)*, 17–19 June 2010, Guang Zhou, China. IEEE Xplore Digital Library, 211–216.

Huang, G.Q. and Qu, T., 2008. Extending analytical target cascading for optimal configuration of supply chains with alternative autonomous suppliers. *International Journal of Production Economics*, 115 (1), 39–54.

Hur, S.M., Jeong, S., and Suh, S.-H., 2009. An experimental approach to RFID system performance prediction model. *International Journal of Computer Integrated Manufacturing*, 22 (7), 686–697.

Ilie-Zudor, E., *et al.*, 2010. A survey of applications and requirements of unique identification systems and RFID techniques. *Computers in Industry*, 62 (3), 227–252.

Leung, A.W.L., *et al.*, 2008. Computerization in Keda: best practices. *IS6930 Residential Trip Final Report*, July 13.

PingQing, L., HuaJie, S., and Qiang, G., 2008. The global value chain and china automotive industry upgrading strategy. *Management Science and Engineering*, 2 (1), 11–19.

Nag, B., *et al.*, 2007. Changing features of the automobile industry in Asia: comparison of production, trade and market structure in selected countries. *Asia-Pacific Research and Training Network on Trade (ARTNeT)*, 37 (7), 1–47.

Qu, T., *et al*., 2010. Optimal configuration of assembly supply chains using analytical target cascading. *International Journal of Production Research*, 48 (23), 6883–6907.

Zhang, Y.F., *et al*., 2010. Real-time work-in-progress management for smart object-enabled ubiquitous shop floor environment. *International Journal of Computer Integrated Manufacturing*, 1, 15.

Zhong, R.Y., *et al*., 2008. Design and implementation of DMES based on RFID. *In*: *Proceeding of 2nd international conference on anti-counterfeiting, security and identification IEEE*, Guiyang, China. New York: IEEE, 475–477.

Zhou, S., Weiqing, L., and Zhongxiao, P., 2007. An RFID-based remote monitoring system for enterprise internal production management. *The International Journal of Advanced Manufacturing Technology*, 33 (7–8), 837–844.

Zhu, Z., *et al*., 2010. RFID application in manufacturing: a case study on a pilot RFID project in household appliance production. *International Journal of Computer Integrated Manufacturing*, 99999 (1), 1–8.