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以多重代理人為基礎之製造規劃與控制系統

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Multi-agent Based Agile Manufacturing Planning and Control Systems

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摘要

隨著產業全球化的趨勢，今日的製造環境所重視的是如何提升顧客服務水準（例如：縮短接單到出貨時間及降低存貨成本等）。然而，目前所使用的製造規劃與控制系統所提供的功能僅侷限於製造廠，當擴及到整體供應鏈時，往往需要其他的系統整合技術。無線射頻識別系統的應用，帶來即時性的資訊，藉由主動獲得這些即時性的資訊，可以有效提升整體供應鏈績效。即使無線射頻技術可帶來即時性的資訊，後端如果沒有一套健全的應用系統，將無法使這些資訊獲得最有效的應用。因此，本篇論文的目的為：（1）應用無線射頻技術與多重代理人系統，提出一個可以快速且動態的回應企業外部與內部變動的製造規劃與控制系統（agent-based manufacturing planning and control system；AMPCS）之系統架構；（2）發展 AMPCS 之系統分析與設計方法；（3）以東海大學自動化實驗室為環境，實做並驗證此系統架構。

關鍵字：無線射頻識別系統、多重代理人、製造規劃與控制

Multi-agent Based Agile Manufacturing Planning and Control System

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Abstract

In today's manufacturing enterprise, the performance of customer service level (e.g., short ordering-to-delivery time, low price) is highly dependent on the effectiveness of its manufacturing planning and control system (MPCS). However, the function of today's manufacturing planning and control is limited inside a manufacturing system and cannot effectively enhance the performance objectives (e.g., customer service level) in a supply chain environment which usually includes several components. Currently, RFID allows the accurate and detailed information of products to be followed in real time across the supply chain. However, RFID technique cannot support a rapid decision-making in a distributed and heterogeneous manufacturing environment. On the contrary, a multi-agent approach may be applied in a distributed and autonomous system which allows negotiation-based decision making. Although MAS can be employed in distributed and dynamic environment, it can not make the correct decision without the real-time information.

To cope with these requirements, it is necessary to develop a manufacturing planning and control system (MPCS) which employs the RFID technique and multi-agent system (MAS) to quickly and dynamically respond to the external and internal environment changes. Therefore, the objective of this research is to introduce an agent-based manufacturing planning and control system (AMPCS) framework and develop a system analysis and design method for an agent-based MPCS. In order to develop AMPCS, an agent-based MPCS in an automated manufacturing cell (AMC) in the Automation Laboratory of Tunghai University is implemented.

KEY WORDS：RFID, Multi-agent, Manufacturing Planning and Control

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研究所的生活轉眼間已成過去，時間雖然短暫但卻讓我體驗諸多事物，不論是研究學習方面或是實際參與業界工作，實際感受實務應用的現況與技術。能夠在這樣優良的環境下訓練與培養研究能力，這都要感謝指導教授—王立志老師給我學習的機會與親身教導的成果，讓我在研究所的生活中學習到做事的方法與待人處世的態度。

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Chapter 1 Introduction

1.1 Background

With the trend of supply chain globalization, today's supply chain network is becoming geographically spread out across the globe. Enterprises are pursuing boundary-less transactions, where raw materials are sourced from one country, manufacturing is done in another and the finished product is shipped to a variety of countries. In order to fully utilize the advantage of a supply chain alliance, RFID (*R*adio *F*requency *ID*entification) is one of the techniques employed to increase the visibility, accountability, trackability, and traceability (VATT) of the global manufacturing supply chains [1]. RFID is an electrical information-storing device, it has characteristics such as active, long-distance reading, and non-line-of-sight. RFID brings a whole new perspective to the term visibility of a supply chain [2]. Besides, RFID allows products to be tracked in real time across the supply chain providing accurate and detailed information on all items (e.g., raw material, WIP, products in factory and products in the down streams) to increase a supply chain's accountability. Furthermore, recording the changes made in every component of a product throughout its life — in other words, documenting the product's genealogy — is known as parts traceability. RFID provides the means to capture and store data in real-time on a tag that accompanies the product. RFID is ideally suited for a large number of traceability applications, especially on more complex products and assemblies [3].

1.2 Motivation

RFID technique cannot support a rapid decision-making in a distributed and heterogeneous manufacturing environment. To utilize the real-time information effectively, RFID must integrate with other application system, such as manufacturing planning and control system. However, most of the current manufacturing planning and control systems employ the hierarchical planning and control approach. That is, planning is usually performed top-down, and varying from aggregate approaches with rough time periods for long-term inventory and production planning to very detailed planning with precise data (daily, hourly, or by the minute) for short-term or immediate production activities. Whereas control is made possible through monitoring production activities and providing feed-back to all system levels [9]. In this situation, a small change in one level may significantly and adversely affect the other levels in the hierarchy [6], the planning results can only be a reference for the next level's planning and execution. Therefore, the application of multi-agent system in MPCS has developed to meet the distributed and heterogeneous environment, which causes by dynamically changing customer demand and uncertainly supplies (e.g. the shortage of material). Although MAS can be employed in distributed and dynamic environment, it can not make the correct decision without the real-time information.

To cope with these requirements, it is necessary to develop a manufacturing planning and control system (MPCS) which employs the RFID technique and MAS to quickly and dynamically respond to the external and internal environment changes.

Therefore, the agent-based manufacturing planning and control system (AMPCS) has the characteristic: (1) capability of monitoring all the production process activities, (2) performing a real-time what-if simulation, (3) dynamically generating production planning and scheduling according to the shop floor situation and demand information, and (4) actively alerting each object's production activity (e.g., what it needs and where it goes) should be developed.

1.3 Research Objectives

The objectives of this research are:

（1） To introduce an agent-based agile manufacturing planning and control system (AMPCS) framework, which employed the RFID technique to obtain the real-time information.

（2） To implement a system analysis and design method for an agent-based MPCS by system development method.

（3） To implement an agent-based MPCS in an automated manufacturing cell (AMC) in the automation laboratory of Tunghai university.

1.4 Outline of the Thesis

In chapter 2, the literature review related to the research is reviewed and evaluated. In chapter 3, the system framework and development method of AMPCS is introduced. In chapter 4, the system analysis and system design of AMPCS is developed to describe the system function goals and each agent’s role and presents the application of AMPCS in practice in Automated Manufacturing Cell (AMC) in the Automation Laboratory of Tunghai University. Finally, a summary of this thesis is presented and areas of further research are suggested.

Chapter 2 Literature Review

In this chapter, we will review some researches that are related to our research. In section 2.1, existing manufacturing planning and control systems are reviewed. In section 2.2, we introduce the basic concept of a multi-agent system and review the applications of MAS in MPCS. In section 2.3, we introduce the basic concept of a Radio Frequency Identification (RFID) System and review the applications of RFID in MPCS.

2.1 Manufacturing Planning and Control System (MPCS)

In today's manufacturing enterprise, the performance of customer service level (e.g., short ordering-to-delivery time, low price) is highly dependent on the effectiveness of its manufacturing planning and control system (MPCS). From an information system's perspective, a MPCS, depicted in Figure 2.1, may be composed of eight major modules: (1) Demand Management (DM), (2) Inventory Planning (IP), (3) Sales and Operations Planning (S&OP), (4) Master Scheduling (MS), (5) Material and Capacity Requirements Planning (MCP), (6) Production Activity Control (PAC) or Shop Floor Control (SFC), (8) Purchasing, and (8) Performance Measurement (PM).

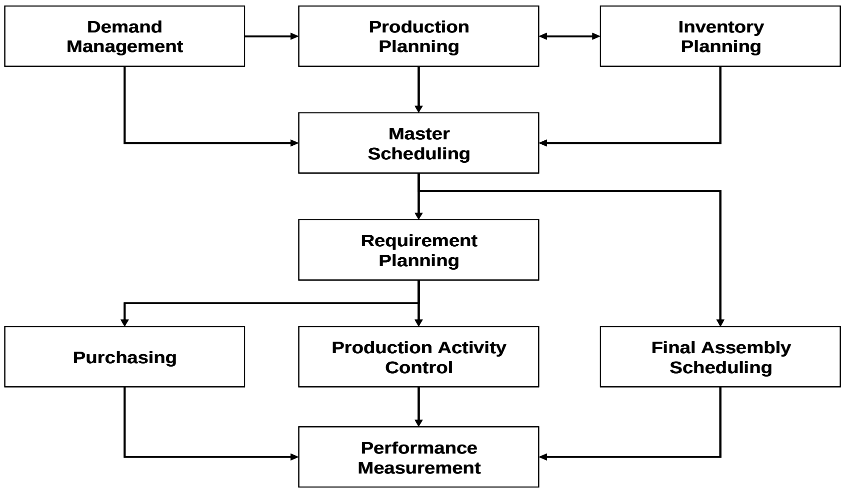

Figure 2.1 The structure of a hierarchical manufacturing planning and control system [15]

Olhager and Rapp [22] designed a MPC system, where the concept of modular design is stressed as being increasingly more important for so-called open system, to provide for different types of sub-systems or stand-alone-alone systems to be connected to the MPC system. But the method or technique of manufacturing planning and control system weren't mentioned.

Bennet [23] introduced that companies do not use the full potential of their MPCS; the average system utilization is approximately 80% of the functions and modules available. If the use of OR models in manufacturing planning and control system, it is most important that the interfaces of OR-based stand-alone systems is opened and standardized. The main points of the research are:

(1) There are some factors restricting the rapid of OR techniques into MPCS.
(2) The use of OR-based system takes time and resource to develop new, or even enhance existing MPCS.
(3) The manufacturing environment is constantly changing, implying that specific applications can rapidly become obsolete.

Maria [24] summarized the techniques of production and control system and introduced that there are four principal moments (eras) of evaluation of production planning technique: optimization era, heuristic era, complexity era, interactive era. It is noted that current MPCS is a hierarchical planning approach which varies from aggregate approaches with rough time periods for long-term inventory and production planning to very detailed planning with precise data (daily, hourly, or by the minute) for short-term or immediate production activities. Thus, planning is usually performed top-down, whereas control is made possible through monitoring production activities and providing feed-back to all system levels [8].

However, most of the current manufacturing planning and control systems employ the hierarchical planning and control approach, which can not quickly respond and make correct decision in the dynamic environment. So, a MPCS which can be used in a dynamic and distributed environment must be developed.

2.2 Multi-Agent System (MAS)

According to O'Hare and Jenning's definition, a MAS is a network of problem solvers that work together to solve problems that are beyond their individual capabilities [17]. Besides, a MAS is an artificial intelligence system composed of a population of autonomous agent that cooperate with each other to reach common goals, while simultaneous pursuing individual objects [9]. In an agent system, the agent specification framework must be capable of capturing the following aspects [16]:

(1) The belief agents: the information they have about the environment, which may be incomplete or incorrect.

(2) The ongoing interaction agents: how agents interact with each other and their environment over time.

(3) The goals that agents will try to achieve.

(4) The actions that agents perform and the effects of these actions.

Lim *et al.* [9] has proposed a multi-agent based dynamic process planning and production scheduling system and Kwangyeol [6] developed a FrMS which focused on formal modeling of agents and the characteristics of a fractal manufacturing system. The framework and the characteristics of agents used in developing these two multi-agent based manufacturing planning and scheduling systems may be applied in a distributed and heterogynous environment, the agents can autonomously perform the tasks based on the shop floor production status and external demand information stored in the related data bases. However, if the information did not update timely, the agent-based planning system cannot timely and effectively respond to the changing situations. Shaw *et al.*[12] employed software agents to develop an integrated manufacturing planning and predictive process model in which agents can control the shop floor production activities according to a set of predetermined control commands. However, this model cannot effectively respond to the current external and internal dynamic changing environments.

Although the application of MAS in developing a MPCS has obtained a number of potential benefits, the following obstacles still need to be overcome [19]:

(1) Ill suited information flows:

Lack of communication among particular production units and low utilization of available information processing solutions is generally what makes the production difficult to understand, model and plan.

(2) Frequent changes of manufacturing environment:

Production is flexible, frequent changes of production targets, manufacturing facilities, system knowledge and planning strategies are inevitable.

Therefore, the application of multi-agent system in MPCS has developed to meet the distributed and heterogeneous environment, which causes by dynamically changing customer demand and uncertainly supplies (e.g. the shortage of material). Although MAS can be employed in distributed and dynamic environment, it can not make the correct decision without the real-time information.

2.3 RFID system

RFID allows products to be tracked in real time across the manufacturing environment providing accurate and detailed information on all items (e.g., raw material, WIP, finished products) to increase a manufacturing environment's accountability. So, this section introduces the RFID and the application of RFID in manufacturing planning and control system.

RFID (*R*adio *F*requency *ID*entification) is an electrical information-storing device, it has characteristics such as active, long-distance reading, and non-line-of-sight. Katina [25] introduced the pros and cons of RFID. The advantages of the application of RFID is shown as follows: automatic non-line-of-sight scan, reduced manpower, enhanced visibility, asset tracking and returnable items, item level tracking, traceable warranties and product recalls, *ea al.* But it still has some disadvantages such as cost, lack of standards, interface and reading considerations, and privacy concerns to cause the deployment issues.

Currently, only few researches studying the applications of RFID in manufacturing systems, Junichi *et al.* [4] has proposed a RFID-based system in construction industry in which each part attached with RFID tag to perform the part tracking for a construction project, however, this system did not integrate with other applications (e.g., planning system). Besides, a framework of product life cycle support system has been developed through the integration of RFID and agent approach to effectively manage the production and assembly process in a highly customization industry [5].

Usually, a RFID solution needs to be an event-driven system. By its nature, a RFID-enabled business process is an event-driven process, which is real time. RFID applications are also very dynamic, with the possibility of multiple, simultaneous events happening all at once, making it critical for organization to design RFID applications not only respond to these dynamic requirements, but also be quickly alerted or adjusted as need dictate. So, even if we have RFID system, the AMPCS cannot be developed without an application system, which can cope with each manufacturing event in a distributed dynamic environment, such as multi-agent system.

Although RFID technique can bring the real-time information, it cannot support a rapid decision-making in a distributed and heterogeneous manufacturing environment. To utilize the real-time information effectively, RFID must integrate with other application system, such as manufacturing planning and control system. To cope with these requirements, it is necessary to develop a manufacturing planning and control system (MPCS) which employs the RFID technique and MAS to quickly and dynamically respond to the external and internal environment changes.

Chapter 3 The System Framework and Development Method of AMPCS

3.1 The System Framework of AMPCS

Based on the RFID technique, the agent-based agile manufacturing planning and control system (AMPCS) has the capability of monitoring all the production process activities, performing a real-time what-if simulation, dynamically generating production planning and scheduling according to the shop floor situation and demand information, actively alerting each object's production activity (e.g., what it needs and where it goes).

Figure 3.1depicts the system framework of an AMPCS which is composed of three major modules: (1) the RFID-based manufacturing control (R-MC), (2) the advanced manufacturing planning (AMP), and (3) the performance analysis (PA). The proposed AMPCS can also integrate with external information systems (e.g., demand management system and purchasing system) to respond to the external changing environment. The characteristics of each module are described as follows:

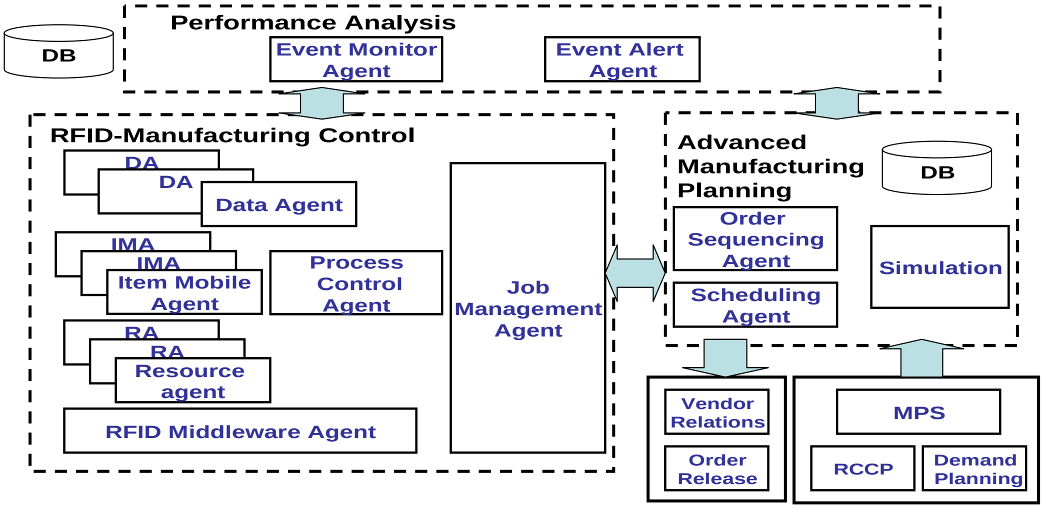

Figure 3.1 The infrastructure of AMPCS

(1) RFID-based Manufacturing Control (R-MC)

R-MC module plays the role of controlling the manufacturing system in which production items (i.e., objects) attached with RFID tags may actively feedback production status (e.g., current production location, processed time) to and receive production schedule from advanced manufacturing planning (AMP) module.

(2) Advanced Manufacturing Planning (AMP)

Based on the demand (e.g., forecast and customer order) information inputs from MPS, and the detailed production information starting from the entry of raw material/component parts, through the work-in-process, to the end of finished product provided from R-MC module, AMP module can effectively generate production plan and schedule in response to the dynamic external and internal environment changes and release the manufacturing orders to the shop floor through R-MC module.

(3) Performance analysis (PA)

Performance analysis (PA) module is an event-driven monitoring mechanism which evaluates the inbound, production, and outbound logistics performance of a manufacturing enterprise, if any unusual events (e.g., rush orders, material shortage) are detected, PA module will alert and trigger both AMP and R-MC modules, and AMP module will take into account all the necessary information obtained from the related information systems and generate a new production plan and schedule to actively plan and control the shop floor production activities through R-MC module.

3.2 System Development Method of AMPCS

3.2.1 The MaSE methodology

The MaSE methodology is a specialization of more traditional software engineering methodologies. The procedure of employing MaSE to develop an agent-based system needs to follow the phases and steps shown in Figure 3.2. The MaSE analysis phase consists of three steps: (1) capturing goals, (2) applying use cases, and (3) refining roles. The design phase has four steps: (1) creating agent classes, (2) constructing conversations, (3) assembling agent class, and (4) system design **[18]**. The steps of the analysis and design phase will be described as follows：

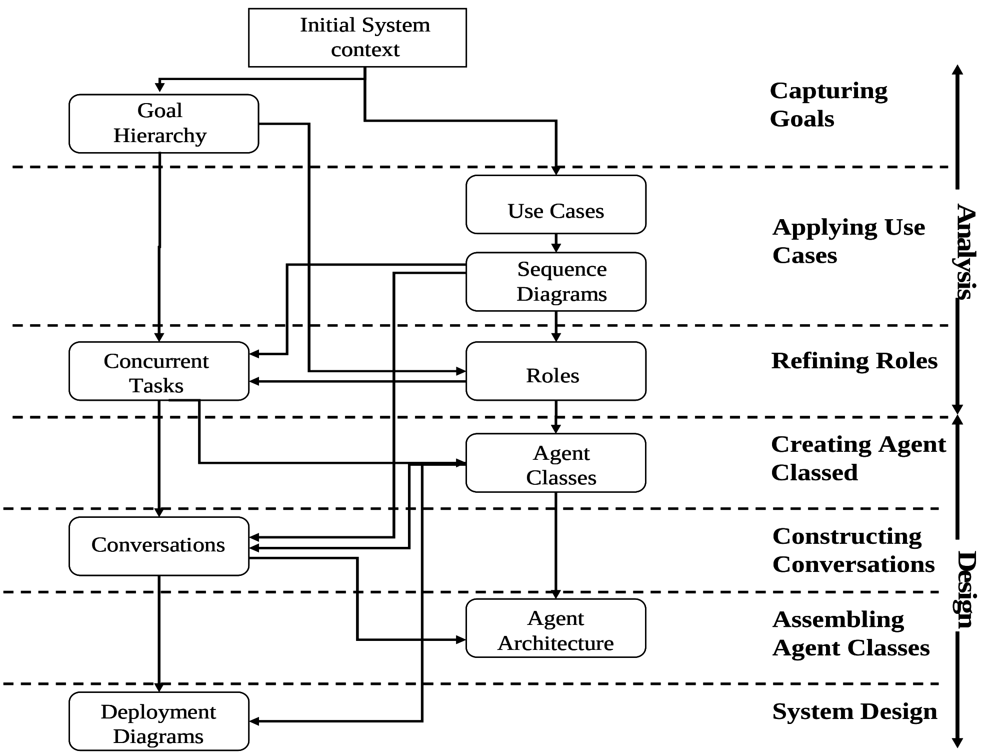

Figure 3.2 MaSE Phase [18]

The purpose of the MaSE analysis phase is to generate a set of roles whose tasks describe what the system has to do in order to meet overall requirements. The approach in the MaSE analysis phase is to define the system goals from a set of functional requirements and then define the roles to meet those goals. While a direct mapping from goals to roles, MaSE employes the use cases approach to help validating the system goals and derive an initial set of roles, the analysis phase is complete of each role has been defined. The MaSE analysis phase may be summarized as follows:

1. Identify goals from user requirements and construct a goal hierarchy diagram.
2. Identify use cases and create sequence diagrams to help identifying an initial set of roles and communications paths.
3. Transform goals into a set of roles by using the following module:
    a. Create a role model to capture roles and their associated tasks.
    b. Define a concurrent task model for each task.

The purpose of the MaSE design phase is to define the overall system organization by transforming the roles and tasks defined in the analysis phase into agent types and conversations. Four steps are involved in the MaSE design phase: the first step is creating agent classes, in which the designer assigns roles to specific agent types. Then, constructing conversations, the actual conversations between agent classes are defined. The third step, is assembling agent classes, the internal architecture and reasoning process of the agent classes are designed. Finally, the designer defines the actual number and location of agents in the deployed system. The MaSE design phase may be summarized as follows:

1. Assign roles to specific agent classes, and identify conversations by examining concurrent task models based on the roles played by each agent class.
2. Construct conversations by extracting the messages and states defined for each communication path in concurrent task models, adding additional messages and states for added robustness.

3. Define the internal architecture of agent classes using component and connectors. If is necessary to ensure that each action defined in a conversation is implemented as a method in the agent architecture.
4. Define the final system structure using deployment diagrams.

MaSE not only provides the generality and the application domain, but also supports for automatic code generation. The identified roles are driven by the capturing goals. The goal of MaSE is to guide the designer from the initial system specification to the implemented agent system. But an agent-based system still needs the communication language to define the communication message of negotiation protocol and the agent inter-constructions to define the agent's status of agent-based system. Therefore, KQML and BDI are deployed to define the communication language and the agent inter-constructions, respectively.

3.2.2 The KQML

KQML, the knowledge Query & Manipulation Language, has been developed under a DARPA funded project and is probably the most well-known and widely-implemented agent communication language [20]. A KQML message usually has the form:

```
(perfName
   :sender A              :receiver B
   :content X             :language L          :ontology N
   :reply-with W          :in-reply-to P)
```

This is a message from A to B in reply to a previous message identified by P. Any message sent in respond to this message should include: in-reply-to W. The content X has a syntax like that specified by the language L whose terms are taken from ontology N. The message's meaning is determined by the combination of perfName and the content X.

3.2.3 BDI

The Belief-Desire-Intention (BDI) agents are developed by employing a set of specialized object-oriented models. In this research, there are two models: external and internal [21].

From the external viewpoint, the system is decomposed into agents, their responsibilities, the services they perform, the information they require, and their external interactions. These characteristics are captured in two models: the Agent Model and the Interactions Model.

(1) The **Agent Model** describes the hierarchical relationship between different abstract and concrete agent classes, and identifies the agent instances that may exist within the system, their multiplicity, and when they come into existence.

(2) The **Interaction Model** describes the responsibilities of an agent class, the services it provides, associated interactions, and control relationships between agent classes. The external viewpoint and associated models are captured in MaSE Agent Class Diagrams using agent classes and conversations.

From the internal viewpoint, the elements required by particular agent architectures are modeled for each agent using three models that describe its informational and motivational state and its potential behavior:

(1) The **Belief Model** describes the information about the environment and internal state that an agent of that class may hold, and the action is may perform.

(2) The **Goal Model** describes the goals that an agent may possibly adopt,

and the events to which it can respond.

(3) The **Plan Model** describes the plans that an agent may possibly employ to achieve its goals or respond to events it perceives. It consists of a plan set which describes the properties and control structure of individual plans.

3.2.4 The system develop method of AMPCS

According to the system framework presented in chapter 3.1, the system development and design of AMPCS are presented as figure 3.3. Firstly, the analysis phase of the system development and design of AMPCS is employed to define the system goals and agents of an AMPCS by using use cases, role model and task model. Secondly, the design phase of the system development and design of AMPCS is employed to define the agents' tasks and infrastructure of AMPCS by using class diagram and activity diagram. Thirdly, KQML is applied to describe the communication message in an AMPCS. Finally, BDI is used to design AMPCS' agents.

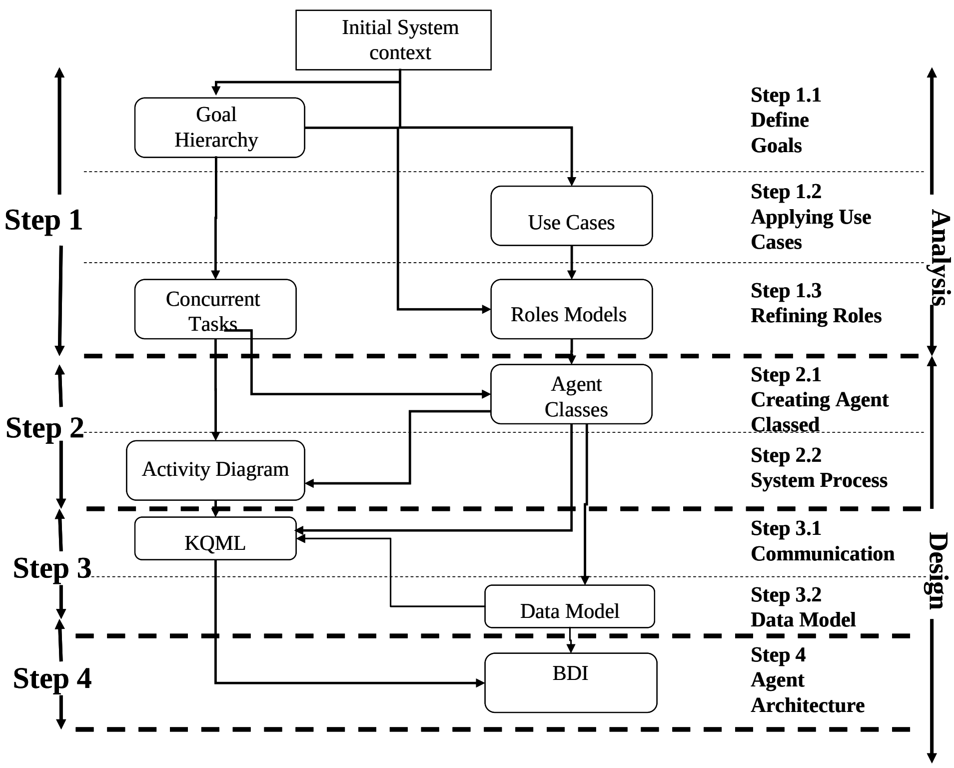

Figure 3.3 The System development method of AMPCS

Chapter 4 The System Analysis and Design of AMPCS

4.1 System analysis phase of AMPCS

According to the framework of AMPCS and the system development method of AMPCS, we define the system goals using goal hierarchy diagram and define the function goal of each agent using use cases, role model and task model. The steps of the analysis phase will be described as follows：

Step 1.1: Define goals

The first step in system analysis phase of AMPCS is to identify goals by employing goal hierarchy diagram, shown in Figure 4.1, which is a directed, acyclic graph in which the nodes represent goals and the arcs define a sub-goal relationship. The goal hierarchy diagram preserves the relationship of goals, and divides goals into levels of detail that are easier to be managed and understood. The goals of AMPCS is classified into six levels: (1) generate production schedule, (2) manufacturing order release, (3) manufacturing process control, (4) manufacturing event monitor, (5) manufacturing information update, and (6) manufacturing resource allocation.

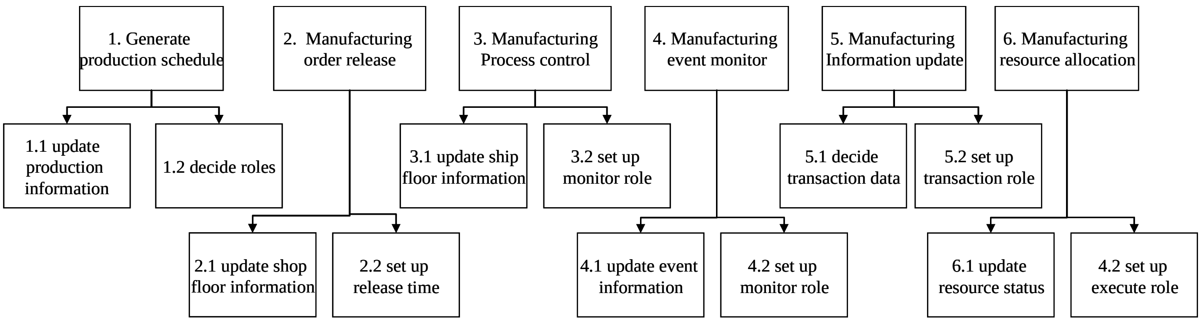

Figure 4.1 The Goal hierarchy diagram of AMPCS

Step 1.2: Use Cases

The objective of employing use cases step is to capture a set of goals from goal hierarchy diagram to help the system analysis identify an initial set of roles and communication paths in AMPCS. There are six kinds of use cases, which define basic scenarios, such as (1) generate production schedule, (2) order release, (3) process control, (4) event monitor, (5) update information, and (6) resource allocation that AMPCS should be able to perform according to goal hierarchy diagram. The use cases are described as followed:

(1) Generate production schedule

The use cases of generate production schedule will classify into: (1) generation production schedule and (2) generation operation schedule, which is shown in table 4.1 and table 4.2.

Table 4.1 The use cases of generating production schedule (1)

Use case	Generate production schedule
Goal	Generate daily production schedule
Actors	Planner
Type	Primary
Description	1. Collect the information of MPS, inventory status, material and capacity availability. 2. Determine production schedule and generate manufacturing order.

Table 4.2 The use cases of generating production schedule (2)

Use case	Generate operation’s sequence and schedule
Goal	Generate shop floor operation’s sequence and schedule
Actors	Planner
Type	Primary
Description	Generate shop floor operations sequence or schedule according to the production schedule

(2) Order release

The use cases of order release will classify into: (1) manufacturing order view and release and (2) reporting finished items, which is shown in table 4.3 and table 4.4.

Table 4.3 The use cases of order release (1)

Use case	Order release
Goal	Manufacturing order review and release
Actors	Operation Manager
Type	Primary
Description	Release manufacturing order to the shop floor according to the production schedule.

Table 4.4 The use cases of order release (2)

Use case	Reporting finished items
Goal	Provide the information of finished items
Actors	Operation manager
Type	Primary
Description	Update the information (e.g., time, quantity) of finished items which are updated in a real-time basis.

(3) Process control

The use cases of process control will classify into: (1) providing manufacturing routing, (2) update shop floor information, and (3) provide production instruction, which is shown in table 4.5, table 4.6, and table 4.7.

Table 4.5 The use cases of process control (1)

Use case	Provide manufacturing routing
Goal	Provide each lot/item's manufacturing routing
Actors	ERP administrator
Type	Primary
Description	Request to provide each lot/item's manufacturing routing.

Table 4.6 The use cases of process control (2)

Use case	Update shop floor information
Goal	Provide the shop floor production status and WIP information
Actors	Shop floor manager
Type	Primary
Description	When an item finished one operation, this item's production information will be reported.

Table 4.7 The use cases of process control (3)

Use case	Provide production instruction
Goal	Provide each item's production instruction
Actors	Shop floor manager
Type	Primary
Description	Shop floor engineer will receive the production instruction of each lot/item if there are some other unfinished operations.

(4) Event monitor

The use cases of event monitor will classify into: (1) set up indicator, (2) monitor manufacturing event, and (3) send alert message, which is shown in table 4.8, table 4.9, and table 4.10.

Table 4.8 The use cases of event monitor (1)

Use case	Set up performance indicator
Goal	Set up the performance indicator to monitor manufacturing tasks
Actors	IT administrator
Type	Primary
Description	To set up the performance indicator (e.g., order fulfill rate, WIP, cycle time, *et al.*) to monitor the performance of each manufacturing task.

Table 4.9 The use cases of event monitor (2)

Use case	Monitor manufacturing event
Goal	Monitor and evaluate the performance
Actors	IT administrator
Type	Primary
Description	Each manufacturing task will be monitor by IT administrator, which is respond to monitor the total performance of the effect of each manufacturing task.

Table 4.10 The use cases of event monitor (3)

Use case	Send alert message
Goal	Send alert message
Actors	IT administrator
Type	Primary
Description	IT administrator will send warring message to alert related manager while abnormal event happened.

(5) Update information

The use cases of update information will classify into: (1) update shop floor information, (2) update demand information, (3) send shop floor reporting information, and (4) send production information, which is shown in table 4.11.

Table 4.11 The use cases of update information (1)

Use case	Update shop floor information
Goal	Collect shop floor data
Actors	Shop floor operator
Type	Primary
Description	Shop floor operator will collect lot/item manufacturing information while each manufacturing task is finished.

Table 4.12 The use cases of update information (2)

Use case	Update demand information
Goal	Review production information
Actors	Shop floor manager
Type	Primary
Description	Shop floor operator will review the production information while each manufacturing task is finished.

Table 4.13 The use cases of update information (3)

Use case	Send shop floor reporting information
Goal	Send shop floor information to planner
Actors	Shop floor operator
Type	Primary
Description	Shop floor operator will report lot/item manufacturing information while each manufacturing task is finished.

Table 4.14 The use cases of update information (4)

Use case	Send production information
Goal	Send production information to shop floor
Actors	Operation manager
Type	Primary
Description	Operation manager will send each lot/item's manufacturing routing.

(6) Resource allocation

The use cases of resource allocation will classify into: (1) execute manufacturing tasks, (2) report resource status, and (3) resource allocation, which is shown in table 4.15.

Table 4.15 The use cases of resource allocation (1)

Use case	Execute manufacturing task
Goal	Perform an item's manufacturing activity
Actors	Shop floor operator
Type	Primary
Description	Each item will execute the manufacturing task according to production instruction

Table 4.16 The use cases of resource allocation (2)

Use case	Report resource status
Goal	Provide manufacturing resource's production information
Actors	Shop floor operator
Type	Primary
Description	Update each manufacturing resource's status (e.g. loading, uploading)

Table 4.17 The use cases of resource allocation (3)

Use case	Resource allocation
Goal	Assign manufacturing resource
Actors	Shop floor manager
Type	Primary
Description	Shop floor manager will allocate manufacturing resource according to production instruction and resource status.

Step 1.3 Role model

The role model of an AMPCS may be depicted in figure 4.2, which includes interaction between roles and transforms system goals into roles. Roles will classify into ten roles, such as (1) machine administrator, (2) shop floor operator, (3) shop floor manager, (4) operation manager, (5) data administrator, (6) MIS, (7) IT administrator, (8) ERP administrator, (9) Middle-term planner, and (10) Short-term planner.

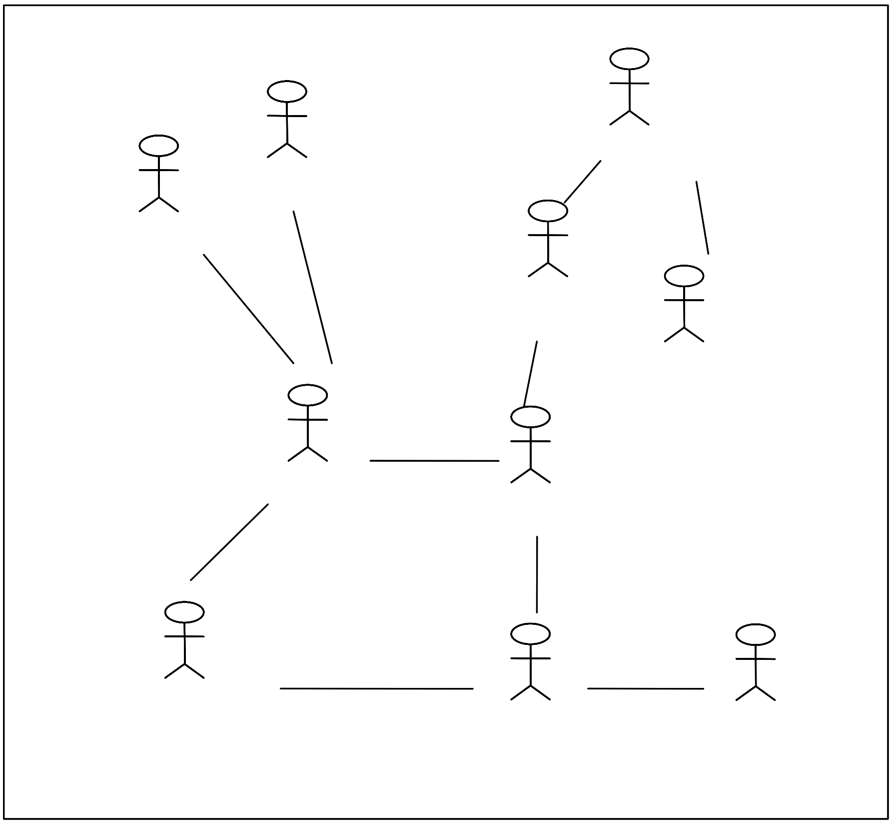

Figure 4.2 Role model of AMPCS

Step 1.4 Task model

To successfully achieve each role's goals, task model is defined to describe the behaviour associated with each role. In generally, a single role may have multiple concurrently executing tasks, which define the required role behaviour. Table 4.18 depicts the task model of AMPCS which includes ten roles, which is according to role model, and each role's corresponding tasks.

Table 4.18 The task model of AMPCS

Role	Tasks
Middle-term Planner	Generate order sequence and daily production schedule
Short-term Planner	Generate shop floor operation sequence and schedule
ERP administrator	Data transaction and administrate
IT administrator	Manufacturing event monitor
Operation manager	Manufacturing order release, and manufacturing order report
Data administrator	Data transaction and data collection
Shop floor manager	Lot/item check in or Lot/item check out
Shop floor operator	Lot/item release and Lot/item report
Machine administrator	Machine load and machine unload
MIS	Data collection, abnormal event alert

4.2 System design phase of AMPCS

We classify ten agents in AMPCS into: (1) Order Sequencing Agent (OSA), (2) Scheduling Agent (SA), (3) Job Management Agent (JMA), (4) Event Monitor Agent (EMA), (5) Event Alert Agent (EAA), (6) Process Control

Agent (PCA), (7) Data Agent (DA), (8) RFID Middleware Agent (RMWA), (9) Item Mobile Agent (IMA), and (10) Resource Agent (RA) is creating by using agent classes according to role model and task model. Each agent has its tasks which is respond to achieve its goals. The interaction of each agent is described as follows:

Step 2.1 Creating agent classes

Agent classes, which are the template for a type of agent in AMPCS and are defined in terms of the roles they will play and the conversations in which they must participate, will be created from roles models defined in the system analysis phase of AMPCS. The agent classes of AMPCS is shown in figure 4.3, which denotes agent classes and contain the class name and the set of roles each agent plays. The lines with arrows identify the information communicates among the distinct agents. For instance, SA will generate the operation production schedule (i.e., message) and trigger JMA, and JMA will review and release manufacturing order and trigger PCA to obtain manufacturing routing which will be sent to IMA through RFID Middleware Agent.

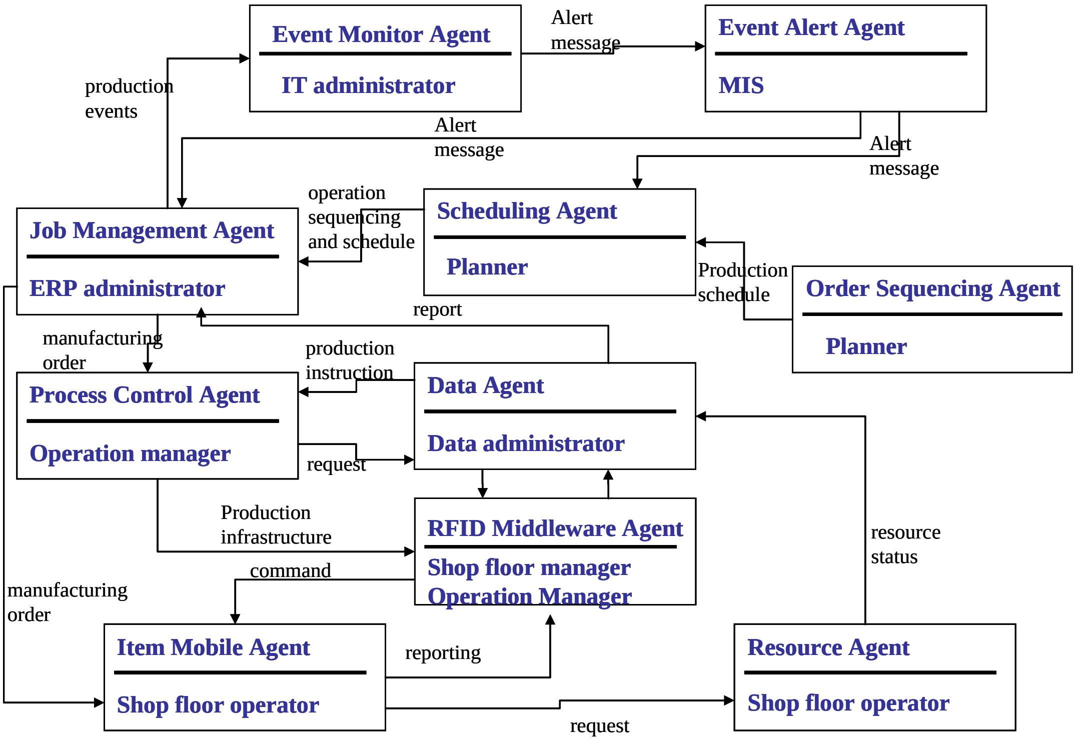

Figure 4.3 Agent classes of AMPCS

Step 2.2 The process of AMPCS

There are three negotiation processes of AMPCS, which include: (1) system process, (2) resource allocation, and (3) process control. The system process is the main process of AMPCS, which presented the process from the generation of production schedule, manufacturing order release, manufacturing routing decide, and stat to do the manufacturing tasks. In the system process, we still need to confirm two activities: (1) to define the manufacturing routing and check the manufacturing is finished or not by the negotiation process of process control, and (2) to decide the manufacturing resource allocation by the negotiation process of resource allocation. The negotiation process is described as follows:

(1) System process

The system process of AMPCS is shown in Figure 4.4 in which Order Scheduling Agent (OSA) will first collect the information of MPS, inventory status, material and capacity availability, and determine production schedule and generate manufacturing order. Then, OSA will trigger Scheduling Agent

(SA) to generate shop floor operations sequence or schedule. Consequently, Job Management Agent (JMA) will release manufacturing orders and request Process Control Agent (PCA) to provide each item/lot's manufacturing routing. Then, any event in the shop floor will trigger Event Monitor Agent (EMA) to evaluate the corresponding performance and send either "abnormal" message to Event Alert Agent (EAA) or "accept" message to Item Mobile Agent (IMA).

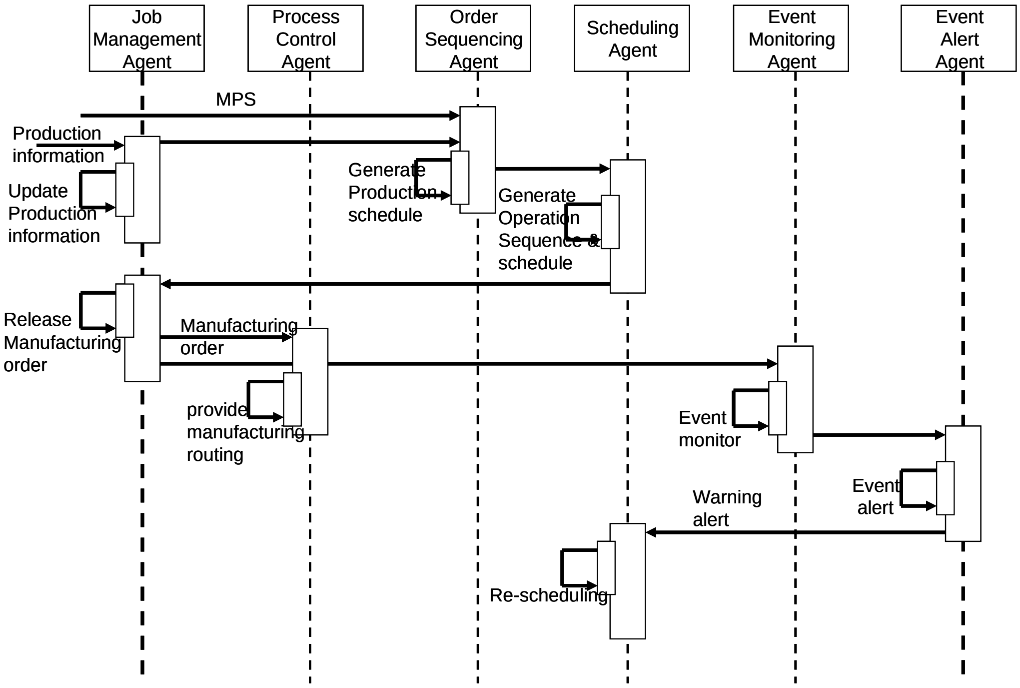

Figure 4.4 The system process of AMPCS

(2) Resource allocation

In an automated manufacturing system (AMS), the manufacturing control system usually needs to make the machine selection decision whenever there are more than one machine (i.e., resource) can process an item/lot. In AMPCS, machine selection decision is made by following the negotiation process of resource allocation which is represented in Figure 4.5 and described as follows.

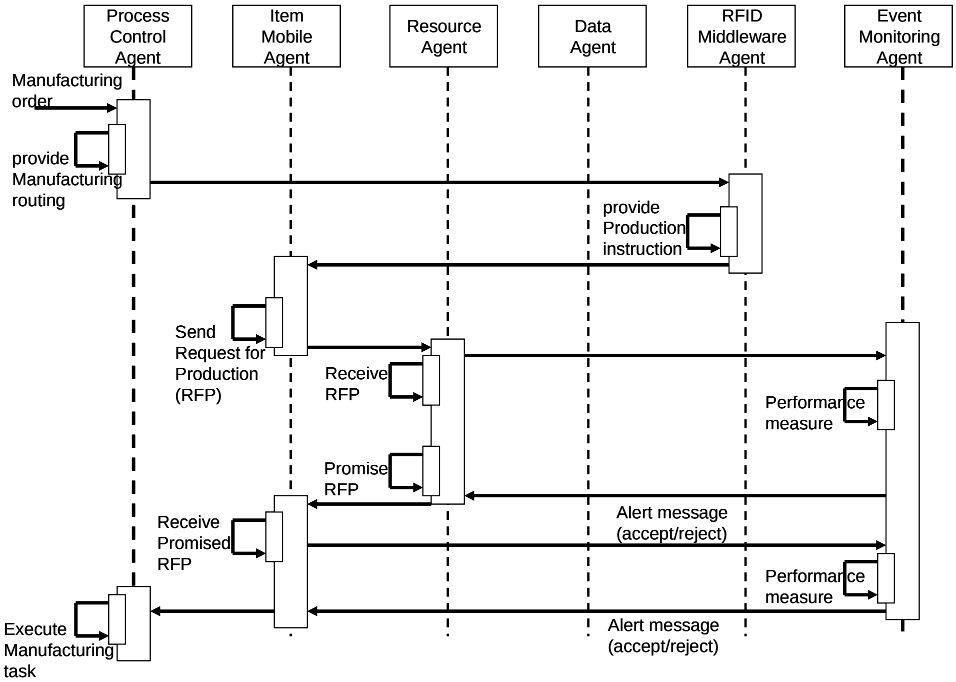

Figure 4.5 The negotiation process of resource allocation

Step1: PCA receives manufacturing order and provides each item/lot's manufacturing routing.

Step2: IMA receives production instruction from PCA through RFID Middleware Agent (RMWA).

Step3: IMA sends "request for production (RFP)" message to RA and EMA, RA will respond "availability" message and EMA will evaluate that resource's performance.

Step4: If the performance (e.g., WIP) is acceptable, EMA will send "accept" message to RA, and RA will send "acknowledged RFP" message to IMA, go to step 5. Otherwise, EMA will send "reject" message to RA, and notice EAA to send "warning" message, go to step 7.

Step5: IMA will send "request for evaluation" message to EMA to evaluate the performance of its corresponding operation.

Step6: If the performance is acceptable, EMA will send "accept" message to IMA, and IMA will start to execute the manufacturing operation; otherwise, EMA will send "reject" message to IMA, and notice EAA to send "warning" message, and go to step 7.

Step7: EAA will send "warning" message to alert SA to modify operations schedule.

(3) Process control

In an AMS, the manufacturing control system usually needs to determine whether an item/lot is complete or still has some remaining operations whenever an item/lot completes its current operations. In AMPCS, an item/lot's process is controlled by following the negotiation process of process control which is depicted in Figure 4.6 and described as follows.

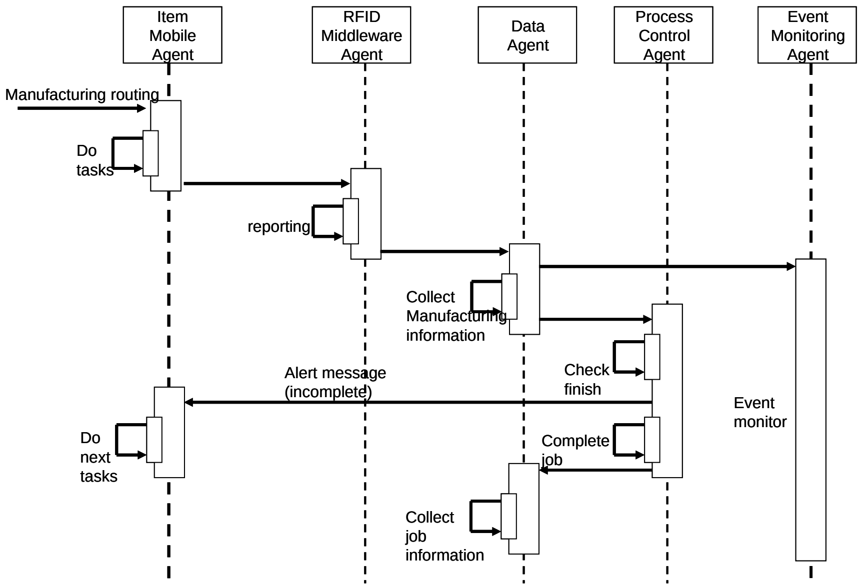

Figure 4.6 The negotiation process of process control for item/lot

Step 1: IMA receives the "production instruction" message from PCA and begines the manufacturing activity.

Step 2: IMA will request RMWA and DA to send this item's production information to PCA

Step 3: PCA will send "production instruction" message to IMA through RMWA and DA if there are some remaining unfinished operations, and go to step 4. Otherwise, the completion information will be sent to JMA.

Step 4: Repeat step 1 to step 3 until an IMA completes all the operations.

4.3 The Communication Message of AMPCS

Step 3.1 Communication message

The communication message of AMPCS is defined with KQML. The contents of KQML, which is classify into three parts, such as (1) the communication message of system process, (2) the communication message of process control, and (3) the communication message of resource allocation according to system process. The message content will be introduced as followed:

(1) System process

The communication message of the negotiation process of system process includes two kinds of messages: (1) alert message and (2) information message. Alert message is respond to change the agent's status or trigger agent to do some tasks to achieve the system goals. The information message is the necessary data which agent needs to achieve its related work. Take the alert message which is form JMA to DA for instance, the message content, which is request to update job information, means JMA request DA to provide the latest job information. So, JMA send an alert message means "job information", and DA will collect the latest job information and feedback the message, which contains job information to JMA.

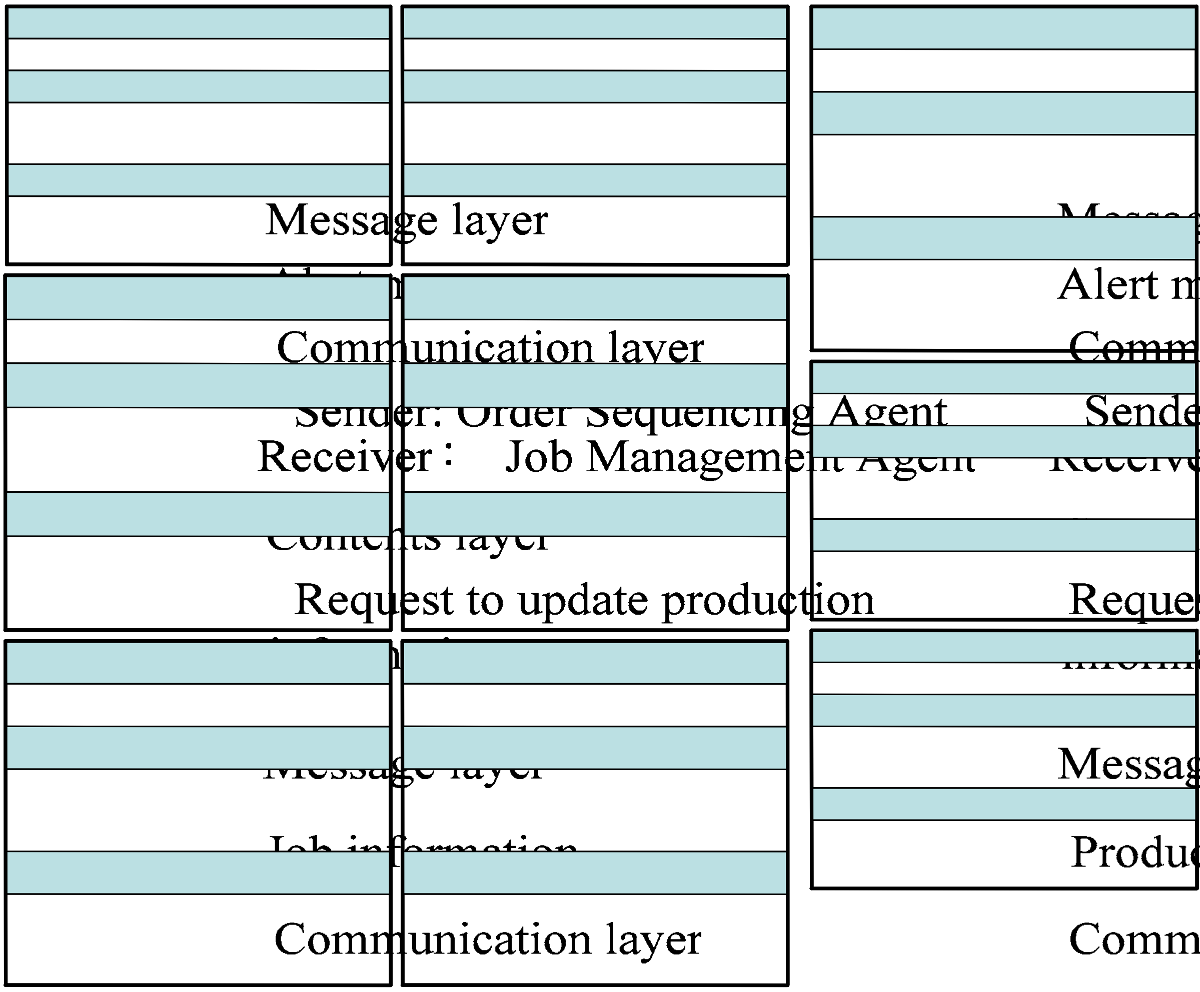

Figure 4.7 The communication message of system process

(2) Resource allocation

The communication message of the negotiation process of resource allocation includes two kinds of messages: (1) alert message and (2) information message as same as the negotiation process of system process. Take the information message which is form PCA to RMWA for instance, the message content, which is about the information of manufacturing routing, means PCA provides the manufacturing routing, such as Routing_ID, Item_ID, Receipe_ID, and status, to RMWA to achieve RMWA's goals (e.g., generate manufacturing command).

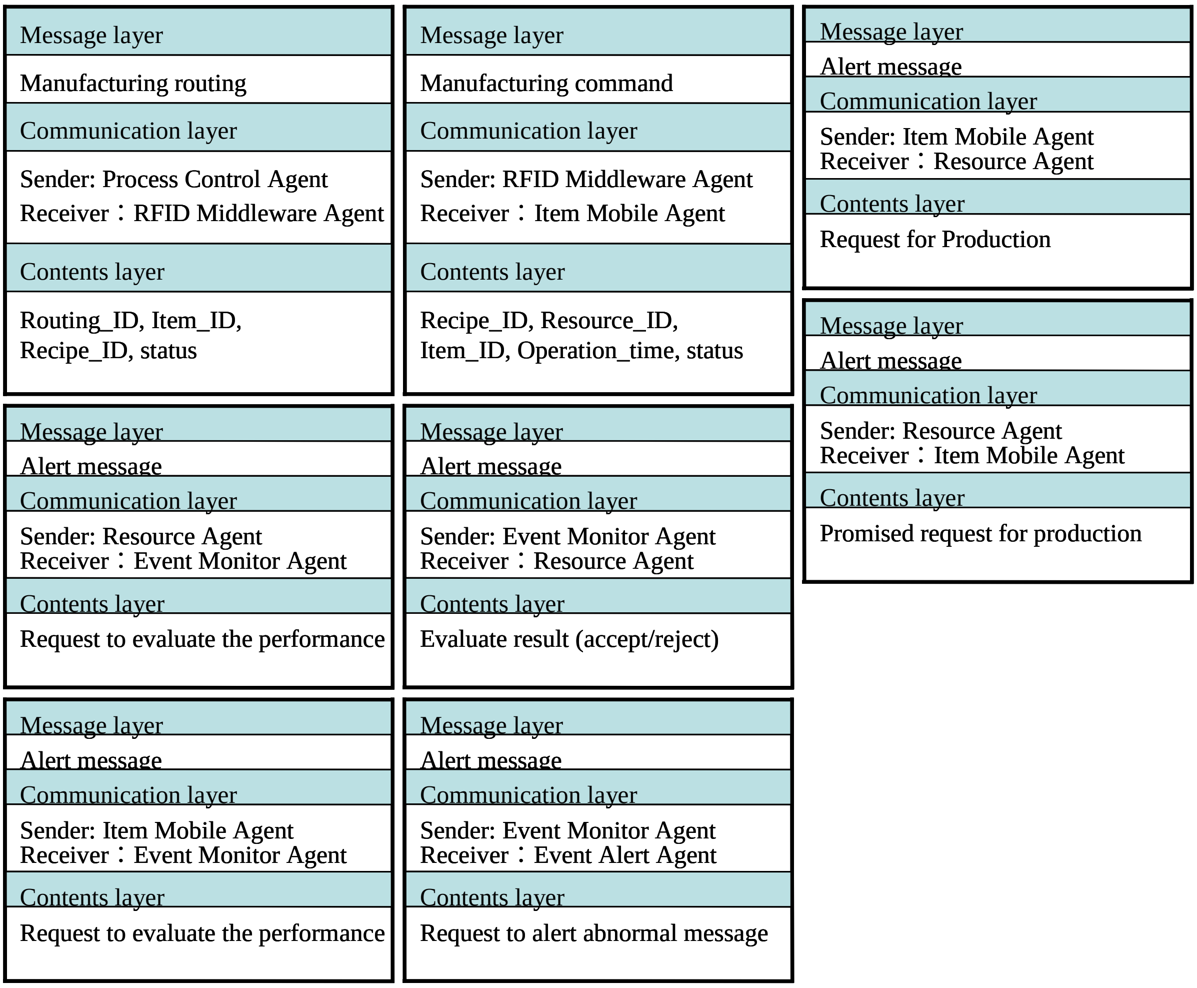

Figure 4.8 The communication message of resource allocation

(3) Process control

The communication message of the negotiation process of resource allocation includes two kinds of messages: (1) alert message and (2) information message as same as the negotiation process of system process. Take the alert message which is form PCA to IMA for instance, the message content, which is unfinished message, means PCA alert DA this lot/item still has incomplete manufacturing tasks to do.

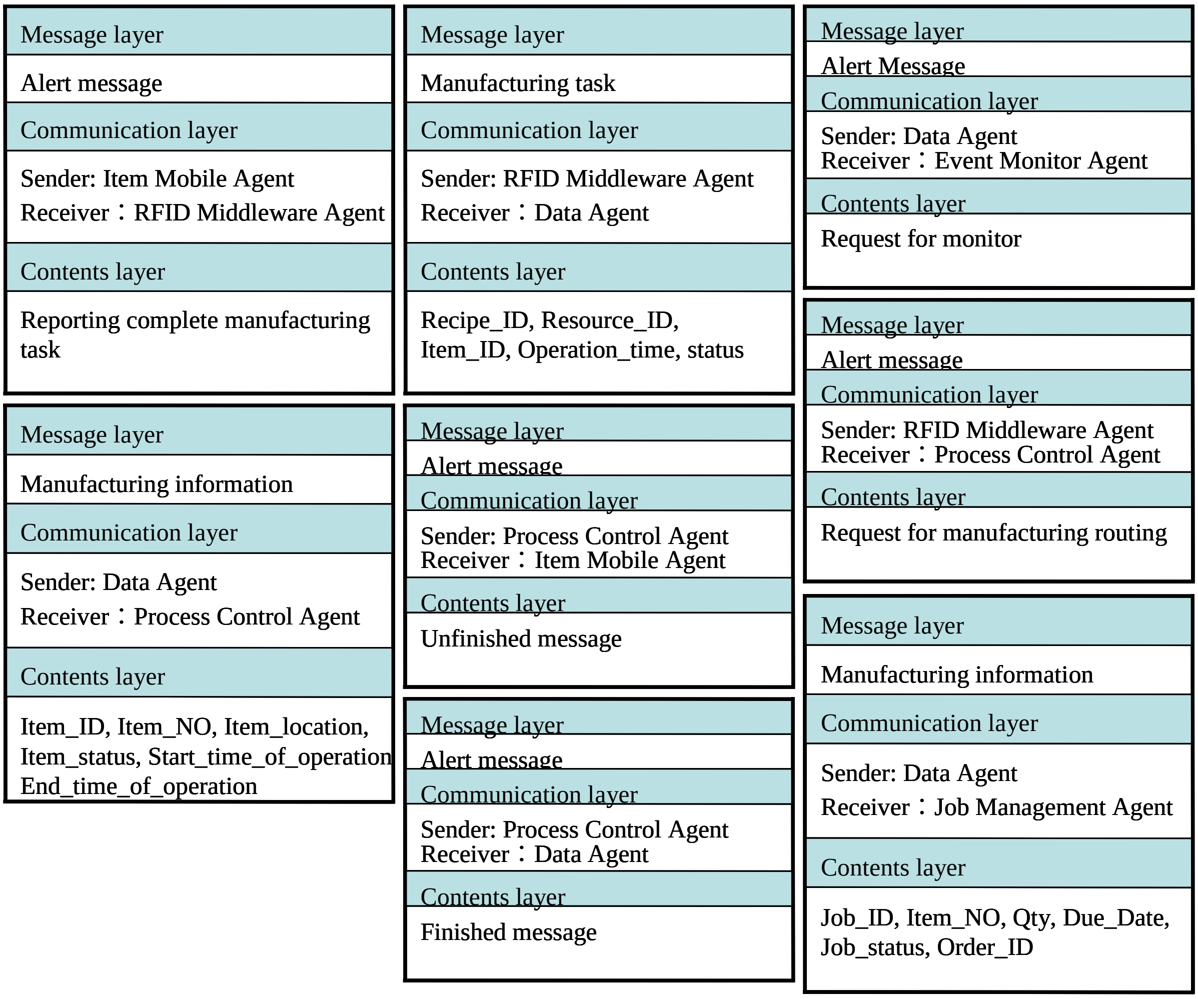

Figure 4.9 The communication message of process control

Step 3.2 Data model

The system framework of AMPCS presented in this research includes a number of agents which need to send and receive message and data between each other, the data model of AMPCS is depicted in Figure 4.10. Take JMA for an example, the information that received from AMP module is Job List, which includes Job_ID, Item_NO, Qty, Due Date, Order ID, etc. However, JMA's responsibility includes not only releasing manufacturing orders, but also collecting the job's information. Therefore, a message status (e.g. Job_status) is required. When a manufacturing operation is completed, its corresponding Job will be sent to PCA through DA, and PCA will change the Job_status from "incomplete" to "complete" if all the operations are completed. Consequently, JMA will collect the quantity of finished items and completion time through DA.

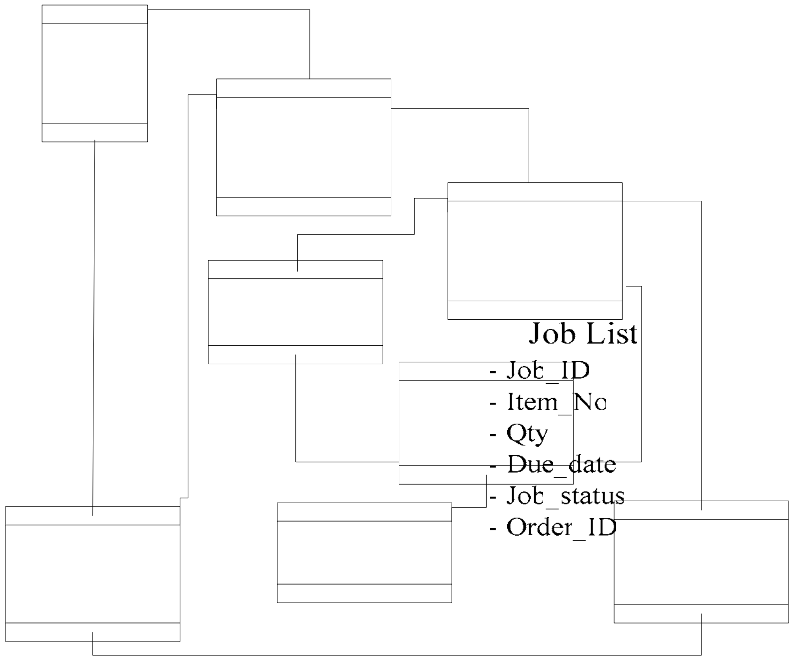

Figure 4.10 The data model of AMPCS

4.4 The architecture of agent in AMPCS

Since a task model specifies the task that each role should be done and agent classes define each role it plays, and the communications messages between separate roles or agents can be mapped by KQML, we will design each agent's architecture in AMPCS by employing BDI method. Each agent's architecture contains goal module, belief module, and plan module. For achieve the goal of each agent, the belief value in each agent will change by other agent's, and plan module will check belief to choose the appropriate plan (e.g., plan1 or plan 2) to execute, and each plan may contains different tasks to choose (e.g., generate order sequencing or update order information), so different parameters of plan will be choose to do the related tasks. Each agent's architecture will be described as follows:

(1) Order Sequencing Agent (OSA)

The OSA is responds to generate daily production schedule. There are two plans needed to do: (1) communication, (2) Task. The task contains three implementation procedures:

a. Generate daily production: to determine production schedule and generate manufacturing order.
b. Update order information: to collect the information of MPS, inventory status, material and capacity availability.
c. Generate order sequencing: to determine order sequencing according to due date and order priority.

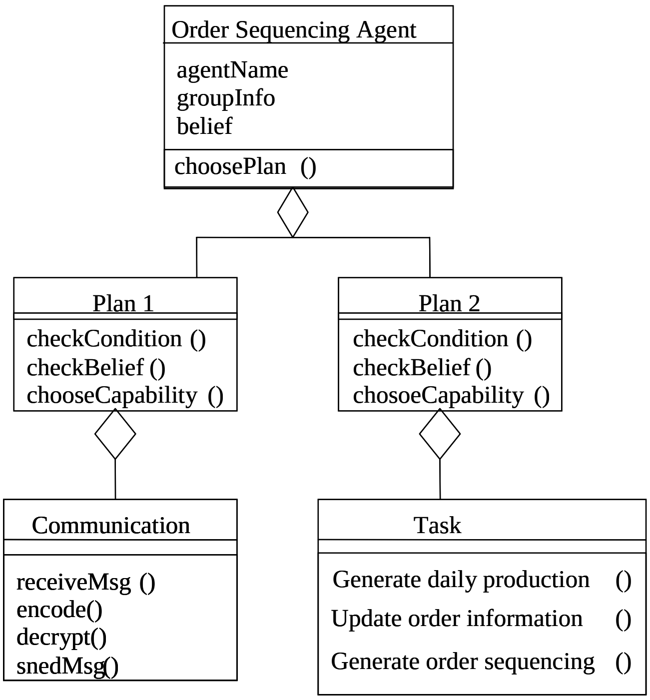

Figure 4.11 The inter-construction of Order Sequencing Agent

(2) Scheduling Agent (SA)

The SA is responds to generate shop floor operation sequencing and scheduling. There are two plans needed to do: (1) communication, (2) Task. The task contains two implementation procedures:

a. Generate operation sequencing: to determine operation sequencing according to the production schedule.
b. Generate operation schedule: to determine operation scheduling according to operation sequencing.

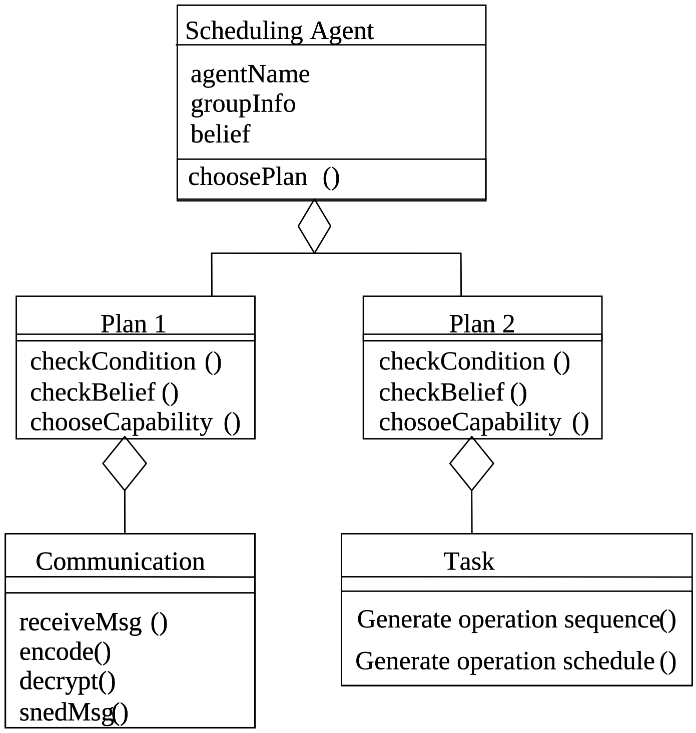

Figure 4.12 The inter-construction of Scheduling Agent

(3) Job Management Agent (JMA)

The JMA is responds to review and release manufacturing order and provide the information of finished goods. There are two plans needed to do: (1) communication, (2) Task. The task contains four implementation procedures:

a. Update production information: to update the information (e.g., time, quantity) of finished item.
b. Manufacturing order review: to review manufacturing orders according to production schedule.
c. Manufacturing order release: to release manufacturing orders according to production schedule.
d. Manufacturing order reporting: to report the manufacturing order if the items of these manufacturing order is all finished.

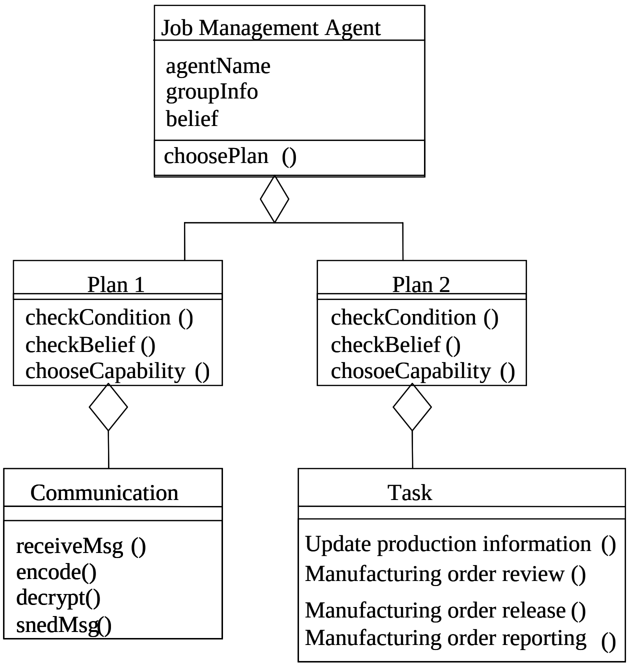

Figure 4.13 The inter-construction of Job Management Agent

(4) Process Control Agent (PCA)

The PCA is responds to provide each lot/item's manufacturing routing, the shop floor production status, and production instruction. There are two plans needed to do: (1) communication, (2) Task. The task contains five implementation procedures:

a. Manufacturing routing check: to provide each lot/item's manufacturing routing.
b. Make manufacturing command: to send manufacturing command to related lot/item according to manufacturing routing.
c. Check lot/item's status: to check if there are some other unfinished operations of lot/item.
d. Lot/item report: to report the lot/item's production information when an item finished one operation.
e. Lot/item release: to release the lot/item according to operation schedule.

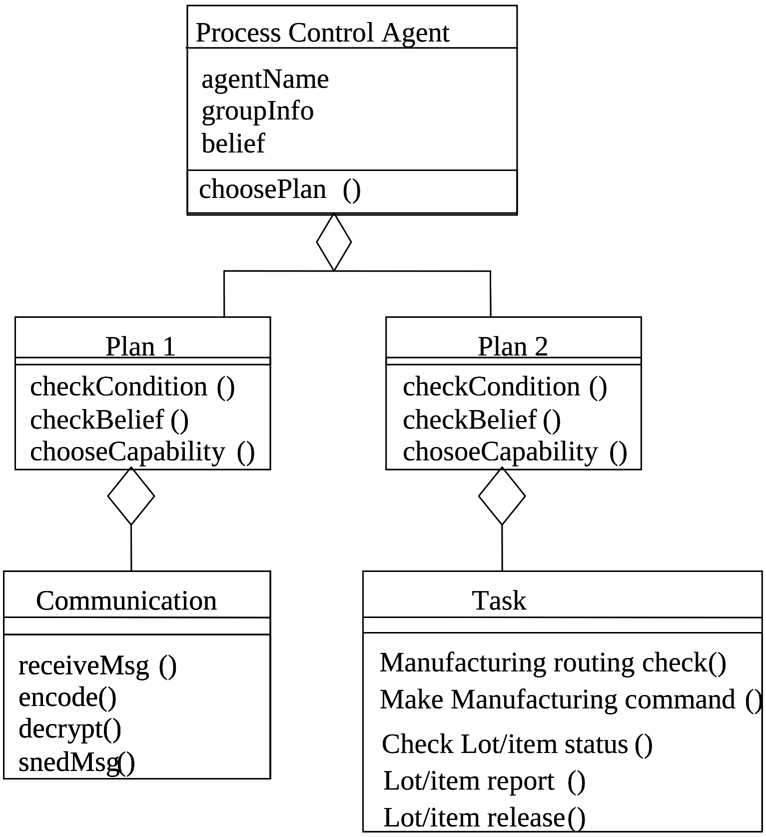

Figure 4.14 The inter-construction of Process Control Agent

(5) RFID Middleware Agent (RMWA)

The RMWA is responds to read data from and write data to RFID tag, there are two plans needed to do: (1) communication, (2) Task. The task contains three implementation procedures:

a. Read Lot/item data: to read the manufacturing completion message from IMA.
b. Write manufacturing command to Lot/item: to write the manufacturing routing obtained from PCA to the lot/item attached with RFID tag.
c. Review manufacturing command: to request DA to send the manufacturing routing.

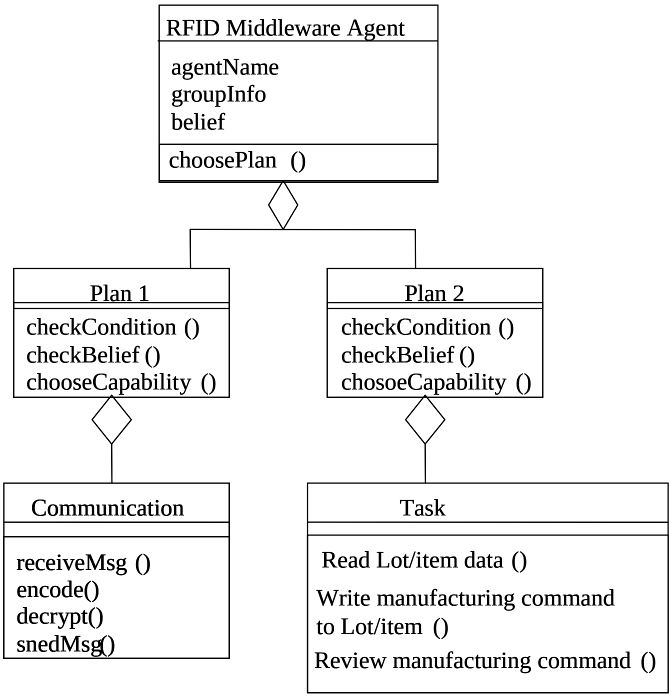

Figure 4.15 The inter-construction of RFID middleware Agent

(6) Item Mobile Agent

The IMA is responds to perform a lot/item’s manufacturing activity, there are two plans needed to do: (1) communication, (2) Task. The task contains six implementation procedures:

a. Receive manufacturing command: to receive manufacturing command (e.g., production instruction)through RMWA from PCA
b. Send request for production: to send the request for production to RA to obtain the manufacturing resource according to production instruction.
c. Execute the manufacturing tasks: IMA will execute the manufacturing task according to production instruction.
d. Receive promised resource: to receive the promised resource from RA.
e. Lot/item check in: Lot/item will move to the manufacturing location and check in when receive the production instruction.
f. Lot/item check out: Lot/item will leave from the manufacturing location and check out when finished one manufacturing task.

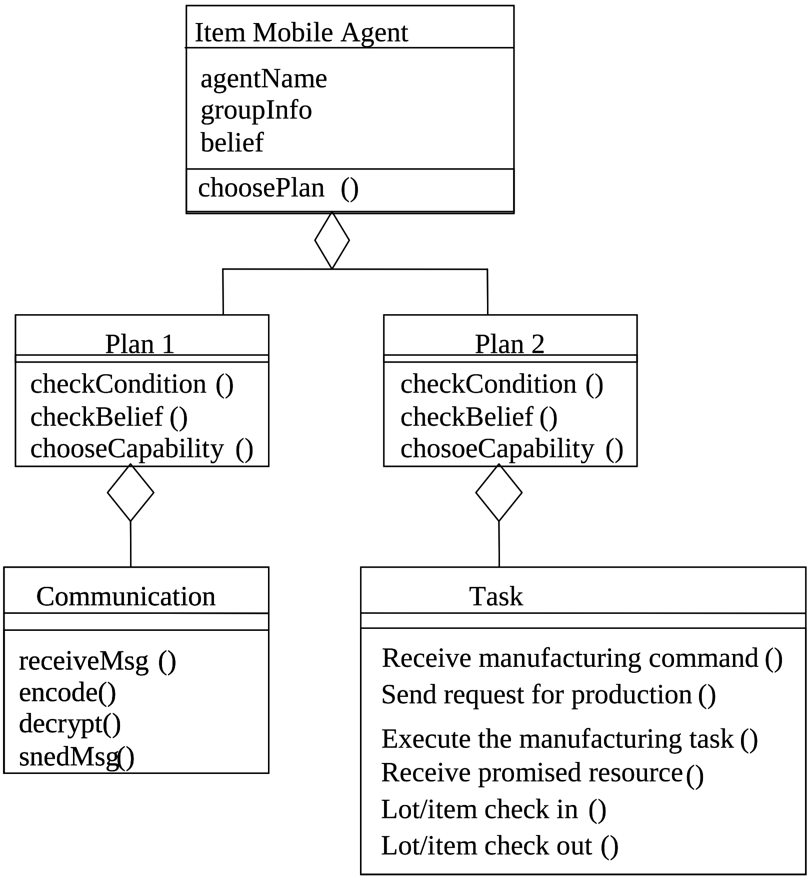

Figure 4.16 The inter-construction of Item Mobile Agent

(7) Resource Agent

The RA is responds to provide manufacturing resource's production information, there are two plans needed to do: (1) communication, (2) Task. The task contains three implementation procedures:

a. Review resource status: to review the request for production form IMA.
b. Machine/tool loading: Machine/tool will be loading when promise the request for production from IMA.
c. Machine/tool unloading: Machine/tool will be unloading when finished one manufacturing task.

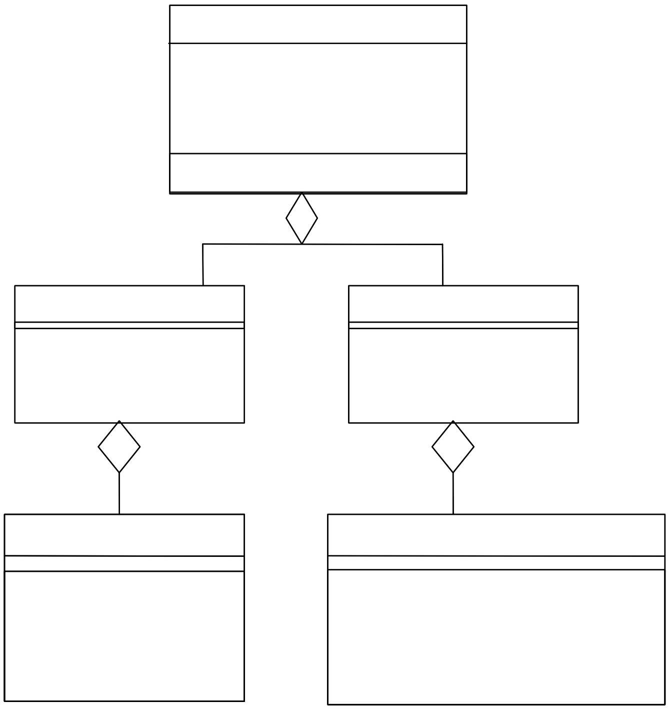

Figure 4.17 The inter-construction of Resource Agent

(8) Data Agent

The DA is responds to collect and provide information from/to other agents, there are two plans needed to do: (1) communication, (2) Task. The task contains three implementation procedures:

a. Collect data: to collect related data when receive the request for data form other agent.
b. Transform data: to transform the data format when the data form different agents.
c. Transact data: to transact data to the related agent, which send the request for data.

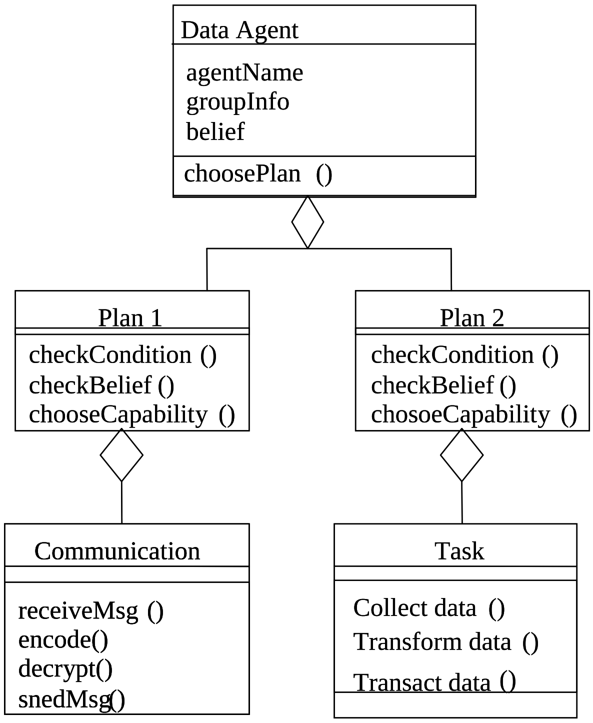

Figure 4.18 The inter-construction of Data Agent

(9) Event Monitor Agent

The EMA is responds to monitor and evaluate the perform of manufacturing activities, there are two plans needed to do: (1) communication, (2) Task. The task contains four implementation procedures:

a. Monitor manufacturing events: to determine the manufacturing events is either normal or abnormal according to the pre-determined performance indicator.
b. Review performance indicator: to review the total performance.
c. Check the performance of resource: to check the performance of resource.
d. Check the performance of Lot/item: to check the performance of Lot/item.

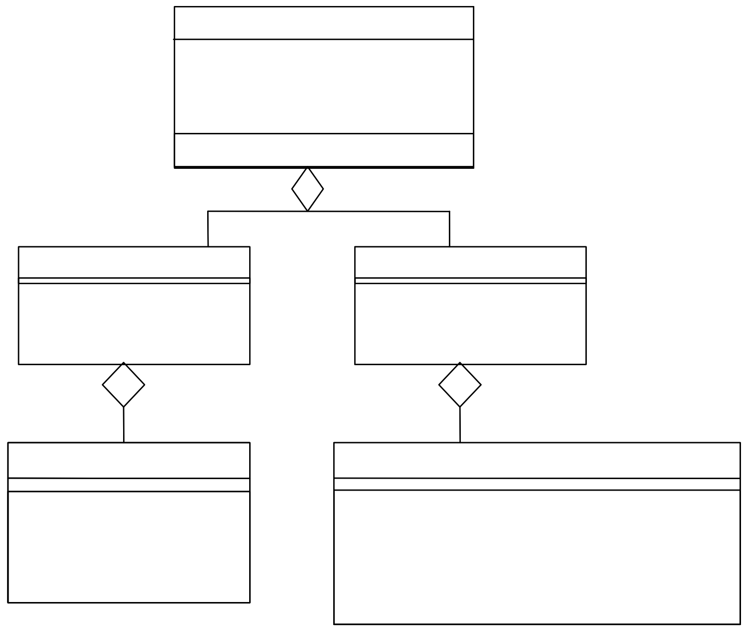

Figure 4.19 The inter-construction of Event Monitor Agent

(10)Event Alert Agent

The EAA is responds to send the alert message, there are two plans needed to do: (1) communication, (2) Task. The task contains one implementation procedures:

a. Send warring message: to send warring message to alert related agents.

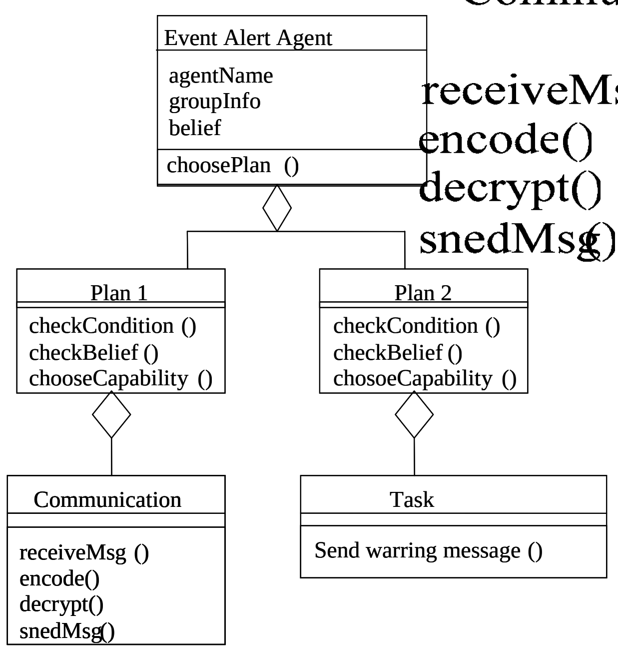

Figure 4.20 The inter-construction of Event Alert Agent

4.5 Case illistration

In this section, we will illustrate the characteristics of an agent-based manufacturing planning and control system (AMPCS) for the Automated Manufacturing Cell (AMC) in the Automation Laboratory of Tunghai University, consisting of one CNC 2-axis lathe, one CNC 3-axis milling machine, one RV-M2 robot, two WIP buffers , one feeder and one ASRS (depicted in Figure 4.21).

We define ERP system as JMA, which responds to review and release manufacturing order, and define APS system as OSA and SA, which responds to generate the production schedule, and define Labview as PCA, which responds to control manufacturing lot/item's status in shop floor. And we develop a RFID system which concludes RFID reader, Tags, and RFID middleware. Each Item which embedded RFID Tag is defined as IMA, which responds to execute the manufacturing task. The RFID middleware is defined as RMWA, which responds to read data from and write data to RFID Tag. The DA, and RA has been design with BDI and Developed with Aglets [26]. Aglet is the Java-based agent development tool which is developed by IBM. The most important reason to use a Java-based language is to facilitate platform-independent systems. Furthermore, Aglets is an open source program so that programmers can customize their own programming environments while they develop agents.

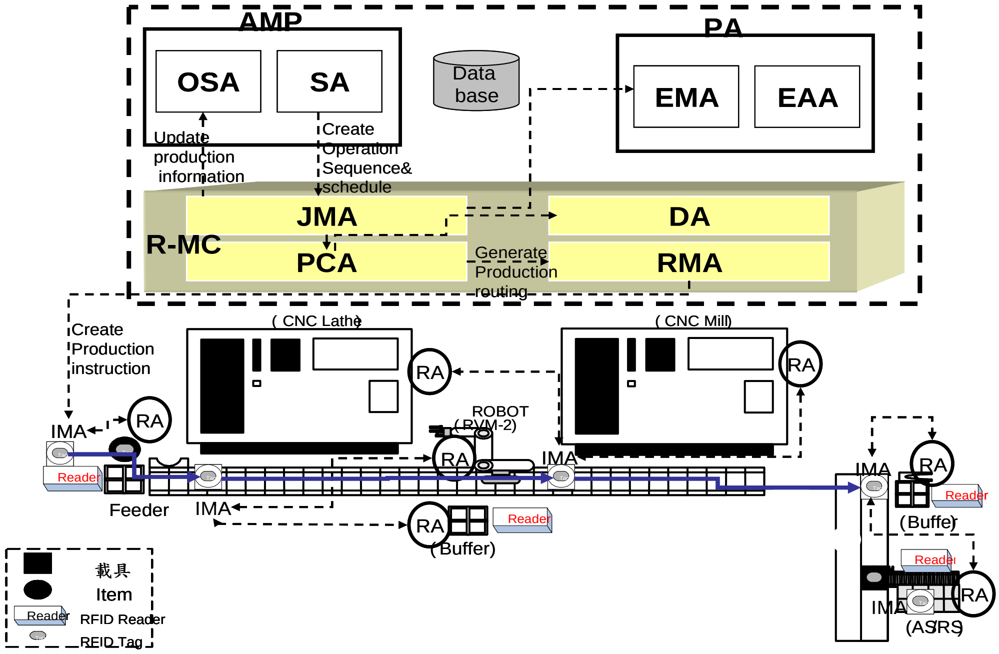

Figure 4.21 The layout of automated manufacturing cell and its corresponding AMPCS

Figure 4.22 illustrate the procedure for creating agents from Tahiti, an agent server based on Aglets. The “create” button can display the list of registered agents.

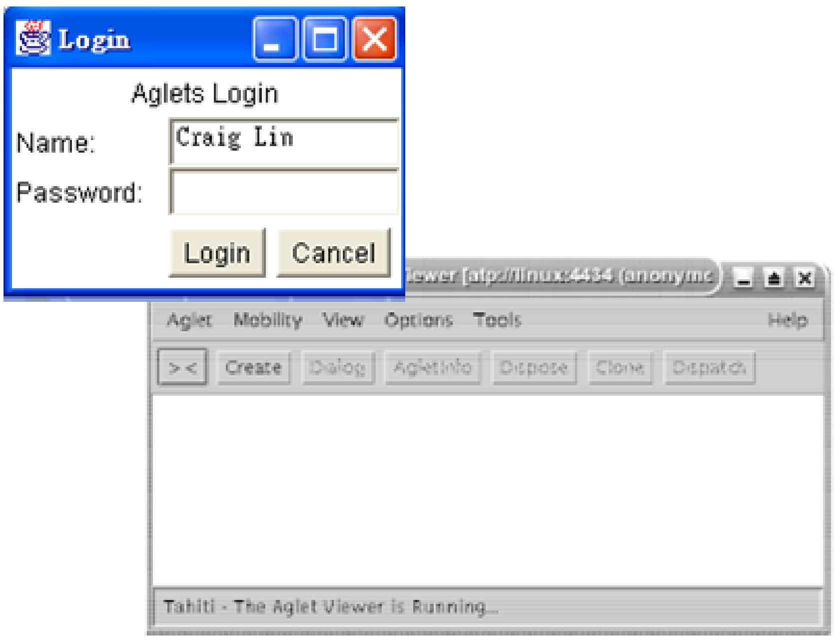

Figure 4.22 The procedure of making agents from Tahiti

The current status creates the Data Agent and Resource Agent by using Aglets. To test a new negotiation scheme for agents, the prototype agents (DA and RA) have been developed and tested. The implementation and testing of AMPCS is left for further research.

Chapter 5 Summary and Conclusion

5.1 Conclusion

This thesis presents an agent based agile manufacturing planning and control system (AMPCS) framework which is event-driven and can respond dynamically to the changing business events and exceptions. In AMPCS, RFID-based manufacturing control (R-MC) module plays the role of controlling the manufacturing system in which production items (i.e., objects) attached with RFID tag may actively feedback production status to and receive production instruction from advanced manufacturing planning (AMP) module. The system development and design method of an agent-based manufacturing planning and control system is presented. The application of AMPCS in an Automated Manufacturing Cell (AMC) in the Automation Laboratory of Tunghai University is implemented.

5.2 Future Research

AMPCS is developed by MAS and RFID systems, this research did not consider the system process logic and the agent’s procedure. Therefore, we suggest three points which should be investigated further:

(1) Advanced Manufacturing Planning module is respond to generate the production and operation schedule, but we didn’t describe the logic of planning and scheduling. Therefore, the planning and scheduling procedure such as heuristic should be investigated further.

(2) Performance Analysis module is respond to monitor the manufacturing task in real-time, but we didn’t set up the performance indicates, such as order fulfil rate. Therefore, the performance indicates which is defined to evaluate the manufacturing tasks should be investigated further.

(3) AMPCS system framework is developed, but we did not implement the system instead of using agent tools, such as aglets, to design the agents, so we did not evaluate the performance of AMPCS. Therefore, the implementation and testing of a complete AMPCS should be investigated further.

Reference

[1] Zhang, J.B., Zhang, D.H., Wong, M.M. & Ng, T.J. (2003). Design and Development of a Cost-effective Fault-tolerant Execution and Control System for Discrete Manufacturing. Emerging Technologies and Factory Automation, 269-275.

[2] Rangarajan, T.S., Vijaykumar, A. & Suraj, S.S. (2004). Stop getting Strangled by your Supply Chain, Forrester Research.

[3] Intermec. Supply Chain RFID: How It Works And Why It Pays. White paper.

[4] Junichi, Y., Eiji, A. & Tatsuo, A. (2005). Parts and packets unification radio frequency identification application for construction. Automation in Construction, 14, 477-490.

[5] Hiroyuki, H., Norishige, I., Yutetsu, F., Takeshi, S. & Hiroyoshi, I. (2003). Network Agents for Life Cycle Support of Mechanical Parts. Third international Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan.

[6] Kwangyeol, R., Youngjun, S. & Mooyoung, J. (2003). Modeling and specifications of dynamic agents in fractal manufacturing systems. Computers in Industry, 52, 161-182.

[7] Tao, X. (2000). Design and implement of a mobile agent structured migration mechanism. J. Software, 11, 7, 918-923.

[8] Rabelo, R.J., Camarinha-Matos, L.M. & Afsarmanesh,H. (1999). Multi-agent-based agile scheduling. Robotics and Autonomous System, 27, 15-28.

[9] Lim, M.K. & Zhang, D.Z. (2004). An integrated agent-based approach for responsive control of manufacturing resources. Computers & Industrial Engineering, 46, 221-232.

[10] Wang, S.L., Xia, H., Liu, F., Tao, G.B., & Zhang, Z. (2002). Agent-based modeling and mapping of a manufacturing system. Journal of Materials Processing Technology, 129, 518-523.

[11] Paulo, S. & Carlos, R. (1999). A distributed architecture and negotiation protocol for scheduling in manufacturing systems. Computers in Industry, 38, 103-113

[12] Shaw, C.F., Keith, A. S. & Kevin K. J. (2005). Manufacturing planning and predictive process model integration using software agents. Advanced Engineering Information, 19, 135-142.

[13] Shen W, Norrie D. Dynamic manufacturing scheduling using both functional and resource related agents. Integrated Computer-Aided Eng 2002;8(1):17–30.

[14] Supply Chain Council. (2003). Supply Chain Operations Reference Model. SCOR-Wizard 5.8, Computer Software.

[15] Jan, O. & Birger, R. (1995). Operations Research Techniques in Manufacturing Planning and Control Systems. International Transactions in Operational Research, Vol. 2, 29-43.

[16] Wooldridge, M. (1997). Agent-based software engineering. IEEE Proceeding an Software Engineering, 144(1), 26-37.

[17] O'Hare, G., Jennings, N.(Eds), Foundations of Distributed Artificial Intelligence, Wiley, New York. 1996.

[18] Scott, A.D., Mark, F.W. & Clint, N.S. (2001). Multi-agent Systems Engineering, International Journal of Software Engineering and Knowledge Engineering, Vol.11, No.3, 231-258

[19] Jiri, L., Olga, S., Vladimir, M. & Michal, P. (2001). Application of multi-agent approach in production planning and modeling. Engineering Application of Artificial Intelligence, 14, 369-376.

[20] Scott, A.M. (1999). KQML & FLBC: Constructing Agent Communication Languages, 32th Hawaii International Conference on System Science.

[21] Kinney, D., Geoegeff, M., and Rao, A. (1996). A Methodology and Modeling Technique for Systems of BDI Agents, Lecture Notes in Artificial Intelligence, Vol.1038

[22] Olhager, J. & Rapp, B. (1990). Modern Concepts for Computer-based Manufacturing Planning and Control Systems. In H.E. Bradley (Ed.) Operational Research, 565-576

[23] Bennet, T., Olhager, J. & Rapp, B. (1994). Computerization of Manufacturing Planning and Control System, Evaluation of Production Management Methods, Amsterdam: North-Kolland, 274-286.

[24] Maria, C., & Andrea, S. (2000). Multi-agent Systems in Production Planning and Control : An Application to the Scheduling of Mixed-model Assembly Lines, Internal Jounral Production Economics, 68, 29-42.

[25] Katina, M., & Luke, M. (2005). The Pros and Cons of RFID in Supply Chain Management, International Conference on Mobile Business.

[26] Lang, D.B., Oshims, M. (1998). Programming and Developing Java Mobile Agents with Aglets, Addison-Wesley, Reading, MA.