# Agent-based Collaborative Maintenance Chain for Engineering Asset Management

Amy J.C. Trappey[a, b, *], David W. Hsiao[b], Lin Ma[c], Yu-Liang Chung[d] and Yong-Lin Kuo[d]

[a] Department of Industrial Engineering and Management, National Taipei University of Technology, Taiwan
[b] Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Taiwan
[c] School of Engineering Systems, Faculty of Build Environment and Engineering, Queensland University of Technology, Australia
[d] Mechanics and System Research Laboratories, Industrial Technology Research Institute, Taiwan

**Abstract.** Engineering asset nowadays mostly replies on self-maintained experiential rule-bases and periodic maintenance, which is lacking a concurrent engineering approach. To enrich the maintenance efficiency and customer relationship, this research proposes collaborative environment integrated by research center with good diagnosis and prognosis expertise. The collaborative maintenance chain jointly combines asset operation sites (i.e., maintenance demanders), research center (i.e., maintenance coordinator), system providers (i.e., maintenance providers), and suppliers. Meanwhile, to realize the automation of communication and negotiation among organizations, multi-agent system technique is applied. With agent-based collaborative environment, the entire service level of engineering asset maintenance chain is increased.

**Keywords.** Engineering asset, Multi-agent system (MAS), Maintenance chain, Concurrent engineering

## 1 Introduction

Integrated Engineering Asset Management is a continuous process covering the whole life cycle of an asset containing conceptual design, construction/manufacture, operational use, maintenance, rehabilitation and/or

* Please send all correspondence to Professor Amy Trappey, Department of Industrial Engineering and Management, National Taipei University of Technology, Taipei (10608), Taiwan, E-mail:trappey@ntut.edu.tw. Tel: +886-2-2771-2171 Ext. 4541; Fax: +886-2-2776-3996

disposal [1]. When speaking of engineering asset management, how to extend the asset operation time is always one of the most concerned issues. Therefore, many researchers are devoted to the field of reaching effective and efficient repair and maintenance works, e.g., condition monitoring, symptom diagnosis, health prognosis [6], [8], [11]. Moreover, in order to enhance the customer relationship and gather more information as the basis for future equipment redesign, system providers start to offer total after-sales service, including maintenance, rehabilitation and professional consultation, after engineering asset installation. However, recent engineering assets, including manufacturing/production machinery and related equipments (e.g., AGVS, transportation equipment, AS/RS), are much more complex in functional design, and are more difficult to be operated and maintained. As a result, self-maintained experiential rule bases are no longer sufficient in dealing with the unpredictable problems [9], [11]. Therefore, enterprises nowadays start outsourcing helps to technical centers to integrate with enterprises' historical experiences to assist themselves dealing with the complexity of assets to have predictive maintenance actions and better utilization of assets. Moreover, different engineering assets may be offered and served by different system providers. Therefore, an integrated high-level maintenance which contains multiple sub-systems requires the cooperation of multiple system providers, and thus increases the difficulty of coordination [4]. To enhance the efficiency of maintenance chain for engineering assets, this research proposes a collaborative maintenance chain integrated by technical centers. In the proposed collaborative maintenance chain, the technical center acts as the prognosis and diagnosis experts who provide professional consultations, including accurate diagnosis and reliable prognosis, as the basis for afterward maintenance arrangement. The technical center also acts as the coordinator for maintenance demanders and suppliers. Moreover, multi-agent system (MAS) technology is applied to complete the collaborative maintenance owing to agent's characteristics, including autonomous, communicative, goal-oriented, proactive, rational, learning and active [2], [3], [7], [10]. In the following sections, the current practice of engineering asset maintenance chain and its concerns are firstly depicted. Afterward, the proposed collaborative maintenance chain combined with multi-agent system technology is discussed in detail. Finally, we will draw the conclusion.

## 2 Current Maintenance Practice and Main Concerns

Current maintenance chain for engineering assets mainly contains three tiers of participants, including asset operation/user sites, system providers (i.e., the asset maintenance provider) and spare part suppliers. In the current practice, the maintenance jobs are either shutdown driven maintenance or periodic maintenance (Figure 1). However, these two types of maintenance are not able to deal with the unexpected shutdowns and consequently cause great damages to the assets and operators.

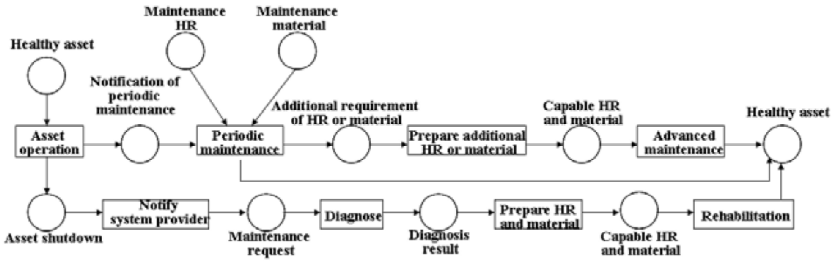


**Figure 1.** Periodic maintenance and shutdown driven maintenance are the primary maintenance actions of current practice

According to the field research and interviews with industrial companies (e.g., automatic parking towers and power plants), it is concluded that the current practice of maintenance chain can be improved from four directions, containing daignosis/prognosis, maintenance demand/provide mismatch, spare part overstock, and system/database linkage.

## 2.1 Prognosis and Diagnosis

In the current practice, prognosis and diagnosis are conducted according to self-maintained experiential rule bases combined with internal condition monitoring data. However, recent engineering assets, including manufacturing/production machinery and related equipments, provide more functions than ever, and make themselves more difficult to be operated and maintained. Consequently, the lacking of experts dealing with symptom diagnosis and health prognosis may result in inefficient maintenance. Thus, the maintenance chain needs experts from diagnosis and prognosis domains integrating historical condition monitoring data to support preventive maintenance.

## 2.2 Maintenance Demand and Supply Mismatch

In a large plant, there are numerous systems which are provided and maintained by different system providers. Therefore, when a higher level maintenance which requires the involvement of different system providers' efforts to accomplish the maintenance job may be a big scheduling problem to both asset operation site and system providers. Therefore, a platform, which brings together the suppliers and demanders of after-sales service to coordinate one another's maintenance schedules, is required.

## 2.3 Spare Part Overstock

In the current practice, individual system provider forecasts requirements of maintenance components to prepare spare part inventory. However their forecasts cannot match real market requirements, and thus, results in overstock or low service level. Therefore, a forum to collaboratively bridge and integrate maintenance demanders (i.e., asset operation site), maintenance providers (i.e., system providers) and spare part suppliers in advance is needed. In the forum, they can cooperatively decide production schedules, safety stock level and lead time.

### 2.4 Inefficient System and Database Linkage

With the improvement of information and database technology, each company is operating more information systems and databases than ever. For example, when maintenance is requested by an asset operation site, the system provider checks the experience rule base, maintenance schedule, and human resource allocation to generate a maintenance decision for the operation site. Afterward, the operation site adjusts its production/service schedule, maintenance schedule, and related systems to support the maintenance decision. It becomes a very complicated problem if a higher level maintenance job is required owing to the complex linkage among these information systems and databases. Consequently, a better communication and negotiation technology among these information systems is required to increase the communication flexibility and efficiency.

## 3 Agent-based Collaborative Maintenance Chain

### 3.1 Integrated Maintenance Chain

To solve the problems depicted in the as-is model, this research proposes a new agent-based collaborative maintenance chain which is integrated by a research center with prognosis and diagnosis expertise (Figure 2).

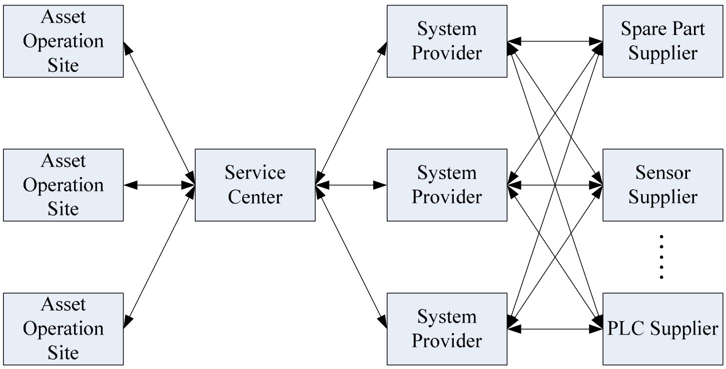


**Figure 2.** The proposed agent-based maintenance chain is integrated by service center with prognosis and diagnosis expertise

In the proposed maintenance chain, the asset operation site automatically monitors the asset condition, and shares these data with service center for following diagnosis and prognosis. The Research center (Service center) receives condition monitoring data, and proceeds following diagnosis and prognosis. Moreover, the research center also brings together maintenance demanders (asset operation sites) and maintenance providers (system providers), and coordinate suitable maintenance schedules. The system provider (maintenance provider) takes charge of regular, emergent and predictive maintenance for asset operation site. Further, the system provider also coordinates resources (human resources and spare parts) to accomplish maintenance and repair jobs. The spare part suppliers supply PLC, monitoring equipments, and related components and materials.

In this new collaborative maintenance chain, engineering asset management can be divided into four stages, including condition monitoring, prognosis/diagnosis, maintenance decision making, and scheduling and dispatching (Figure 3). These four stages will be discussed in detail as follows.

In the condition monitoring phase, with the improvement of condition monitoring techniques and database technologies, the asset is hierarchally monitored to provide complete asset information for further asset health prognosis and symptom diagnosis. If the engineering asset requires diagnosis or prognosis, corresponding experts will proceed the prognosis and diagnosis jobs. To provide accurate diagnosis and reliable prognosis, the experts need to communicate interactively with the asset sites. After generating the prognosis and diagnosis results, subsequent maintenance decisions, including maintenance start time, maintenance period, maintenance cost and supporting enterprise resources, are made. However, the same maintenance job has different meanings to different departments/organizations. For production department, how to prevent shutdowns, especially during the peak time, is the major concern. For finance department, how to extend the asset operation life with minimum maintenance cost is the major concern. For maintenance organization, how to minimize maintenance cost (e.g., least overtime work) or maximize the maintenance benefits is the major concern. Consequently, iterative communication and negotiation among these parties are required to gather satisfactory maintenance decisions for these parties. After the maintenance decisions are made, production department or service proving department adjust its dispatching based on the determined schedules. Meanwhile, maintenance organization dispatches its human resource allocation and prepares corresponding maintenance materials.

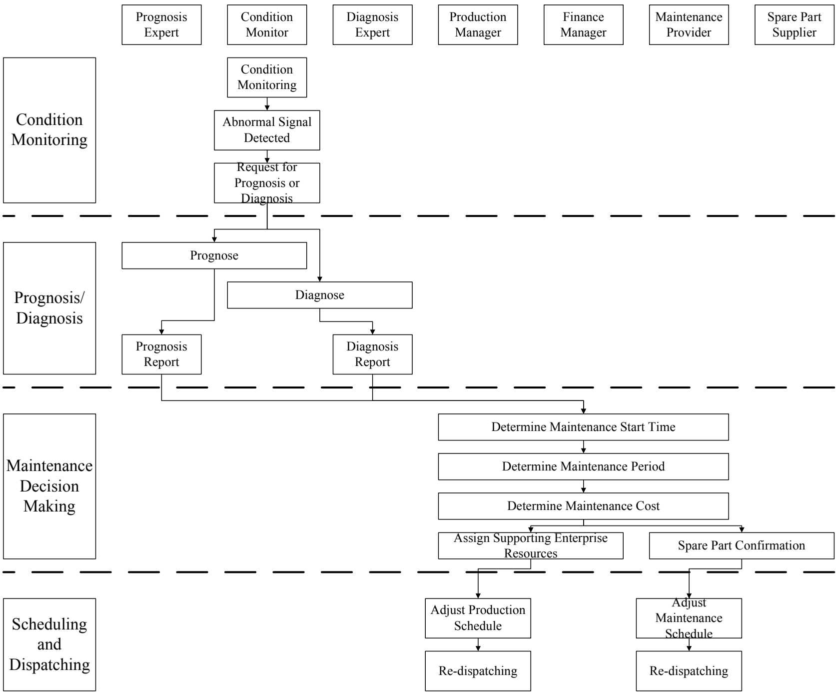


**Figure 3.** There are four phases of engineering asset management in the proposed maintenance chain

### 3.1 System Requirement

Since the maintenance chain is jointly integrated by the research center, this chain still needs some information technology to enhance the automation mechanism to increase the chain efficiency.

During the diagnosis and prognosis phase, diagnosis and prognosis experts have to communicate with asset operation site frequently to gather enough information for precise diagnosis and prognosis. Therefore, an autonomous information exchange is required to eliminate the constraints from locations and time.

In making maintenance decisions, multiple participants in the maintenance chain are invited to jointly discuss and negotiate the related time, cost and resources of certain maintenance job. However, the distributed environment and numerous information systems diminish the discussion efficiency. Therefore, a mechanism that can represent human beings with certain authority to proceed the discussion and negotiation is demanded.

After maintenance decisions are made, internal production, service and maintenance schedules are changed. These changes affects following human resource and machine dispatching and the preparation of required materials. To quickly respond to the changes in a timely matter to keep the enterprise working efficiency, a mechanism that interlinks the scheduling and dispatching effectively and efficiently is required.

Based on above requirements, it is concluded that a mechanism that can represent human beings do the discussion, negotiation and decision making is required to complete the proposed integrated maintenance chain. Consequently, agent technology, with the characteristics of autonomous, communicative, goal-oriented, proactive, rational, learning and active, is embedded to the maintenance chain. Under multi-agent system environment, agents are authorized with certain range of authorization. Within the authorization, agents can help condition monitor, prognosis experts and diagnosis experts progress the data confirmation, data request, data response and results confirmation. Afterward, the agents help production/service manger, finance manager, maintenance provider, and spare part supplier proceed the discussion and negotiation about detailed maintenance decisions without being restricted by the physical location boundaries and time limitation. Moreover, the agents efficiently and effectively interlink the scheduling database and dispatching database to generate the adjusted arrangement of human resources and related material preparation.

### 3.2 System Analysis

The proposed MAS for collaborative maintenance chain mainly contains eight function modules, including condition monitoring, production or service scheduling, diagnosis or prognosis, maintenance schedule coordination, maintenance cost coordination, spare part inventory, production or service dispatching, and maintenance dispatching.

Condition monitoring focuses on continuous condition monitoring, and send abnormal signal and real-time information to service center for further diagnosis and prognosis. Production or service scheduling module records and balances the utilization of engineering assets. Diagnosis and prognosis helps to find out the potential symptoms and predict asset health of engineering assets. Maintenance schedule coordination module coordinates maintenance schedule both considering asset operation site's constraints (production or service schedule) and system provider's constraints (human resource and spare part inventory). Maintenance cost coordination focus on coordinating the maintenance cost which is accepted by both the maintenance demander and maintenance supplier. Spare part inventory continuously checks system providers' inventory level, and reminds system providers of replenishment. Production or service dispatching adjusts production or service human resources and corresponding materials. Maintenance dispatching adjusts maintenance human resources and corresponding spare parts. Figure 4 shows the use case diagram of agent-based collaborative maintenance chain.

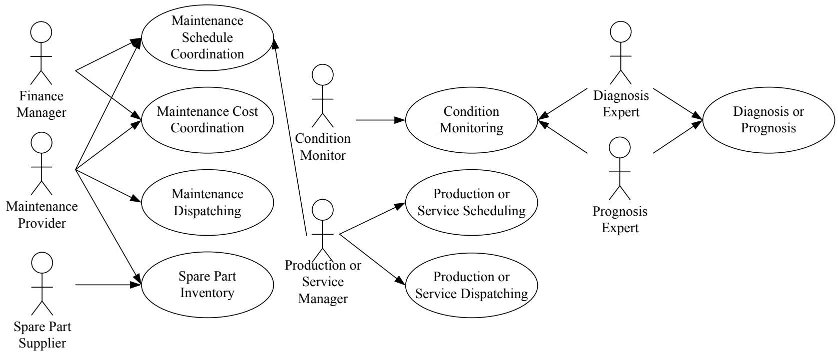


**Figure 4.** The use case diagram of the agent-based collaborative maintenance chain

To increase the efficiency of the collaborative maintenance chain, there are corresponding agents in different departments and organizations to assist synchronous discussion, communication and negotiation. Figure 5 demonstrates the agent relationship.

In asset operation site, Monitoring Agent (MA) continuously monitors the parameters of engineering assets. While anomaly is detected, MA actively informs asset manager, and sends the formatted data to Asset Agent upon request. Maintenance Scheduling Agent (MSA) takes charge of arranging the maintenance schedule of certain engineering asset. Dispatching Service Agent (DSA) coordinates with MSA to adjust following production/service dispatching of human resources and machineries. Asset Agent (AA) acts as the manager of engineering asset, who cooperates with Diagnosis Agent (DA) from research center to determine diagnosis results, collaborates with Prognosis Agent (PA) from research center to determine the risk distribution, and co-works with Finance Agent (FA) and Maintenance Decision Support Agent (MSDA) to make final maintenance decisions. After making the maintenance decision, Dispatching Service Agent (DSA) rearranges the following dispatching jobs.

In research center (service center), there are three kinds of agent, including Service System Agent (SSA), Diagnosis Agent (DA), and Prognosis Agent (PA). SSA is the coordinator of maintenance demanders and maintenance suppliers. DA and PA represent diagnosis experts and prognosis experts to collect data and generate diagnosis and prognosis results based pre-developed algorithms.

Maintenance Decision Support Agent (MDSA), System-provider Maintenance Scheduling Agent (SMSA), Human Resource Agent (HRA), and Spare Part Agent (SPA) come from system provider. While making the maintenance decisions, e.g., maintenance start time, maintenance period and maintenance cost, these agents are invoked and join the virtual forum to discuss with agents from asset site and suppliers.

In supplier site, when Supplier Interface Agent (SIA) is requested about when the spare parts are available, it turns to communicate with Inventory Agent (IA) or Production Line Agent (PLA) to determine the precise time.

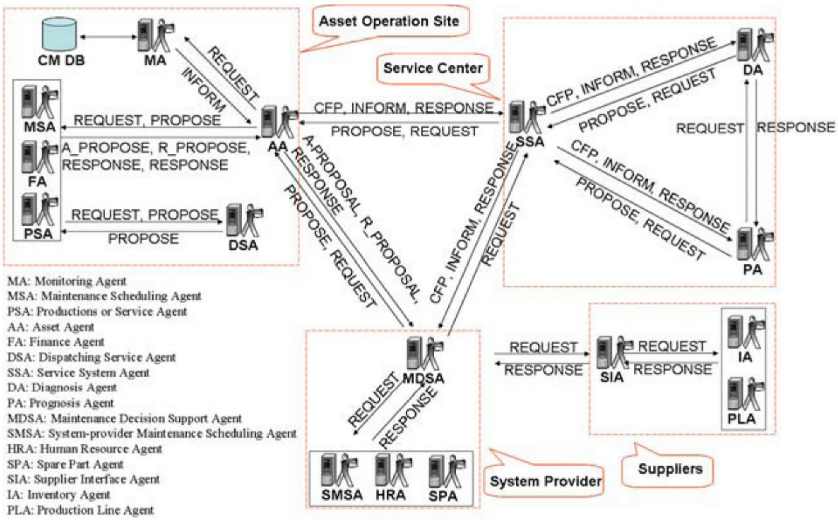


**Figure 5.** Agent relationship diagram

### 3.3 System Design

The proposed multi-agent system of this research is based on Java Agent DEvelopment Framework (JADE) [5] which simplifies the implementation of MAS. JADE follows Foundation for Intelligent Physical Agents (FIPA) specifications and provides Graphical User Interface (GUI) to enable users debug and develop systems more efficiently. Figure 6 shows the MAS architecture of collaborative maintenance chain. The agent community is contributed from three sites, containing asset operation site, research center site, system provider site and supplier site. Moreover, agent communication on JADE is based on IIOP protocol. The service layer provides interfaces for agents to perform their behaviors based on their pre-defined logics, and data access layer provides functions for service layer to access the databases.

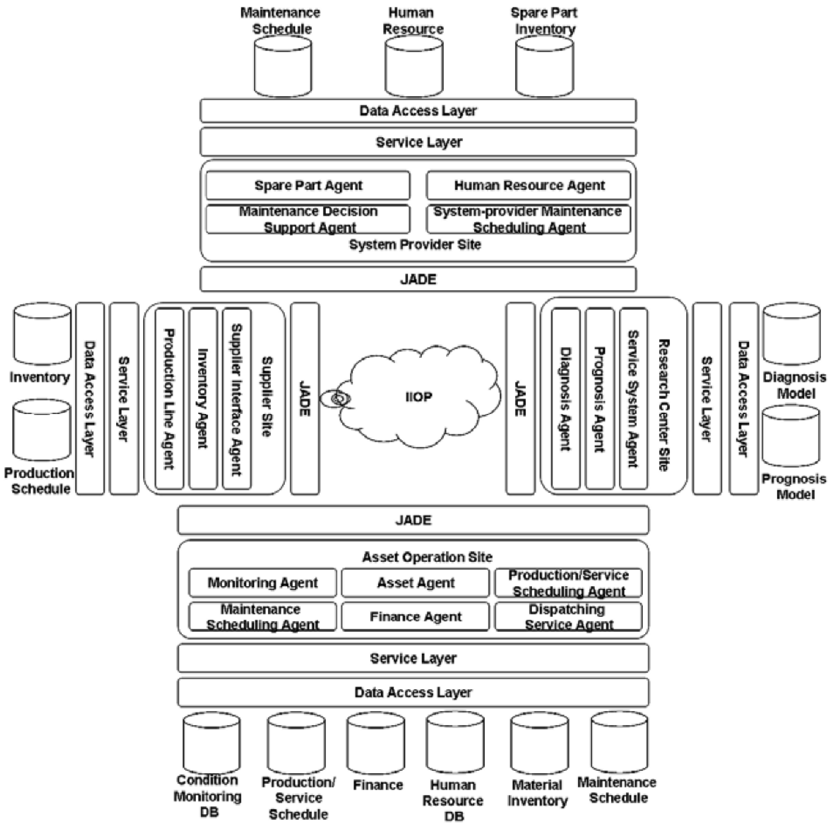


**Figure 6.** System architecture of agent-based collaborative maintenance chain

To clearly clarify the agent interactions, agent communication models based on unified modeling language (UML) sequence diagram with communication performative based on the agent communication language (ACL) specification of FIPA are drawn. Figure 7 to Figure 9 depict three critical agent communication models. Figure 7 shows the interactions among condition monitoring agent, asset agent and diagnosis agent of generating accurate diagnosis results. Figure 8 shows the interactions among condition monitoring agent, asset agent, diagnosis agent and prognosis agent of determining the asset health prediction. With the predicted asset health distribution, agents, including asset agent, production agent, maintenance decision supporting agent, prognosis agent and enterprise resource agent (i.e., SMSA, HRA and SPA), cooperate and communicate iteratively to generate satisfactory maintenance and production schedules (Figure 9).

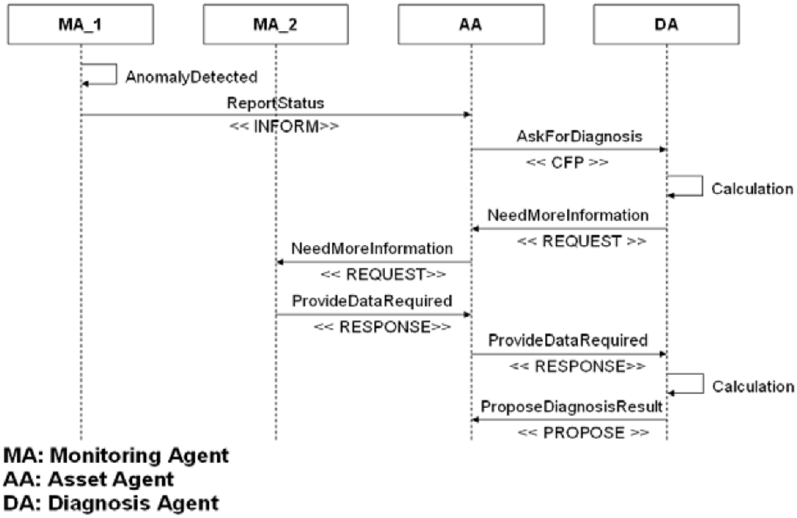


**Figure 7.** Agent communication model of generating symptom diagnosis

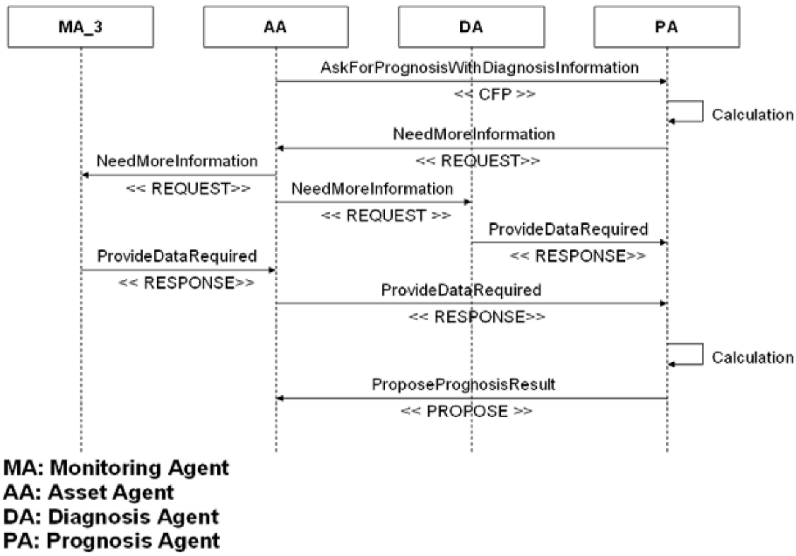


**Figure 8.** Agent communication model of generating asset health prognosis

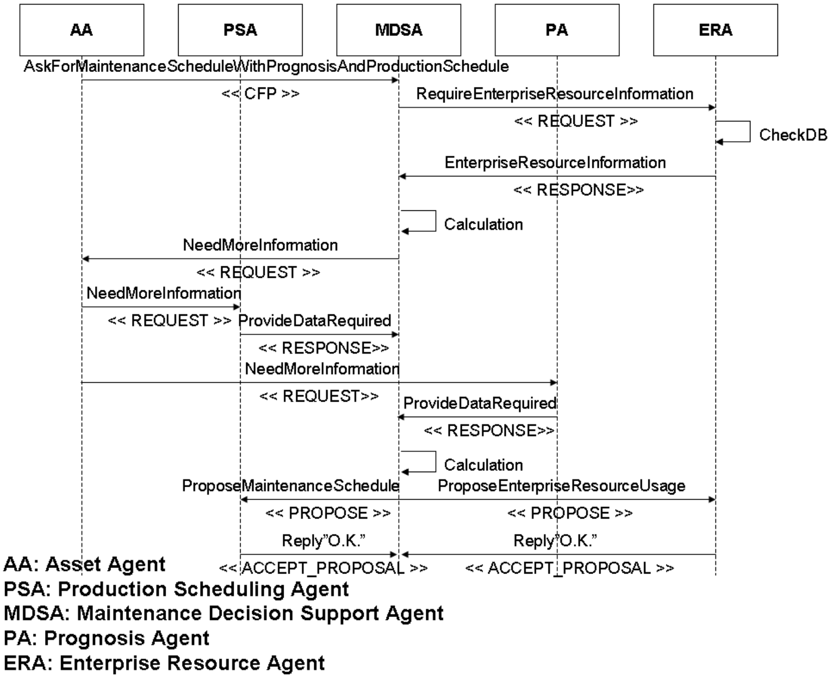


**Figure 9.** Agent communication model of determining production schedule and communication schedule

# 5 Conclusion

The purpose of this research is to provide complete collaborative maintenance chain architecture, and realize the architecture via multi-agent techniques. Detailed agent relationship and agent communication models are depicted as the basic guidelines of further implementation. There are mainly four advantages of this research. First, the complicated diagnosis and prognosis are outsourced to research center so as to help enterprise keep their focuses on their core competences. Second, the research center acts as the coordinator of maintenance suppliers and demanders, which contributes to enrich the chain efficiency and customer satisfaction. Third, the research center provides a forum for maintenance chain participants to discuss their requirements in advance and afterward determine the production schedules, safety stock level and lead time. With these information considered in advance, the maintenance service level is increased without being overstocked. Finally, the agents contribute to consistent communication among enterprises, which enables better capability for dealing emergent events and reduces physical boundary constraints.

## 6 Acknowledgements

This research is partially supported by Industrial Technology Research Institute and National Science Council, Taiwan.

## 7 References

[1] CIEAM (CRC for Integrated Engineering Asset Management). Available at: <http://www.cieam.com/>, Accessed on: Mar. 15th 2008.

[2] Davidson, E.M., McArthur, S.D.J., McDonald, J.R., Cumming, T., and Watt, I., "Applying multi-agent system technology in practice: automated management and analysis of SCADA and digital fault recorder data," IEEE Transactions on Power Systems, Vol. 21, Issue2, pp. 559 – 567 (2006)

[3] Hossack, J.A., Menal, J., McArthur S.D.J., and McDonald, J.R., "A multiagent architecture for protection engineering diagnostic assistance," IEEE Transactions on Power Systems, Vol. 18, Issue 2, pp. 639 – 647 (2003)

[4] Huang, C.J., Trappey, A.J.C., and Yao, Y.H., "Developing an agent-based workflow management system for collaborative product design," Industrial Management and Data System, Vol. 106, No. 5, pp. 680-699 (2006)

[5] JADE (Java Agent DEvelopment framework). Available at: <http://jade.tilab.com>. Accessed on: Mar. 12th 2008.

[6] Majidian, A. and Saidi, M.H., "Comparison of fuzzy logic and neural network in life prediction of boiler tubes," International Journal of Fatigue, Vol. 29, pp. 489-498 (2007)

[7] McArthur, S.D.J., Booth, C.D., McDonald, J.R., and McFadyen, I.T., "An agent-based anomaly detection architecture for condition monitoring," IEEE Transactions on Power Systems, Vol. 20, Issue 4, pp. 1675 – 1682 (2005)

[8] Sun, Y., Ma, L., Mathew, J., and Zhang, S., "An analytical model for interactive failures," Reliability Engineering & System Safety, Vol. 91, Issue 5, pp. 495-504 (2006)

[9] Sun, Y., Ma, L., Mathew, J., Wang, Y., and Zhang, S., "Mechanical systems hazard estimation using condition monitoring," Mechanical Systems and Signal Processing, Vol. 20, Issue 5, pp. 1189-1201 (2006)

[10] Trappey, A.J.C., Trappey, C.V., and Lin, F.T.L., "Automated silicon intellectual property trade using mobile agent technology," Robotics and CIM, Vol. 22, pp. 189-202 (2006)

[11] Yao, Y.H., Lin, G.Y.P., and Trappey, A.J.C., "Using knowledge-based intelligent reasoning to support dynamic equipment diagnosis and maintenance," International Journal of Enterprise Information Systems, Vol. 2, No. 1, pp. 17-29 (2005)