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A multi-agent collaborative maintenance platform applying game theory negotiation strategies

Amy J. C. Trappey · Charles V. Trappey · Wei-Chun Ni

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Abstract Engineering asset management (EAM) is a broad discipline with distributed functions and services. When engineering assets are capital intensive, management requires specialized expertise for diagnosis, prognosis, maintenance and repairs. The current practice of EAM relies on self maintained experiential rules with coordinated collaboration and outsourcing for maintenance and repairs. In order to enhance the life long asset value and efficiency (from the stakeholder's viewpoint) and after sales service quality (from the asset provider's viewpoint), this research proposes a collaborative maintenance platform that integrates real time data collection with diagnostic and prognostic expertise. The collaborative system combines and delivers services among asset operation sites (the maintenance demanders), the service center (the intermediary coordinator), the system providers, the first tier maintenance collaborators, and the second and lower tier parts suppliers. Multi-agent system technology is used to integrate different systems and databases. Agents with autonomy and authority work to assist service providers and coordinate communications, negotiations, and maintenance decision support. Finally, game theory is used to design the decision models for strategic, tactical, and operational decision making during collaborative maintenance practices.

Keywords Engineering asset management · Maintenance decision · Intelligent multi-agent system · Game theory · Negotiation mechanisms

Introduction

Engineering asset management (EAM) includes stages of continuous lifecycle management including the design, construction, use, maintenance, repair, disposal, and recycling of assets (CIEAM 2008). Enterprises often focus on operational aspects of engineering assets, since these assets may fail due to lack of proper maintenance which in turn causes production or service delays. Therefore, poor EAM incurs financial loss of the asset itself as well as production delays and loss of services.

Many academic studies review asset diagnosis based on asset condition monitoring and life cycle prediction (Majidian and Saidi 2007). Engineering assets and equipment are shutdown for repair when maintenance personnel become aware of a malfunction. Repair work is often reactive to a cause rather than based on real time condition monitoring, prediction, diagnostics and pre-scheduled maintenance (Yao et al. 2005). Further, traditional asset management approaches are not well suited for predicting equipment failure (Sun et al. 2006). Therefore, many enterprises cooperate with research institutes to improve diagnostic and forecasting skills. Research in these areas has helped enterprises solve complicated engineering asset problems and reduce the cost of equipment malfunctions. The demand for high level maintenance services has led to the creation of new services offered by system providers offering specialized maintenance consulting. These service companies negotiate costs and repair specifications with equipment holders and maintenance chain participants and

A. J. C. Trappey · W. -C. Ni
Department of Industrial Engineering and Engineering Management, National Tsing Hwa University, Hsinchu, Taiwan

C. V. Trappey (✉)
Department of Management Science, National Chiao Tung University, Hsinchu, Taiwan
e-mail: trappey@faculty.nctu.edu.tw

fulfill maintenance requests according to a time schedule. Consequently, maintenance scheduling, coordination, and communication are critical for the success of the business model and ongoing sales relationship. This research studies the problem of how to effectively coordinate the operations among different service providers and asset holders. A general EAM decision model is developed using game theory. A case is used to describe the relationships between a network of power transmission and distribution equipment providers and to demonstrate the EAM methodology and information technology (IT) solutions.

The proposed preventive maintenance decision support system is applied to the EAM of a company managing large electrical transformers. Multi-agent system (MAS) technology enables autonomous, social, goal-oriented, reactive, rational choice, self-learning, and better enables information exchange, communication, and decision support (Hossack et al. 2003; McArthur et al. 2005). Agent behavioral modeling is used to design and develop negotiation mechanisms which strengthen cooperation across the maintenance chain. The research implements an intelligent collaborative process system that supports maintenance chain monitoring and repair as well as negotiation between members.

Literature review

The literature covering EAM, agent technology for asset management, and game theory are reviewed. The directions for collaborative and intelligent EAM are identified. Moreover, game theory and negotiation mechanisms are studied to select appropriate models for integrated maintenance chain applications.

Engineering asset management

Integrated Engineering Asset Management (IEAM) is a continuous process covering the asset life cycle from the conceptual design, construction, manufacturing, operational usage, maintenance, rehabilitation, disposal, and recycling (CIEAM 2008). Many engineering assets, such as water pipeline systems and electrical transmission systems, are large scale facilities which directly affect the quality of life. A key research issue concerns ways to extend the operational life of assets and the means to effectively and efficiently arrange routine, emergent, and preventive maintenance based on the assets condition. Li et al. (2005) demonstrate in their field research that maintenance costs range from 15% for manufacturing companies to 40% for iron and steel companies, percentages which translate to almost $200 billion US dollars every year. Bangemann et al. (2006) and Han and Yang (2006) noted that successful predictive maintenance requires the integration of condition monitoring, prognosis, diagnosis expertise, maintenance schedule coordination, human resource allocation, and maintenance part preparation. They also note that MAS are suitable for the integration of these elements that are widely distributed among organizations.

An EAM framework focuses on real time condition monitoring techniques to provide continuous data flows for rule based systems to derive timely maintenance schedules. Bretthauer et al. (1998) proposed an integrated maintenance scheduling (IMS) system which separates maintenance scheduling into device specific and system specific levels. The device specific level collects maintenance requests, analyzes potential maintenance actions and maintenance times from individual machines. At the system specific level, the intelligent condition estimation (ICE) module determines feasible maintenance schedules. Fuzzy logic is used to derive the final maintenance schedule to enhance maintenance teams' decision making capabilities. Further, Yang et al. (2008) use another approach, namely genetic algorithms, to generate cost-effective maintenance schedules that predict machine degradation.

Fu et al. (2004) recognize that traditional maintenance concepts and scheduling systems are outmoded for dynamic engineering environments. They identified monitoring and forecasting, diagnosis and prognosis, and maintenance decision making as the key elements in maintenance management systems. In their research, these elements are integrated with a trained artificial neural network (ANN) and a prediction model to build a maintenance management system for a dynamic environment.

Agent technology for integrated asset management

The linkage and communication efficiency among maintenance chain participants ensures flexible and accurate asset management decision making. Scholars have applied multi-agent technology for system integration and heterogeneous decision making. Li et al. (2005) proposed a basic agent framework for maintenance coordination using various agent roles, such as monitoring, diagnostic, prognostic and maintenance decision making agents. Several frameworks of MAS for collaborative e-maintenance applications were also designed by Iung (2003); Han and Yang (2006), and Hsiao et al. (2008). Further, Jenab and Zolfaghari (2008) developed an analytical model to measure the performance of the virtual collaborative e-maintenance architecture.

The current research trend in the agent based EAM focuses on integrating goals, objectives and constraints between maintenance chain participants (i.e., asset owners, operators, equipment providers and maintenance parts suppliers). The functions and resources required for preventive maintenance (condition monitoring, data transformation and transmission, asset condition database, diagnosis and prognosis expertise,

Table 1 Major categories of game theory

	Static	Dynamic
Complete information	Static games of complete information: Nash equilibrium	Dynamic games of complete information: Subgame Perfect Nash Equilibrium
Incomplete information	Static games of incomplete information: Bayesian Nash equilibrium	Dynamic games of incomplete information: Perfect Bayesian Nash equilibrium

human resources allocation and maintenance parts preparation) must be considered when decisions are made among different organizations. For our proposed collaborative maintenance platform, participants from different organizations in the maintenance chain are inter-connected by agents to increase communication and negotiation efficiency to predict equipment malfunctions without geographic constraints.

Game theory and negotiation mechanisms

In 1940, game theory was proposed to model the way humans think as a practical solution for problems in economics and other social sciences (Nagarajan and Sosic 2008). Game theory is used to manage conflicts and help decision makers develop strategies that yield benefits and encourage cooperation. Since conflict and cooperation in and of itself may influence decision making, a decision maker chooses a strategy by studying their own interests, conducting dependence analysis, and predicting others' behaviors. Consequently, game theory provides mathematical models that generate outcomes when there are conflicting interests among participants and relies on the competitive and dynamic features of information (Kreps 1990). Game theory considers the game state (static or dynamic) and information completeness (complete or incomplete). Table 1 shows that there are four types of games including Nash Equilibrium, Subgame Perfect Nash Equilibrium, Bayesian Nash Equilibrium and Perfect Bayesian Nash Equilibrium.

Nash equilibrium

A set of strategies selected by participating members to reach the best suitable conditions in game theory. In other words, if all members select their strategies, one cannot raise his own benefits without changing the others' strategies under the Nash equilibrium.

Subgame perfect Nash equilibrium

In game theory, a subgame perfect equilibrium (or subgame perfect Nash equilibrium) is a refinement of a Nash equilibrium used in dynamic games. A strategic profile is a subgame perfect equilibrium if it represents the Nash equilibrium of every subgame of the original game. If the players played any smaller game that is only one part of the larger game then their behaviour represents a Nash equilibrium of that smaller game. Their behavior is then a subgame perfect equilibrium of the larger game.

Bayesian Nash equilibrium

In a Bayesian game, rational players (or risk neutral players) seek to maximize their expected payoff given their beliefs about the other players. When players are risk averse or risk seekers, the assumption is that players will maximize their utility. A Bayesian Nash equilibrium is defined as strategic profiles and beliefs specified for each player to maximize the expected payoff given their beliefs about the other players' types and strategies.

Perfect Bayesian Nash equilibrium

A perfect Bayesian equilibrium is a strategy profile and a belief system such that the strategies are sequentially rational given the belief system is consistent, wherever possible.

Current practices for a collaborative maintenance chain

Maintenance and repair are critical issues for large companies that are heavily invested in engineering assets that have long depreciation and complicated and costly repair procedures. Electrical transformers for power plants match this description since the life of a transformer can be considerably shortened though poor maintenance. Further, the excessive loss of transformers through poor asset management can easily lead to financial ruin. Thus, we use electrical transformers as the case to compare the current practice (as-is) and the improved (to-be) general decision models in the construction of a multi-agent collaborative maintenance platform. In this section, we analyze the existing problems with current transformer maintenance procedures and form the framework for improved decision models.

Case description

The network system for power transmission and transformation consists of electrical power generators, voltage transformers, and connecting power cables. Figure 1 depicts the processes for power generation by wind turbine, power collection, power transmission, power distribution and power consumption. The wind turbine uses a rotating blade to drive a power generator, which yields about 600 volts. The power collection transformers collect the power from wind turbines and steps up the voltage to around 35,000 volts. After receiving power from the collection transformer, the large size transformer (the case-study transformer) steps up the voltage to about 220 kilovolts. High voltage transmission from the power grid helps minimize power loss. Before consumption by end users, the power transmission facility must step down or lower the high power transmission voltage. High voltage power users, such as manufacturing companies, operate their own step down transformers to match their needs. For home and other users, the high voltage power is first stepped down by power distribution centers, and then again by small local transformers to provide 110 volts. The critical issue is to determine the maintenance schedule for the numerous transformers in the system to ensure a reliable and uninterrupted power supply. The profit and reliability of the electric power system is used to measure the competitive status of the utility company and also provides an indicator of a nation's social welfare.

Common maintenance for the power transmission and distribution network relies on the facility's staff to identify

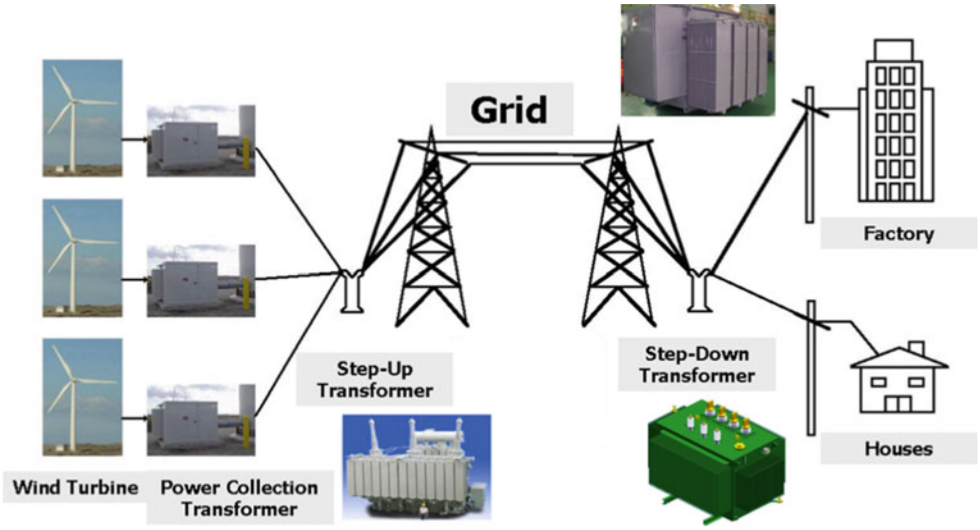


Fig. 1 Transmission and distribution for wind turbine power

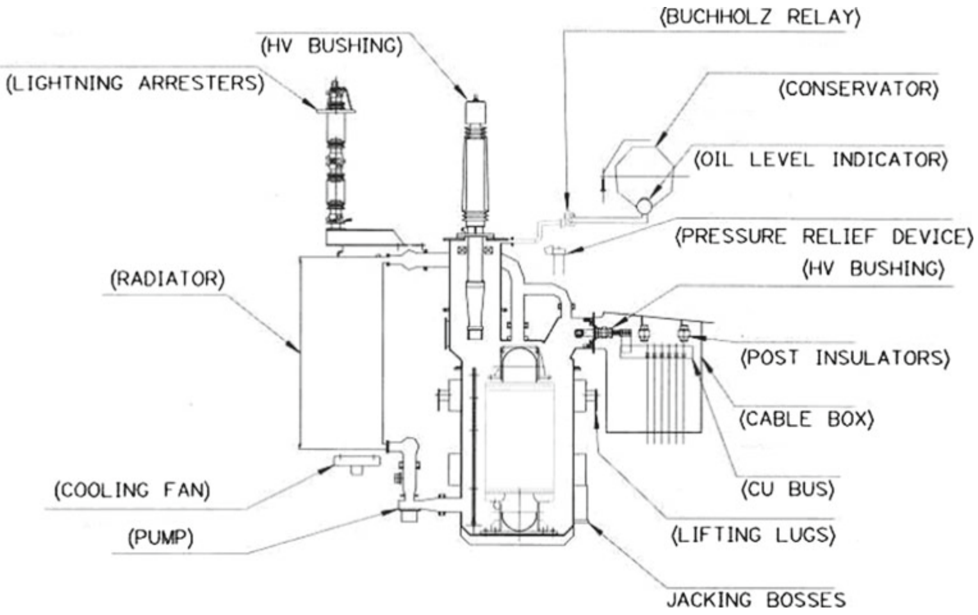


Fig. 2 The schematic drawing of a large-size voltage transformer

maintenance demands. In most cases, the staff issue maintenance orders after the equipment shutdown has occurred. In order to overcome crisis reactions to problems, this research studies a new approach to maintaining large size voltage transformers (Fig. 2). The research constructs a negotiation model for an agent based collaborative maintenance chain applying game theory to maximize the system benefits.

As-Is maintenance analysis

The maintenance procedure begins with accident repair and is followed by daily maintenance and then periodic maintenance. Since it is difficult to prevent unexpected shutdowns in equipment, system monitoring and data analysis using agents are employed. The participants of the maintenance chain are shown in Fig. 3.

Asset operation sites: The stakeholder and operator of the voltage transformer utilize the engineering asset for production or services and is the asset maintenance service receiver.

System provider: The engineering asset producer or maintenance service provider performs jobs such as routine, emergency and preventive maintenance for the asset operation sites.

First-tier collaborators: The first-tier collaborators provide maintenance crews and maintenance parts for the jobs.

The as-is voltage transformer's current maintenance model is shown in Fig. 4. In this diagram, the asset operation sites and the system providers prioritize their objectives while conducting maintenance tasks, which can cause resource limitations for the entire system. After the as-is analysis, two improvements are implemented for routine maintenance and emergency repair. According to the above analysis, several problems occur in the current maintenance practice.

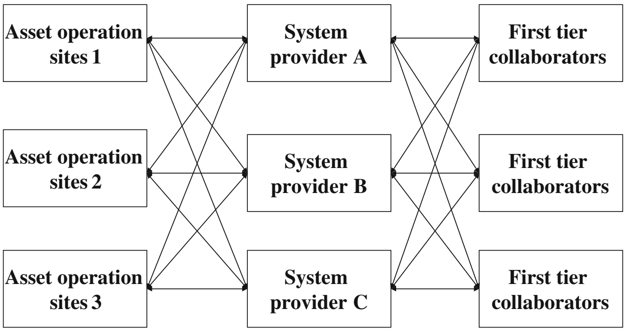


Fig. 3 The current maintenance chain structure

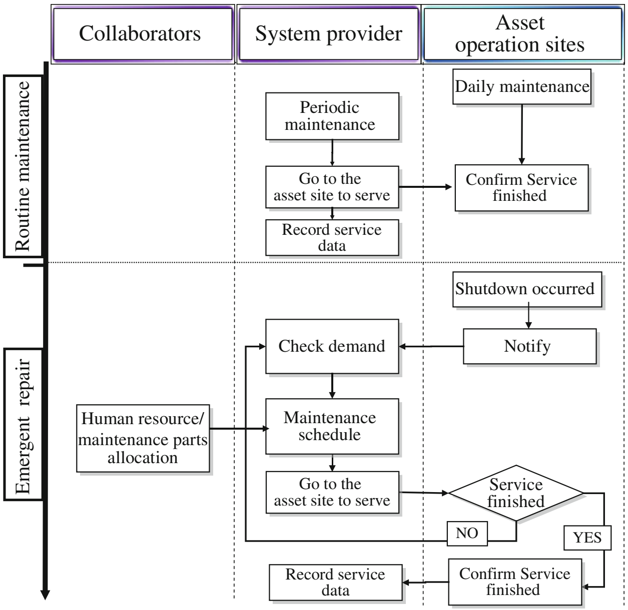


Fig. 4 The as-is operational sequence for current maintenance procedures

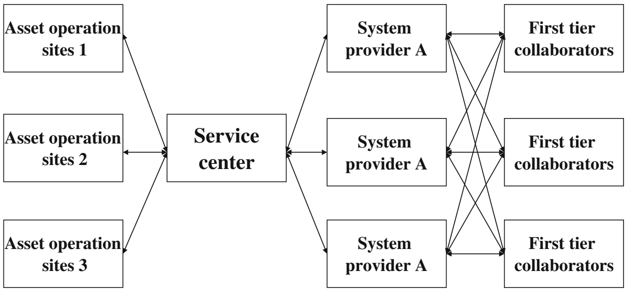


Fig. 5 The to-be maintenance chain structure

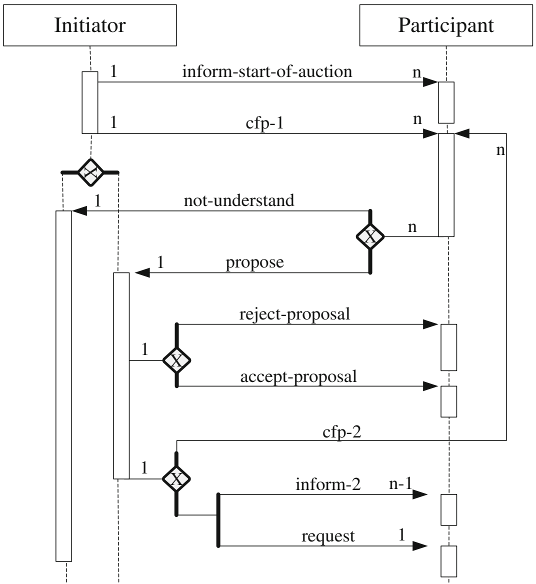


Fig. 6 FIPA English auction protocol architecture (FIPA 2008)

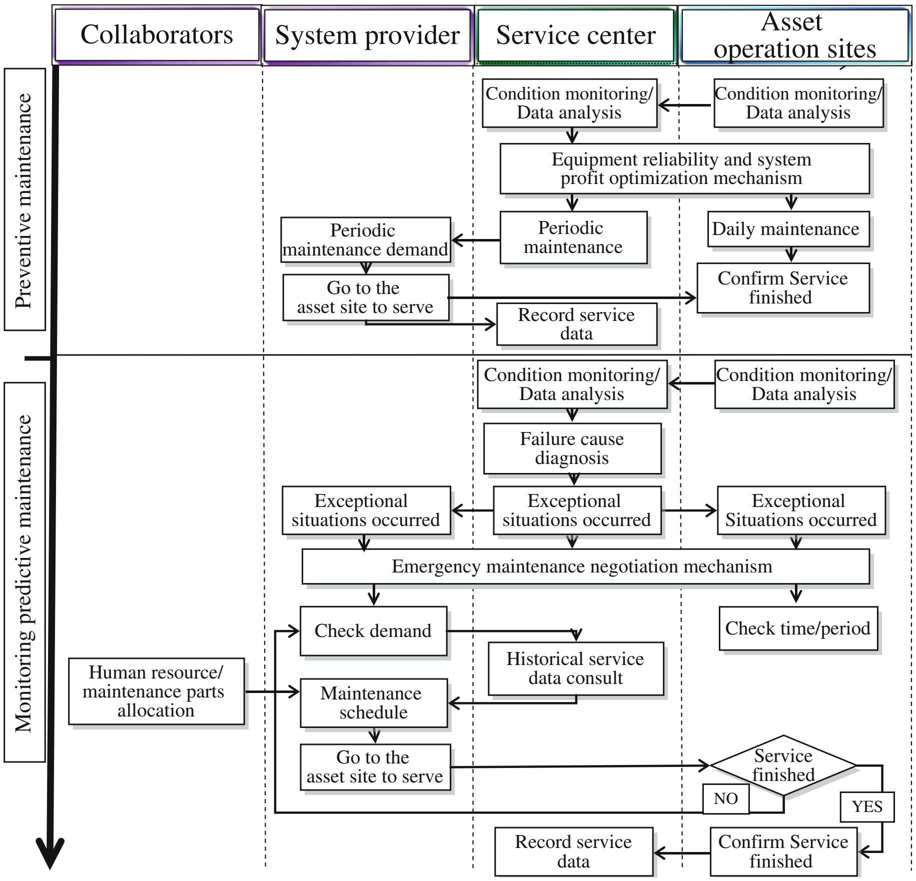


Fig. 7 The operational sequence for the to-be collaborative maintenance chain

Table 2 Goals and agent task analysis

Goal	Agent type	How to achieve the goal
Data/signal extraction	Monitoring Agent (MA)	• Condition monitoring system
	Asset Agent (AA)	• Data/ signal transformation
Accurate diagnosis	Diagnosis Agent (DA)	• Collect knowledge from diagnosis experts
		• Integrate expert knowledge into diagnosis knowledge base
		• Provide diagnosis result
Reliable prognosis	Prognosis Agent (PA)	• Collect knowledge from prognosis expert
		• Integrate expert knowledge into prognosis knowledge base
		• Provide prognosis result
		• Provide system profit optimization mechanism
Timely and reliable maintenance	Service System Agent (SSA)	• Arrange maintenance provider
	Maintenance Decision Support Agent (MDSA)	• Provide emergency maintenance negotiation mechanism
	System-Provider Maintenance Scheduling Agent (SMSA)	
		• Provide expected maintenance time
		• Provide expected maintenance start time
		• Have enough maintenance resources
Personalized interface	Human-Resource Agent (HRA)	• Provide personalized work list
Inventory management	Spare Part Agent (SPA)	• Notification of procurement

Fig. 8 Case diagram for the agent based collaborative maintenance chain

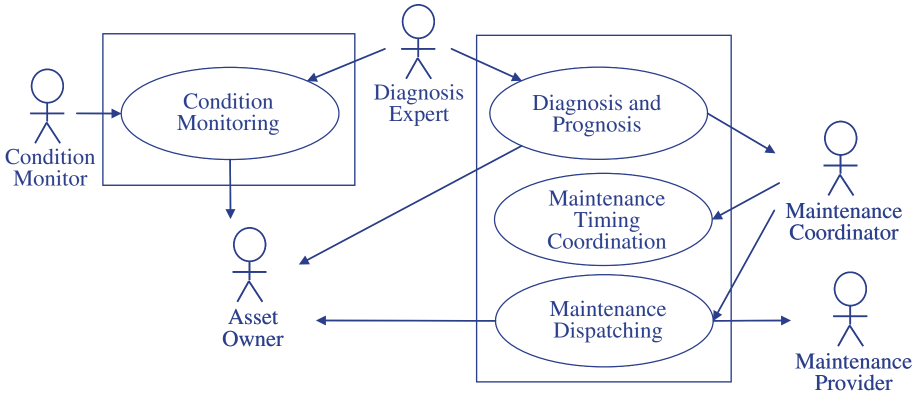
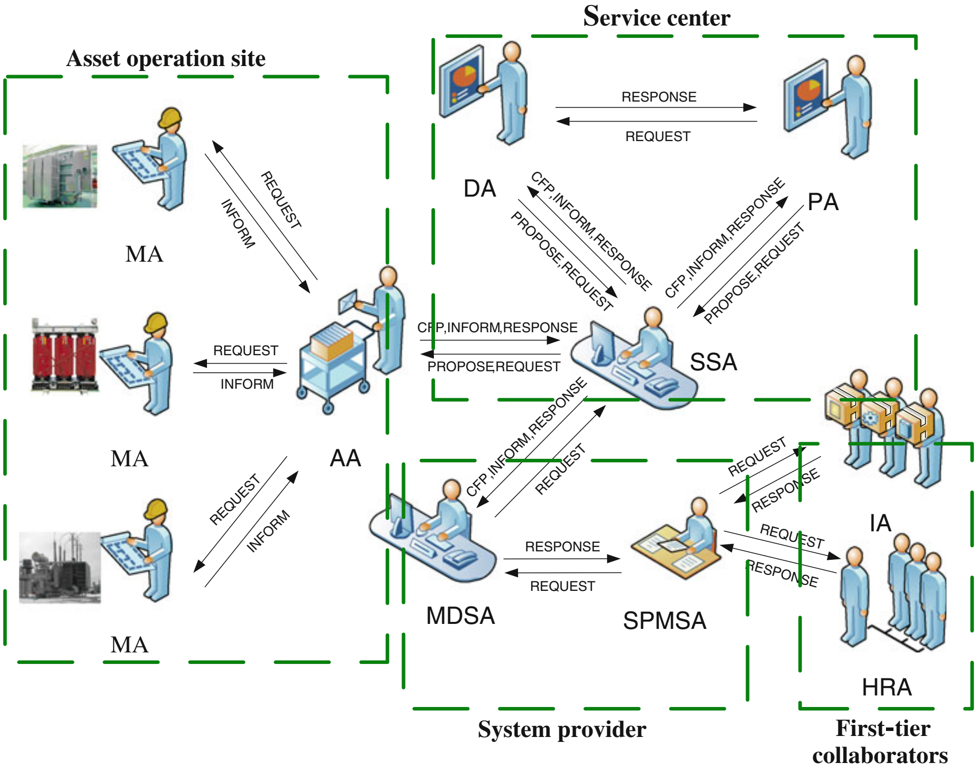


Fig. 9 Agent relationship diagram incorporating different scenarios



- Lack of life cycle information for the voltage tranformer. Besides daily maintenance and periodic maintenance, there is no preventive maintenance.
- Lack of historical maintenance records and condition monitoring data.
- When asset operation sites notify the system provider of a malfunction, the service delivery time delays often further damage the equipment.

The to-be model for collaborative maintenance

In order to solve the problems mentioned above, this research proposes a service center model. The service center coordinates the expert diagnosis and dispatch of repair services. The center monitors the engineering asset data constantly and integrates the supply and demand decisions between asset operation sites and the system providers (Fig. 5).

There are three steps for the maintenance decision-making including the strategic, tactical, and the operational decisions (Tien 2005; Hipel et al. 2007). The strategic level includes the preparation and recovery stages and considers the organizational and financial impacts of the decisions. In this research, the maintenance cost is evaluated based on a reliability centered asset maintenance approach (Bertling et al. 2005).

Total maintenance cost [cost/year]: $TCPM(S) = CPM_f(S) + CPM_{PM}(S) + CPM_{\text{int}}(S)$

$CPM_f(S)$	The cost of failure (repair costs)
$CPM_{PM}(S)$	The cost of preventive maintenance

	(planed maintenance or replacement of a transformer in advance of failure)
$CPM_{\mathrm{int}}(S)$	The cost of interruption (power interruption direct costs and affects the user who incurs must be compensated via a penalty payment)
S	Preventive maintenance strategy

After converting to the marginal cost $CPM_i^i(S)$ [cost/MWh], the model is combined with the Cournot-Nash equilibrium model (CNE) (Chattopadhyay 2004) to consider both equipment reliability and system profit.

$$\text{Maximize } \sum_t \left(\alpha_t - \frac{1}{2}\beta_t Y_t\right) - \sum_{i,t} G_{i,t} CPM_t^i(S) - \sum_{i,t} \frac{1}{2}\beta_t G_{i,t}^2$$

$$\text{Subject to } \sum_i G_{i,t} = Y_t \forall t$$

$$G_{i,t} \le G_{i,t}^{\max} \times \left(1 - \sigma_{i,t}\right) \forall (i, t)$$

$$\sum_t \sigma_{i,t} = \Omega \forall i$$

$$\sum_t \left(G_{i,t}^{\max} \times \left(1 - \sigma_{i,t}\right) - G_{i,t}\right) \ge R_t \forall t$$

$$G_{i,t} Y_t \ge 0$$

$$\sigma_{i,t} = 0 \text{ or } 1$$

α_t, β_t	Linear demand equation parameters for t
$G_{i,t}$	Transformer i load in t [MW]
$G_{i,t}^{\max}$	Transformer i max load capacity in t [MW];
Y_t	Total power supply in t [MW]
$\sigma_{i,t}$	Binary maintenance decision variable for i in t
Ω	Number of periods transformer needs to be maintained
R_t	Reserve requirement in period t

The decision making for preventive maintenance models the voltage transformer's loading. In the other words, the model determines the maintenance time and the service period ($\sigma_{i,t}$) according to the system losses while the transformer is down ($CPM_i^i(S)$). Thus, the model accounts for both system reliability and profit.

The tactical level decision making includes prediction and prevention. The decision marking considers medium term problems and associated objectives. The Java Agent Development Framework (JADE 2007) is deployed to construct a MAS for enabling a collaborative maintenance chain. Each agent makes decisions that are influenced directly by the environment or indirectly through communication and negotiation. An agent can decide to cooperate or compete with other agents and an agent is programmed to effectively solve problems. For agent communication and negotiation, the Foundation for Intelligent Physical Agents (FIPA) English auction protocol (Fig. 6) is used to negotiate maintenance expenses and determine the successful bidder.

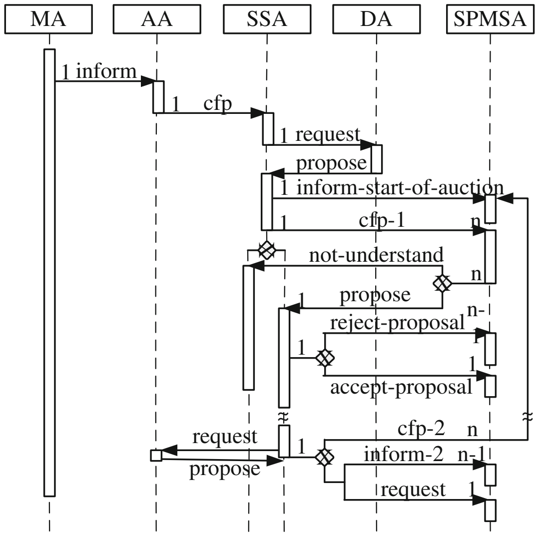


Fig. 10 Sequence of negotiations for a repair proposal

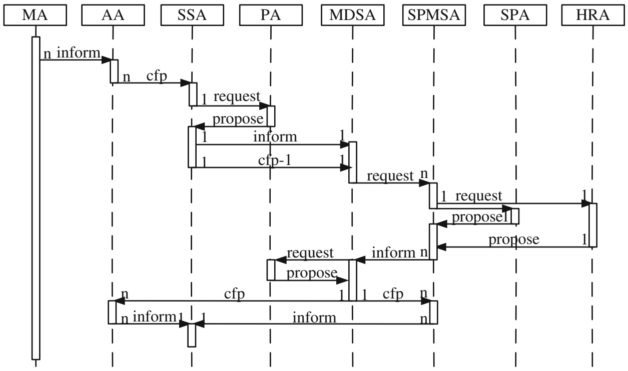


Fig. 11 Sequence for condition based preventive maintenance

The operational level includes the detection and response stages. This stage requires timely decision making. A maintenance decision support agent (MDSA) and a service system agent (SSA) are used for constructing emergency maintenance negotiations. The steps of the negotiation mechanism are described as follows.

- Step 1, Initialization. When an exceptional situations occurs, the MDSA provides the maintenance costs and compensation to the SSA.
- Step 2, Feasibility Analysis. Check all constraints, including service time, service region, and technology constraints.
- Step 3, Evaluation of the maintenance cost, time and period. The danger level is evaluated and the maintenance time and cost are determined.
- Step 4, Updates of maintenance decisions. MDSA and SSA negotiate a settlement and a response.

The operational sequence diagram for collaborative maintenance is shown in Fig. 7.

Agent-based collaborative maintenance chain platform

Strategic, tactical and operational levels of multi-agent designs are depicted in the following sub-sections. The implementation of the agent-based platform are described in detail.

MAS requirement analysis with strategic level decision making

The proposed information platform is supported by software agents to autonomously communicate and negotiate among the maintenance chain participants. The IT platform design, the expected goals, and the agent roles are summarized in Table 2. The case diagram for the MAS is depicted in Fig. 8.

Agent relationship analysis with tactical level decision making

After defining the goals of the MAS, the organizations with related resources and knowledge are determined. The integrated relationships incorporating different scenarios are shown in Fig. 9.

Agent conversation design for operational decision making

To complete the design and development of MAS for the collaborative maintenance chain, the blueprints for agent conversations are defined. Figure 10 depicts the negotiation for a repair proposal when an asset malfunctions. Figure 11 portrays the condition based preventive maintenance sequence.

Agent-based collaborative maintenance chain MAS implementation

Using detailed requirement analysis (from strategic level decisions), agent relationship analysis (from tactical level decisions), and agent conversation design (from operational level decisions), the branches and leaves of the collaborative maintenance chain are carefully depicted. Afterward, this research uses the agent development tool, JADE, which follows the FIPA specifications and provides a Graphical User Interface (GUI) to enable the development and debugging of the agent-based system. The web interfaces are designed for all maintenance platform users, including the engineering asset owners and users (at the asset operation site), the service center, the system providers, and the lower tier collaborators and parts suppliers, for real time data displays and decision support. All engineering assets across dispersed locations and their key condition parameters (e.g., temperatures, loads, and noise) are constantly monitored and displayed by a web-based dashboard interfaces as shown in Fig. 12. Historical data are held in the service center database and can be viewed using the Internet. For example, the equipment malfunction records may be reviewed by the asset owners as well as the preventive maintenance schedules which are updated periodically based on the decision model described in section "The to-be model for collaborative maintenance". Finally, Fig. 13 depicts the action view of the autonomous agents that

60MVA_WW_Tr1

設備名稱	WW-1
Base 容量 (MVA)	60
一次電壓 (kV)	161
二次電壓 (kV)	22
油溫升保證值 (℃)	AUTO
線圈溫升保證值 (℃)	65
噪音等級 (dB)/標準	77 / 79
供電區域型態	商業型態

日期: 2009/6/1 上午 10:17:48
最高溫: 61
最低溫: 45
溫度相差: 16
最高負載: 62
最低負載: 39
負載差距: 23
389103 /525600 (MVA) 74%

60MVA_WW_Tr2

設備名稱	WW-2
Base 容量 (MVA)	60
一次電壓 (kV)	161
二次電壓 (kV)	22
油溫升保證值 (℃)	AUTO
線圈溫升保證值 (℃)	65
噪音等級 (dB)/標準	76 / 79
供電區域型態	商業型態

日期: 2009/6/1 上午 10:17:48
最高溫: 57
最低溫: 41
溫度相差: 16
最高負載: 58
最低負載: 33
負載差距: 25
289208 /525600 (MVA) 55%

25MVA_WW_Tr3

設備名稱	WW-3
Base 容量 (MVA)	25
一次電壓 (kV)	161
二次電壓 (kV)	22
油溫升保證值 (℃)	AUTO
線圈溫升保證值 (℃)	65
噪音等級 (dB)/標準	71 / 72
供電區域型態	商業型態

日期: 2009/6/1 上午 10:17:48
最高溫: 47
最低溫: 34
溫度相差: 13
最高負載: 21
最低負載: 14
負載差距: 7
92035 /219000 (MVA) 42%

Fig. 12 Web-based dashboard for displaying equipment condition parameters

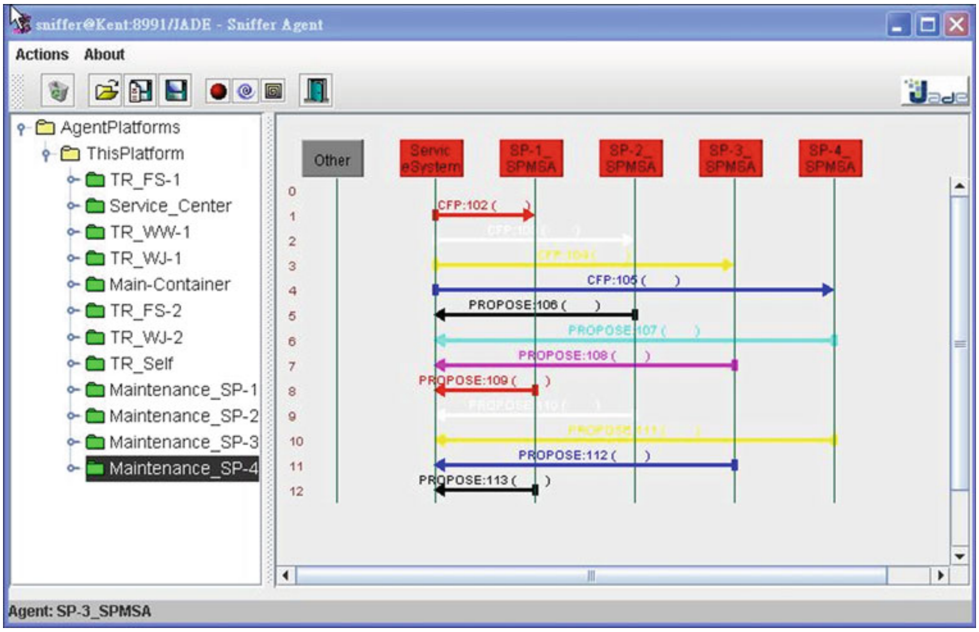


Fig. 13 The execution sequence of agents working in the background of the collaborative maintenance platform

interactively execute the predefined tasks in the system background.

Conclusions

This research provides an engineering asset maintenance architecture using agents to support maintenance chain collaboration and decision making. A collaborative business model integrates maintenance chain members with an intermediary service center. The collaborative business model links asset sites, system providers, and first tier and lower tier collaborators. The platform provides a reliability and profit optimization mechanism with an emergency negotiation mechanism to enable intelligent and collaborative maintenance procedures. Maintenance resources, asset conditions, multi-goals, and constraints, are considered to achieve improved maintenance system benefits.

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