Development of Computerized Facility Maintenance Management System Based on Reliability Centered Maintenance and Automated Data Gathering

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Abstract

In this study, we propose a computerized maintenance management system based on integration of reliability centered maintenance (RCM) and automated data gathering using multi-agent technology. The objective of the proposed system is to support decision-making of maintenance managers by providing up-to-date reliability assessment of facilities in automated manner. To do so, this system was integrated by the following S/W components; 1) a computerized maintenance management system (CMMS) to record failure and maintenance history of facilities, 2) a multi-agent system (MAS) to automate data gathering to monitor condition of facilities in real time. A web based application was also developed, which analyzes failure patterns in order to provides reliability risk assessment such as expected remaining life of facilities, expected failure rates, and risk of parts to fail. A case study of implementing the proposed system in an automotive part production company was represented.

Keywords: *Reliability centered maintenance, multi-agent system, decision support system, computerized maintenance management system*

1. Introduction

Although information technology (IT) have brought significant benefits to manufacturing systems, facility maintenance management including planning, monitoring, and control are still recognized as an area of deeply relying on know-how of experienced engineers. The primary reason may be the reality that decision-makings with facility maintenance management are conservative in nature, in that machines and facilities are usually highly cost resources, thus even their small malfunction can cause huge financial loss to manufacturing companies. However, the concept of e-maintenance has been steadily recognized as a powerful approach of computerized maintenance management during the last decades [1]. Use of IT to support decision-making in maintenance management includes planning activities, selecting policies, scheduling, documentation of history, and predicting facility reliability and maintainability [2, 3].

Before the e-maintenance, as a traditional facility maintenance management, reliability centered maintenance (RCM) has been used as a systematic approach to establish an effective maintenance policy toward a system or a facility. RCM enables to not only create a maintenance strategy to address dominant causes of equipment failure but also provide systematic approach to defining a routine maintenance program. Compared to the other maintenance management approaches such as time-based maintenance (TBM) or condition-based maintenance (CBM), RCM enables maintenance engineers to focus on preserving core functions of a system or equipment with cost-effective tasks [4].

In spite of the benefits of RCM, it has a few fundamental hurdles to be overcome. One major problem is that RCM implementation is normally required of preliminary reliability assessment which is based on large amount of operation data. Hence implementing RCM has been successful in large-scaled and long-term maintaining systems such as power systems [5], chemical plant [6], railway networks [7], and weapon systems. The RCM projects on these systems usually employ well-structured data gathering infrastructure, reliability experts, training programs, and sufficient history data to analyze. On the other hands, relatively smaller sized organizations have difficulties in utilizing RCM. The quality of RCM implementation has highly depend on the experience and skills of RCM analysts [8], thus the projects used to fail when maintenance engineers are lack of the capability for reliability engineering and statistics.

With the wide spread of the e-maintenance, a few meaningful approaches have tried of using IT into RCM implementation. Because failure data analysis is a fundamental part of RCM, integrating a CMMS (computerized maintenance management system) into RCM has been tried [9, 10]. Recent literatures show that artificial intelligence (AI) can be used for case based reasoning to find similar history records of RCM analysis on similar items to new item [8]. An expert system using fuzzy reasoning algorithms was also tried in a design phase of industrial chemical processes [11]. Nonetheless there are two predominant difficulties which maintenance managers and engineers usually have. One is that the data which are required for RCM analysis are distributed in manufacturing fields, formatted as papers and unstructured, thus required of pre-processing. Although a CMMS supports a systematic way of collecting and storing the data, data processing still relies on human analysts. The other is that RCM requires statistical background to the engineers. For the reasons, the quality of RCM implementation used to relied on the experience and skills of RCM analysts.

In this paper, we developed an integrated maintenance management system based on RCM and multi-agent technology. Our approach is to integrate the two systems; 1) a multi-agent system (MAS) was used to automate data gathering and processing, 2) a CMMS was also used to store and utilize maintenance history for the MAS. Based on the integration, a decision support application for reliability assessment was added as an expert system. It provides up-to-date facility status using control charts as well as key indicators of reliability assessment such as expected remaining life or parts, priorities of maintenance tasks, and failure patterns. Maintenance engineers can prevent potential problems of facilities based on the information.

The rest of this paper is structured as follows. Section 2 describes the background of this study. Section 3 describes design concept, architecture, and core functions of the proposed system. In Section 4, we implemented the proposed system for maintenance management of injection molding machines in an automotive part industry in South Korea. Conclusion and discussion are also added to represent the contribution and limitation of this study.

2. Background

RCM and CMMS

The concept of RCM originated and has been applied within the aircraft industry with considerable success for more than 20 years. However, regardless of the usefulness of RCM, applying it to entire systems or parts is usually too difficult. Therefore, RCM engineers may start with identifying a few critical components to conduct core functions of a system. In addition, since RCM requires large amount of data collection regarding failure history and failure mechanism, its effectiveness has been highly dependent on the quality of the facility data collected.

Realistically, the collectable data for RCM are test reports, failure history, maintenance protocols, part repair or replace history, and operation logs, *etc.* A CMMS can be used to satisfy the requirement of handling these big data by storing them as structure data. Recent cases of computerized maintenance management are based on the Internet, such as web enablement of computerized maintenance management systems and remote condition monitoring or diagnostic, to avoid the expense and distraction of software maintenance, security, and hardware upgrade [12]. When maintenance data is tracked completely and accurately, CMMSs can make great contribution to RCM analysis by improving the reliability of prediction [9, 7, 10].

MAS

Although CMMSs enable to store data in a systematic way, gathering the data from manufacturing fields is another big issue. Collecting data consists of 1) measuring raw data using automated measuring devices and 2) storing them into a database. This information flow is actually repetitive and routine processes, meaning that some of its tasks are repeatable, such as capturing raw data at particular period, filtering measurement errors, and detecting predefined outliers from the raw data.

In manufacturing industry, a noticeable AI technology to be used for automating data collection is intelligent software agents, which are originated from an approach of interaction-based computational model. Software agents are designed to handle autonomous tasks using their intelligence. These agents commonly have capabilities to take initiative, reason, act, and communicate with each other and their environment [13]. Because of their conceptual features, there is no general agreement over the precise definition of intelligent software agents yet. Nevertheless, an expanding number of S/W applications of intelligent multi-agent systems have been reported during the last years. They indicate that the benefits of using software agents are prominent, particularly when the industry requires the features of software agent; autonomy and intelligence. In reliability engineering, it was proposed a multi-agent based remote maintenance support to use expert knowledge system, integrating the agents distributed in difference layers by cooperation and negotiation, so as to fully utilize the knowledge of the experts from different domains, and make the maintenance decision satisfy the global target of the enterprise [14].

3. Design Concept

This section describes the overall feature of the multi-agent based maintenance decision support system that we propose. The use of multi-agent in this study focuses on automated data gathering and condition monitoring for facilities. The MAS is connected to measurement devices to retrieve condition data of the facilities. The type of data and devices to be used are determined based on FMEA, which prioritizes potential failures of a system based on their critical effects. In particular, in case of a part of a facility indicating significant symptoms of failures, it is required of continuous and intensive observation. Maintenance managers may be notified of these situations so that they can prevent critical failures proactively.

In this paper, five types of specific software agents were suggested; configurator agent, diagnosis agent, scheduler agent, data collector agent, and analysis agent as shown in Figure 1. A configurator agent controls data collector agents by set up their configurations. For example, data sample size, sampling periods, control limits of control charts, and communication types for notifying abnormal symptoms to managers can be set up by a configurator agent. A data collector agent gathers facility condition data based on the settings such as target data source identification, interface, sampling policies by the configurator agents. A diagnosis agent determines a status of a facility based on the recorded data in the storage. A scheduler agent generates work orders based on the results of diagnosis. An analyzer agent has an intelligence of assessing reliability of facilities and creates indicators such as mean time between failures (MTBF), mean time to repair (MTTR), expected life time, and appropriate probabilistic model to represent the life time.

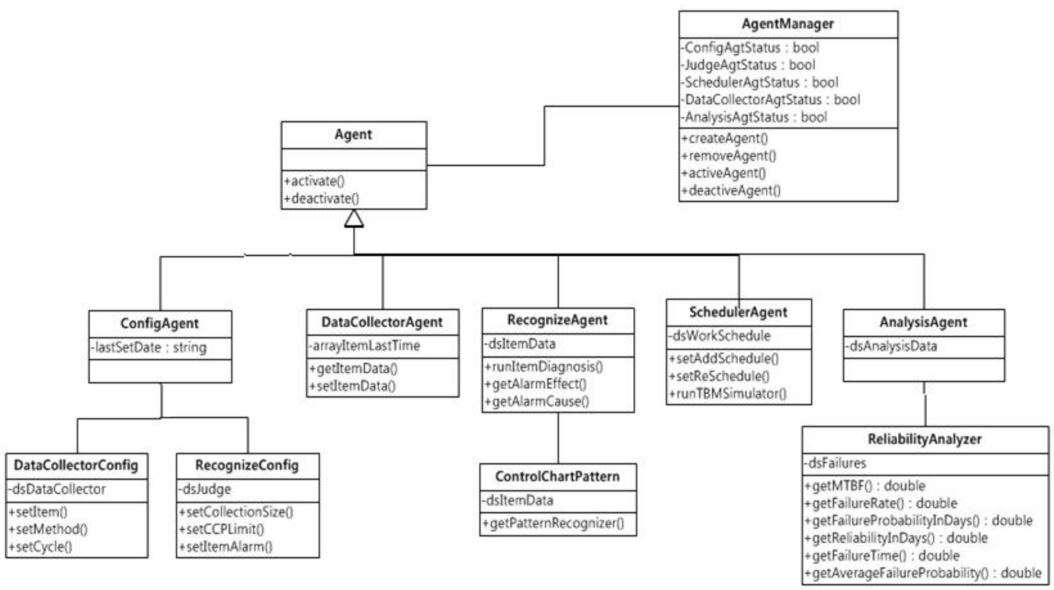

Figure 1. Class Diagram; Agent Manager and Five Agent Types; configure, data collector, recognizer, scheduler, and analyzer

The overall feature of the proposed system is shown as Figure 2. It consists of four layers; manufacturing field, agent system, database, and maintenance management application. Facility data may be retrieved from data sources in manufacturing field and may be transferred to maintenance engineers via the agent system. There are several types of data sources such as manufacturing information systems (*e.g.* MES, ERP, CMMS), machine sensors, vision cameras, and terminals.

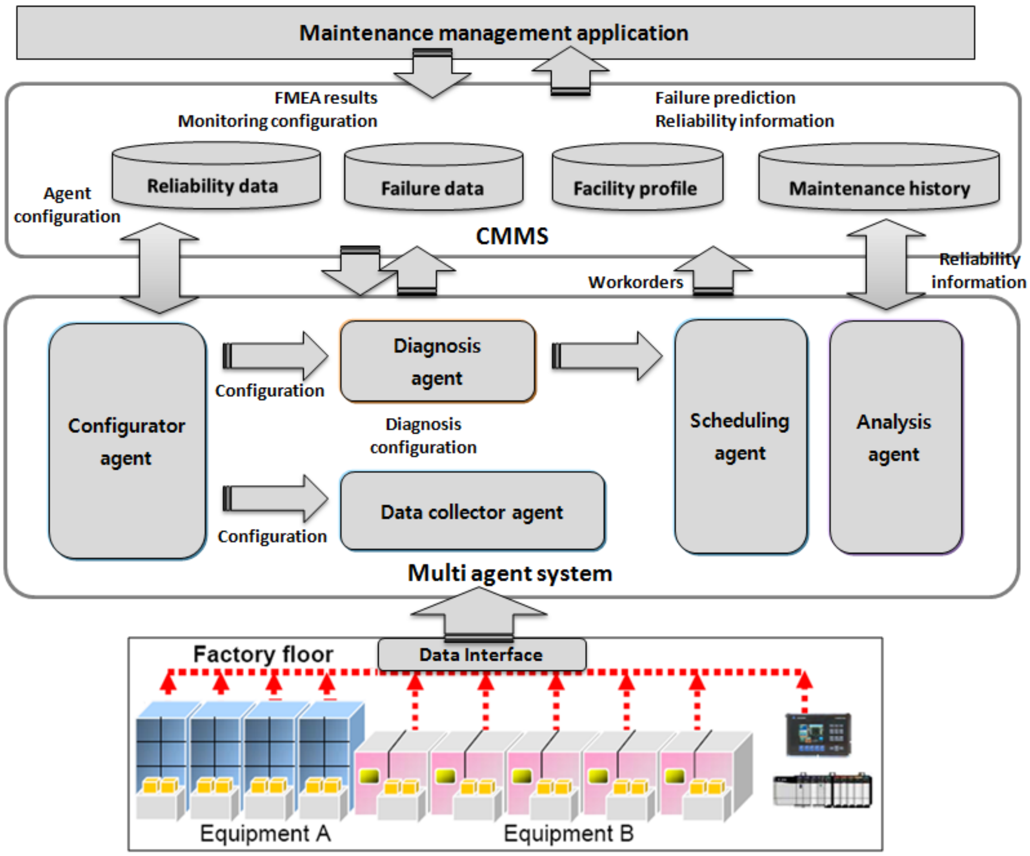

Figure 2. System Architecture

The agent system consists of the five agents; data collector agent, configurator agent, diagnosis agent, scheduling agent and analyzer agent. Upon the agent layer, there is a database which stores reliability assessment data, failure history, facility profile, and maintenance history. This information will be provided to the user layer through maintenance management application. On the front-end of the system, there are system users; maintenance engineers, managers and experts, who make role of decision making, advanced analysis and system improvement.

The prototype agent system was developed by C# language based on the .Net framework. We developed a MAS and integrated it into a commercial CMMS. The kernel of the MAS controls the life cycle of agents and the communication between systems. The maintenance application was developed as a web based application, so that users can access to the system via the Internet. This application shows the profile of registered machines, currently planned maintenance activities, and the reliability assessment measures.

Figure 3 depicts a use case diagram which represents decision support scenarios using the application. When a maintenance manager wants to monitor a facility, he/she may set up properties of data sources and collection methods for the facility. Then the MAS will assign agents and the agents will automatically watch and monitor the status of the facility. If an abnormal condition of the facility is detected, a recognizer agent detects and records it into the CMMS, and sends a message to managers automatically through the decision support application. The maintenance engineer can see status of the facility and related reports to find out the root cause of problem.

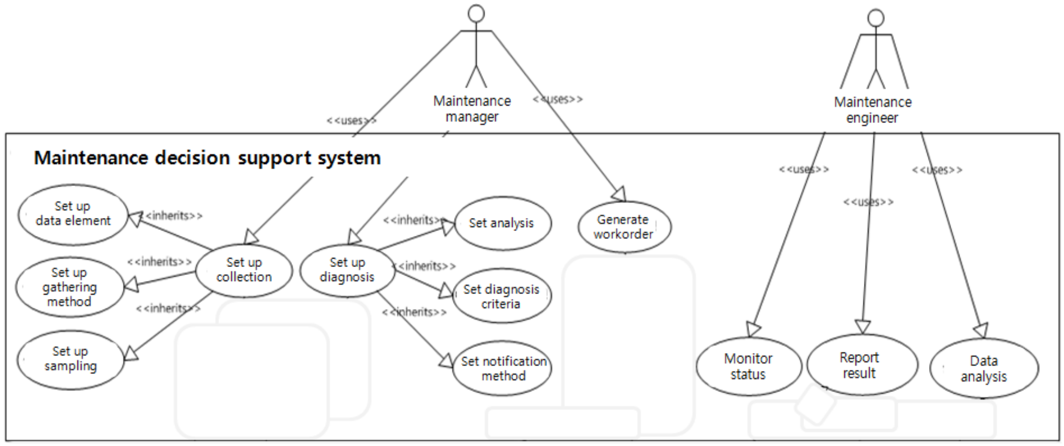

Figure 3. Decision Support Scenario; a Use Case Diagram

4. Real World Implementation

The proposed system was implemented at an automotive part manufacturing company in South Korea. This factory produces plastic car interior parts such as dashboards, center fascia panels, cup holders, and inner door frames, which are produced by injection molding machines. Therefore stabilized operation of the facilities is important to maintain good quality of the plastic products. The factory owns seven large-type machines and eleven middle-type machines. Operation history of the machines had been manually recorded on papers by facility operators. At the first step of our project, we stored the data into the CMMS. The operators entered profiles of the machines such as part list, structure of the parts, and adopted dates, and the history of facility operations from the paper records into the CMMS.

In order to identify critical parts of the machines, we conducted failure modes and effects analysis (FMEA) using the failure history. FMEA is an inductive failure analysis used in product development, systems engineering, reliability engineering and operations management for analysis of failure modes within a system for classification by the severity and likelihood of the failures. As a result of the analysis, we derived critical failure modes of the molding machines as Table 1. The parts having the dominant failure modes were selected as the target of monitoring.

Table 1. Critical Failure Modes

Category	Part	Failure mode
Body	Main body	Malfunction by S/W problem / Solenoid valve problem, Oil leakage at pipe block
	Brake	Malfunctioning by circuit board failure
	Ejector	Out of control by sensor failure
Pump	Oil pressure clamp	ON/OFF function disabled, Air leakage, Oil leakage
	Clamp	Oil leakage at hose
	Pump	O-ring wear-out
	Nozzle	Resin leakage, Rocket-ring failure
Mold	Cooling coupler	Burn-out
	Moving conveyor	Out of control by shorted remote controller, Overloaded by bearing wear-out
	Clamp	Oil leakage at hose, Malfunction by solenoid valve problem, Electronic out of control

Emission	Solenoid valve	Oil leakage by O-ring wear-out
	Sensor	Forward sensor failure by shock
	Oil valve	Unbalancing, Short of circuit board, Overload, Unbalancing, Flowing backward, Overheated cooling water by heater malfunction, Oil leakage
Cylinder	Cylinder	Malfunctioning by overload, Broken casting, Lubricant supplier malfunction, Oil leakage at hose
	Screw Cylinder	Malfunctioning by wear-out
	Oil pressure cylinder	Oil leakage from damaged plunge
	Weighing cylinder	Poor welding
	Air cylinder	Damage by shock
Safety door	Motor	Malfunctioning by solenoid valve problem, Damage
	Door part	Out of control by damaged roller and disconnection
	Cover	Damage
Oil pressure controller	Weighing oil pressure pump	Noise by bearing wear-out
	Weighing pump	Oil leakage at hose
	Oil cooler	Temperature increase by contamination
	Oil tank	Oil leakage
	Oil gage	Oil leakage
	Oil proportional valve	Malfunctioning by foreign object invasion
	Oil pressure motor	Start function failure, Noise by bearing wear-out
	Oil pressure motor pump	Oil leakage by O-Ring wear-out, Noise by suction filter problem
	Oil plumb	Oil leakage by poor welding quality
	Oil block	Oil leakage by O-ring wear-out
	Oil pump	Malfunctioning, Oil leakage by poor welding quality
	Oil pipe	Oil leakage by poor welding quality
	Oil coupler	Oil leakage
	Clamp pump	Oil leakage by O-ring wear-out
	Tank	Oil leakage
Heater	Nozzle heater	Out of control by short and internal circuit damage, Damage by resin leakage, Open, Malfunctioning by wiring problems
	Temperature controller	Out of control by relay damage
	Timer	Malfunctioning by fuse failure
	Cylinder heater	Heating malfunction from PCB damage, Out of control from electric shortage, Resin leakage, Electronic damage, Malfunction

After initializing the CMMS, we assigned data collector agents to the critical parts. After the agents are activated to work on the monitoring, maintenance engineers could access to the system. Figure 4 shows a screen shot of the web based application showing condition of the molding machines at operation. The chart on the right shows a weekly trend of body temperatures of a cylinder measured by a sensor. A warning message detecting a periodic pattern is shown on the bottom.

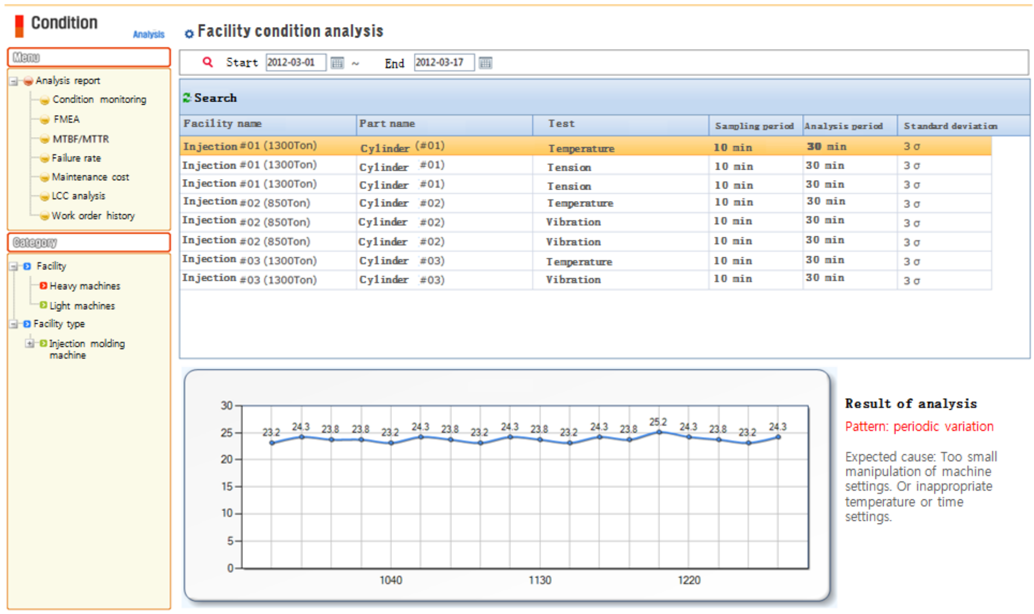

Figure 4. Screen Shot; Decision Support Application

Table 2 shows a summary statistics of the failure history and results of reliability assessment conducted by the application. The result shows that the failure interval of the machines fits to the Weibull distribution. Using the estimated parameters of the Weibull distributions, the proposed system may suggest maintenance engineers recommendations of reliability predictions of the machines such as failure probability during a period, failure rate, and remaining life in the future.

Table 2. Failure History Analysis

Machine type	Level	Descriptive statistics			Estimated probabilistic distribution		
		No. of failures	Mean	Std.dev	Type	Shape	Scale
Large	Machine	127	122	134	Weibull	0.8841	114
	Part	79	377	453	Weibull	0.8142	337
Middle	Machine	219	63	82	Weibull	0.8354	56.7
	Part	194	422	677	Weibull	0.7007	327.2

Using the data stored in the CMMS, we additionally analyzed failure patterns of the machines. The charts shown in Figure 5 and 6 represent annual average failure frequency and failure rates of the machines. In Figure 5 a), that the annual failure rates are stable with time frame implies that a probabilistic distribution of life time fits an exponential distribution, meaning that the machines have uniform failure rate over time. In Figure 5 b), the radio charts shows monthly average failure rates of the machines. Both two chart commonly show that the failure rate increases during summer and decreases during winter. This seasonal trend indicates that failure trends of the machines are strongly affected by air temperature. So to speak, high temperature in summer causes various problems to mechanical parts.

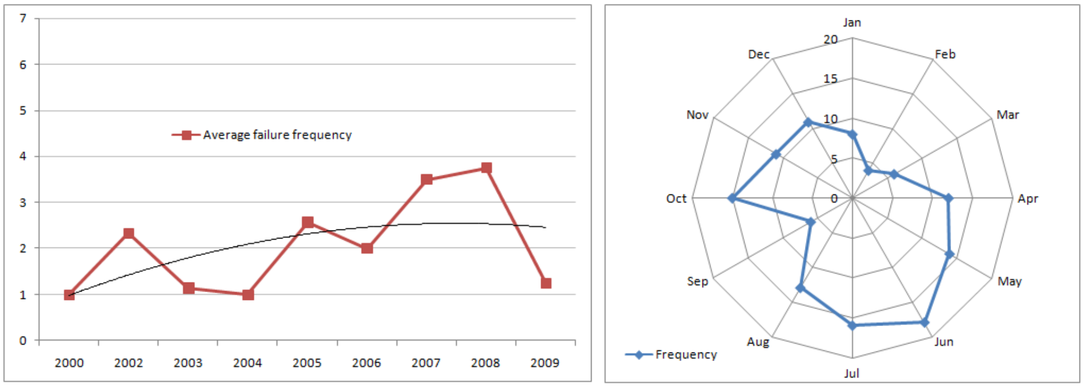

Figure 5. Failure Pattern of Large Type Machines; a) Annual Failure Frequency, b) Seasonal Trend

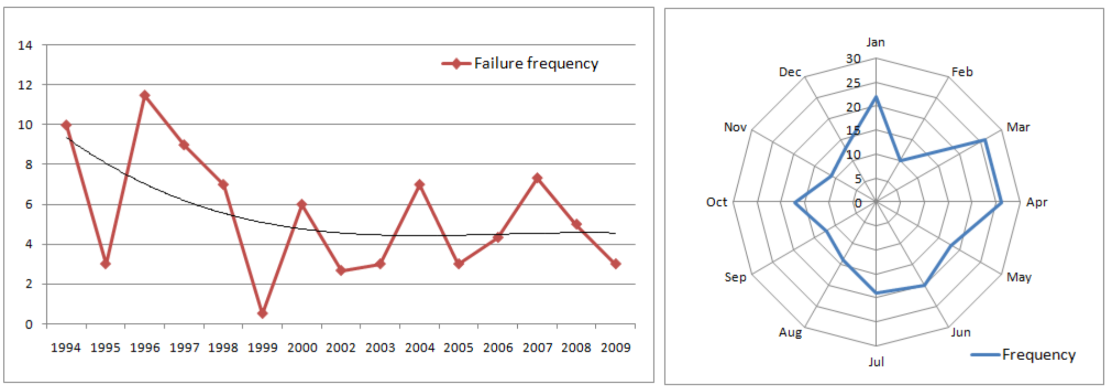

Figure 6. Failure Pattern of Middle Type Machines; a) Monthly Failure Frequency, b) Seasonal Trend

In order to get more detailed information, failure patterns at individual parts were also analyzed. Our interest was to find out common failure behaviors of the parts. Figure 7 shows that the failure patterns of the parts of both middle and large type machines appears similar. This implies that we can assume that both machines have common failure patterns and there is no part which is particularly vulnerable to failures.

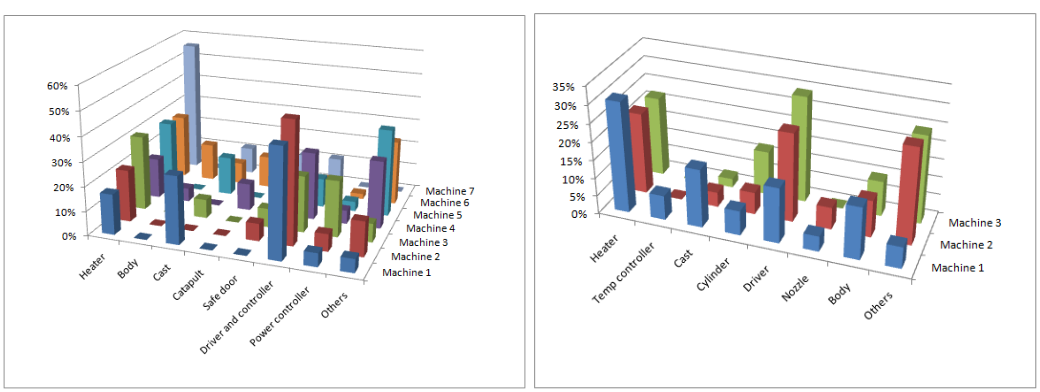

Figure 7. Failure Pattern by Parts; a) Large Type, b) Middle Type

5. Conclusion

In this paper, we developed an computerized maintenance management system based on integration of RCM and a multi agent based automated data gathering. The system was implemented in an automotive part manufacturing company in Korea. The result of prototyping proved that the complicated information processing for maintenance management can be effectively automated through the proposed system. The multi agent technology enables to automate data gathering, and support intelligence for diagnosis and reliability assessment for the manufacturing facilities. The web based reliability assessment application provide managers and engineers valuable reliability indicators. It ultimately supports maintenance managers and engineers to concentrate their works by automating repetitive and non-valuable data gathering tasks.

The future works are expected to two directions. First, reinforcing intelligence to the S/W agents will allow advanced diagnosis and analysis of the MAS. Not only mathematical and statistical functions, but also expanded information over the entire manufacturing process data can be utilized to find the root causes of outliers and their relations. Secondly, adding more realistic agents such as workflow based agent or work order scheduling agents are promising. Agents for complicated actions can assist human engineers by suggesting related case history or information to find the root causes of a failure. The benefits of utilizing intelligent agents are expected to be maximized in modern manufacturing systems which are dealing with huge amount of data and globally distributed.

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