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Development of a Web-based RCM system for the driverless Rubber-Tired K-AGT system †

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Abstract

The Korean Railroad Research Institute (KRRI) developed the rubber-tired AGT system (Model: K-AGT) between 1999 and 2005. The K-AGT is a light rail transit system does not require a driver and generally operates on an elevated railroad for transporting passengers. Accidents caused by driverless vehicles can severely affect social confidence, safety and economy. Therefore, it is very important to minimize the occurrences of such faults, and to accurately perform detailed maintenance tasks and thoroughly investigate the cause of any repeated failures. This research develops the web-based reliability centered maintenance (RCM) system for the K-AGT train system. The framework of the RCM system is based on performing a failure mode and effects analyses (FMEA) procedure on all the sub-systems in the K-AGT system. Out of the devices that have a low reliability, the high failure ranked devices are included high on the list for performing the overall maintenance plans. Through registration of historical failure data and the reliability indexes, the results of the FMEA can be updated. Such a process is repeated continuously and can achieve very accurate predictions for device operational lifetimes and failure rates. Also, the RCM system is designed so that workers can refer to the expert system for the latest procedures to perform the required diagnosis and repair of any failure. The overall RCM system consists of a failure/task management system, a preventive maintenance system, an expert system, a material management system, and an approval system. This research describes the development of the preventive maintenance system and the expert system that have been produced because these are the main functions for the RCM system.

Keywords: Failure rate; FMEA (Failure Mode and Effects Analysis); MTBF (Mean Time between Failures); Preventive maintenance system; Expert system; RCM (Reliability Centered Maintenance)

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1. Introduction

In 1999 the Korea Railroad Research Institute (KRRI) began development of the rubber-tired Korean AGT (K-AGT) train system. The K-AGT is a light rail transit system with no driver that generally operates on an elevated railroad for transporting passengers in cities and their surrounding regions. The rail system is suitable for main line use in a medium-sized city, or for a providing a quick connection line between downtown and suburbs, etc., depending on passenger demand. The main characteristics of the K-AGT system are its great adaptability to rapidly changing gradients, traversing small curved radii, and having low noise and low vibrations when it operates. It also has good acceleration and deceleration capacities.

Fig. 1 presents a picture of K-AGT developed by KRRI. The train can flexibly utilize a combination of

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Table 1. Material properties of SCP10.

Subsystem	Characteristics
Rolling-stock system	Max. speed 70km/h, Rubber-tired wheel, Train composition: 2 motor cars
Power supply system	DC 750V, the 3rd rail power supply
Signal system	Communication-based Train Control for driverless train control(CBTC), 90 sec interval
Track system	U-Type rail road, Horizontally operated guided turnout

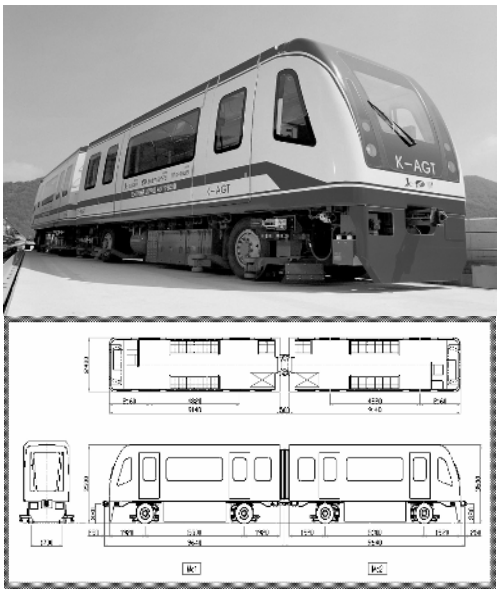


Fig. 1. Overview of the K-AGT vehicle system.

passenger cars, from two cars to six cars, according to the transportation demand. Table 1 shows the main characteristics the of K-AGT system.

KRRI also constructed a 2.37km test line for the K-AGT at GyeongSan-city, Gyeongbuk-Do, Korea, which was fully tested in December 2005 [1]. The test line is combined with its associated subordinate systems such as the rolling stock, power supplies, signal/ communication systems, and the actual railroad track. The facility was developed to test the reliability and safety of the overall K-AGT system, which was felt to be absolutely necessary because accidents caused by driverless trains will affect the confidence of the general public and seriously hinder acceptance. It is therefore very important to minimize occurrences of any failure, and to meticulously perform maintenance tasks and thoroughly investigate the cause of any repeated failures.

The concept of reliability has been considered as the key issue for improving safety and is generally known as the RCM (Reliability Centered Maintenance) system. Generally, reliability is defined as the 'probability that an item will perform a required function without failure under stated conditions for a specified period of time' [2]. The reasons for interest shown in developing a good RCM system may vary but often include the following objectives:

(1) Maintaining a level of functionality without a critical failure for a desired period.
(2) Reducing the cost to maintain and support the system.
(3) Managing the safety issues arising from the consequence of a failure.

This research develops a web-based RCM system for the driverless rubber-tired K-AGT system. The framework of the RCM system is based on identifying the devices having a low reliability (and hence having high failure ranks) as assessed from a full FMEA so that proper maintenance plans are established. Through registration of historical failure data, the reliability indexes and the results of the FMEA can be updated regularly or even repeated continuously to achieve a more accurate prediction of the devices' operational lifetimes and failure rates. Also, the RCM system is designed so that workers can refer to the expert system for procedures to diagnose and repair any failure as needed. The RCM system consists of a failure/task management system, a preventive maintenance system, an expert system, a materials management system, and an approval system. This research describes the development of the preventive maintenance system and expert system of the RCM system that has been produced for the K-AGT system.

2. Standardization for K-AGT RCM System

Standardization for the K-AGT RCM system is divided into the Bill of Materials (BOM) and a classification of the failure codes. This ensures that the RCM system gathers, accumulates, and processes all historical failure data systematically.

2.1 Construction of the master BOM

The BOM, which is a hierarchical product tree consisting of LRU (Line Replacement Units), is necessary for listing all the components and parts that make up a product as an inventory list. This research constructed the master BOM of the K-AGT, and then

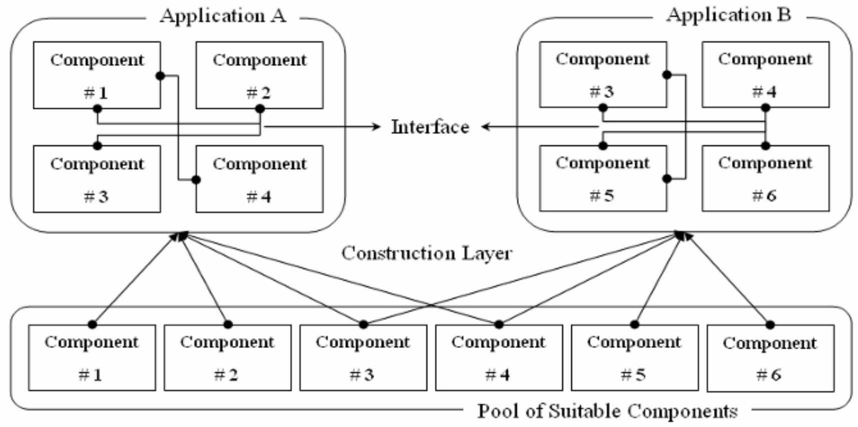
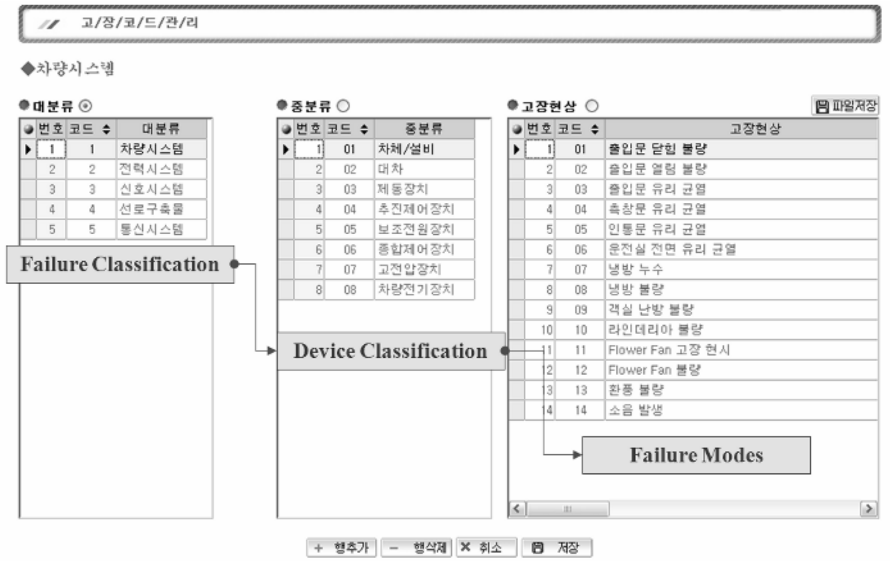


Fig. 2. Component based BOM management.



● 대분류 ◉

번호	코드	대분류
1	1	차량시스템
2	2	전력시스템
3	3	신호시스템
4	4	선로구축물
5	5	통신시스템

● 중분류 ○

번호	코드	중분류
1	01	차체/설비
2	02	대차
3	03	제동장치
4	04	추진제어장치
5	05	보조전원장치
6	06	종합제어장치
7	07	고전압장치
8	08	차량전기장치

● 고장현상 ○

번호	코드	고장현상
1	01	출입문 닫힘 불량
2	02	출입문 열림 불량
3	03	출입문 유리 균열
4	04	측창문 유리 균열
5	05	인통문 유리 균열
6	06	운전실 전면 유리 균열
7	07	냉방 누수
8	08	냉방 불량
9	09	객실 난방 불량
10	10	라인데리아 불량
11	11	Flower Fan 고장 현시
12	12	Flower Fan 불량
13	13	환풍 불량
14	14	소음 발생

Fig. 3. An example of failure code generation.

designed a component-based BOM management system to extract the functional BOM from the master BOM according to its rule sets. The master BOM is the entity responsible for managing its components and investigating their physical locations and their status at any time. Also, constituent elements in the master BOM can interact with each other using some mediation rule-set. This rule-set is a group of interface rules that constructs independent components and makes the BOM system suitable and functional. The relationships between the master BOM and the functional BOM are illustrated in Fig. 2 which also shows a sample of the master BOM for the K-AGT system.

2.2 Definition of failure code classification

As part of standardizing the K-AGT's RCM system, it is necessary to classify and standardize the failure codes which are designed to illustrate the condition for a failed asset. To express the various, and even complex, failure modes, the failure codes need to be defined along with the classification of the failure parts and the failure modes, etc. Each defined failure code can then require data gathering for it to obtain the required standardized maintenance tasks.

To achieve reliable failure codes, the currently available failure data in the work space was analyzed and structured in terms of a defined failure classification methodology. Finally, a standard code system was designed that includes the standardized classification for the rules of failure, and a code numbering system, as seen in Fig. 3. The failure code is a six-position pattern consisting of three items: failure classification, the name of the device itself, and its failure modes. Failure classification and device classification indicate five main areas of the K-AGT system and its subsystems in the lower levels.

3. RCM based preventive maintenance system

In this research a reliability analysis using historical maintenance data of the K-AGT is established based on the following four assumptions:

(1) Subcomponents of the K-AGT system are mutually independent in terms of failure.
(2) All systems and their components have only two states, failed and operational.
(3) Failure is equal to repair/exchange historical data at the maintenance stage.
(4) All devices follow random failure.

When the line replacement unit (LRU) is repaired or exchanged due to failure, the failure rate of the relevant device is first changed by performing a component reliability analysis. Then, the updated failure rate is raised to the upper level devices. The last process depends on the reliability relationship derived from the mutual function between each device.

3.1 Component reliability analysis

This research applies the AMSAA (Army Materiel Systems Analysis Activity) model [3] and underlying Weibull distributions, as this can estimate the parameters of the distributions under any condition, of both the complete and censored failure data, for analyzing the overall reliability procedures. With the result, the reliability indexes can be monitored; these include indices such as failure rate and MTBF over time in the real number area. The distribution parameters consisting of $\hat{\lambda}$ and $\hat{\beta}$ can be calculated by using Eq. (1) derived from maximum likelihood estimators. In Eq. (1), $\hat{\lambda}$ is a scaling parameter, which determines the mathematical scale of the distribution, and $\hat{\beta}$ is a shape parameter, which affects the shape of the distribution. If the shape parameter $\hat{\beta}$ of any part is greater than 1, the curve of the failure rate versus time would show a decreasing trend, and the MTBF curve illustrates an increasing-trend.

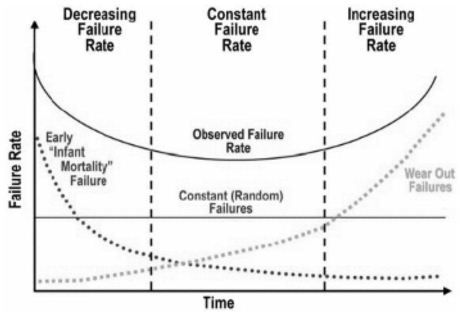


Fig. 4. Bath tub curve for a typical component life-cycle.

$$\hat{\lambda} = \frac{n}{T^{\beta}}$$
$$\hat{\beta} = \frac{n}{n\ln T - \sum_{i=1}^{n} \ln T_i} \qquad (1)$$

Where, $\hat{\lambda}$ = the scale parameter, $\hat{\beta}$ = the shape parameter, T = the elapsed operational time, and n = the accumulative failure number.

The failure rates and MTBFs are determined by using Eq. (2) with both the distribution parameters.

$$m_c = \frac{1}{\hat{\lambda}} T^{1-\hat{\beta}}, \lambda_c = \hat{\lambda} T^{\hat{\beta}-1} \qquad (2)$$

Where, m_c = the cumulative MTBF and λ_c = the cumulative failure rate. The components' reliability in the overall K-AGT system's operation is the main consideration in determining the system maintenance plan. Fig. 4 shows a complete failure-rate curve that contains the useful life span to which Eq. (3) can be applied. The characteristic failure curve of each component when placed in normal service simultaneously includes a break-in period, a chance failure region, and a wear-out zone, as shown in Fig. 4. After an initial region of high failure rates, the breakdown rate becomes constant. The failures occurring in this period are random and follow statistical chance laws. It is well known that such random breakdowns follow a pattern of constant failure rate. The constant failure rate period represents the useful working life of the component and an expression of the failure rate curve for this component should be developed. The failure rate eventually begins to rise again as individual components start to wear out. The AMSAA model can describe the phases from the early failures to the constant failure phases. In the random breakdown period, the components' reliability can be written as:

$$R(t) = \exp\left(-\lambda_c t\right) = \exp\left(-\frac{t}{m_c}\right) \tag{3}$$

Where, m_c = the cumulative MTBF, λ_c = the cumulative failure rate, and t = the elapsed operational time.

3.2 System reliability analysis

To analyze the reliability of the K-AGT system, the system reliability indexes must be calculated first from the failure rates or the MTBF of its elemental members. In a serially connected system composed of n parts, the overall system reliability indexes can be expressed as shown in Eqs. (4) and (5).

$$\lambda_s(t) = \frac{1}{m_s(t)} = \sum_{i=1}^{n} \lambda_i(t) \tag{4}$$

Table 2. The relationship between failure grades and failure ranks.

Failure rank	Failure grades (C_s)	Failure classification
Ⅰ	7 ~ 10	Critical failure
Ⅱ	4 ~ 7	Major failure
Ⅲ	2 ~ 4	Minor failure
Ⅳ	Below 2	Negligible failure

Where $\lambda_s(t)$ = the system failure rate, $m_s(t)$ = the system MTBF, and $\lambda_i(t)$ = the failure rate of the i-th part.

$$\begin{aligned} R_s(t) &= \prod_{i=1}^{n} R_i(t) = \prod_{i=1}^{n} \exp(-\lambda_s(t)\times t) \\ &= \exp\left(-\sum_{i=1}^{n} \lambda_i(t)\times t\right) \end{aligned} \tag{5}$$

Where $R_s(t)$ = the system reliability, $R_i(t)$ = the reliability of the i-th part.

In a parallel connected system composed of n parts, the reliability indexes are described as:

$$\lambda_s(t) = 1 \Bigg/ \left(\int_0^{\infty} \left(1 - \prod_{i=1}^{n} \left(1 - \exp\left(\lambda_i(t)\times t\right)\right) \right) \right) \tag{6}$$

$$\begin{aligned} R_s(t) &= \exp\left(1 \Bigg/ \left(\int_0^{\infty} \left(1 - \prod_{i=1}^{n} \left(1 - \exp\left(\lambda_i(t)\times t\right)\right) \right) \right) \times t \right) \\ &= \exp\left(-\lambda_s(t)\times t\right) \end{aligned} \tag{7}$$

The failure rate, the MTBF, and the reliability of the overall K-AGT system consisting of a mixture of serially and parallel connected structures can be obtained by a combination of Eqs. (4)-(7) according to the work flow of the system. Because the failure rates, the MTBFs, and the reliabilities are in the time do

Table 3. Severity classification of failures.

Level	Severity	Definition	C_1
1	Catastrophic	Major system damage/loss – impossibility of attainment of mission	10
2	Critical	Partial system damage – interruption of attainment of mission - attainment of mission by using supplementary means	7
3	Marginal	Minor system damage – interruption of attainment of minor mission - attainment of mission by using supplementary means	4
4	Negligible	Minor failure – has no effect on mission	1

Table 4. Occurrence classification of failures.

Level	Occurrence	Definition	C_2
1	Frequent	A single failure mode probability is greater than 0.20 of the overall probability of failure during the item operating time interval.	10
2	Probable	A single failure mode probability is more than 0.10 but less than 0.20 of the overall probability of failure during the item operating time interval.	7
3	Occasional	A single failure mode probability is more than 0.010 but less than 0.010 of the overall probability of failure during the item operating time interval.	5
4	Remote	A single failure mode probability is more than 0.0010 but less than 0.10 of the overall probability of failure during the item operating time interval.	3
5	Improbable	A single failure mode probability is less than 0.0010 of the overall probability of failure during the item operating time interval.	1

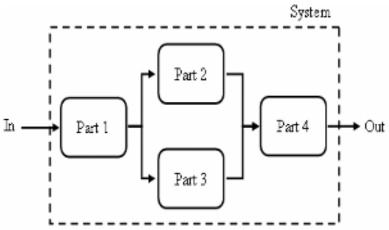


Fig. 5. A sample model reliability block diagram.

main, it is possible to analyze the reliability growth due to the operational time of the overall K-AGT system.

3.3 Failure mode and effects analysis (FMEA)

Generally, FMEA is defined as the 'procedure and tools that helps to find all the potential failure modes of a given system or its components, to check and to evaluate its effect on other sub-systems and on the required functions of the system'. Through FMEA, the failure modes, which influence the entire system, can be identified and ranked. In this research, a failure grade method for FMEA was applied [4]. Each failure mode is given a numeric score that quantifies the likelihood of failure and the amount of harm or damage, which the failure mode may cause, to a person or to equipment. In other words, a failure grade is a mathematical product of its severity and occurrence. According to these scores, the failure modes are classified into four failure ranks as shown in Table 2. A failure grade is calculated as shown in Eq. (8).

$$C_s = (C_1 \times C_2)^{\frac{1}{2}} \tag{8}$$

Where C_s = failure grade, C_1 and C_2 = grades of severity and occurrence respectively. Such grades of severity and occurrence are based on MIL-STD-1629A as shown in Table 3 and Table 4, respectively.

All the failure modes are ranked from Ⅰ to Ⅳ according to the failure grades shown in Table 2.

3.4 Application to a sample model and verification

We constructed a sample model for applying the reliability analysis framework to a practical model of the K-AGT system. Fig. 5 shows the RBD (reliability block diagram) of a sample model [5] which is composed of four components and has a mixed series-parallel structure. The model's operational data contains the repair data for the four components obtained over a period of 5 years (43,800 hrs) and comprises the failed part code, the cumulative failure number, and the operational time. Table 5 shows the partial data of the model's operational data.

Table 5. Maintenance data of a sample model.

Part Code	Failure Number	Operational Time (hrs)	Part Code	Failure Number	Operational Time (hrs)
3	1	124	:	:	:
2	1	214	4	20	41679
1	1	354	3	44	41897
4	1	512	1	28	42512
3	2	845	2	42	42598
2	2	1108	3	45	42598
3	3	1754	3	46	42598
1	2	1854	2	43	43754
4	2	2145	4	21	43754

Table 6. Reliability analysis results for a sample model.

Part	Time	ln_t	Failure Number	β	λ
1	42,512	10.657	28	0.9349	1.318 E-3
2	43,754	10.686	43	0.9719	1.327 E-3
3	42,598	10.659	46	0.9738	1.427 E-3
4	43,754	10.686	21	0.9647	7.00 E-4

Part	Developed system		Relex		Error (%)
	Failure rate	MTBF (hr)	Failure rate	MTBF (hr)	
1	657 E-6	1,521.2	639 E-6	1,564.3	2.83
2	980 E-6	1,020.5	982 E-6	1,018.6	0.19
3	1,076 E-6	929.2	105 E-6	952.2	2.47
4	478 E-6	2,091.3	479 E-6	2,085.7	0.27
System	1,818 E-6	549.9	1,794 E-6	557.3	1.34

The data is based on two suppositions: first, the four components are not exchanged for 5 years, and second, if the components are repaired because of failure, they perfectly recover their function to 100% reliability following the repair.

Table 6 shows the total failure number for the four components and parameters over the 5 years (43,800 hrs), the failure rates, and MTBFs, which are calculated by using Eq. (1). The failure rates of the four components are analyzed by applying parameters ($\hat{\beta}$, $\hat{\lambda}$) to Eq. (2). The result is illustrated in Fig. 6 and shows that historical failure rates assume the

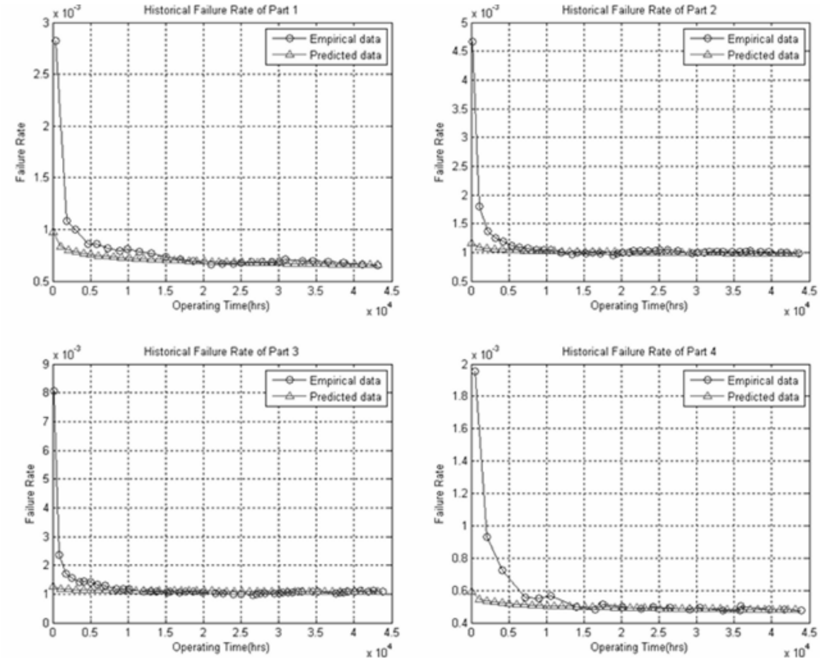


Fig. 6. The historical failure rate of each component in the sample model.

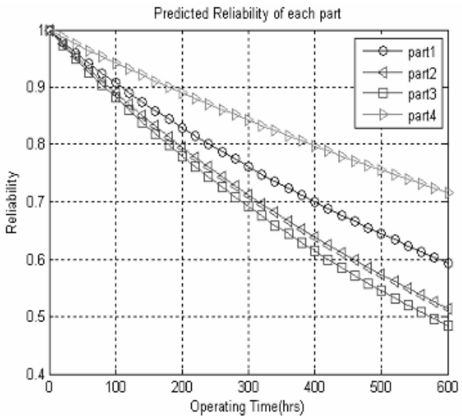


Fig. 7. The predicted reliability of each component of the sample model.

form of a bath-curve that converges into a unique constant. The convergence values in Fig. 6, are the failure rates of each component at the current operating time, are 657 E-6, 980 E-6, 1,076 E-6, and 478 E-6, respectively. Table 7 also shows that this result has validity due to an error rate of only 1.34% when compared with the commercial program (Relex 7.0) result based on the MIL-HDBK-217F standard. The reliability change graph based on the reliability index, such as the failure rate and MTBF, is shown in Fig. 7. At the current time, component 1 has an especially low reliability, because its previous maintenance was carried out the earliest. Comparison with the decreasing rate of each component indicates that the slope of the reliability change is influenced by the values of the failure rate and the MTBF. This means that the rate of reliability decrease of a component with a small failure rate or big MTBF is low. Component 3 has the highest gradient of reliability reduction.

4. Hybrid expert system

A hybrid expert system consists of a knowledge base, an inference engine, user interface, and a DBMS (database management system). The expert system establishes the inspection and repair procedures on the basis of accumulated knowledge history for maintaining the K-AGT system. The knowledge-based system is a computer program that contains the subject-specific knowledge of human experts. An artificial algorithm, adapted to a failure diagnosis system, helps users decide an objective standard. Therefore, the efficiency is maximized by minimizing the maintenance task.

There are generally two types of algorithm in the expert system: rule-based and case-based reasoning algorithms. Rule-based expert systems [6] use technical knowledge such as a maintenance manual, and

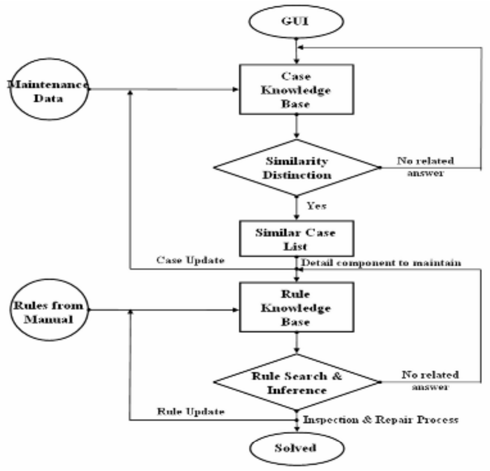


Fig. 8. The flowchart of the hybrid expert system.

they have the following merits and demerits:

- Merits: Quick search time and high reliability of the reasoning results
- Demerit: Difficult knowledge (especially rules) acquisition

Case-based expert systems use experimental knowledge such as maintenance history, and they have the following good and not so good issues:

- Merits: Easy knowledge (especially cases) acquisition and good extension of the application area
- Demerit: Lower reliability when the cases available are not sufficient

This research presents a hybrid expert system, which mixes the rule-based reasoning with the case-based method to take advantage of the merits and complement for the demerits of each method. Fig. 8 shows the logic of operation of the hybrid expert system for the K-AGT system.

4.1 Inference engine

An inference engine, which is the “brain” of an expert system, derives the correct answers from the knowledge-base using some computing technique. This architecture relies on a data store, some working memory, and a global database of symbols representing facts and assertions about the problem. The concept of an expert system affects the inference engine type which is decided by considering the size of the knowledge base and the required efficiency for the application.

4.2 Case Case-based reasoning

Case based reasoning offers the possibility to determine a solution by using previously experienced cases to solve a new problem [7]. Case-based reasoning solves a problem through the use of a search method that is a document retrieval system designed to help find information stored on a computer system. This search method allows one to ask for case content data meeting specific criteria; it then retrieves a list of items that match those criteria as closely as possible.

Case-based reasoning modules are defined as follows:

Retrieve Module: Searching for an existing case in the database for solving a new problem and evaluating the similarity between an input as a question and the existing cases.

Reuse Module: Solving a new problem through the searched solutions of available cases.

Revise Module: In the case that a failure diagnosis system could not solve the new problem, the Revise Module in the system researches the database for new cases.

Retain Module: Retain Module acquires knowledge including the recording of the solution process for solving a new problem.

If the user searches relevant cases, by using an enquiry keyword containing a space between words, without a general information retrieval engine, the system would not be able to present all the appropriate cases. However, if a general information retrieval engine for case-based searching is used, the development and maintenance costs would be increased due to the complicated system architecture required. Therefore it is necessary to apply a method that does not increase the complexity of the overall system architecture, but can effectively perform the searching on a case-by-case basis. The case-based expert system in this paper adopts a combination of three search methods which could search for the enquiry keywords and case documents containing spaced words. The first of the three search methods uses a data base management system (DBMS); the second uses a keyword searching method that distinguishes compound nouns by using a Korean morpheme analyzer. This method offers convenience while searching by expanding enquiry keywords, with a thesaurus for distinguishing keywords. The third method uses the Bigram search method. Combining the three search methods has two advantages: first, it does not increase the complexity of the overall system architecture, because it does not create an indexing database for each case, and second, it efficiently manages the overall system by not having to index and periodically renew the database.

4.3 Rule based reasoning

A rule-based expert system achieves its reasoning skills by solving the problem using experiential knowledge from expert-based rules [8]. An understanding of the inference rule concept is important in understanding expert systems. An inference rule is a statement that has two parts: an IF-clause and a THEN-clause. It is this type of "IF-THEN" rule that gives an expert system the ability to find solutions to diagnostic and prescriptive problems. There are two main methods of reasoning when using such inference rules, namely, backward chaining and forward chaining. In this research, the rule based reasoning approach is used for forward chaining, which starts with the data available and uses the inference rules to conclude more data until the desired goal is reached. An inference engine based on forward chaining searches the inference rules until it finds one which satisfies the IF-clause. It then concludes the THEN-clause and adds this information to its data. It will continue to do this until the desired goal is reached.

This method is referred to as "data driven" because the data available determine which inference rules are used.

However, rule-based expert systems have two disadvantages. First, there is a limit to the expansive knowledge that is available due to the creation of rules through expert's experience. Second, the created rules do not apply to every engineering field and most tend to be application specific. Therefore, in this study a hybrid expert system was constructed, combining case-based reasoning and rule-based reasoning to compensate for the disadvantages of the rule-based reasoning. Table 7 shows the main functions of the case-based reasoning and rule-based reasoning approaches. The rule-based expert system is comprised of three modules:

- Knowledge Base: This module creates experiential knowledge from expert-based rules and offers suitable rules for solving the problem.
- Knowledge Acquisition: This module modifies unsuitable rules as occasions and expands the knowledge base through modified rules.
- Inference Engine: This module solves the caused inference problem by reasoning using suitable knowledge and reasons using a stack type working memory.

Table 7. The function of the expert system.

Case-based Failure diagnosis System
1. Index keyword and distinguish a compound noun using analyzer morpheme of Korean. 2. Rank indexed cases by using keywords. 3. Index Bigram using question and answer. 4. Search included Bigram cases using DBMS function. 5. Rank indexed cases using Bigram search method.
Rule-based Failure diagnosis System
1. Fast-Match Algorithm (RETE, TREAT Algorithm) 2. Data Gathering, Indexing

4.4 A sample application of reasoning for the K-AGT system

An example of reasoning is as follows:

Step 1: The occurrence of a failure event or a maintenance request

Date: 05/25/2006, 2pm

Related Vehicle: Main line – K-AGT unit – MC1 vehicle

Failure Mode: Sending out smoke from the truck (bogie)

Step 2: Case-based reasoning for similar case search

Search Keyword: Sending out smoke from the truck (bogie)

Search Result:

- Occurrence Date: 07/11/2005, 5pm
- Occurrence Place: Mi-Rae Station
- Related Vehicle: Main line – K-AGT unit – MC1 vehicle
- Failure Mode: Sending out smoke from the truck (bogie)
- Failure Cause: Damaged Valve seat of Air Compressor
- Inspection Content: Test whether a valve bracket is damaged or not
- Result: Inspect the air compressor

Step 3: Rule-based reasoning for the diagnosis process

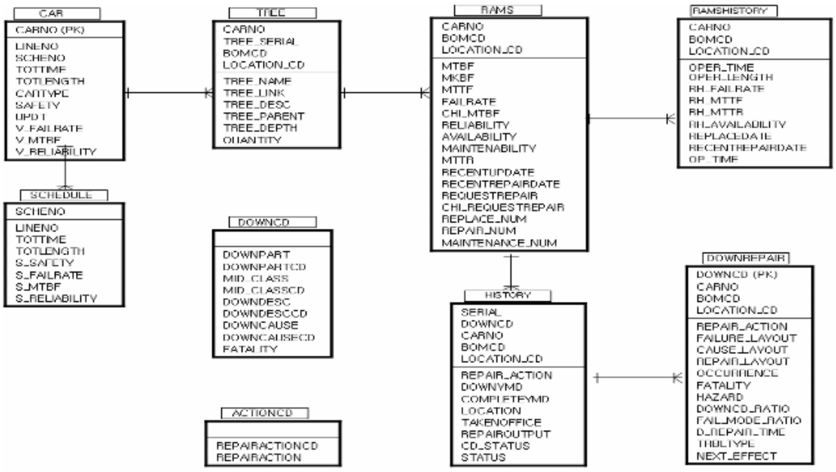
Device Keyword: Air Compressor

Diagnosis Reasoning:

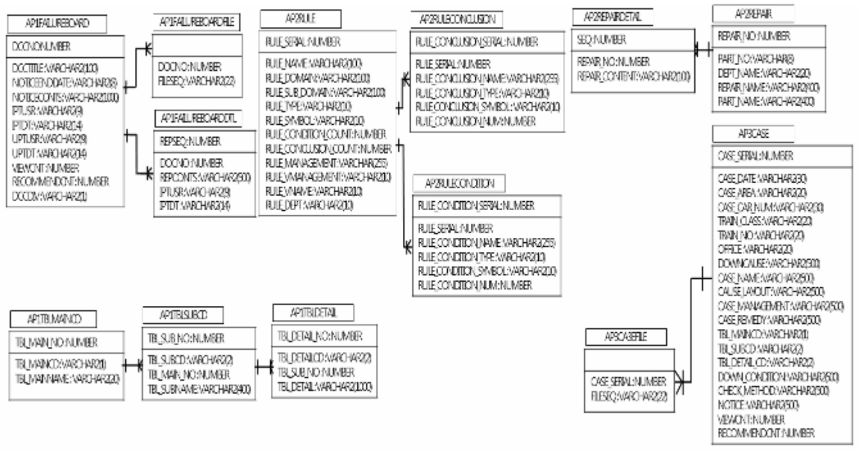
- Step 1: Is there continuously exhaust gas from the safety valve? Y
- Step 2: Is V-three valve covered with dust? Y

Result: Change the valve bracket

Step 4: Rule-based reasoning for repair process



(a) The preventive maintenance system ERD



(b) The expert system ERD

Fig. 9. Database design of web-based RCM system for the K-AGT system.

Repair Reasoning:
- Step 1: Shut off the power supply.
- Step 2: Disassemble the air compressor.
- Step 3: Make sure whether the valve bracket is damaged or not.
- Step 4: Change the valve bracket.
- Step 5: Clear out and assemble the air compressor.
- Step 6: Make a test run.

5. Development of web-based system for K-AGT

The construction of the BOM and the standardization of the failure code classification system were done in advance and a reliability analysis framework was introduced, based on historical failure data. Through a series of processes as described previously, a web-based maintenance system was developed so that the following advantages could be achieved:

(1) Collection of the failure historical data is easy and quick.
(2) Real-time response of information retrieval is related with repair.

In this research, the development language of the RCM system used Java [9] and JSP (Java Sever Page) [10] which are believed to be the most effective web development language systems available. This system also used Oracle 9i [11] as the database operating tool.

5.1 Database design

A database was constructed so that it could be easily, and quickly, accessed, updated and extended. An

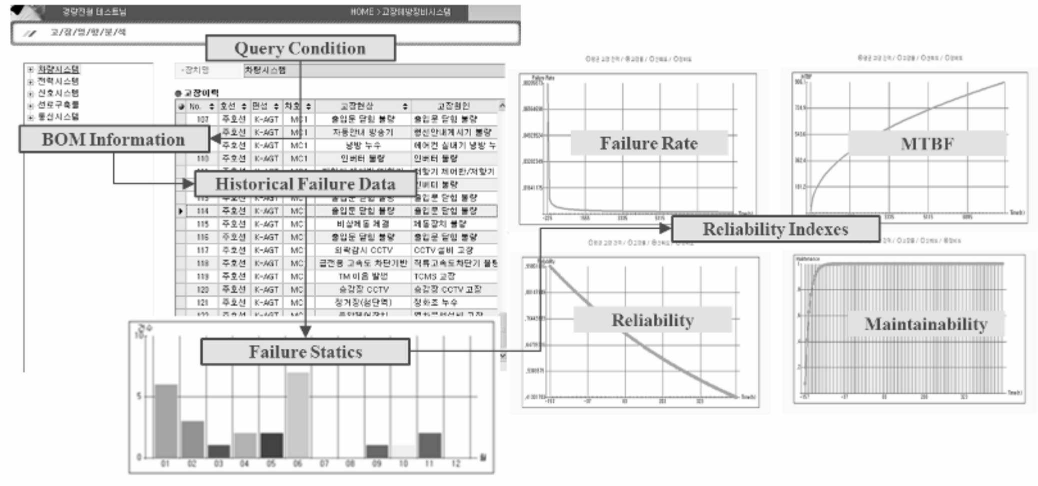


Fig. 10. Reliability analysis module.

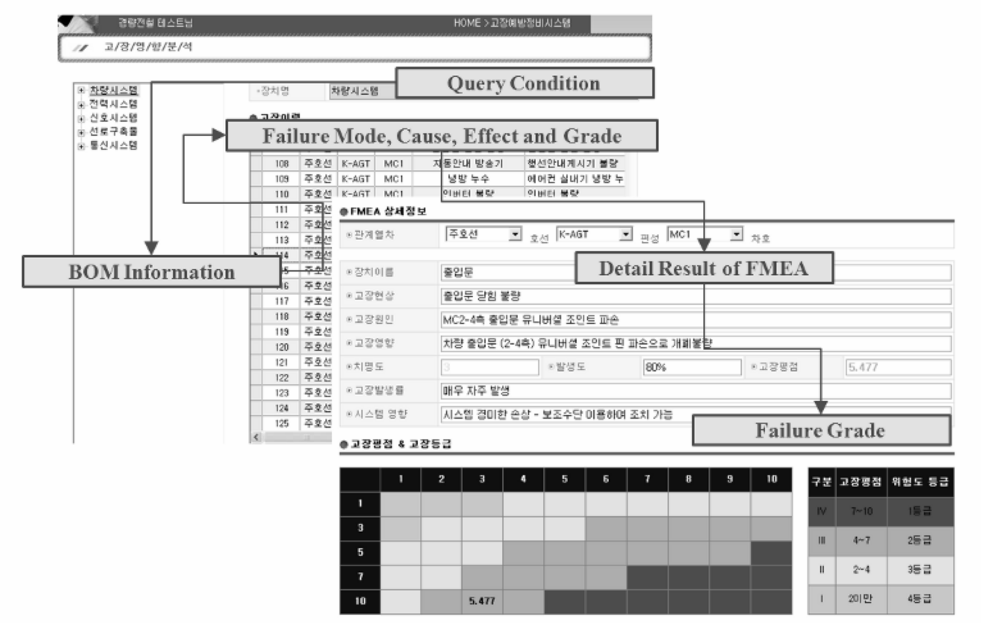


Fig. 11. FMEA module.

Entity Relationship Diagram is illustrated in Fig. 9; in Fig. 9(a) for the preventive maintenance system, the RAMS table shows the results of the reliability analysis. The RAMSHISTORY table contains historical data of the reliability analysis and this data is used for plotting the graphs of the failure rate, MTBF, reliability indexes and MTTF (Mean Time to Failure). The DOWNREPAIR table includes results of the FMEA process and the DOWNCD table contains the failure codes. The CAR table has basic information according to K-AGT system, the HISTORY table shows the accumulated maintenance history, and the TREE table contains information on the hierarchical tree of the BOM. To uniquely store, process and retrieve every possible data in the table, we set a sub system number, the BOM code, and the position numbers as Primary Keys.

In Fig. 9(b) for the expert system, the AP2RULE table has results of the rule-based reasoning; the AP2RULE table consists of the following processes:

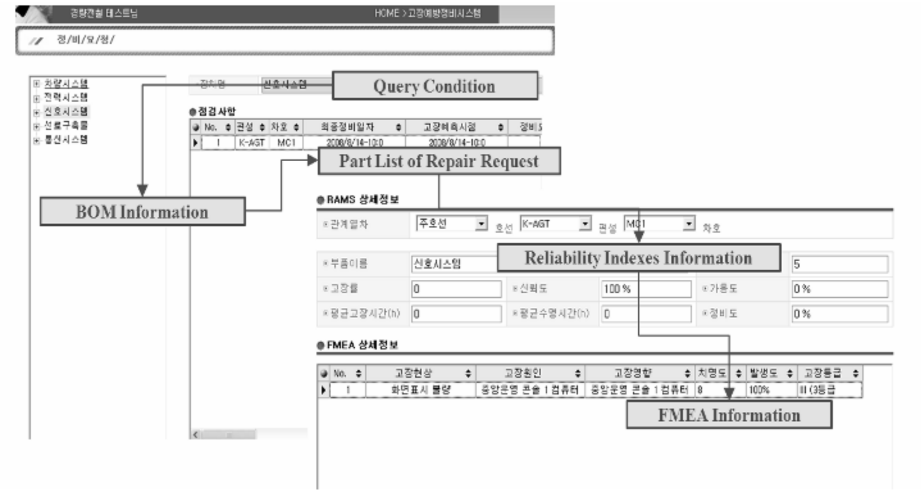


Fig. 12. Repair request module.

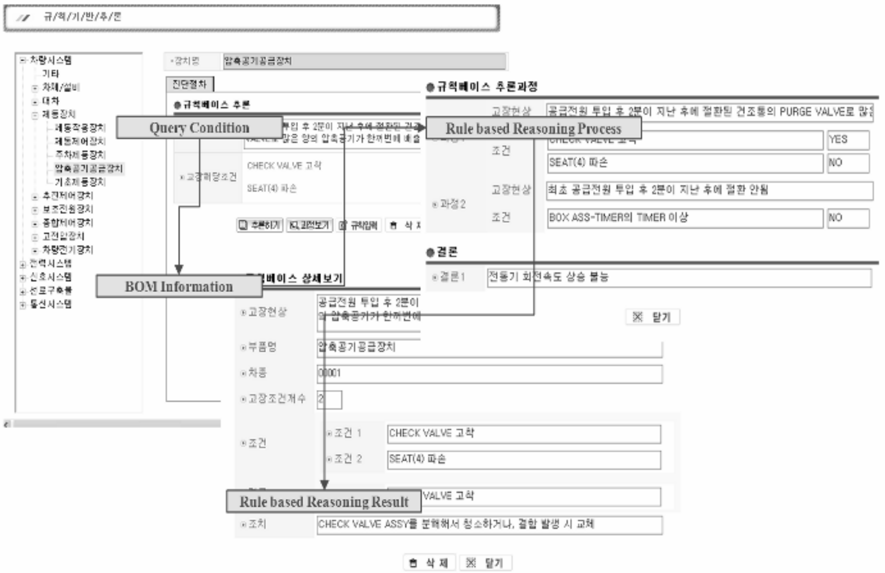
Fig. 13. Case-based reasoning module.

AP2RULECONCLUSION, AP2RULECONDITION, AP2REPAIR, and AP2REPAIRDETIL. Each table contains historical maintenance data of the components that is used for establishing a diagnosis and a repair procedure through a reasoning process of interactive (Yes/No) type questions. In the AP2RULE table, the BOM column contains a hierarchical tree structure of the system or equipment. The AP3CASE table has the results of the case-based reasoning. The basic information contains aspects such as failure cause, failure mode, outbreak time, measure, notice, attached file, and so on. In addition, AP1FAILUREBOARD manages untypical failure data. AP1TBLMAINCD, AP1TBLSUBCD, and AP1TBL-DETAIL contain the various failure codes.

5.2 Modules and graphic user interface for the RCM system

The web-based RCM system developed in this research consists of a reliability analysis module, a FMEA module, repair request module, case-based reasoning module, and a rule-based reasoning module.

The reliability analysis module displays the following: failure rate, MTBF, reliability, availability, and



장치명: 압축공기공급장치

고장해당조건: CHECK VALVE 고착 / SEAT(4) 파손

과정1 고장현상: 공급전원 투입 후 2분이 지난 후에 절환된 건조통의 PURGE VALVE로 많은

조건: CHECK VALVE 고착 — YES

조건: SEAT(4) 파손 — NO

과정2 고장현상: 최초 공급전원 투입 후 2분이 지난 후에 절환 안됨

조건: BOX ASS-TIMER의 TIMER 이상 — NO

결론1: 전동기 회전속도 상승 불능

고장현상: 공급전원 투입 후 2분이 … 압축공기가 한꺼번에

부품명: 압축공기공급장치

차종: 00001

고장조건개수: 2

조건 1: CHECK VALVE 고착

조건 2: SEAT(4) 파손

VALVE 고착

조치: CHECK VALVE ASSY를 분해해서 청소하거나, 결함 발생 시 교체

Fig. 14. Rule-based reasoning module.

maintainability of subsystems, equipment, and parts according to the subsystem of the K-AGT system. Through graphs, changes of these indexes, according to free operating time, can be checked. The GUI (graphic user interface) is shown in Fig. 10.

In FMEA module, the failure modes, failure causes, actions taken, failure ranks, next effects, etc., by the equipment and parts can be identified. When some equipment fails, this module provides the information related to such failures. The GUI is illustrated in Fig. 11.

The repair request module gives a list of parts whose life cycle is almost completed. This module also presents the reliability indexes and the FMEA results related with these modules. The principle of a repair request is that, through reliability analysis and FMEA, out of the equipment whose lifetime is due to expire, those which exert critical effects on the entire system must be first checked and ensured for correct operation. In this checking process, reference to the process of repair can be made by linking with the expert system. The GUI is designed as Fig. 12.

The case-based reasoning module represents the failure mode, failure cause, outbreak time, relevant part.

The GUI is illustrated in Fig. 13. The results of this module present the diagnosis and maintenance procedures through reasoning at the time of the failure occurrence.

The rule-based reasoning module displays the BOM tree, part name, and rule conditions of the subsystems, equipment, and parts according to the subsystem of the K-AGT system. The GUI is illustrated in Fig. 14. The results of this module are used to establish repair or inspection procedures.

6. Conclusions

This research established an IT-based RCM system for the K-AGT system using qualitative and quantitative analyses of conventional RCM techniques. The above quantitative analysis was used for the purpose of providing preventive maintenance by following a reliability analysis. The qualitative analysis aims at improving maintenance work by adopting an expert system, which evaluates the available measures, and, in case of failure, suggests appropriate strategies by following thorough FMEA, case-based reasoning, and rule-based reasoning processes. From the development of the RCM system for the K-AGT, this research has reached the following conclusions.

(1) A component technique was applied in designing the structure of the database. Then, the functional BOM was derived from the master BOM according to the rule-set. Hereby, when the data structure requires changing, the management system can enhance the flexibility as the relevant rule-set simply needs to be changed. In addition, the information of material (such as the total failure number, operating time, and plan of maintenance) can be accurately obtained. Finally, a unique device that feeds historical failure

data into the RCM system can be defined.

(2) This research has provided a standardized failure code classification that can be used by analyzing the failure data that each maintenance base has gathered. By constructing the failure code data in a directory structure and by matching the BOM material codes with the failure codes, the history of failure devices can be managed. This history can then be used to predict the reliability of the relevant devices.

(3) For predicting the reliability of the K-AGT system, a reliability analysis method using a complex system was introduced. Then, this research compared the MTBF using a commercial program with the calculated MTBF using the developed program. In the case of an example model, the result showed a 1.34 % error rate when comparing the calculated MTBF of 549.9 hrs with the result from a commercial program (557.3 hrs). Through comparison with the MTBF using the application program, this research has verified that the developed system is reliable.

(4) As qualitative effect analysis of the accident/failure events is indispensable for expert analysis, this research has set up an analysis system of these accident/failure events. With a view of usability enhancement, it lists the cases and their regularities to establish a reliability-based maintenance system with new concepts. Based on the regularity of the vehicle system and the case analysis of actual accident/failures, the study suggests a hybrid WEB-based expert system, which provides two complementary functions. This feature allows the system a ubiquitous environment so that the operator could get help from anywhere at any time.

The successful RCM system would reduce the number of unnecessarily repeated repair/inspection operations, and presents a good countermeasure against future failures. This will not only reduce the operating and maintenance costs of the K-AGT system, but also contribute to raising public confidence in the system.

Acknowledgment

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