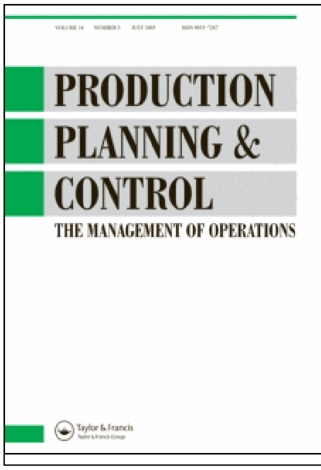

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Won Young Yun [a]; Ilkyeong Moon [a]; Guerae Kim
[a] Department of Industrial Engineering, Pusan National University, Busan, Korea

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Simulation-based maintenance support system for multi-functional complex systems

Won Young Yun[a], Ilkyeong Moon[a]* and Guerae Kim[b]

[a]*Department of Industrial Engineering, Pusan National University, Busan, Korea;* [b]*Statistical Analysis Office, City of Busan, Busan, Korea*

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We define a complex system with a complex structure that performs several functions as a multi-functional complex system, and represent it as a pseudo-tree structure using gates. In addition, we develop an object-oriented simulation model to estimate the reliability, availability, and maintainability of the multi-functional system with complex structures. We define attributes, methods, and events for objects and develop logics for the random number generation, breakdowns, maintenance, etc. for simulation. We obtain simulation statistics on availability, utilisation of repairmen and stock probability of spare parts. The user-friendly simulation model is implemented as simulation software using general object-oriented language. Its potentials for application are demonstrated in the case of a transfer crane, which can be considered a representative example of a multi-functional complex system.

Keywords: maintenance; simulation; multi-functional complex system; decision support system

1. Introduction

Modern systems such as aircraft, automobiles, and electrical appliances become more complex and diverse as users require various functions. Modern systems tend to have many elements as well as complex hierarchical structures. To operate the system efficiently, it is very important to preventively maintain it for an appropriate time period and prepare its spare parts in advance. A mission can be defined as a task that must be performed by a system. A mission may have a predetermined or an uncertain order depending on the system environment. In order to carry out a mission, one or more functions are required. These functions are performed independently or are complementary. A system also simultaneously requires many different elements to support these functions. These elements, in turn, have varying reliability structures. Regardless of whether they are dependent or independent, complex relationships exist among the missions, functions, and elements. These systems are called 'multi-functional system with a complex structure' (MFSCS) and we will be discussing the same in this article.

It is important to assess the reliability and availability of this type of system in order to establish effective maintenance policies. The estimation of the reliability and availability of complex and multi-functional systems have been studied by Birolini (2004), Black *et al.* (1995), Chisman (1998), Dekker *et al.* (1996), Sols (1992), and Yanez *et al.* (1997). The analysis of reliability for the existence of transitions between missions has been conducted, and a maintenance optimisation problem for a multi-components system has been considered (L'Ecuyer *et al.* 1983, Smith 1993). Hartman (2005) outlined strategies for the replacement of capital intensive equipment when considering influences such as increasing maintenance costs, inflation, discount rates, and depreciation with net present value analysis. However, all of these studies considered a fragmentary aspect of the problem or simplified models, and the overall aspects of the multi-functional system with a complex structure have not been addressed. Therefore, we provide a framework that enables us to analyse and represent multi-functional systems with complex structures. We estimate the reliability, availability, and maintainability of the multi-functional system with a complex structure by using simulation, and provide decision aids for maintenance policies.

Simulation has been accepted as one of the main techniques to study maintenance policies. Andijani and Duffuaa (2002) reviewed the literature on simulations of maintenance systems. The complexity of modern industrial plants is increasing and the conception of maintenance management is now considered a key element for the improvement of operation and safety, cost reduction, increase of availability, etc.

*Corresponding author. Email: ikmoon@pusan.ac.kr

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Ntuen and Park (1999) developed a simple discrete event simulation model to estimate the level of maintenance crew size required in a maintained reliability system. Marseguerra and Zio (2000) combined both genetic algorithms and Monte Carlo simulation to solve the maintenance problem for an industrial plant. Barata *et al*. (2002) developed a simulation model for repairable multi-component deteriorating systems, and found the optimal degradation thresholds of maintenance intervention. Borgonovo *et al*. (2002) applied the Monte Carlo simulation to the complex systems under periodic maintenances in order to analyse the availability. Macchi and Garetti (2006) proved that maintenance decisions at the equipment level may significantly be different from decisions at the system level. They proved the concept using a simulation model.

This paper is organised as follows. In Section 2, we introduce a multi-functional system with a complex structure (MFSCS), and present a hierarchical analysis of it. The object-oriented simulation logic of the MFSCS is presented in Section 3. In Section 4, we introduce a simulation system for the MFSCS, called RAMSIM, which has been developed using an object-oriented language.

2. Multi-functional system with a complex structure (MFSCS)

2.1. *Definition of MFSCS*

When a system is capable of performing various types of missions, we call it a 'multi-functional system'. In order to accomplish a mission, a multi-functional system must have one or more 'functions' that make an attempt to perform the designated goals. Each function is then supported by one or more 'elements'. A function can be functional (or operational) when the minimum set of elements supports the function in a good condition. As mentioned earlier, most of the recent systems are often characterised by a multi-functional capability. A simple, but essential example of the multi-functional system is a typical household air-conditioner with an air-cleaning feature. In this example, the air-conditioner has roughly three missions: (1) cool the room, (2) heat the room, and (3) clean the air. In summer, the missions of the air-conditioner are to cool the room and clean the air. Note that the mission of heating the room is unnecessary. Likewise, in the winter season, the system's missions are replaced with heating the room and cleaning the air. Several functions are required to carry out the mission of heating room, for example, blowing air, heating, and temperature control. A complex system exists in which several different types (series, parallel, standby, k out of n, etc.) of reliability structures exist. We define it as a multi-functional system with complex structures: that is, the system contains more than one reliability structure.

2.2. *Hierarchical analysis of MFSCS*

A multi-functional system is assumed to consist of missions, functions, and elements. The elements, which physically comprise the system, are organised in a predetermined manner to provide several functions. These functions are subsequently utilised to accomplish several different missions. For a function to run correctly, one or more elements are required for its support. When an element breaks down, the function that is supported by it may or may not stop running depending on the structure and relationship of the elements with those functions.

System: It is the object that we will analyse. Several sequential missions are required to be achieved.

Mission: It is the actual task of achieving the goals of a system. The execution of a distinct mission requires the activation of some of the several specific functions. The state of the system that is running or down depends on the state of the mission that is in the activated state. We assume that the system can perform only one mission at a time.

Function: It is the subset of activities of a system. When all the functions that support a mission are available during the mission time, the mission operates without failure. Each function, in general, supports more than one mission simultaneously. A breakdown in the function immediately terminates the mission because all the functions in a mission are serially connected.

Element: It is the lowest object in a system and has a physical failure and repair process. Therefore, the actual failures and repairs occur at this level. Elements may constitute various reliability structures of a function. The failure process entirely depends on the structure between elements, i.e. if an element that supports a function is not available at a given instant, it does not necessarily imply that the function it supports is down at that moment because the element may be a redundant unit in a parallel structure. Typical examples of reliability structures include series, parallel, stand-by, and network, etc. Structures in an element may comprise one or more different reliability structures. This makes the structure of the element complex.

2.3 *Representation of MFSCS*

We apply the gate concept in fault tree analysis to represent the reliability structure of elements and missions. Gates are symbols used to represent the reliability structures of the components, and these are listed in Table 1. Using this definition, we can represent an example of MFSCS as shown in Figure 1.

Remark: This hierarchical modelling is not restricted to a tree structure. Thus, one lower component can be connected to many upper components.

2.4 *Failures and maintenance of MFSCS*

We assume that a system may perform multiple missions, but it can perform only one mission at a time. Under this assumption, we define the failure and maintenance of the multi-functional system with complex structures as follows:

Element failure: The element is the only component that is susceptible to physical breakdown. The break-down of an element may cause the failure of several functions or missions depending on its relationship with them. We assume that the time to failure follows an exponential distribution or a Weibull distribution. The exponential distribution is widely used as the time to failure. This distribution is appropriate for the failure caused by chance rather than aging. It is often used for the failure distribution for electronics and assembled items. Meanwhile, the Weibull distribution is widely used for the case that the failure rate increases with time. It is often used for the failure distribution for mechanical parts.

Function failure: Failures of function depends on the reliability structure of the elements or lower level functions.

Mission failure: We assume that all the top-level functions must operate to accomplish a mission. Since a mission has a series structure of functions, it fails when any function contributing to it fails to complete its task.

System failure: A system may perform multiple missions. However, it can perform only one mission at a time. Thus, a system fails if either a mission cannot be completed or a mission cannot be started.

Table 1. Gates for representing reliability structures.

Gate	Symbol	Application
AND gate		Series structures
OR gate		Parallel structures
Stand-by gate	S	Stand-by structures
1/2 stand-by gate	1/2	Optional stand-by structures

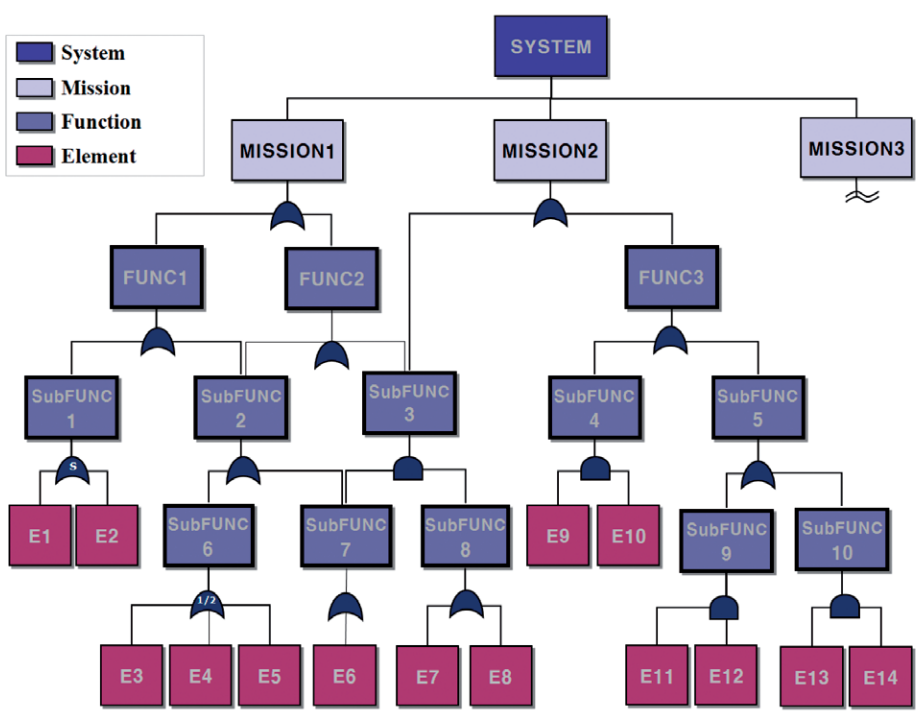

Figure 1. An example of MFSCS.

Maintenance: An element is the unit that requires maintenance. Maintenance involves either repairing the failed element or replacing it with a new one. We consider two types of maintenance policies.

- *Corrective maintenance*: When an element is broken down, it can either be replaced with a new one or repaired.
- *Preventive maintenance*: Scheduled actions are taken to either reduce the possibility of a failure or improve the reliability of the element by replacing it with a new one or by repairing it.

Depending on the state of the element after repairing, they are classified into several repair models (see Pham and Wang 1996 for details).

- *Perfect repair*: A repair action that restores the element to a state that is equivalent to a new one. A complete overhaul of an engine with a broken connecting rod is an example.
- *Minimal repair*: A repair action that restores the element to its state just before the failure. Thus, there is no change in age. Changing a flat tyre on a car or a broken fan belt on an engine is an example of this kind of repair.
- *Imperfect repair*: A repair action that turns into minimal and perfect repair with probabilities of p and $1-p$, respectively. Usually, it is assumed that imperfect repair restores the system operating state to somewhere between as good as new and as bad as old. Engine tune-up is an example of this type of repair because it may not make an engine as good as new but its performance might be greatly improved.
- *Improve repair*: A repair action that uses newly developed parts. Therefore, it may restore the system to a state that is intermediate of a new and old one. Using a newly developed electronic part which replaces the existing one may or may not improve the total system is an example of this type of repair.

The state (age) of the element is significantly affected by the repair model. Thus, the repair model influences the availabilities of the element and system.

Maintenance policies: We consider a preventive maintenance for an element. The preventive maintenance includes not only preventive replacement but also preventive inspection and repair.

3. Design of object-oriented simulation logic

3.1 *Object-oriented simulation logic*

The object-oriented analysis designs the simulation operation logic using the activities of objects, regarding them as key elements in modelling. Process is defined as an object that operates by changing states over time (Garrido 1998). Simulations are executed based on the operations of the processes and their interactions. The initialisation routine is required to invoke the simulation at time 0. The simulation control routine is also required to manage the time advance mechanism and the event list.

3.2 *Design of simulation object, event, logic, and statistics*

Object schema: Missions, functions, and elements constitute the most important classes. We define objects in Table 2.

Event schema: An event is defined as an instantaneous occurrence that may change the state of an object. In this study, an event can be divided into two categories: global and interactive. A global event is enrolled into the event list by objects such as mission, function, and element. When the simulation clock reaches the specified time, the event controller invokes the event (see Table 3). An interactive event is one in which an object is invoked by another object that has just finished its process.

Logic design: We analyse the manner in which the state of the object changes with the help of the state transition diagram. The important objects such as mission, function, and element have RUN, DOWN,

Table 2. Definition of objects.

Object	Top object	Description
Process		Activate as time passes by and have phase attribute.
Mission	Process	Have mission start, mission change, and mission end tasks.
Function		Perform an assigned mission.
Element	Process	Perform an assigned function and have failure and repair tasks.
Maintenance	Process	Perform preventive maintenance and have start and end tasks.
Repairman		Perform maintenance.
Event list		Manage event list.

and IDLE states. The event/operation diagram has been developed to represent the relationship between events and tasks resulting from the events. After analysing events and activities, we design the simulation logic (refer to Figure 2).

Design of statistics: The statistics in this study have been classified into four categories as shown in Table 4: statistics related to reliability (MTBF), availability (total breakdown time and number of breakdowns), maintainability (utilisation of spare parts, time delay, number of PMs), and cost (breakdowns, spare parts, repair, and PM costs). These statistics can be used to decide policies such as preventive maintenances, spare parts, and level of repairman. We provide the mean, standard deviation, maximum value, minimum value, and 95% confidence interval through multiple replications of simulation.

Table 3. Global events for objects.

Object	Event	Explanations
Mission	START	Invoke mission
	STOP	Halt current mission Generate and invoke next mission
	END	Close mission
Element	BREAKDOWN	Generate element failure
	ENDFIX	Complete element repair
Maintenance	PMSTART	Invoke preventive maintenance
	PMEND	Close preventive maintenance

4. Simulation system

4.1 *Modules of the simulation system*

We develop RAMSIM using the objects and the simulation logic described in previous sections. It was coded using the object-oriented language, C++. The simulation system consists of six modules excluding the database (Figure 3):

- data module (data management),
- simulation processing module (performs simulation),
- simulation evaluation module (verifies simulation using random numbers),
- report module (reports simulation results using Excel),
- graphic module (performs animation that indicates the progress of the simulation), and
- sensitivity analysis module (supports decision making by sensitivity analysis).

We use Microsoft Access for the relational database to effectively manage the information. RAMSIM database includes system structure,

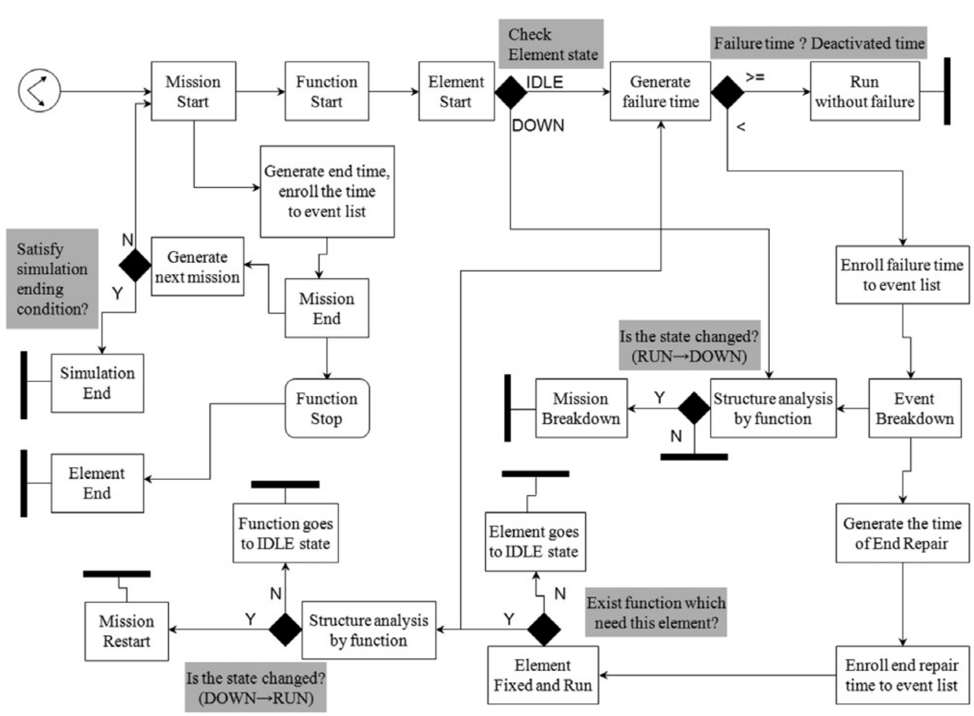

Figure 2. Event diagram.

Table 4. Simulation statistics.

Classification	Name	Explanations
Reliability	MTBF	Mean time between failures
Availability	Total time	Total time a certain unit performs
	Total run time	Total time a certain unit performs without failures
	Total breakdown time	Total time a certain unit had been broken down
	Availability	Ratio of total run time to total time
	Number of breakdowns	Number of breakdowns
Maintainability	Used spare parts	Number of spare parts used
	Utilization of spare part	Percentage of spare parts used
	Service level	Percentage that spare parts are available
	Total time for repair	Total time spent for repair by each repairman
	Time to delay	Total waiting time of elements for repair
	Utilisation	Utilisation of repairman
	Counts of PM	Number of preventive maintenances performed
Cost	Down cost	Sum of mission failure cost and system failure cost
	Spare parts cost	Sum of procurement and holding cost of spare parts
	Repair cost	Repair cost composed of fixed and variable cost
	Preventive cost	Cost used for preventive maintenances

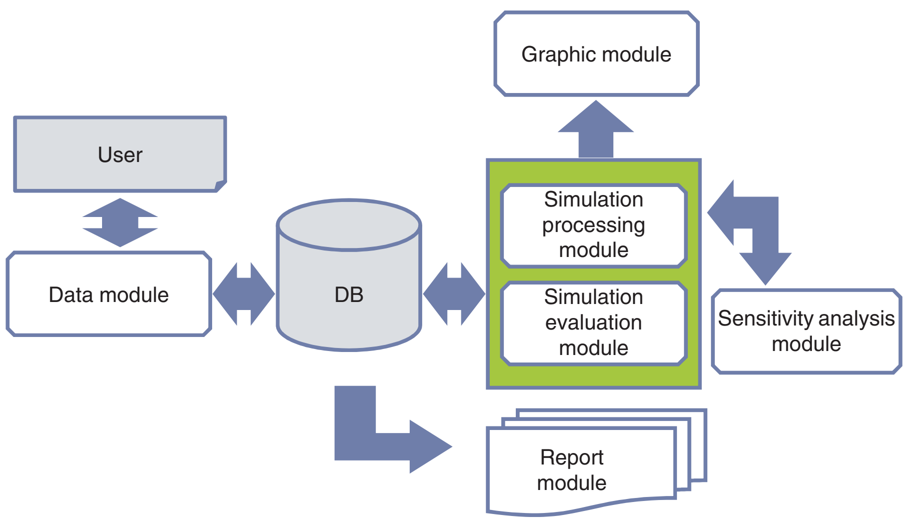

Figure 3. System structure.

maintenance policy, and output statistics. The outlined relations between tables are shown in Figure 4.

There are tables which manage the basic information on the missions, functions, and elements. MissFuncRelay table represents the relationship between missions and functions, and FuncElem Relay table represents the relationship between functions or functions and elements. MissTranProb is related to the changes of the missions. Maintenance table is used for managing the basic information on preventive maintenances. MaintElem Relay table defines the relationship between elements and preventive maintenances. There are three tables for the information on repairmen: Repairman table, RepairmanSet table, RepairmanRelay table. Simulation results are saved in StatSystem table, StatMission table, StatFunction table, StatElement table, StatRepairman, and StatMaintenance table. The system can be used for sensitivity analysis and the results are saved in Sens StatElement table and SensStatMaintenance table.

4.2 *Input/output design*

We consider the transfer crane in a container terminal in Busan, Korea, as a field example and analyse the

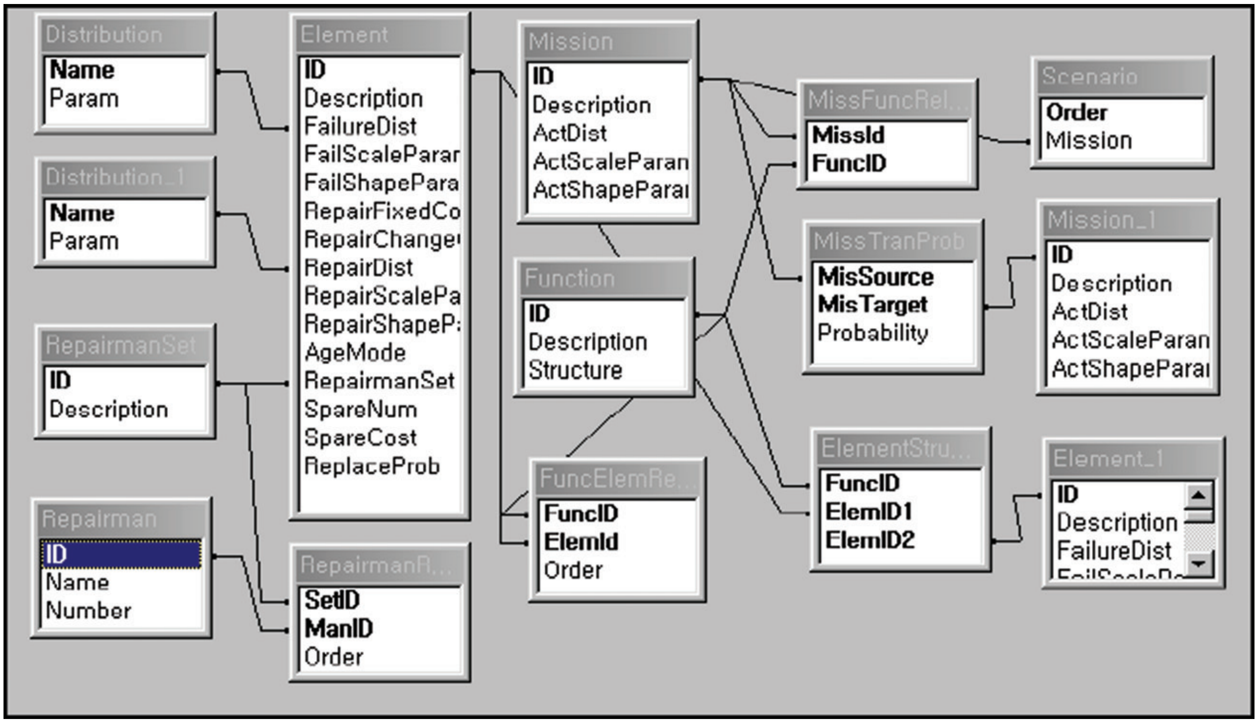

Figure 4. Database structure.

maintenance problem of the crane using the proposed method. First, FMEA (failure mode effect analysis) is conducted and the functional structure is analysed. The tasks of the transfer crane are empty travelling, loaded travelling, empty traversing, loaded traversing, empty hoisting, loaded hoisting, and picking/releasing. We can define this unit task as a mission since the conventional manual transfer crane can perform only a task at a time. We define the functions necessary to perform the missions and hardware components used for the functions. These components are regarded as elements. The missions, functions, and elements for the transfer crane are listed in Table 5, and represented in a tree structure which has been omitted here for brevity.

Next, we collect failure data and other parameters in the model. We input data for system, missions, functions, elements, operations, repairmen, and preventive maintenance. In particular, for each element, we input the failure distribution, repair time distribution, repair cost, type of spare parts and repairman, repair model. We input the basic information on the system, and select the scenario of the mission, and the transition probabilities between missions can be provided. We input the basic information on each mission, corresponding functions, the distribution of the length of each mission, and transition probabilities to other missions as shown in Figure 5. Figure 6 shows the input screen for each function. The basic information on each function and enrolment of each element (series, parallel, standby, 1/2 standby) should be provided. The data for the elements include the basic information on each element, distribution between failures, distribution of repair times, types and costs of repairs, etc (Figure 7). We input the information on preventive maintenances and the relationship with each element as shown in Figure 8. After we input the data, the overall structure of the system is represented as a tree structure in the left window in Figure 9.

4.3 *Simulation results*

The simulation results for a given input data are shown in Figure 9. Figure 9 also shows the main view with summarised results of all the missions, functions, and elements. The system gives us availability, MTBF, and total system cost. The average, standard deviation, minimum, maximum values of the availability and MTBF are computed for each mission, function, and element, and an example screen of the elements is shown in Figure 10. The overall simulation results provide the usage of spare parts, utilisation of repairmen, results of preventive maintenances, and system costs. The system costs are categorised into spare parts costs, repair costs, costs due to mission

Table 5. Transfer Crane Analysis.

System	Mission	Function	Element
Transfer crane	Empty travelling	Traversing	DC motor (1)
	Loaded travelling	Troll speed control	Gear reducer (1)
	Empty traversing	Anti-shock	Pinion
	Loaded traversing	Fixing	Speed limit (1)
	Empty hoisting	Anti-sway	Magnetic brake
	Loaded hoisting	Hoisting	Trolley stopper
	Picking/releasing	Safety control	Hydraulic buffer fixer
		Spreading	Skew device
		Locking/unlocking	Trolley drum
		Positioning	Spring brake
		Power supplying	Cam clutch
		Strut	Torque motor
		Monitoring	DC motor (2)
		Gantry travelling	Gear reducer (2)
			Hoisting drum (1)
			Hoisting wire clamp
			Speed limit (2)
			Limit switch (1)
			Hoisting drum (2)
			Main frame
			Telescopic beam
			Hydraulic pump
			Oil tank
			Hydraulic motor stopper
			Hydraulic cylinder gear
			Twist lock pin
			Bracket
			Limit lamp
			Cummins engine
			Fuel filter
			Lubrication
			AC motor
			Tyre
			Bearing
			Chain
			Limit switch (2)
			TC main frame monitor

stoppages, and preventive maintenance costs as shown in Figure 11.

Sensitivity analysis can be performed in a few parameters and decision variables: failure distribution of the elements, amount of spare parts, and intervals between preventive maintenances. For example, we can input the initial value, final value, and increment of the preventive maintenance interval, and select the statistics to be collected as shown in Figure 12. The results of the sensitivity analysis are shown in Figure 13, and those are helpful for decision makers to decide the appropriate maintenance interval and amount of spare parts to be carried.

Using the simulation results and sensitivity analysis, decision makings on the following managerial issues can be determined.

Estimation of reliability and costs: We can easily estimate the reliability and costs for a given circumstances. For example, a life time of certain items is well-known by the manufacturer.

Support of decision making: The results can be used for the manager to decide the following things.

- *Policy on the repairmen*: Decide the number of repairmen required and the effect of changing the size.
- *Policy for preventive maintenance*: Decide the effect of the maintenance interval on the reliability and costs.
- *Policy on spare parts*: Estimate the effect of number of spare parts on the reliability and costs.

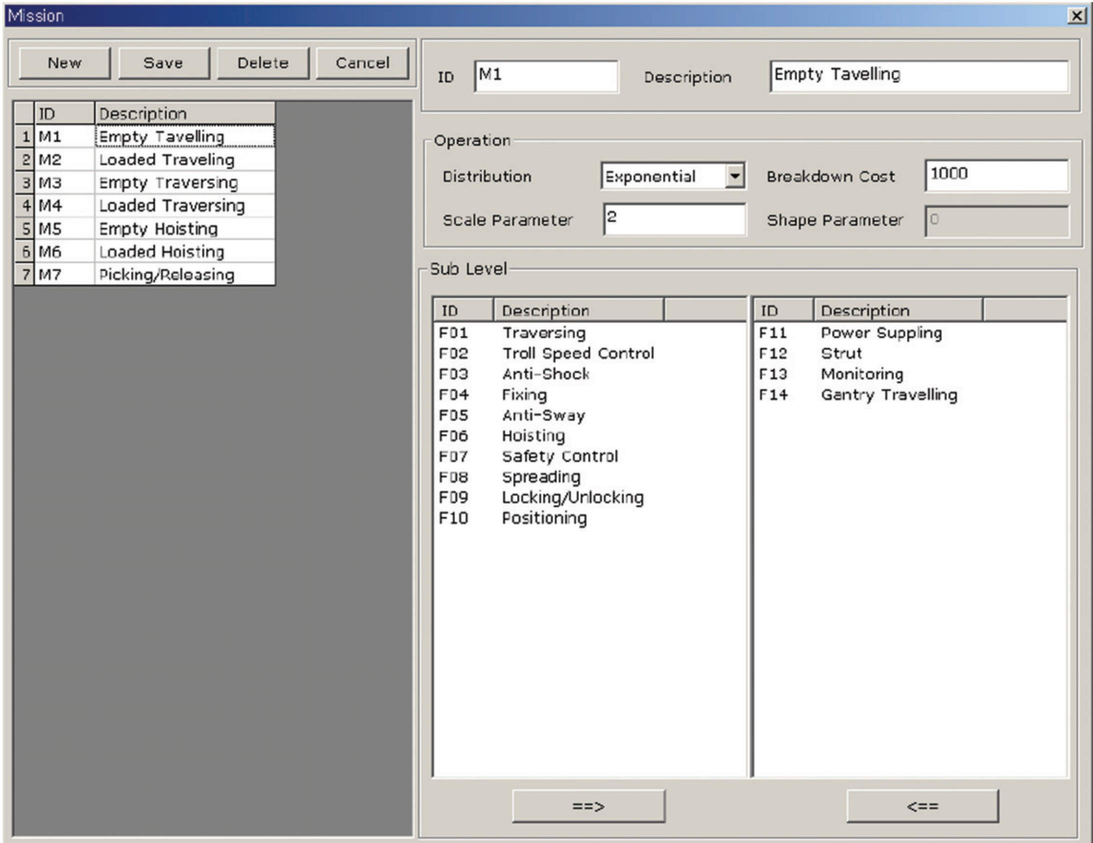

Figure 5. Input for missions.

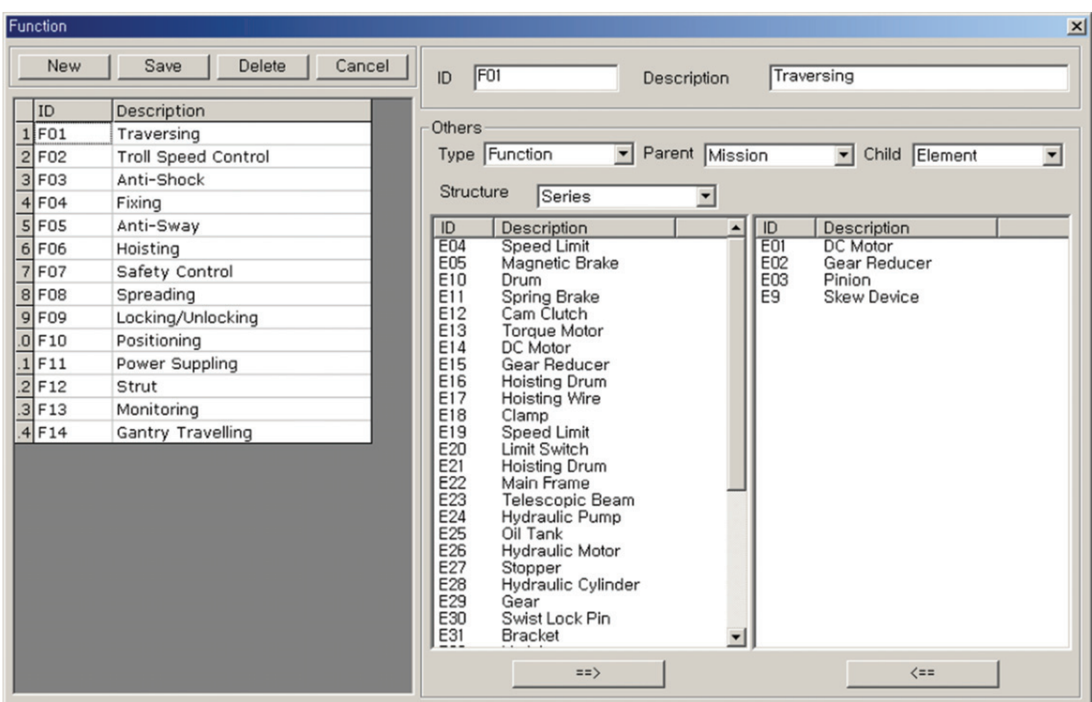

Figure 6. Input for functions.

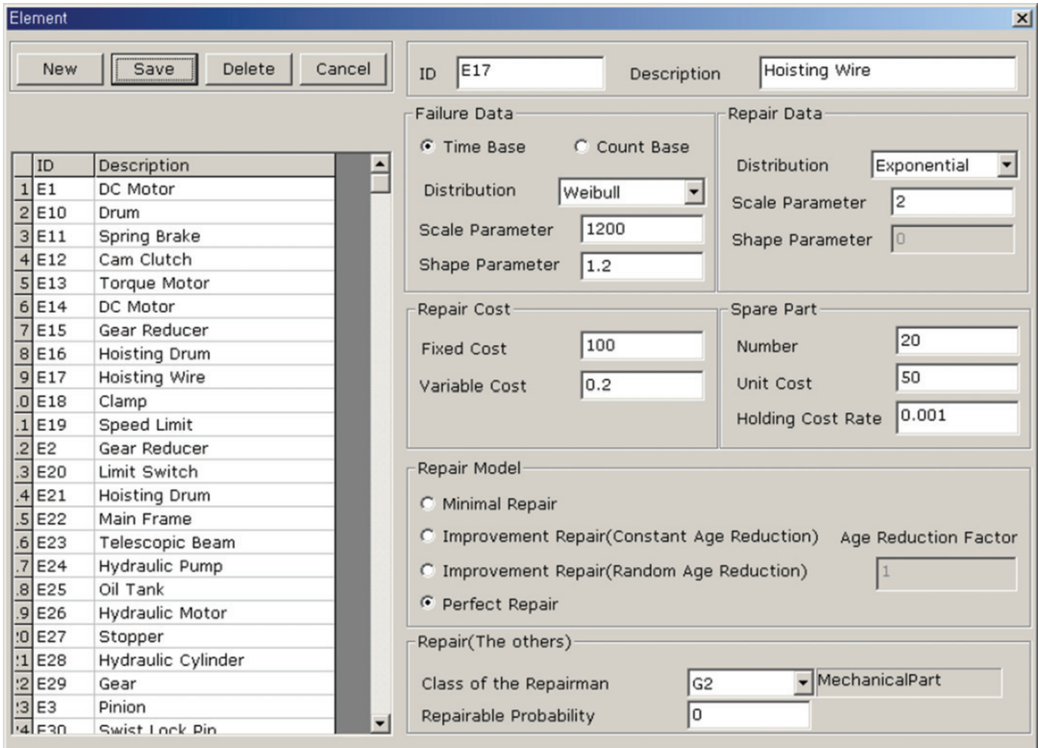

Figure 7. Input for elements.

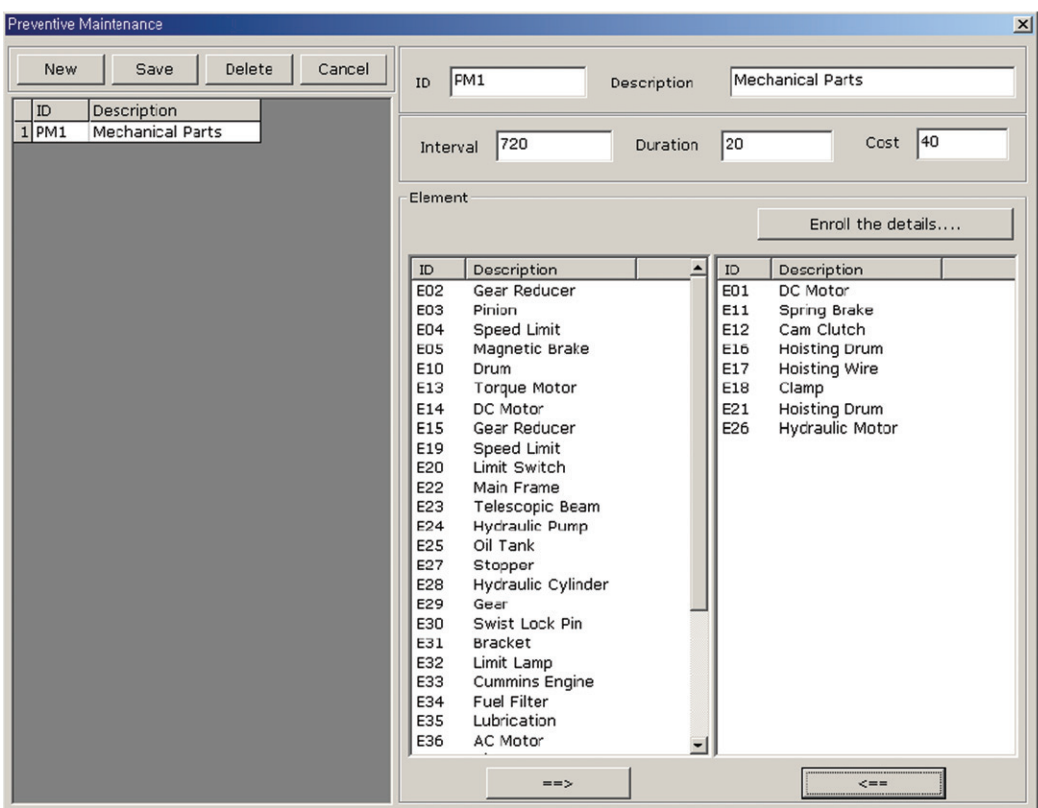

Figure 8. Input for maintenances.

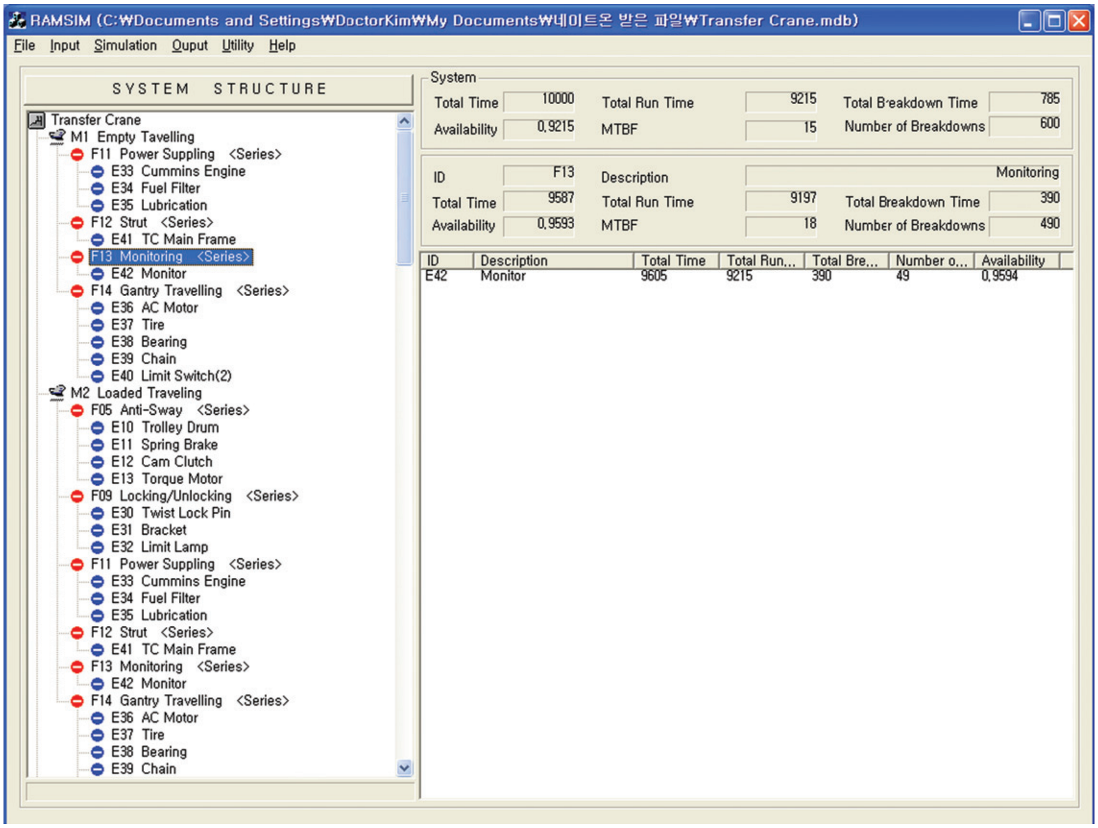

Figure 9. Summary of results at overview menu.

[Element]

ID	Description	Average	Standard Deviation	Min	Max
E01	DC Motor(1)	1784.40	1136.9216	326.00	3178.00
E02	Gear Reducer(1)	1935.60	783.4326	841.00	3178.00
E03	Pinion	753.80	128.0116	609.00	906.00
E04	Speed Limit(1)	298.40	113.8799	224.00	522.00
E05	Magnetic Brake	586.40	163.5954	300.00	788.00
E06	Trolley Stopper	1379.40	881.2093	545.00	2696.00
E07	Hydraulic Buffer	973.20	228.6241	518.00	1115.00
E08	Fixer	740.00	258.2239	365.00	1170.00
E09	Skew Device	1124.60	538.1474	552.00	2137.00
E10	Trolley Drum	1465.00	527.6385	908.00	2254.00
E11	Spring Brake	1280.20	602.0191	767.00	2431.00
E12	Cam Clutch	738.40	73.0249	653.00	869.00
E13	Torque Motor	1444.60	568.9649	976.00	2486.00
E14	DC Motor(2)	1238.20	831.9559	367.00	2722.00
E15	Gear Reducer(2)	1521.40	902.3065	824.00	3277.00
E16	Hoisting Drum(1)	1069.20	226.2356	895.00	1513.00
E17	Hoisting Wire	1202.60	770.3419	548.00	2678.00
E18	Clamp	1300.20	1014.5396	492.00	3202.00
E19	Speed Limit(2)	581.60	212.9860	251.00	849.00
E20	Limit Switch(1)	284.60	39.6817	242.00	350.00

Figure 10. Simulation results of the MTBF of elements.

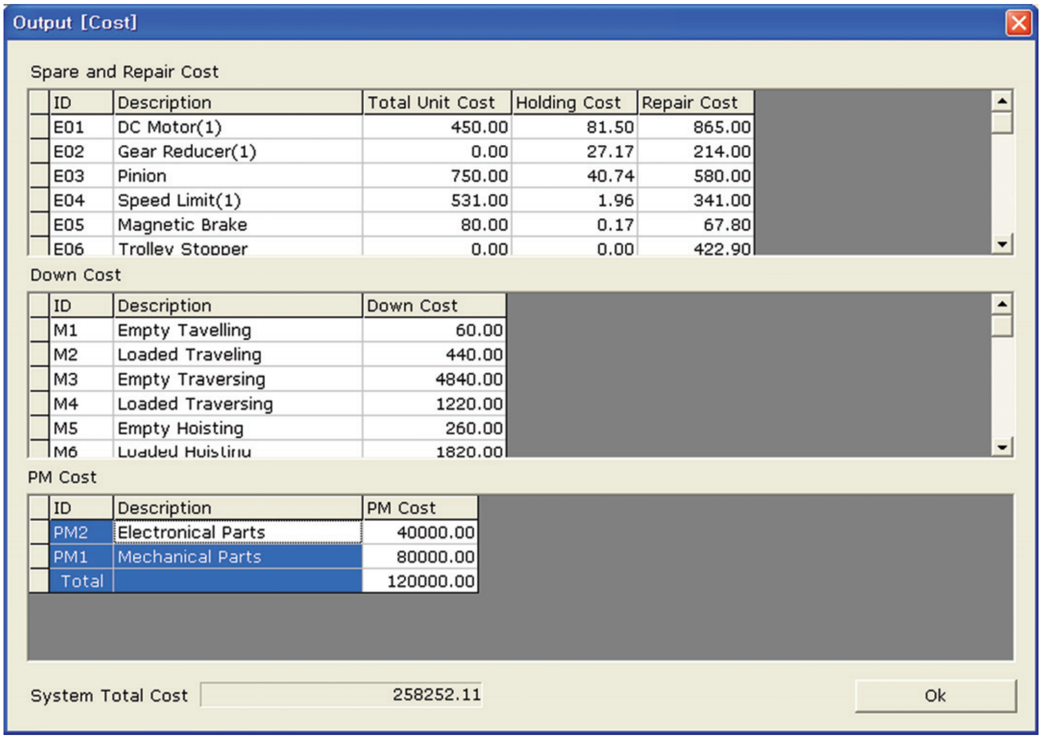

Figure 11. Simulation results of the system costs.

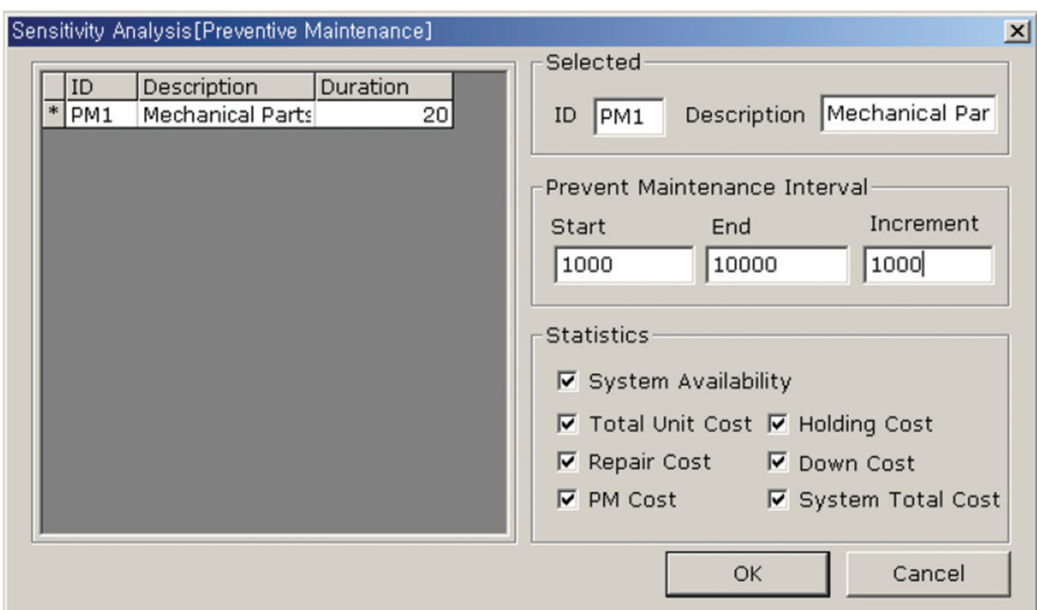

Figure 12. Input for the sensitivity analysis of preventive maintenances.

- *Assignment of target reliability*: Assign each item's target reliability to achieve the target system reliability. Estimate the effect of assigned target reliability on the system reliability and costs.

5. Conclusions

In this study, we proposed a procedure to analyse systems that perform multiple functions but cannot be represented as a single reliability structure. We defined objects, their attributes, and events in order to develop

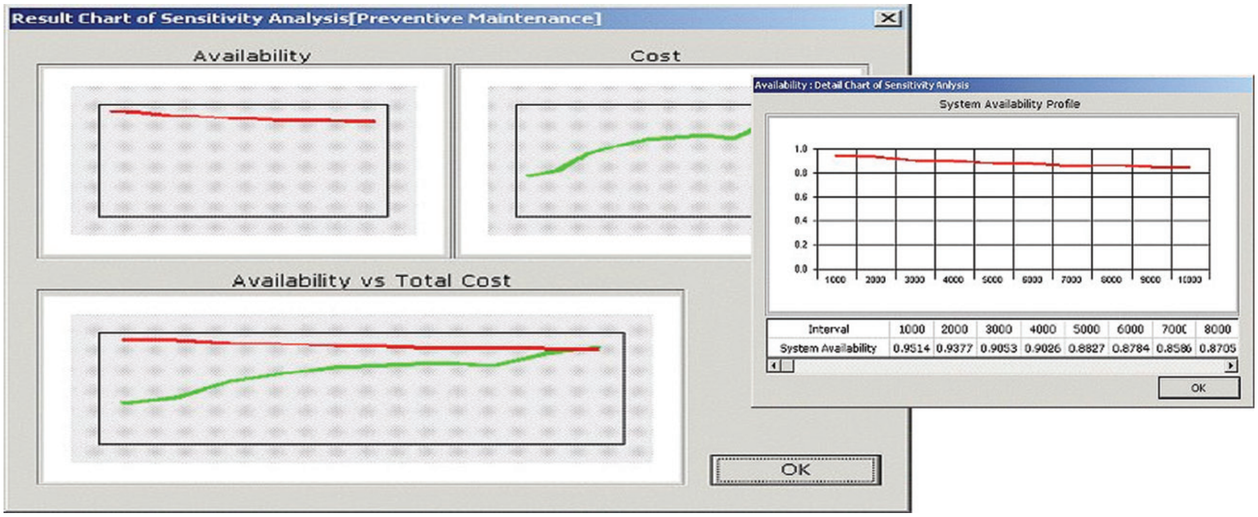

Figure 13. Sensitivity results of preventive maintenances.

a simulation system that can be used to estimate the reliability, availability, and maintainability of a multi-functional system with a complex structure. Moreover, we designed the simulation logic using the discrete-event simulation and developed a simulator using C++, an object-oriented language. The simulator can be effectively used to estimate the reliability, availability, and maintainability of the advanced equipments and vehicles in transportation and container terminals, e.g., AGV or cranes.

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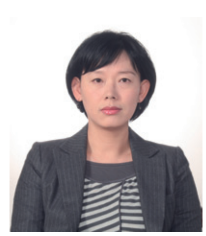
Notes on contributors

Won Young Yun is a Professor at the Department of Industrial Engineering, Pusan National University, Busan, Korea. He received his BS in Industrial Engineering from Seoul National University, Korea, and MS and PhD degrees from Korea Advanced Institute of Science and Technology (KAIST). His current research interests focus on system reliability, simulation-based optimisation in reliability and maintenance, and logistics.

Ilkyeong Moon is a Professor of Industrial Engineering at Pusan National University in Korea. He received his BS and MS in Industrial Engineering from Seoul National University, Korea, and PhD in Operations Research from Columbia University. His work has appeared in journals such as *Computers & Industrial Engineering*, *Computers & Operations Research*, *European Journal of Operational Research*, *IIE Transactions*, *International Journal of Production Economics*, *International Journal of Production Research*, *Journal of the Operational Research Society*, *Management Science*, *Naval Research Logistics*, *Omega*, *Operations Research*, *Production Planning & Control*, *The Engineering Economist* and *Transportation Research*. He currently serves on the editorial boards of several international journals and as Editor-in-Chief of *Journal of the Korean Institute of Industrial Engineers*.



Guerae Kim got her PhD degree from Pusan National University, Korea. Her research interests focus on system reliability and simulation based optimisation in reliability and maintenance. Now she works for the local government of Busan metropolitan city.

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