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Development of Design Alternative Analysis Program Considering RAM Parameter and Cost

Han-sol Kim[*], Seong-Dae Choi[*], Jang-wook Hur[*,#]
[*]Department of Mechanical System Engineering, Kumoh National Institute of Technology

RAM 파라미터와 비용을 고려한 설계대안 분석 프로그램 개발

김한솔[*], 최성대[*], 허장욱[*,#]
[*]금오공과대학교 기계시스템공학과

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ABSTRACT

Modern weapon systems are multifunctional, with capabilities for executing complex missions. However, they are required to be highly reliable, which increases their total cost of ownership. Because it is necessary to produce the best results within a limited budget, there is an increasing interest in development, acquisition, and maintenance costs. Consequently, there is a need for tools that calculate the lifecycle costs of weapons systems development to facilitate decision making. In this study, we propose a cost calculation function based on the Markov process simulator–a reliability, availability, and maintainability analysis tool developed by applying the Markov-Monte Carlo method–as an alternative to these requirements to facilitate decision-making in systems development.

Keywords : Condition Monitoring(상태감시),RAM Parameter(신뢰도, 가용도, 정비도 파라미터), Markov Process(마코프 과정), Acquisition Cost(획득비용), Operation Support Cost(운용유지비용), Life Cycle Cost(수명주기비용), Cost Estimating(비용추정), Design alternative(설계대안)

1. Introduction

With the growing sophistication, refinement, and complexity of modern weapons systems, their LCC are increasing. This increase has highlighted the importance of reliability, availability, and maintainability (RAM) in research and development through amendments to the RAM guidelines[1]. Currently, it is essential to develop and distribute a RAM analysis tool that can support decision-making by helping identify expensive core parts/components that are prone to failure at the system development stage and designing alternatives for such parts[2-5]. The Markov process is described in the US Department of Defense RAM Practice Guide as a RAM analysis simulation technique[6]. Extensive literature pertaining

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Corresponding Author : hhjw88@kumoh.ac.kr
Tel: +82-53-478-7399, Fax: +82-53-478-7399

to this topic is available[7-8]. Based on these requirements, the Markov process simulator (MPS)—a RAM analysis tool that uses the Markov‐Monte Carlo technique—has been developed, demonstrated in simulations, and validated[9]. However, there is a practical limit to the analysis of design alternatives of core parts/components based on RAM analysis alone, especially with the addition of cost elements.

In this study, we propose a methodology to support decisions pertaining to core parts and component selection between the cost‐benefit indicator derivation system development by adding a cost-calculation function to the MPS.

2. Markov Process Simulation

The general probability problem does not consider the concept of time, but phenomena that appear over time are often stochastic. A set of random variables that considers time is called a stochastic process—probability theory without time is static, while time-based probability theory is dynamic.

When the state space is X, and the state at time t is X(t), the Markov process must satisfy the condition given in Eq. (1) for all $x(u),\ 0 \le u < s$[10].

$$P[X(t+s)=j|X(s)=i, X(u)=x(u), 0 \le u < s] \qquad (1)$$
$$= P(X(t+s)|X(s)=i)$$

The above properties are called Markov properties—that is to say, when information about the past and present is available, the conditional distribution in the future depends only on the current information and not on the past information.

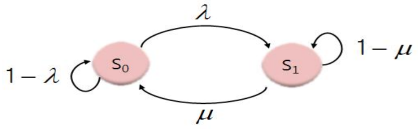


Fig. 1 Two state Markov model

Fig. 1 shows a simple Markov model that considers only operational and failure states.

In the above figure, S0 is operational and usable, S1 is faulty and under repair, λ is the failure rate, and μ is the repair rate. The conditional probability of the failure rate at time (t, t + dt) is λdt, and the conditional probability of repair completion at (t, t + dt) is μdt.

The probability that the system is operational at time t, that is, system availability A (t), is given by Eq. (2)[9], where the first term represents the steady state, and the second term represents the transient state.

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \qquad (2)$$

Transition matrices are transformed into probability matrices by using the Chapman‐Kolmogorov differential equations and are repeated over time to program analytical models that satisfy specific confidence levels by using C, C++, and C# languages. The cost-calculation function is added to estimate LCC, including acquisition cost and operation and maintenance cost, such that the influence of these costs on the LCC can be considered when selecting core parts and components.d while selecting core parts and components.

3. Cost Model and Design Alternative Methodology

3.1 Cost Model

Lifecycle cost can be divided into acquisition cost and maintenance cost. The former comprises development and production costs. Operational maintenance cost is expressed in the cost model as the sum of the costs of replacement repair, maintenance personnel labor, test and support equipment maintenance, and transportation.

3.2 Acquisition Cost

3.2.1 Development Cost

The development cost is the sum of component development costs, excluding purchased products. If the component development cost is C_D, the development cost (C_{RND}) can be expressed as follows:

$$C_{RND} = \sum_{i=1}^{n} (C_D)_i \tag{3}$$

3.2.2 Production Cost

The production cost (C_{SPD}) can be expressed as the product of unit purchase price and inflation rate, as given by Eq. (4). In case of the inflation rate, the concepts of isolation and compounding can be applied, but the model is defined by applying the isolation method to the defense budget. Thus,

$$C_{SPD} = \sum_{k=1}^{n} \left[a_k \times \sum_{i=1}^{n} (C_S)_i \times (1 + \frac{b \times k}{100}) \right] \tag{4}$$

where a_k is the quantity of production in the k^{th} year, b is the inflation rate, [1+(b×k)/100] is the isolation calculation method, and C_S is the unit repair price.

3.3 Operation and Maintenance Cost

3.3.1 Repair Replacement Cost

The cost of replacement parts (C_{TSP}) can be expressed as the sum of consumable item cost (C_{ESP}) and combined component cost (C_{STR}), as given by the following equation:

$$C_{TSP} = C_{ESP} + C_{RSP} \tag{5}$$

The cost of consumable items can be defined as product of the number of repairs (N_{RSV}) of each component and the repair cost (C_S), as given by the following equation:

$$C_{ESP} = \sum_{i=1}^{n} [(N_{RSV})_i \times (C_S)_i] \tag{6}$$

The C_{RSP} is the sum of the number of repairs for each component (N_{RSV}) and the cost of repair (C_S) multiplied by the product of the partial repair coverage (R_{PR}) that can be obtained from the maintenance data of a similar system. It can be calculated as follows:

$$C_{STR} = \sum_{i=1}^{n} [(N_{RSV})_i \times (C_S)_i \times R_{PR}] \tag{7}$$

3.3.2 Maintenance Manpower Cost

The maintenance manpower cost(C_{TML}) can be used to calculate the maintenance labor cost per rank(C_{MLR}) when there is information on the number of personnel assigned to maintenance. However, if there is no personnel information per rank used for maintenance, it can be calculated by applying an average labor rate(C_{MHR}).

Therefore, the model is defined as below to select the method of applying the labor cost and the average rate applying method according to whether the information about the maintenance manpower is available:

$$C_{TML} = \sum_{i=1}^{n} (C_{MLR}) \text{ or } \sum_{i=1}^{n} (C_{MHR}) \tag{8}$$

The method of applying the labor cost by class can be calculated by multiplying the maintenance cost by the maintenance cost and the number of people per hour of the maintenance personnel classified into maintenance and preventive maintenance. The hourly labor cost per class can be calculated using the KIDA report published annually in order to provide consistent and standardized data on defense sector cost analysis[11-12].

$$C_{MLR} = \left[\sum_{i=1}^{n}(C_{CMR} \times N_{CMR} \times T_{CMR})\right] + \left[\sum_{j=1}^{m}(C_{PMR} \times N_{PMR} \times T_{PMR})\right] \tag{9}$$

In this case, C_{CMR} is the labor cost per hour classified by class, N_{CMR} is the number of employees per class, T_{CMR} is the failure maintenance execution time, C_{PMR} is the hourly labor cost per class assigned to preventive maintenance, N_{PMR} is the number of persons, and T_{PMR} is the time to perform preventive maintenance.

In addition, the average rate of application can be calculated as the product of the time(T_{CMH}, T_{PMH}) spent on maintenance and preventive maintenance of the component. The average rate of failure(C_{CMH}, C_{PMH}) can be expressed as follows:

$$C_{MHR} = \left[\sum_{i=1}^{n}(C_{CMH} \times T_{CMH})\right] + \left[\sum_{j=1}^{m}(C_{PMH} \times T_{PMH})\right] \tag{10}$$

3.3.3 Test and Support Equipment Maintenance Costs

The test and support equipment maintenance costs (C_{OMS}) can be input if the information about the related costs is provided. If this information is not available, the cost of testing and support equipment (R_{OMS}) is added to the acquisition cost (C_{RND}), and it can be calculated as follows:

$$C_{OMS} = C_{RND} \times R_{OMS} \tag{11}$$

3.3.4 Transportation Cost

The transportation cost (C_T) is the cost related to transportation in the maintenance, field maintenance, and maintenance costs that supports maintenance work among the costs incurred by the maintenance. The transportation cost can be calculated as a product of transportation cost per weight (C_{TS}), weight (W), and the transport quantity (Q_T).

$$C_T = C_{TS} \times W \times Q_T \tag{12}$$

In this study, because the repair replacement parts are transported in the simulation period maintenance status visit, the number of maintenance state visits (Q_i) can be expressed similarly to the transportation quantity (Q_T).

$$C_T = \sum_{i=1}^{n}[W_i \times (C_{TS})_i \times Q_i] \tag{13}$$

3.4 Selection Method of Design alternative

The methodology for selecting design alternative employs cost-effectiveness indicators. The cost-effectiveness indicator is computed based on the first alternative and the differences between the costs associated with each alternative and their inherent availability (A_i).

$$Cost\,Effectiveness = \frac{(A_i)_\beta - (A_i)_\alpha}{(Cost)_\beta - (Cost)_\alpha} \tag{14}$$

In the above equation, the cost-effectiveness of the first alternative is 1; an alternative with cost-effectiveness higher than 1 is considered superior to the first alternative. Conversely, if the cost-effectiveness of an alternative is lower than 1, it is considered inferior to the first alternative. Thus, if the cost-effectiveness indicator of an alternative is lower than 1, the same cost would be associated with a lower inherent availability because of the shorter mean time between failures (MTBF) or longer mean time to repair (MTTR).

4. Results and Discussion

4.1 The characteristics of surface roughness

As shown in Fig. 2, we modeled five components of an artillery system. The reliability and maintainability of each component are given in Table 1.

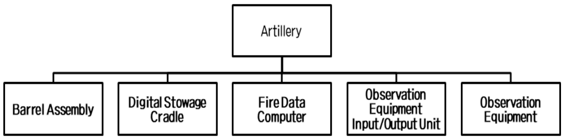


Fig. 2 System model of artillery

Table 1 MTBF and MTTR by component

Name of Item	MTBF	MTTR
Barrel Assembly	936	0.858
Digital Stowage Cradle	176	1.180
Fire Data Computer	825	1.302
Observation Equipment Input/Output Unit	1718	1.222
Observation Equipment	506	1.442

Table 2 OMS/MP of artillery

Classification		Hour(Hr)
Total Operating Hours	OT	806
	ST	7099
	AT	154
Total Down Time	TPM	290.2
	TCM	20.8
	TALDT	390

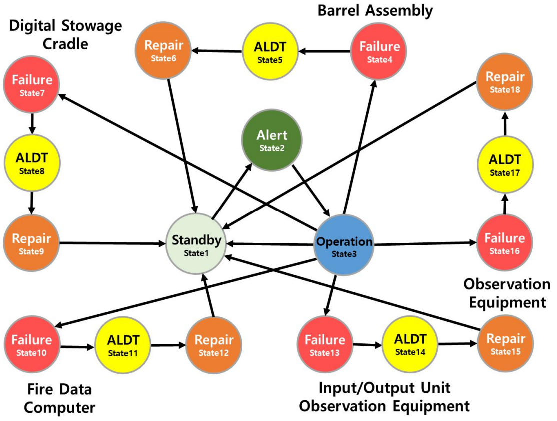


Fig. 3 MPS artillery modeling

The MTTR based on part load analysis and the MTTR based on maintenance forecast were used, and the time by status from the OMS/MP operation type was classified, as given in Table 2. The model was implemented as shown in Fig. 3.

Table 3 lists the development cost and the unit production cost of each canvas system. The labor costs are given in Table 4, and the cost input value and cost input example screen (barrel assembly) are shown in Fig. 4.

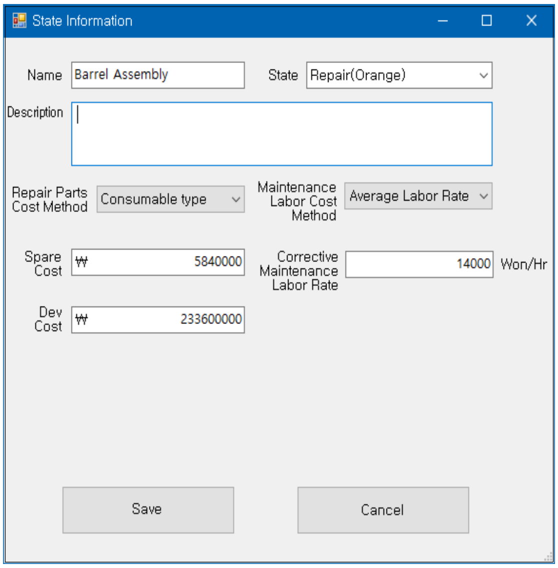
Figure 5 shows that the numbers of units produced in the first, fourth, and fifth years are 100, 600, and 500, respectively. In addition, the estimated maintenance costs of the test and support equipment were 3.5% of the acquisition cost, and the inflation rate for each fiscal year was set to 1.8%.

Table 3 Development cost and unit cost

Name of Item	Development Cost	Production Cost
Barrel Assembly	233,600kWon	5,840kWon
Digital Stowage Cradle	4,202,800kWon	10,507kWon
Fire Data Computer	425,600kWon	10,640kWon
Observation Equipment Input/Output Unit	302,400kWon	7,560kWon
Observation Equipment	472,000kWon	11,800kWon

Table 4 Cost input value for global data

Classification		Input Value
Corrective Maintenance Labor Rate		14,000Won
Preventive Maintenance Labor Rate		13,000Won
Cost per Weight Section	$0 \leq W_i < 5$	5,000Won
	$5 \leq W_i < 10$	7,000Won
	$10 \leq W_i$	10,000Won
Test/Support Equipment Maintenance Cost Ratio		3.5%
Production Quantity	1st Year	100
	2nd Year	600
	3rd Year	500
Inflation Rate		1.8%

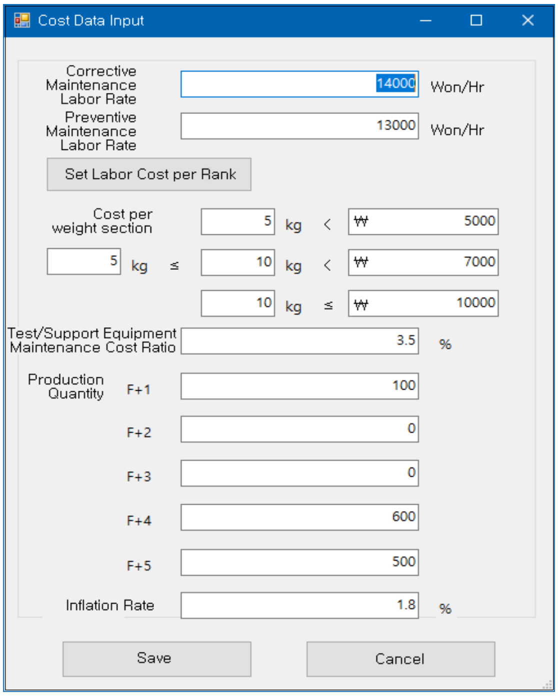


Name: Barrel Assembly
State: Repair(Orange)
Description:
Repair Parts Cost Method: Consumable type
Maintenance Labor Cost Method: Average Labor Rate
Spare Cost: ₩ 5840000
Corrective Maintenance Labor Rate: 14000 Won/Hr
Dev Cost: ₩ 233600000

Fig. 4 Cost input value (Barrel assembly)

To obtain a stable average value of adequate operating time and probability results, we performed a simulation with a simulation time of 15 years (131,400 h) and iteration of 200 cycles.

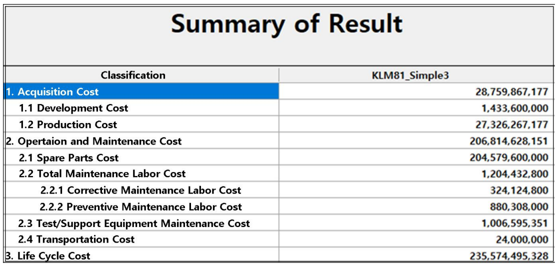
The simulation results are shown in Fig. 6. The acquisition cost is 28,759,867,177 KRW, maintenance cost is 206,814,628,151 KRW, and LCC is 235,574,495,328 KRW.



Corrective Maintenance Labor Rate: 14000 Won/Hr
Preventive Maintenance Labor Rate: 13000 Won/Hr

Cost per weight section: 5 kg < ₩ 5000
5 kg ≤ 10 kg < ₩ 7000
10 kg ≤ ₩ 10000
Test/Support Equipment Maintenance Cost Ratio: 3.5 %
Production Quantity F+1: 100
F+2: 0
F+3: 0
F+4: 600
F+5: 500
Inflation Rate: 1.8 %

Fig. 5 Cost input value window (Global)



Summary of Result

Classification	KLM81_Simple3
1. Acquisition Cost	28,759,867,177
1.1 Development Cost	1,433,600,000
1.2 Production Cost	27,326,267,177
2. Opertaion and Maintenance Cost	206,814,628,151
2.1 Spare Parts Cost	204,579,600,000
2.2 Total Maintenance Labor Cost	1,204,432,800
2.2.1 Corrective Maintenance Labor Cost	324,124,800
2.2.2 Preventive Maintenance Labor Cost	880,308,000
2.3 Test/Support Equipment Maintenance Cost	1,006,595,351
2.4 Transportation Cost	24,000,000
3. Life Cycle Cost	235,574,495,328

Fig. 6 Cost result screen

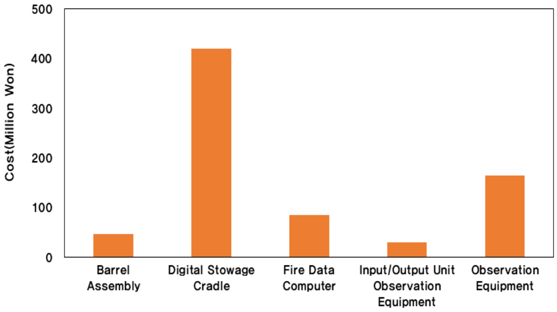


Fig. 7 Repair parts costs of artillery system

Table 5 A_i, MTBF and MTTR by alternative

Type	A_i	MTBF	Development Cost (Won)	Spare Parts Cost (Won)
Alt. 1	0.986	176	5,320,000,000	13,300,000
Alt. 2	0.987	193.6	6,916,000,000	17,290,000
Alt. 3	0.988	228.8	10,108,000,000	25,270,000
Alt. 4	0.988	123.2	4,202,800,000	10,507,000

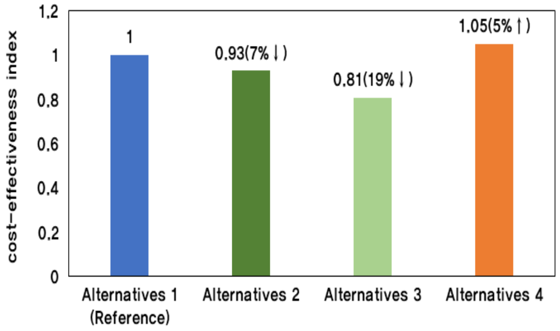


Fig. 8 Simulation result of alternative

The cost of the repair parts is the highest on the digital scale (Fig. 7), calculated in the order of observation equipment, shooting parameters calculator, barrel assembly, and observation data input/output units.

We examined various design alternatives for the digital stowage cradle, which is a core part/component with the highest number of failures. In this case, each alternative must meet the target inherent availability (89.4%) according to OMS/MP. As given in Table 5, alternative 2 has 10% longer MTBF and 30% higher component and development costs than alternative 1, alternative 3 has 30% longer MTBF and 90% higher component and development costs than alternative 1, and alternative 4 has 30% shorter MTBF and 21% lower component and development costs than alternative 1.

The results of the alternative analysis are shown in Fig. 8 in the form of a cost-effectiveness indicator that considers LCC.

The cost-effectiveness index values of alternatives 2, 3, and 4 are lower by 7%, 19%, and 5% compared to that of alternative 1. Thus, we selected alternative 4 from among the various design alternatives as the best option in terms of the cost-effectiveness indicator.

5. Conclusion

In this study, we developed a software application (MPS) that reflects the RAM parameters and costs of the design alternatives to the core parts/components at the system development stage and presented a methodology for selecting the best design alternative. Based on our findings, the following conclusions can be drawn:

1. The proposed Markov model can simulate a design alternative for a given component that reflects the RAM parameters (MTBF, MTTR, etc.) and LCC.
2. The cost model can reflect the development, production, repair replacement, maintenance personnel labor, test and support equipment maintenance, and transportation costs.
3. The cost-effectiveness indicator considering the cost variability and the LCC of each alternative can be determined using the proposed design alternative methodology.

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