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OPTIMIZING SHIP MACHINERY MAINTENANCE SCHEDULING THROUGH RISK ANALYSIS AND LIFE CYCLE COST ANALYSIS

Lahar Baliwangi
Faculty of Maritime Sciences
Kobe University Japan

Kenji Ishida
Faculty of Maritime Sciences
Kobe University Japan

Hidetoshi Arima
Faculty of Maritime Sciences
Kobe University Japan

Ketut Buda Artana
Faculty of Marine Technology
Institute of Technology of Sepuluh Nopember (ITS)
Surabaya Indonesia

ABSTRACT

Ship maintenance scheduling management integrated with risk evaluation and Life Cycle Cost (LCC) assessment approach is developed in this research. It improves upon existing practices in arranging an optimal maintenance schedule by modeling operational and economical risks. This paper researches maintenance scheduling algorithm with explicitly consider risks associated with some operation problems such as operating schedule, routes, ship position, resources availability, and achievement of reliability-availability-maintainability (RAM) of system. Modeling of components RAM with their failures consequences results risk evaluation. Time value of maintenance cost, replacement cost, earning rate, and penalty cost are also simulated. When the system reaches the lowest level of lower limit reliability, one or more components should be maintained or replaced. Since maintenance task may interrupt the operation, to minimize time-to-maintain all possible events of maintaining other components at the same time will be evaluated together with resources availability. By researching those possibilities, constraining the risk, and based on LCC calculation result, an optimal maintenance scheduling can be then well established.

Key Words: Ship maintenance, maintenance scheduling, optimization, life cycle cost, LCC

INTRODUCTION

Various studies regarding reliability engineering, minimizing risk and minimizing maintenance cost have been reported. Since Walter Shewhart -the grandfather of statistical quality control working in Bell Laboratories- introduced applied statistic and probability to control quality, reliability engineering started to become well known. Many events were carried out and many technical ideas and innovations have been developed and been brought to the rise of Reliability Engineering [1]. However, up to present reliability engineering is still a challenge and an interesting subject to develop. One of the very interesting sub-topics related to reliability engineering is risk analysis and maintenance management.

In order to keep a system operates in designed condition; components of system should be continually well maintained. Maintenance tasks ideally should not really interrupt the operation. Due to the complexity of the maintenance tasks and limited time available, ship maintenance and repairing often lack of sufficient evaluation. It is common to maintain ship in a certain periodic time without considering the real condition of each component and possible risks associated. To minimize risk and maintenance cost, a study of maintenance scheduling is needed to provide a more thorough and consistent approach to maintenance and repairing decisions. Research in maintenance engineering has been conducted since more than 30 years ago and, in 1996, has found more than 40 mathematical models of imperfect maintenance [2].

A system would never be aside from economical matter when achieving certain level of reliability and availability. Keeping system in high level of reliability and availability may not always be fruitful. As well as the system maintenance, over or under maintained may not always be profitable. Hence, it becomes a natural problem in managing maintenance because among maintenance section, production section, and finance section sometimes try to keep their own way to improve their own section. Maintenance section is always in luckless positions. When maintenance section asks for maintaining, of course other two sections will try to say "*no*" since maintenance will interrupt production process and increases overall cost and reduces income as well. Hence, the two sections prefer less maintenance, as minimum they can be. Regrettably, when the system fails, maintenance section would be faulted as any failure break the production process and result less revenue. Some ideas to reduce breakdown event have been researched and one of them is by adding redundant component(s) or equipment. One great work has been done to propose an optimal level of reliability and economical value of redundancy for non-repairable system using Net Present Value criterion [3].

Other research related to navy ship maintenance is determined based on factors: running hour of ship, operational requirement, part availability, operational defect, and dockyard availability [4]. In this work, availability level is the most considered than any other factors including economic factor. Therefore, this technique is absolutely not suitable for commercial ship.

The main objective of this research is to establish a method arranging optimum maintenance schedule by analyzing possible risks, maintenance cost and other costs over defined study time (t_s). In this research, decision making criterion utilizes LCC. Several steps in assigning maintenance schedule are proposed by predicting the appropriate time of those activities based on system reliability and LCC. The steps include determining component functions, generating the time predicted and possible component combinations, analyzing alternatives and uncertainties associated, and at last selecting the best alternative using a criterion LCC.

RISK ASSESSMENT

Risk assessment is an information gathering and compilation process to develop an understanding of the risk of a plant [5]. American Bureau of Shipping (ABS) in [5] gives following processes to determine risk levels which consist of four basic steps:

i) Hazard Identification
ii) Frequency Assessment
iii) Consequence Assessment, and
iv) Risk Evaluation

A good assessment assists to determine some actions to minimize disruptions to the plant and plan. Risk assessment also helps to decide whether the strategies to control risk are cost-effective or not. Frequency of risk of a system is studied based on reliability or unreliability of the system.

In short words, risk is a product of two main parts: frequency and consequence [5]. Frequency is related to how often failure occurs and it refers to the probability (Pr) of system failure (system unreliability). Consequence shows what will happen if failure occurs. Any failure impact could be considered as risk consequence such as damage equipment, fire, explosion, environment impact, human injured, human loss, business loss, etc. To simplify and be enumerable, any consequence is then converted in term of money.

Risk = Probability of system failure x **Consequence of system failure**

A risk assessment involves identifying potential fails, predicting the frequency at which failures will occur, and calculating the consequences that would result if they occurred. Risk assessment is performed to inform us operation risk level and commonly followed by risk mitigation such as plant modification, design improvement, operation improvement, maintenance management improvement, etc. An idea in regard to mitigate risk of a system is by maintaining components of system carefully. Therefore, since a system may consist of thousands even more components that need to maintain, maintenance tasks should be well assigned according to the real operating conditions in accomplishing adequate safety level and economical value. Once fault in maintenance scheduling may result very inconvenient business condition and operation, and can be extremely expensive to cover.

LIFE CYCLE COST (LCC) ANALISYS

Combining engineering analysis and economic analysis is commonly called engineering economic analysis. LCC is one of many engineering economic analysis tools has been utilized in many fields [6]. LCC analysis is an engineering economic analysis tool that allows us to quantify the differential costs of alternative investment options for given activities and to find total cost (by analyzing initial costs, annuity or routine cost and discounted future costs) of owning and operating including maintaining an asset over period of time. A research involving LCC in maintenance management is conducted by Carretero et. al. [7]. Further note on applying LCC in maintenance scheduling will be presented in next section.

MAINTENANCE SHCEDULING ALGORITHM

A ship is just like an isolated island where some people live in. To keep their own life and to achieve the purposes, a ship should survive on her own effort for energy, water, food, etc. Thus, all components should be in proper condition to fulfill their functions which means they need proper maintenance. There are many factors stimulating the difficulties of maintaining a ship such as operating schedule, number of components/equipment, classification regulation, wide variety of possible risks, etc. In this research we combine risk analysis result to be utilized as a maintenance management constraint. In addition, economic analysis -LCC- is required as final decision making criterion.

a. Data Collecting and Modeling

First step assigning maintenance schedule is defining component functions. They are reliability (R) function, maintenance cost (CM) function, time to maintain (TTM) function, and reliability after maintained (RFM) function. Those functions are changed by time. Ship earning rate ($/unit time) is also defined. Study time is needed to limit simulation time. Next paragraphs will show how the proposed method works in detail.

Each component has its own reliability function which indicates that the probability of component perform its function in the system at certain time operation and in defined condition. Reducing reliability of mechanical component is caused by deterioration, aging, wear-out, fatigue, etc. To increase the level of reliability, component should be either maintained or replaced. It depends on how good or bad the component is. The Decision of maintaining or replacing is taken based on economic value after safety reason.

Studies of estimating reliability and availability after maintenance have also been figured out in many techniques since 1976 [2]. Treatment methods are also adopted in respect of imperfect maintenance. Thus the reliability of component after maintenance process could be estimated. One of the simplest methods used in many studies is by assumed that the component is perfectly maintained; which means that the component after maintained could be considered as new component. Other method assumes that the component after maintenance could not be as new component rather than younger in term of its age [2,8]. In practice, operating time of component after maintenance is then reduced to a time that related to the quality of the maintenance performed. Better maintenance would shift the time closer to 0 (to the time of the component is new or zero operating time). In simulation, this value is generated by a random number follows a distribution which is data of TTM best fitted.

Maintenance cost function has also been studied for long time. The more aging component (identified from operating time), mostly be the more cost needed for maintenance while replacement cost for mechanical component commonly tends to be the same whenever it is done. If there is any deviation, it is caused merely by time value of money.

Figure 1. shows some typical functions of component: (A) Reliability function; (B) Time to maintain function and time to replace function; (C) Reliability after maintained/replaced function; and (D) Maintenance Cost function and replacement cost function. Each component has its own function.

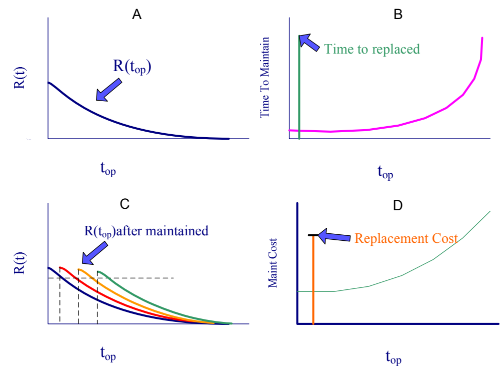


Figure 1. Some typical of component functions.

With t represents the operating period of related component, thus for each component then can be expressed as,

If t_{op} of component *i* , $t_{op-i}= t$ *then*,

$$C_i(t) = f\{R_i(t), MT_i(t), TTM_i(t), CM_i(t), TTR_i(t), CR_i(t), RFM_i(t)\} \quad \text{....(1)}$$

Where

$C_i(t) =$ Component *i* function

$R_i(t) =$ Reliability function of component *i*

$MT_i(t) =$ Type Maintenance of component *i*

$TTM_i(t) =$ Required time to maintain of component *i*

$CM_i(t) =$ Maintenance cost of component *i*

$TTR_i(t) =$ Required time to replace of component *i*

$CR_i(t) =$ Replacement cost of component *i*

$RFM_i(t) =$ Reliability after maintain function of component *i*

t_{op} = operating period of component *i*

b. Failure and reliability modeling

Let us define *T* is random time of a component failure then the distribution of failure or recognized as unreliability function given by,

$$F(t) = \Pr(T < t) \quad (2)$$

Reliability function *R*(*t*) represents the probability that a component does not fail within a certain time interval (0,t), it can be expressed as [9],

$$R(t) = 1 - F(t) \quad (3)$$

By given component data, the reliability of system then be computed. When system reliability function is established, we can start the process of arranging maintenance schedule.

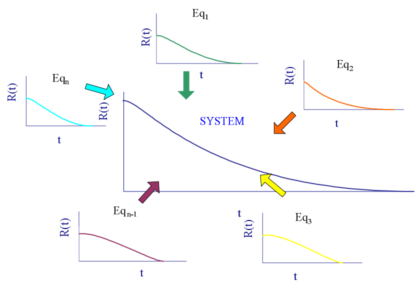


Figure 2. System reliability functions formed by components reliability function

A system configuration could either be a series, parallel, series-parallel, parallel-series, k out of n, redundant, or even complex configuration. Following is a short discussion of system configurations reliability modeling: series and parallel configuration.

Series configuration

The series configuration is the simplest configuration and the most commonly used in practice. The block diagram of series configuration and parallel configuration is given in figure 3.

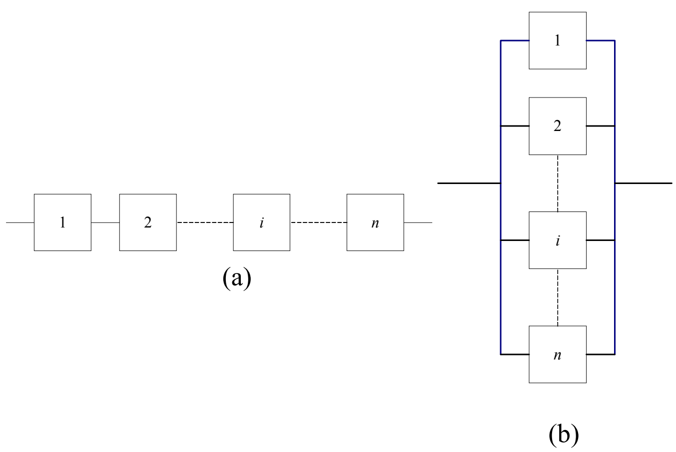


Figure 3. A series configuration (a) and parallel configuration (b)

In this configuration, all components must be operating to assure system operation. The system fails if one of the components fails. If $\Pr(E_i)$ is probability of an event E_i that component i operates successfully during a certain period of time thus reliability function of a series configuration is given by,

$$R_s = \Pr \text{ (all components operate successfully)}$$
$$R_s = \Pr(E_1 \cap E_2 \cap ... E_{n-1} \cap E_n)$$
$$R_s = \prod_{i=1}^{n} \Pr(E_i)$$

Therefore, when assumed that each component operates independently, the system reliability for series configuration could be expressed by,

$$R_s = \prod_{i=1}^{n} R_i \tag{4}$$

Where R_i is reliability of component *i.*

Parallel configuration

In parallel configuration, system fails if all components fail. In other words, system will successfully operate if any component performs its function. Thus, probability of parallel configuration being success is union probability of all paralleled component which can be written as,

$$R_p = \Pr \text{ (any component operates successfully)}$$
$$R_p = \Pr(E_1 \cup E_2 \cup ... E_{n-1} \cup E_n)$$
$$R_p = 1 - \Pr(E_1 \cap E_2 \cap ... E_{n-1} \cap E_n)$$
$$R_p = 1 - \prod_{i=1}^{n} \Pr(E_i) \tag{5}$$

c. Limiting reliability level

In order to limit and speed up simulation, defining system reliability range is needed. That means it is better in that range maintenance of component(s) be performed. When the time for maintenance is selected based on the reliability of the system, the next step is to decide what component(s) should be maintained. Consequently, this process is preceded by defining the reliability range to maintain (RRTM) of component. If we suppose it is decided that the system should be maintenance only if the system reliability less than R_{up} (upper limit of reliability) and for safety reason the system reliability could not less than R_{low} (lower limit of reliability level). On other words, maintenance should be done in between R_{up} and R_{low}.

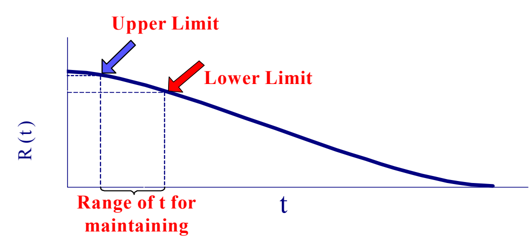


Figure 4. Range of t to execute maintenance

It is noted that operation schedule is also defined to give time constraint where maintenance could not be done at the time when ship could not stop operating. If there is no option and we are about to decide to maintain while ship operates, the consequence of penalty of delayed cargo and ship earning value loss have to be considered. In simulation, all possible times are examined. Simulation tried to trade off between doing maintenance and, loss of earning money and getting penalty. In addition, classification inspection and survey schedule can also be considered in simulation.

d. Possible combinations of components to maintain or/and replaced.

When the upper limit is accomplished and time is running until it reaches below the upper limit point, the next question is what component(s) should be maintained. To avoid unpredicted component maintained, we decide to simulate all possible component combinations. For instance, a system with 2 components will have possible events:

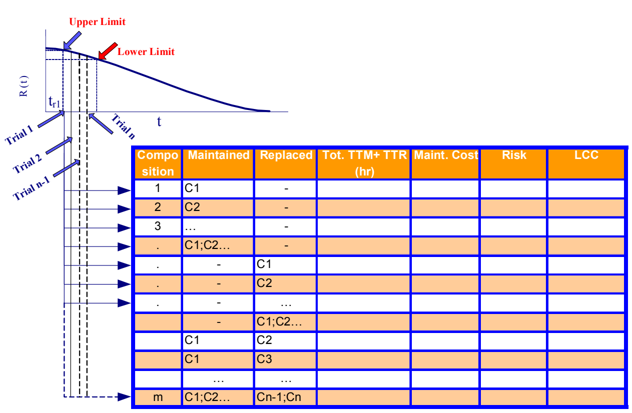
1. C_1 only maintained
2. C_2 only maintained
3. C_1 and C_2 maintained
4. C_1 only replaced
5. C_2 only replaced
6. C_1 and C_2 replaced
7. C1 maintained and C2 replaced
8. C1 replaced and C2 maintained
9. No component maintained or replaced

Thus for a system with n components will have a number of possible events of being maintained or/and replaced or doing nothing that can be expressed as,

$$\text{Number of combinations} = \sum_{i=1}^{2n} x - (n-1) \qquad (6)$$

Where n = number of components

Having all component combinations, we then do trial to execute all combinations at certain range of time (we discussed previously).



Composition	Maintained	Replaced	Tot. TTM+ TTR (hr)	Maint. Cost	Risk	LCC
1	C1	-				
2	C2	-				
3	…	-				
.	C1;C2…	-				
.	-	C1				
.	-	C2				
.	-	…				
	-	C1;C2…				
	C1	C2				
	C1	C3				
	…	…				
m	C1;C2…	Cn-1;Cn				

Figure 5. Simulation trials for all possible combinations

e. Downtime calculation

TTM function is a formulated form work measurement. It is easy to count for a single work of maintenance but with a limited resource onboard and other constrains such as operating schedule, we need to define maintenance type of component i (MT_i) as:

- Floating work without interrupting ship operates as $MT_i(t) = 1$
- Floating work interrupting ship operates as $MT_i\,(t) = 2$ and,
- Docking work as $MT_i\,(t) = 3$

Classifying maintenance work is very important related to calculating the total TTM component(s) in a trial time and maintenance cost counting. Due to the total TTM and to simplify the problem it is assumed that data of TTM is taken in condition where maintenance uses maximum resources. Thus, for instance if we decided to maintain two or more components for $MT_i = 1$ or $MT_i = 2$, the total TTM does not depend on number of available workers. The total time to maintain is sum of TTM of each component. But for the other type of maintenance, $MT_i = 3$, total downtime is calculated as docking time where commonly doing maintenance for many components and using a flexible number of workers.

f. Calculating risk

Risk assessment result can be employed to find the consequence(s) if a failure event happened. For example, in an extreme condition that fuel pipe is overheating, one possible consequence is the occurrence of an explosion. And if explosion occurred it would fire up the engine room and hence all over the ship. Thus, to avoid catastrophic severity, attention should be given to components that contribute to the high risk. Hence, from previous risk assessment of system/ship, we can calculate the risk of all possible compositions; the risk is expressed in term of cost. One simplest countable consequence is downtime caused by maintenance, especially maintenance type 2 and 3 where maintenance interrupts operation. In this condition risk can be given by multiplication of probability of the occurrence and losses regarding of downtime of doing maintenance.

To calculate the loss of interrupting operation, let us define the ship earning rate as CE per unit time or CE(t). Therefore, the consequence of ship during downtime/ maintenance is earning rate function multiplied by total downtime. Other important consequence due to executing maintenance is penalty cost. Penalty cost comes from either renting equipment or claimed delayed cargo. Penalty cost is also given per unit time, CP(t).

g. Calculate LCC for each trial

In this section we discuss how to calculate LCC of each component in different maintenance scenarios. Each scenario has its own economic value. Summarized possible costs is given as,

1. Maintenance cost (CM)
2. Replacement cost (CR) including order cost, administration cost, storing cost etc.
3. Ship earning lost (CE)
4. Penalty cost (CP)

In finding of LCC, the simplest way is to convert all cost to present worth or present value. Therefore, for each trial and each combination at trial time (t_{trial}) j^{th}, all occurred costs are converted to the present value (PV) by a factor called future to present value factor (P/F, *i%, m*),

$$PV_{c,j} = F\,(P/F,\ ir\%,\ m) = F\ \frac{1}{(1+ir\%)^{m}} \qquad (7)$$

Where $PV_{c,j}$ = Present value of activity in time trial j^{th} for a combination c
F = Future value of doing maintenance
ir% = interest rate per unit time
m = number of unit time

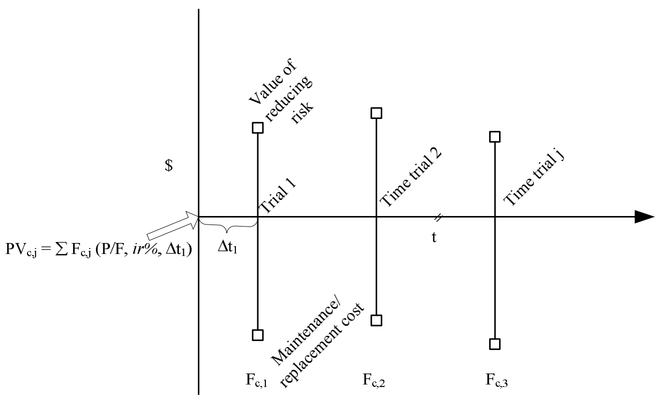


Figure 6. Costs – time diagram

h. Updated reliability after maintained or/and replaced.

Once maintenance executed, the reliability of component(s) should be updated. Updating component reliability has been researched and reported in many techniques. One of them is by shifting to a younger condition point or even assumed to as a good as new. How far the shifting time is, depends on how well the maintenance is. In the simulation, it is represented by the degree of goodness with value between 0-1. 1 (one) means that maintenance is perfect; and 0 (zero) shows that maintenance is worst or fails to bring a component performs its function.

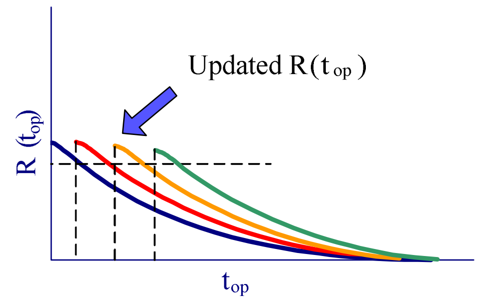


Figure 7. Illustration of updated component reliability

After the component reliability is updated, we recalculate or update the system reliability as well.

i. Simulation result

At this point, we can find whether doing maintenance is economically yielded or not by considering that doing maintenance,

- will reduce the risk in some level that means it will reduce the possible consequences.

but on the other hand it also

- increases the cost by adding maintenance cost or/and replacement

On the other words, it can be expressed as a tradeoff,

Maintenance or/and replacement cost	⟩⟨	Effect of doing maintenance

or

Maintenance or/and replacement cost	⟩⟨	Value of reducing risk

or

Maintenance or/and replacement cost	⟩⟨	Increasing system reliability which means reducing risk

A single point calculation may result local solution. Even in one trial carried out, a combination of components results in a minimum LCC, but it is not guaranteed as the best solution for over time study. Therefore, by trying all possibilities of all combinations in all time trials for over time study will result global minimum LCC.

By repeating for the next period of maintenance for all possible combinations until time of study reached, would result all possibilities of the system maintenance schedule and what components should be maintained. Therefore, from the simulation results, the optimum risk and minimum LCC for over time study are found. To obtain the optimum maintenance schedule is done by minimizing the total cost, CT,

$$\min CT = \sum_{j=1}^{j=time\,study} PV(CM_j(t_{trial\,j}) + CR_j(t_{trial\,j}) + CE_j(t_{trial\,j}) + CP_j(t_{trial\,j}) \quad (8)$$

By setting different level of acceptable reliability, the simulation would result different maintenance schedule with different risk and LCC value. Available operation schedule and times for certain inspection, maintenance, and replacement schedule decided by classification can also be included in this simulation by cancelling t_{trial} when $t_{trial(s)}$ the same with those operation schedules.

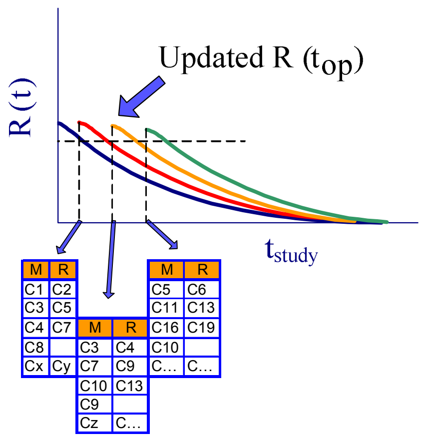


Figure 8. Typical global optimum result for all over time study

CONCLUSION AND FUTURE STUDY

Maintaining components of a system is now not only based on a certain period of time without taking any consideration of operating condition. This consideration is taken by a reason that the component in a system would never have the same operating condition and characteristic. LCC and risk are indicators used for establishing the best maintenance schedule without neglecting the operation schedule.

Research on finding searching of global solution(s) of this algorithm using some optimization methods such as genetic algorithm (GA) and simulated annealing (SA) is in progress.

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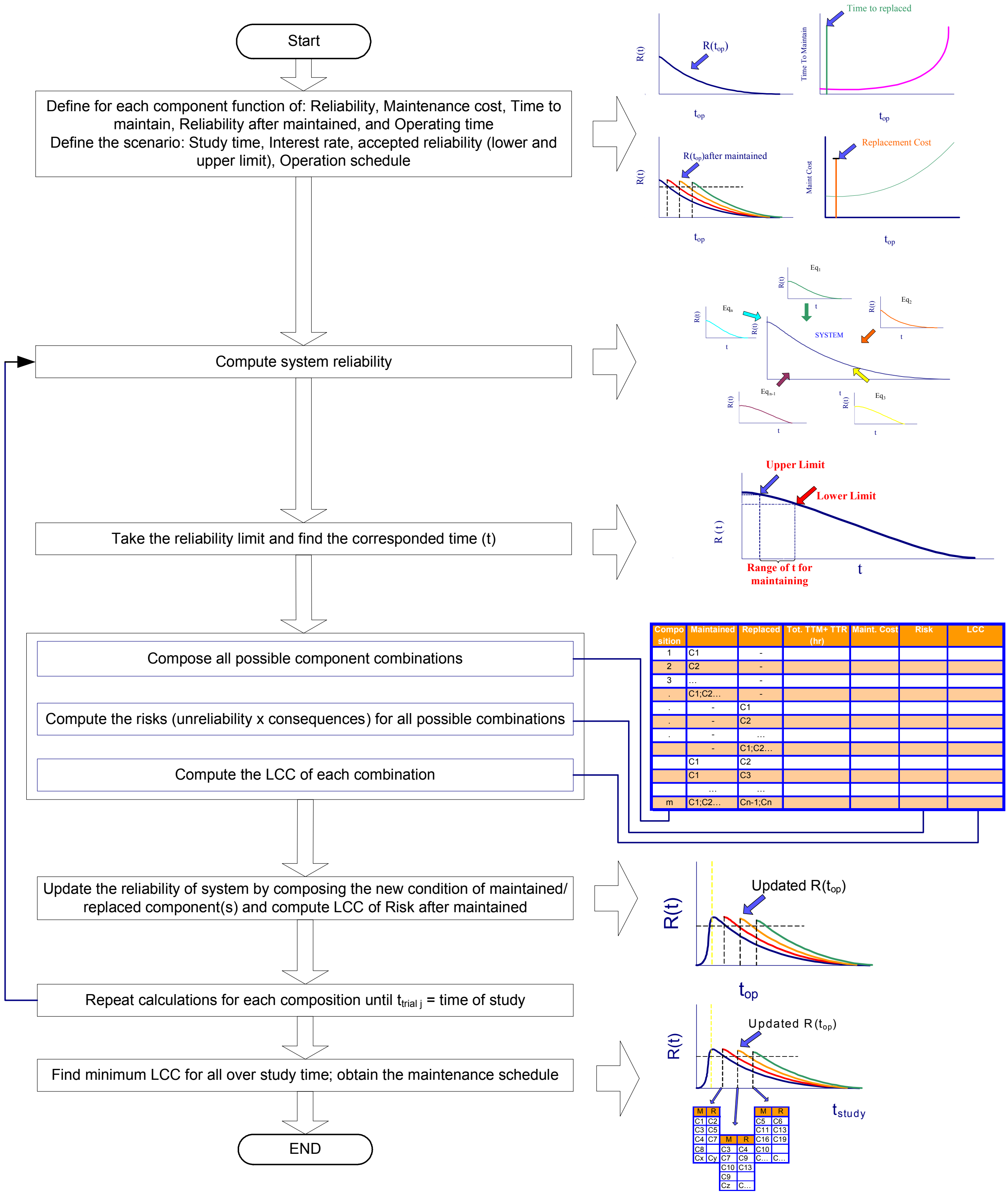
ANNEX A

ALGORITHM FLOWCHART



Compo sition	Maintained	Replaced	Tot. TTM+ TTR (hr)	Maint. Cost	Risk	LCC
1	C1	-				
2	C2	-				
3	...	-				
.	C1;C2...	-				
.	-	C1				
.	-	C2				
.	-	...				
	-	C1;C2...				
	C1	C2				
	C1	C3				
	...	...				
m	C1;C2...	Cn-1;Cn				