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Selection of Non-Repairable Series Systems' Components with Weibull-Life and Lognormal-Repair Distributions through Minimizing Expected Total Cost of Ownership Approach

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Abstract

In this paper a model for selecting Weibull-life and Lognormal-repair components for a series system using Total Cost of Ownership (TCO) approach is proposed. The model has been used for selecting the suppliers of the different components constituting the system. The TCO of the system is calculated for each possible combination of components available in the market and then the combination that gives the minimum TCO is considered for purchasing. The results have showed that the model is able to compromise between the different cost categories such that the optimal cost elements values are between the minimum and maximum values of the cost categories.

Keywords: weibull, lognormal, total cost of ownership, preventive maintenance, corrective maintenance

1. Introduction

System designers usually design their systems according to one of two criteria: The first criterion is based on maximizing the reliability of the system under initial purchasing cost constraint. Under this criterion the designer usually selects the components of the system that will maximize the reliability of the system such that the total initial purchasing cost of the system does not exceed a certain budget. The second criterion for designing the system is based on minimizing the initial purchasing system cost under minimum reliability constraint. Under this criterion the designer usually selects the components for the system that will minimize the total initial purchasing cost of the system such that the overall reliability of the system is not below a certain value. The drawback of these two criteria is that they neglect all other costs required to support and maintain the system during its useful life. Knowing the precise cost of owning the system helps designers to make better designs regarding their systems.

Total Cost of Ownership (TCO) helps designers to make educated financial decisions regarding the designs of their system. TCO goes beyond the purchase price of the asset as it looks at the purchasing price and all other costs required to support and maintain the asset purchased during its useful life. Designers should build their comparison among several alternative designs based on the TCO for these designs. Depending on the type of the application, the calculation of the TCO for a specific system design may include but not limited to the initial purchasing cost of the system, the operating costs of the system, the downtime cost of the system, and the warranty policy of the components. Operating costs are those costs that depend on the hourly usage of the system. Maintenance cost is a major chunk of it. It includes both the corrective and the preventive maintenance costs for the system. Energy consumption is another type of operating costs. The energy consumption depends on many factors like operator's habit and the basic design of the system. Downtime cost includes the cost incurred when the asset stops working for any reason such as maintenance and malfunction. Moreover, warranties for the components play a vital role in the calculation of the TCO as the warranty cost usually is incorporated in the initial purchasing cost of the component while the income from warranty claims can be seen as a reduction in the TCO of that component.

Since Gartner research first proposed TCO model that described the 'hard' and 'soft' costs in 1987, it was widely accepted and used by other researchers. Ellram (1995) examined 11 case study firms that used TCO in their purchases and he discussed the pros and cons associated with the TCO approach. Hitt et al. (1998) describe the application of TCO as a decision tool for managing business processes in government and industry as TCO provides the actual costs and their drivers. Sohn and Moon (1999) provided a three years TCO analysis for four manufacturers of RISC-based server clusters. Results indicate major differences among the TCOs of the four manufacturers. Castellani et al. (2005) addressed the relation between the break-fix group of costs and TCO and discussed the barriers of implementing a successful break-fix strategy and the technologies that facilitate the application of such a strategy. Ellram (1993) explored the pros and cons of TCO. The paper also proposed an eight stage framework for TCO implementation based on case studies of seven firms that used TCO in purchasing. Carrubba (1992) showed how life cycle cost model and cost of ownership model can be used to optimize the life cycle cost from the manufacturer and the customer point of views. Kanagaraj and Jawahar (2011) used the TCO for simultaneous allocation of reliability and redundancy level of components based on three objective goals namely maximization of system reliability, minimization of cost and minimization of TCO under resource constraints. Kumar et al. (2007) used TCO to simultaneously allocate reliability and maintainability in series parallel system subject to minimum availability constraint. Kanagaraj and Jawahar (2009) developed a non-linear Integer Programming to model reliability-based TCO model and solved it using Simulated Annealing Algorithm. Supplier selection and evaluation also found its applications on TCO. Ramanathan (2007) used the TCO as a base for supplier selection. Degraeve et al. (2005) used mathematical programming model based on TCO and Activity -based costing method for supplier selection. Garfamy (2006) used 15 hypothetical firms to demonstrate the usage of TCO in supplier selection.

In this paper a TCO model for a series systems with Weibull-life and Lognormal-repair components has been proposed and used to design these systems. The elements encountered in the TCO calculation are the expected total initial purchasing cost, the expected operating costs, the expected downtime, and the expected warranty reimbursement for the system. All the elements of the TCO have been expressed as a function of the basic characteristics of the components i.e. the life and the repair distributions parameters.

2. Total Cost of Ownership Elements

Considering a series system with k components, the elements that affect the TCO of the system can be divided into four main elements namely, the total initial purchasing cost, the operating costs, the downtime cost, and the warranty reimbursement. The elements of the TCO for a Weibull-life and lognormal-repair components under a full rebate warranty policy will be discussed next.

2.1 Initial Purchasing Cost

Under the assumptions of rational buyers and free and availability of the information about the different components in the market, the initial purchasing costs of the components should depend on their reliabilities, maintainabilities, and warranty policies providing that the supply exceeds the demand for the components. The initial purchasing cost of the component should increase with increasing the reliability and maintainability of the component. The reliability and the warranty policy of the component depend on the parameters of the life distribution, i.e., the Weibull distribution in this case, while the maintainability of the component depends on the repair distribution, i.e., the parameters of the Lognormal distribution.

The total initial cost of k-components system can be expressed mathematically as follows:

$$C_{TotInitCom_s} = \sum_{i=1}^{K} \left(At_{d_i} + \frac{B}{t_{medcm_i}} + \frac{C}{S^2{}_{cm_i}} + \frac{D}{t_{medpm_i}} + \frac{E}{S^2{}_{pm_i}} + \frac{F}{C_{op_i}} - G \times TW_i \right)$$

where $C_{TotInitCom_s}$ is the total initial purchasing cost of the system, A, B, C, D, E, F, G are constants that reflect the relative importance between the different elements of the cost, t_{d_i} is the design life of component *i*, t_{medcm_i} and t_{medpm_i} are the median repair time for corrective and preventive maintenance for product i respectively, $S^2{}_{cm_i}$ and $S^2{}_{pm_i}$ are the shape parameter of the repair time for the corrective and preventive maintenance for product i respectively, C_{op_i} is the cost of other operating cost such as lubricant, energy consumption ... etc for component *i*, and TW_i is the warranty coverage period for component *i*. It should be noticed here that

$$t_{d_i} = \theta_i[-ln(P)]^{1/\beta_i}$$

where P is the reliability of the component at t_{d_i}, θ_i and β_i are the scale and shape parameters for component i, respectively. Also

$$TW_i = \theta_i[-ln(P_w)]^{1/\beta_i}$$

where P_w is the reliability at warranty coverage period TW_i of component *i*.

2.2 Operating Cost

Usually, the operating cost of the component does not depend on the reliability or maintainability of that component, it depends on factors like the size of engine, operator's habits, and loading. This cost information is usually available for the buyer from the suppliers. The total operating cost of the system with k-components can be expressed mathematically as follows:

$$C_{op_s} = \sum_{i=1}^{K} C_{op_i},$$

where C_{op_s} is the operating cost of the system accumulated during the design life and C_{op_i} is the operating cost for component *i*.

2.3 Corrective Maintenance Cost

For a system with non-repairable components, the expected corrective maintenance cost can be divided into two basic costs: component replacement cost and labor. The component replacement cost is the same as the initial purchasing cost of the component as the component has to be replaced and not repaired. The labor cost is a function of crew size, repair time, and hourly wage. The total corrective maintenance cost can be expressed mathematically as follows:

$$C_{cm_s} = \sum_{i=1}^{k} f_{cm_i} \times \left(MTTR_i \times \sum_{j=1}^{CR_{cm_i}} \left(CROW_{cm_{ij}} \times L_{cm_{ij}} \right) + \left(At_{d_i} + \frac{B}{t_{medcm_i}} + \frac{C}{S^2{}_{cm_i}} + \frac{D}{t_{medpm_i}} + \frac{E}{S^2{}_{pm_i}} + \frac{F}{C_{op_i}} - G \times TW_i \right) \right)$$

where f_{cm_i} is the number of times the corrective maintenance is performed during the design life of the component, $MTTR_i$ is the mean time to repair for component *i*, CR_{cm_i} is the corrective maintenance crow size needed to replace component *i*, $CROW_{cm_{ij}}$ is the crow member *j* needed in replacing component *i* when performing corrective maintenance, $L_{cm_{ij}}$ is the wage per hour for corrective maintenance crow member *j* for component *i*.

It should be noticed that

$$f_{cm_i} = \frac{t_{d_s}}{MTBF_i},$$

where $MTBF_i = \int_0^{T_i} exp\left(\left(\frac{-t}{\theta_i}\right)^{\beta_i}\right)$, T_i is the preventive maintenance cycle time for component *i*, t_{d_s} is the design life of the system and can be calculated as follows :

$$R_s(t_{d_s}|\boldsymbol{\theta},\boldsymbol{\beta}) = exp\left(-\sum_{i=1}^{K}\left(\frac{t_{d_s}}{\theta_i}\right)^{\beta_i}\right) = P_s,$$

where P_s is the reliability of the system at t_{d_s} and $\boldsymbol{\theta}$ and $\boldsymbol{\beta}$ are the scale and shape parameters vectors of the k Weibull-life components, respectively**.**

2.4 Preventive Maintenance Cost

The preventive maintenance cost can be divided into two basic costs: fixed cost for each time the preventive maintenance is carried out and the labor associated with this maintenance. The labor cost is a function of crew size, repair time, and hourly wage. The total preventive maintenance cost can be expressed mathematically as follows:

$$C_{pm_s} = \sum_{i=1}^{k} \left(f_{pm_i} \times \left(MPMT_i \times \sum_{j=1}^{CR_{pm_i}} \left(CROW_{pm_{ij}} \times L_{pm_{ij}} \right) + PRCost_i \right) \right),$$

where f_{pm_i} is the number of times the preventive maintenance is performed during the design life of the component, $MPMT_i$ is the mean preventive maintenance time for component i, CR_{pm_i} is the preventive maintenance crow size needed for component i, $CROW_{pm_{ij}}$ is the crow member j needed in performing preventive maintenance for component *i*, $L_{pm_{ij}}$ is the wage per hour for preventive maintenance crow member *j* for component i, $PRCost_i$ is a fixed cost per preventive maintenance associated with component *i*.

It should be noticed that

$$f_{pm_i} = \frac{t_{d_s}}{T_i}.$$

2.5 Downtime Cost

For this paper purposes, the downtime is the total time that the system cannot work due to performing the corrective or preventive maintenance. The downtime cost can be calculated by multiplying the total time of performing maintenance by the unit cost of downtime. Mathematically it can be expressed as follows:

$$C_{DT} = \left(\sum_{i=1}^{k} floor\left(f_{cm_i}\right) \times MTTR_i + \sum_{i=1}^{k} floor\left(f_{pm_i}\right) \times MPMT_i\right) \times UDT,$$

where UDT is the time unit cost of downtime and $floor(X)$ is the smallest integer of X.

2.6 Warranty Reimbursement

The warranty reimbursement is the sum of the payments that the component's manufacturer will pay to compensate for the failure of the component. Under full rebate policy, the manufacturer will pay the full cost of the initial purchasing price when the component fails within the coverage period. The warranty reimbursement can be calculated by multiplying the initial purchasing cost of the component by the number that this component will fail within the coverage period. Mathematically, it can be expressed as:

$$P_{w_s} = \sum_{i=1}^{K} \frac{TW_i}{MTBF_i}\left(At_{d_i} + \frac{B}{t_{medcm_i}} + \frac{C}{S^2{}_{cm_i}} + \frac{D}{t_{medpm_i}} + \frac{E}{S^2{}_{pm_i}} + \frac{F}{C_{op_i}} - G \times TW_i\right)$$

2.7 Total Cost of Ownership for the System

The total cost of ownership for the system, TCO_s, is simple the sum of the different elements mentioned earlier, mathematically it can be expressed as:

$$TCO_s = C_{TotInitCom_s} + C_{op_s} + C_{cm_s} + C_{pm_s} + C_{DT} - P_{w_s}.$$

It should be noticed here that the TCO is a function of the life and repair distributions parameters. Unfortunately, the effect of changing the values of these parameters may differ from element to element of the TCO. For example increasing the values of the scales parameters of the system components results in increasing the initial purchasing cost of the system as the system becomes more reliable, but in the same time this increase in the reliability will decrease the corrective maintenance cost of the system as less failures will occur among its components. Also increasing the shape parameter will decrease the reliability of the system the matter that will decrease the initial purchasing cost of it, but in the same time will increase the corrective maintenance cost as more failures will occur. The inconsistency in the effects calls for optimizing the parameters of the life and repair distributions through minimizing the TCO of the system to design the best system under practical constraints. The solution for the minimization problem can be seen as a design for the system as the parameters values can help the designer to determine the needed components for the system and then contact the manufacturers to manufacture them. Another way this model can be used is in supplier selection. The TCO of the system is calculated for each possible combination of components available in the market and then the combination that gives the minimum TCO is considered for purchasing.

3. The Proposed Model

The complete model can be written as:

$$min\ TCO_s | \boldsymbol{\theta}, \boldsymbol{\beta}, \boldsymbol{t_{medcm}}, \boldsymbol{S^2{}_{cm}}, \boldsymbol{t_{medpm}}, \boldsymbol{S^2{}_{pm}}, \boldsymbol{T}$$

s.t

$$\boldsymbol{\beta} > 1$$

$$\boldsymbol{t_{medcm}} \ll \boldsymbol{T} \ll \boldsymbol{t_d}$$

$$\boldsymbol{t_{medpm}} \ll \boldsymbol{T}$$

$$\boldsymbol{LL_{\theta}} \leq \boldsymbol{\theta} \leq \boldsymbol{UL_{\theta}}$$

$$\boldsymbol{LL_{L_{pm}}} \leq \boldsymbol{L_{pm}} \leq \boldsymbol{UL_{pm}}$$

$$\boldsymbol{LL_{t_{medcm}}} \leq \boldsymbol{t_{medcm_i}} \geq \boldsymbol{UL_{t_{medcm}}}$$

$$\boldsymbol{LL_{S^2{}_{cm}}} \leq \boldsymbol{S^2{}_{cm}} \geq \boldsymbol{UL_{S^2{}_{cm}}}$$

$$\boldsymbol{LL_{t_{medpm}}} \leq \boldsymbol{t_{medpm}} \geq \boldsymbol{UL_{t_{medpm}}}$$

$$\boldsymbol{LL_{S^2{}_{pm}}} \leq \boldsymbol{S^2{}_{pm}} \geq \boldsymbol{UL_{S^2{}_{pm}}}$$

$$\boldsymbol{\theta}, \boldsymbol{\beta}, \boldsymbol{t_{medcm}}\,, \boldsymbol{S^2{}_{cm}}\,, \boldsymbol{t_{medpm}}\,, \boldsymbol{S^2{}_{pm}}, \boldsymbol{T} \geq 0$$

The first constraint demands that all the components used in the system should be in the wear out region of the bathtub model as the shape parameters of the components are assumed to be more than 1. The second constraint demands that the times for the scheduled preventive maintenance of the components are much less than the design lives of the corresponding components and in the same time the corrective maintenance times are much less than the times for the scheduled preventive maintenance. The third constraint also demands that the times for the scheduled preventive maintenance of the components should be much more than the time needed to perform the preventive maintenance. All these constraints are achievable in practice. Moreover, the model assumes that the units fail independently and this assumption is also feasible as the components are in a series configuration.

Caution should be taken in reading the results of this model. The Parameters values limits involved in calculating the TCO depend on the available manufacturing technology. For example, having extremely high reliability or extremely low repair time for a component may not be feasible in terms of available manufacturing technology. Therefore, combinations of parameters that do not make sense should be neglected from the feasible set of results for the model. This can be easily done by having an upper and lower limits constraints for the parameters values. Constraints 4 to 9 impose practical limits on the different parameters values.

This model can be used in two ways: components design and supplier selection. In supplier selection, there is no need to include constraints 4-9 as the list of components along with their characteristics are already available.

4. Illustrative Example

To demonstrate the effectiveness of the model as a supplier selection tool, a system with 9 subsystems and four different subsystems' manufacturers is considered. The total number of different combinations for building the system is 262144 combinations, from which, the best combination with minimum expected TCO is selected as the optimal system design. The components follow a Weibull life distributions and lognormal preventive and corrective maintenance time distributions with a fixed preventive maintenance schedules.

The number of corrective maintenance crow needed per subsystem is 2, 3, 5, 4, 2, 3, 4, 2, and 3 respectively while the numbers for the preventive maintenance are 3, 4, 2, 2, 2, 3, 2, 2, and 3 respectively. The cost per subsystem of material needed for the preventive maintenance is 1000, 1500, 1210, 1425, 1348, 2416, 1997, 2105, and 2406 respectively. The down time unit cost is $1000.

The constants used in calculating the initial system cost are as follows: A =$10, B = 0.1 $.month, C= 0.1 $.month, D=0.01 $.month, E= 0.01 $.month, F= 1e10 $^{2}, G=$100. It should be noticed here that the values for the constants are decision maker choice that reflect the relative importance of the different cost elements. The other pertaining information for the problem is given in Tables 1, 2, and 3.

Table 1. Characteristics of the different components produced by the different manufacturers

Parameter	Subsystem 1				Subsystem 2				Subsystem 3			
Manuf.	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
Theta/month	30	15	43	58	50	18	17	59	67	45	19	62
Shape	3	3	3	2	2	2	3	3	3	2	3	2
TmedCm/hr	5	8	7	5	9	4	6	5	7	4	6	4
S2medcm/hr	2	2	2	2	2	2	2	2	2	2	2	2
tmedpm/hr	2	1	1	1	1	1	1	2	1	1	1	1
S2medpm/hr	2	1	1	1	1	1	1	1	1	1	1	1
T/Month	9	12	4	12	10	8	7	5	10	5	3	10

Parameter	Subsystem 4				Subsystem 5				Subsystem 6			
Manuf.	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
Theta/month	33	30	57	13	15	53	49	44	56	55	59	30
Shape	2	3	2	3	3	3	3	2	3	3	3	2
TmedCm/hr	4	9	6	8	10	7	8	9	7	8	4	10
S2medcm/hr	2	2	2	2	2	2	2	2	2	2	2	2
tmedpm/hr	1	2	2	1	1	1	1	2	1	1	1	1
S2medpm/hr	1	1	1	1	1	1	1	1	2	1	1	1
T/Month	9	10	9	7	6	11	6	11	10	11	8	9

Parameter	Subsystem 7				Subsystem 8				Subsystem 9			
Manuf.	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
Theta/month	54	46	36	16	59	33	49	57	19	20	45	42
Shape	2	2	3	3	3	2	2	2	3	2	2	3
TmedCm/hr	5	5	9	7	9	6	5	4	8	7	7	8
S2medcm/hr	2	2	2	2	2	2	2	2	2	2	2	2
tmedpm/hr	1	1	1	1	1	1	1	1	1	1	1	2
S2medpm/hr	1	1	1	1	1	1	1	1	1	1	1	2
T/Month	12	7	3	11	9	6	12	5	9	9	6	4

Table 2. Wages per hour for the corrective maintenance crow

	Subsystem								
Crow member	1	2	3	4	5	6	7	8	9
1	18	11	23	13	17	22	15	16	28
2	12	36	12	16	14	12	11	30	23
3	0	20	30	20	0	34	10	0	16
4	0	0	10	16	0	0	14	0	0
5	0	0	19	0	0	0	0	0	0

Table 3. Wages per hour for the preventive maintenance crow

	Subsystem								
Crow member	1	2	3	4	5	6	7	8	9
1	13	15	12	14	19	14	24	15	12
2	12	18	12	13	11	16	21	15	17
3	10	12	0	0	0	14	0	0	16
4	0	12	0	0	0	0	0	0	0

From Table 1, it should be clear that there are 262144 different combinations for building the system. Table 4 shows the best combination chosen by the model. For example, the model chose the component from manufacturer 3 for the subsystem 1. The overall system is shown in Figure 1.

Table 4. The best combination chosen by the model

Parameter	Subsystem 1				Subsystem 2				Subsystem 3			
Manuf.	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
Theta/month	30	15	43	58	50	18	17	59	67	45	19	62
Shape	3	3	3	2	2	2	3	3	3	2	3	2
TmedCm/hr	5	8	7	5	9	4	6	5	7	4	6	4
S2medcm/hr	2	2	2	2	2	2	2	2	2	2	2	2
tmedpm/hr	2	1	1	1	1	1	1	2	1	1	1	1
S2medpm/hr	2	1	1	1	1	1	1	1	1	1	1	1
T/Month	9	12	4	12	10	8	7	5	10	5	3	10

Parameter	Subsystem 4				Subsystem 5				Subsystem 6			
Manuf.	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
Theta/month	33	30	57	13	15	53	49	44	56	55	59	30
Shape	2	3	2	3	3	3	3	2	3	3	3	2
TmedCm/hr	4	9	6	8	10	7	8	9	7	8	4	10
S2medcm/hr	2	2	2	2	2	2	2	2	2	2	2	2
tmedpm/hr	1	2	2	1	1	1	1	2	1	1	1	1
S2medpm/hr	1	1	1	1	1	1	1	1	2	1	1	1
T/Month	9	10	9	7	6	11	6	11	10	11	8	9

Parameter	Subsystem 7				Subsystem 8				Subsystem 9			
Manuf.	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
Theta/month	54	46	36	16	59	33	49	57	19	20	45	42
Shape	2	2	3	3	3	2	2	2	3	2	2	3
TmedCm/hr	5	5	9	7	9	6	5	4	8	7	7	8
S2medcm/hr	2	2	2	2	2	2	2	2	2	2	2	2
tmedpm/hr	1	1	1	1	1	1	1	1	1	1	1	2
S2medpm/hr	1	1	1	1	1	1	1	1	1	1	1	2
T/Month	12	7	3	11	9	6	12	5	9	9	6	4

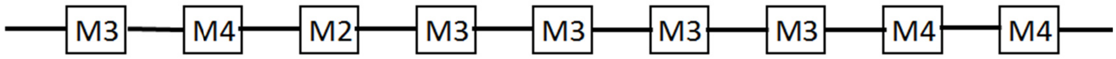

Figure 1. A schematic diagram for the optimal system

The costs associated with this choice over the design life of the system is as follows: TCO $579850.6, Initial purchasing cost $142742.4, Operating cost $567479, Corrective maintenance cost $155540.9, Preventive maintenance cost $10789.51, Downtime cost $56000, and the Warranty payments $352701.2.

Table 6 shows the minimum and the maximum values of the different cost elements in the 262144 combinations. Comparing the optimal cost values obtained by the model with Table 6, one can see that the model compromises between the different cost categorize such that the optimal cost elements values are between the minimum and maximum values of the cost categories.

Table 6. Minimum and the maximum values of the different cost elements

	Initial	Operating	CorMainCost	PrMaCost	DTC	Warranty
min	140142.4	567479	155127.6	3438.244	44000	15351.7
max	148319.8	567479	173190.6	23895.4	85000	352821.9

5. Conclusions

In this paper a model for selecting Weibull-life and Lognormal-repair components for a series system using Total Cost of Ownership (TCO) approach is proposed. The model has been used for selecting the suppliers of the different components constituting the system. The TCO of the system is calculated for each possible combination of components available in the market and then the combination that gives the minimum TCO is considered for purchasing. The results have showed that the model is able to compromise between the different cost categories such that the optimal cost elements values are between the minimum and maximum values of the cost categories.

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