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Economy of Reliability

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Abstract

The simultaneous influence of several random quantities can be studied by the Latin hypercube sampling method (LHS). The values of distribution functions of each quantity are distributed uniformly in the interval (0; 1) and these values of all variables are randomly combined. This method yields statistical characteristics with less simulation experiments than the Monte Carlo method. In this chapter, the creation of the randomized input values is explained.

Keywords: Probability, Monte Carlo method, Latin Hypercube Sampling, probabilistic transformation, randomization

Permanent effort exists to make the components and constructions more reliable and with longer life. Higher reliability can be achieved by better design and more ample dimensioning of load-carrying parts and by better maintenance. However, all these cost money, and one can ask: How is reliability related to the costs? Does an optimum reliability exist from the costs' point of view? How can it be found? This chapter is devoted to the following issues: (1) optimum time for the renewal of objects with gradual deterioration, (2) optimum dimensions of the cross-section of load-carrying components that can fail suddenly (e.g. due to overloading) or due to fatigue or similar processes, (3) optimum probability of failure, and (4) cost-based optimum strategy of the maintenance and renewal of a group of objects.

1. Optimum time for the renewal of deteriorating objects

Examples of deteriorating objects are machines, cars, bridges, cutting tools, pumps, or aircrafts. Basically, there are three kinds of costs related to these objects: (1) purchase costs C_0 , (2) costs for operation C_{op} , and (3) costs caused by a failure $C_{f,p}$. Their sum creates the total costs C_{tot} .

$$C_{\text{tot}}(t) = C_0 + C_{\text{op}}(t) + C_{\text{f,p}}(t) ; \quad (1)$$

t denotes the time of operation. The general time course of the costs is depicted in Figure 1. The purchase costs C_0 is the money spent for buying or manufacturing or building the object. C_0 is spent at the instant of its purchase and remains constant until the failure or replacement by another object. The operation costs $C_{\text{op}}(t)$ have several components, such as costs of energies, fuels, processed material, common maintenance, and small repairs. Basically, these costs should grow approximately linearly with the time. For example, fuel is consumed continuously during any car ride. However, as the technical condition of the object gets gradually worse, the operation costs after some time start growing faster (the fuel consumption of a worn engine becomes higher, some small parts must be exchanged more often, etc.). The failure-related costs $C_{\text{f,p}}(t)$ mean here the probable costs, which can be determined as

$$C_{\text{f,p}}(t) = C_{\text{f,tot}} \times F(t) ; \quad (2)$$

$C_{\text{f,tot}}$ is the total costs caused by the failure, which consist of the price for the replacement of failed components or parts and additional costs, such as damages of other objects caused by this failure, costs due to the fall-out of production, and costs related to injuries or casualties. $F(t)$ means the probability of failure caused by gradual deterioration (see Figure 1 and Chapter 16). When a new object is put into service, this probability equals zero and remains very low for a relatively long part of its life. Later, however, it gradually grows faster and faster due to the worsening condition of the object.

Note: The concept of probable failure-related costs $C_{\text{f,p}}$ and economic optimization of the allowable probability of failure makes sense in cases with many objects involved, where failures can occur more often, but the total managed property is so high that the administrator can include the average losses easily into his expenses. For example, a collapse of a bridge is a very costly event. However, the administrator of a bridge network comprising hundreds of bridges knows that several million Euros will be needed every year for repairs and thus prepares funds for them. On the contrary, a small manufacturer, who owns only one workshop, can become bankrupt if the workshop collapses due to overloading by snow, just because he has not enough money to build a new one. The total actual loss C_0 (e.g. 10^5 €) is incomparably higher than the probable loss $C_{\text{f,tot}} \times F$ included into the economic optimization, which would make only 1 € for failure probability $F = 1:10^5$. All insurance systems are based on the idea of distributing the rarely occurring high losses over many subjects. (This also illustrates the fact that the concept of probable costs $C_{\text{f,p}}$ is sometimes inadequate, and the allowable failure probability must be based on the other criteria.)

The optimum lifetime from the economic point of view is that the object attains during its life the minimum costs per unit of the demanded production or service [e.g. per 1 km for a vehicle, per one machined part in the case of a cutting tool, per time unit of service (e.g. year) of a

Figure 1. Development of costs with time (a schematic). C_0 , purchase costs; C_{op} , operation costs ($C_{op,id}$, ideal case); $C_{f,p}$, failure-related probable costs; C_{tot} , total costs; t , time.

bridge, etc.]. The lifetime means the time until the demolition, complete overhaul, or replacement by a new one. Equation (1) can be rewritten as

$$C_{tot,1}(t) = C_{tot}(t)/t = C_0/t + C_{op}(t)/t + C_{f,p}(t)/t. \quad (3)$$

The time course of individual components and of the total unit costs is depicted schematically in Figure 2. One can see that the total unit costs $C_{tot,1}$ attain a minimum at certain time t_{opt} . This is the optimum time for replacement. For all other times, the economy of operation is worse. This can be illustrated on the example of a car. Everybody understands that it will not be economical to buy a new car every year. Similarly, it will not be reasonable to use one car for 50 years or more because of the increasing fuel consumption and the necessity to buy spare parts more often (provided they would be available for so long time).

The optimum condition for renewal must be understood in a wider sense. From a mathematical point of view, the optimum is exactly the time, for which $dC_{tot,1}/dt = 0$, and nowhere else. However, only seldom can a repair be done at just this instant. On the other hand, the curve $C_{tot,1}(t)$ changes very slowly near the optimum (Fig. 2), and often it does not matter if the reconstruction of a bridge, for example, is done 1 month earlier or later. This makes the planning of maintenance and repairs easier.

2. Optimum dimensioning of load-carrying components — sudden failure

Sudden failures occur due to a “weak” component or overloading from external cause (e.g. snow, wind, flood, or error in operation). The failure can be a fracture, permanent deformation,

Figure 2. Development of unit costs with time. (The symbols are explained in Figure 1.)

or collapse of a structure. Failure by overloading can occur at any time. If it happens before the end of the assumed service life, the system must be put back into its original state either by repairing the failed component or by replacing it by a new one. More ample dimensioning of the load-carrying parts means higher safety and lower probability of failure due to overloading, but also higher price of the component. One can thus seek such dimensions, which will guarantee the best combination of high reliability and low costs.

The influence of the size of the cross-section on the probability of failure and total costs was studied by Menčík [1]. The main results for a bar loaded by tensile force are shown in Figures 3 to 5. The nondimensional scales express the ratio of individual values (C_{tot} and A) to the reference values C^* or A^* as a function of the cross-section area. Also, the failure probability P_f is shown. The individual curves correspond to various magnitudes of the failure-related costs (Fig. 3a) and to the various rates of the cost increase with the cross-section area (Fig. 3b).

Typical is the fast increase of costs with the decreasing cross-section at the left part of the diagram. For small cross-sections, the probability of failure increases and the failure-related costs are no more negligible. The cost growth after the minimum has been reached is usually much slower. The analysis for various cases has also revealed that the economically optimal failure probability is sometimes relatively high (e.g. 10^{-3} or even more). This is acceptable if the costs caused by a failure are low. For higher failure losses, the optimum failure probability will be lower. It is thus important that all possible losses be included into $C_{f,a}$. The relatively high number of failures of some product can even cause the loss of customer reliance, which can lead to the bankruptcy of the manufacturer. Another example is the disaster of the space shuttle Challenger in 1986 due to the failure of a sealing ring. The price of such sealing ring is minute. If, however, the price of a destroyed space shuttle should be added to it, the total costs and $P_{f,opt}$ would be quite different. The differences in optimum dimensions can exist if big differences in the probable failure-related losses exist (e.g. due to the different financial compensation for the accident victims in various countries).

Figure 3. Total costs C_{tot} and failure probability P_f as functions of the cross-section area A (a schematic, after [1]). Curves 1 to 3 in (a) correspond to increasing failure costs and curves 4 to 6 in (b) correspond to increasing costs per unit of the cross-section area. The scales for costs and the cross-section area are standardized, and the scale for P_f is logarithmic.

Based on the same data as above, Figure 4 shows the total costs C_{tot} as a function of the failure probability P_f . Obvious is the fast increase of the costs for higher values of P_f due to the growing probable costs $P_f(C_0 + C_{f,a})$. The probable failure-related costs are usually negligible for $P_f < 10^{-6}$, but significant for $P_f > 10^{-1}$. It is also obvious that the probability of failure, corresponding to the minimum total costs, is relatively high. Sometimes, other criteria are thus decisive rather than the costs.

These examples assumed that the cross-section area can change continuously. The reality is often more complex: the cross-section of standardized components changes stepwise, and so also the price. The computations should thus be done for all possible nominal cross-sections and arrangements, and the variant with minimum total costs can be chosen.

Figure 4. Total costs C_{tot} as functions of failure probability P_f [1]. Curves 1 to 3 correspond to increasing failure costs and curve 7 shows the probable failure costs P_f . The curves correspond to the same input values as in Figure 3a.

3. Optimum dimensioning of components with stress-enhanced deterioration

Examples of gradual deterioration are fatigue or wear of metallic parts as well as corrosion, creep at increased temperature, or carbonation of concrete. In these cases, the failure occurs after some time of operation depending on the load. Thus, the costs must be related to the time to failure or replacement of the component T_f , and the cost-effectiveness is evaluated according to the unit costs (i.e. the costs per unit time of operation),

$$C_{\text{tot},1}(t) = C_{\text{tot}} / T_f. \quad (4)$$

The time to failure depends on the load effect S , which is the stress amplitude in cyclical loading, the force acting on a ball bearing, or the intensity of creep or corrosive environment. In the simplest case, the lifetime T_f decreases with increasing S according to the formula:

$$T_f = BS^{-m}; \quad (5)$$

B and m are material constants. Equation (5) is known as $S-N$ curve for fatigue, with S denoting the stress amplitude. However, as shown in Chapter 6, Equation (5) can also be used for the prediction of the time to failure of a body with a slow crack growth or the endurance of components exposed to creep at high temperatures, the lifetime of bearings, as well as several other cases.

The load effect S depends on the load L and the size of the cross-section under load as

$$S = L / Z, \quad (6)$$

where L is the amplitude of characteristic load (tensile force or bending moment) and Z is the characteristic parameter of the cross-section (the area for tension or section modulus for bending). The expected lifetime T_f may thus be expressed as

$$T_f = B(Z / L)^m, \quad (7)$$

and can be ensured by proper dimensioning (Z).

The relationships between cross-section size, costs, and time to failure may be used for studying the influence of the cross-section size on the cost-effectiveness. Figures 5 and 6 show the development of unit costs and time to failure as the function of the diameter of a shaft loaded in tension (Fig. 5) and bending (Fig. 6a,b). Also, these diagrams can be plotted in non-dimensional coordinates.

Figure 5. Unit costs C_1 and time to failure T_f as functions of shaft diameter D (a schematic, [1]). Component loaded in tension, fatigue exponent $m = 3.0$.

Several important conclusions can be drawn from this analysis. An optimum with minimum unit costs exists only in some cases. Sometimes, it lies outside the suitable interval of service times or acceptable dimensions of the cross-section. An important role is played by the kind of loading and fatigue exponent m . The situation for tensile loading is better: for the common values of fatigue exponent in metals ($2 < m < 6$), an optimum often exists (Fig. 5). For bending, the increase of the characteristic cross-section dimension (e.g. diameter D) causes the increase of the cross-section area, $A \sim D^2$, and also a faster increase of the section modulus ($Z \sim D^3$) and thus much faster growth of useful life ($T_f \sim Z^m$). As a consequence, any enlargement of the

Figure 6. Unit costs C_1 and time to failure T_f as functions of shaft diameter D [1]. Bending load, fatigue exponent $m = 3.0$ (a) and $m = 1.7$ (b).

cross-section usually leads to the reduction of unit costs C_1 (Fig. 6a); the exception is low values of fatigue exponent, $m < 1.7$, where also a cost minimum exists (Fig. 6b).

Because of the many factors involved, it is impossible to formulate simple universal rules for finding the optimum size. A more practical way is to model the situation for admissible ranges of the input quantities. A graphical representation is very useful. Sometimes, it becomes obvious that the unit costs vary only monotonously or insignificantly in the possible range of input variables, which can make the choice of optimum dimensions easier.

4. Cost-based maintenance optimization of long-life objects

Examples of such objects are bridges, cooling towers, locomotives, or heavy machines in power plants. Two cases can be distinguished: maintenance optimization of a single object, and of a group of similar objects, such as bridges in a railway or road network.

Single object

The optimization tries to minimize the total costs spent from putting the object into operation until its replacement or reconstruction. The total costs C in the period T are [1 – 4]:

$$C = C_i + C_m + C_r + C_{f,p} + C_u + C_a - V_s; \quad (8)$$

C_i = inspection costs, C_m = maintenance costs, C_r = repair costs, C_u = user costs, C_a = additional costs, V_s = salvage value of the object at the end of the considered period, and $C_{f,p}$ = probable failure costs, as defined by Equation (2). These include the costs due to a collapse of the object (e.g. a bridge) or its closing if the collapse is imminent. Also, the expenses of users C_u should be included (delays and the necessity to use longer alternative routes).

Various strategies can be used for organizing the maintenance and repairs (e.g. no repair until the replacement, or regular maintenance plus small repairs), which would enable a longer time of operation until replacement. The optimization consists of comparing the costs C for several variants and choosing that with the lowest possible costs. For each variant, the total costs C , Equation (8), are calculated for the time interval considered (e.g. 5 or 20 years), and the costs for individual variants are rank-ordered and compared (Fig. 7). As some of the input data are only estimated, it is recommended to make several estimates for each maintenance strategy: with optimistic, probable, and pessimistic input values.

Figure 7. Comparison of total costs for six variants (an example).

Maintenance optimization for a group of objects

In an ideal case, the optimum variant for maintenance of each object in the network is found as described above. In real life, however, various constraints must often be respected. Very important is the amount of money available for maintenance and repairs in the individual years. It could happen that more bridges should be reconstructed simultaneously than the budget would permit, whereas, in other years, the working capacities for repairs would not be fully used. Thus, it is necessary to calculate the cost components for every bridge and maintenance variant for every year in the considered time interval, in which the renewal should be optimized (e.g. 20 years). These costs can be written into a table with the columns corresponding to years and the rows to individual bridges and maintenance variants (Fig. 8) and compared with the money available. A comparison of all variants reveals the best strategy.

In addition to the demand of uniform flow of money for maintenance and repairs, several other factors must be considered when prioritizing the objects (e.g. bridges) for repairs:

- The condition of the stock as a whole (the worst objects are of special interest);
- The rate of deterioration, as some objects can be in a better condition but deteriorate faster;

The importance of the object in the whole network or in some region.

	2015	2020	2025	2030	2035	SUM
Br. 1, V2						
Br. 2, V1						
Br. 3, V2						
Br. 4, V1						
Br. 5, V3						
Br. 6, V2						
Br. 7, V1						
SUM						

Figure 8. Example of cost matrix for seven bridges during the period 2015 to 2035. Br – bridge; Vj – maintenance variant.

For these reasons, maintenance optimization is sometimes divided into three steps [1, 3, 4]:

Step 1. Condition rating prioritization. All objects are ranked according to their condition as revealed by inspections. Only those with condition worse than a certain value will be considered for the maintenance in the near future. This preselection significantly reduces the number of candidates for further steps.

Step 2. Object importance prioritization. The role of individual objects in the network is considered. One bridge can be in a worse condition than another bridge. However, if it lies on an unimportant road, whereas the other is on a main road, the latter one will be repaired preferably.

Step 3. Optimization of money allocation. The possible maintenance strategies are compared with respect to the available money and the work capacities. Then, the strategy is chosen, which is economically most favorable for the stock in the longer period.

5. Time value of money

In long-term planning, one must be aware of the difference between spending money today and in the future. Due to interests, the value of (suitably deposited) money gradually increases,

so that the today's value V will, in n years, correspond to $V(1+r)^n$, where r is the interest rate. Thus, when the total costs during a long period are calculated as a sum of expenses arising in various times, the values of individual components should be converted to the same time base, usually to the time T_0 when the study is made. The common formula for the conversion of the j -th component C_{j,T_i} paid at time T_i is

$$C_{j,T,0} = C_{j,T_i} \frac{1}{(1+r)^{T_i-T_0}}. \quad (9)$$

However, due to inflation, the prices of material, components, and work gradually grow, and the gain from postponing an investment is smaller. If the inflation rate is close to the interest rate, the profit can be negligible, and the standardization (9) is not necessary for the comparison of individual variants.

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