Study on spare parts requirement modelling of multi-component system under stochastic shock condition

Qiang Wang¹,², a, Xisheng Jia¹, b, Zhonghua Cheng¹, *, Qian Wang¹, c, Shuangchuan Wang¹, d

¹Department of Equipment Command and Administration, Army Engineering University, Shijiazhuang 050003, China
²Army Military Transportation University, Tianjin, 300161, China
*Corresponding author e-mail: 511091065@qq.com, aqw_up@foxmail.com, b734234341@qq.com, c18003131595@163.com, d17778891902@163.com

Abstract. In the field of modern industry, equipment is becoming larger and more complex. Some precision components, especially electronic components and mechanical components, will suffer from external vibration and shock and traumatic failures during operation. Therefore, the analysis of the failure process of multi-component system under the condition of common cause failure is of great significance to improve the guarantee efficiency of multi-component equipment system. When multi-component equipment system is running, the problem of traumatic failures of components under shock is not considered in the calculation of spare parts demand for the system. Based on the analysis of the correlation between equipment degradation failure and shock failure, a spare parts demand calculation model under random shock is established in this paper. Finally, the feasibility of the method is verified by an example. The simulation results show that the model can solve the problem of spare parts demand calculation of multi-component mechanical equipment under random shock.

1. Introduction
With the continuous development of the industrial field, the production equipment of enterprises tends to be large-scale and complicated. For highly integrated mechanical equipment, its precision components are vulnerable to external shocks and cause common cause failure. Especially for the tunnel construction equipment with harsh working environment, the impact of external shock on the reliability of the equipment is obvious. And in case of failure of equipment components, replacement maintenance is usually carried out to reduce downtime and ensure the best economic performance of enterprises. Therefore, it is of great practical significance to research the multi-component demand calculation model under the condition of common cause failure to improve the equipment availability and reduce the economic loss of enterprises.

At present, the literature on spare parts demand usually assumes that the failure rate of equipment components is known. The literature mainly analyses from the perspective of system level, and the spare parts demand model is established based on the historical data of spare parts demand [¹-³]. In the above literature, the failure mode analysis of equipment operation are simplified for analysis. In fact, when the
equipment fails during operation, it not only includes the failure caused by the degradation of the equipment itself, but also the component damage caused by external shock. Because of the strong random city and concurrency of external shocks and the high degree of equipment integration, external shocks often cause simultaneous damage of multiple components of equipment with different probabilities. The equipment will cause extreme shock and traumatic failures with a certain probability after being hit, and it belongs to a typical common cause failure event [4].

The concept of common cause failure is mainly applied to reliability analysis and evaluation of multi-component equipment systems, and great achievements have been achieved. Many scholars have deeply studied the reliability of multi-component equipment system based on common cause failure theory. In engineering applications, the theory has been applied in the fields of electronics [5, 6], machinery [7, 8] and so on.

With the deepening of the research on common cause failure, this theory shows a new idea in the industrial field is proposed for reliability analysis of multi-unit system. Compared with traditional spare parts demand forecasting and equipment single failure mode analysis, common cause failure theory can more accurately describe the damage process of multi-component system under shock. The theory can show the effect of equipment competition failure on equipment reliability in two modes. However, in the application of common cause failure theory, most of the mathematical models assume that the equipment failure is the ideal state, that is, the affected traumatic failure and degradation are independent of each other. In the actual industrial environment, there may be a correlation between equipment degradation and traumatic failure.

To sum up, this paper combined the characteristics of equipment operations, considered the relationship between shock and degradation, and the spare parts demand model was established under the situation of related common cause failure, which based on considering the characteristics of multi-equipment operations and the relationship between shock and degradation. Finally, an example is given to verify the feasibility of the model.

2. Problem Description and Assumption

For large tunnel construction equipment, its integration is high, the precision components are complex. When the equipment is running normally, it may be affected by the surrounding environment. In addition to the deterioration of equipment in its own use, it is also faced with the uncertainty of rock stratum texture structure when excavating rock wall, which makes the performance of equipment affected by external random impact environment. Therefore, under the combined action of the two fault modes, the equipment maintenance personnel should reserve the spare parts in advance. When the equipment fails, replacement maintenance should be carried out to realize the rapid recovery of equipment performance. In this paper, the research object is limited to the production equipment of multi-component system, and the demand for spare parts during the production is predicted and calculated. Firstly, considering the random event of equipment being subjected to external shocks, the relationship between equipment failure under shocks and self-degradation is analyzed. Then, according to the maintenance strategy, the demand for spare parts in the production time stage is calculated. The random failure of multi-type equipment caused by shock is strong. Therefore, in order to facilitate the analysis of spare parts requirements, the following assumptions are made:

1. Equipment failure is mainly caused by extreme impact failure and natural degradation failure caused by external shock. In addition, non-extreme shock caused by external shock will increase the failure rate of equipment degradation in a geometric process [9]. The specific process of spare parts support for multi-part equipment system is shown in Fig. 1.

2. The attack process of equipment is assumed to be Poisson process. The service life of equipment obeys exponential distribution.

3. When the equipment is subjected to external shocks, multiple components would be damaged at the same time, and the probability of extreme shock failure caused by each component is different.

4. The replacement repair strategy would be taken after equipment failure.
(5) In engineering operation, multi-type equipment is needed to complete together. For the same kind of equipment, assume that its key functional spare parts are in series structure.

(6) The repair and replacement time of the faulty parts is not considered.

![Diagram of Maintenance Support Flow Chart of Equipment System](image)

**Figure 1.** Maintenance support flow chart of equipment system

### 3. Modelling of Spare Parts Requirement for the System

The failure of tunnel construction equipment is caused by the combination of impact failure mode and self-degradation failure mode, which is a competitive failure process with extreme impact [10]. Therefore, the process of random common cause failure is essentially the event that multiple components of a multi-component system compete for failure at the same time under the action of the same external shock inducement. In tunnel construction, various types of equipment are needed to cooperate with the implementation. Therefore, when the rock wall is friction with mechanical parts, it will cause random shock on the equipment, which may cause damage to multiple parts of our different types of equipment at the same time. According to the performance of different equipment parts, the probability of extreme shock failure is different. Therefore, this section considers the calculation of spare parts demand of multi-model equipment and multi-component system under the condition of random common-cause failure.

Assuming that there are $N$ types of equipment, the first type of equipment is $Q_i$ sets. And each equipment has $M_i$ key functional components. The life of the components obey the exponential distribution with the parameter $\lambda_{ij}(t, 0)$, which represents the initial life distribution parameters of the $j$th component in the $i$th equipment. During the mission time $t$, the equipment group is attacked by the shock, which is subject to the Poisson distribution with parameter $\{N(t), t \geq 0\}$. $\tau_k$ is the time when the $k$th shock occurs. $\tau_k$ is the interval time between the $k$th shock and the $(k-1)$th shock. Each time the equipment is attacked by the shock, there are two states: taking the probability of $p_i'$ as the extreme shock and making the equipment invalid; taking the probability of $1 - p_i'$ as the non-extreme shock, which increases the failure rate of equipment degradation. Firstly, the influence of non-extreme shock on equipment system is analysed. The initial failure rate of the equipment system is $\dot{\lambda}(t = 0)$. When the $k$th non-extreme shock occurs, the system failure rate increases to $\dot{\lambda}(t) = \alpha^{k-1} \lambda(t = 0), (\alpha > 1; k = 1, 2...)$.

As shown in Fig. 2.
Secondly, the process of common cause failure of equipment system is analyzed. As shown in Fig. 3, let $t_k$ be the time for the occurrence of the $k$ th shock, and $\tau_k$ be the time between the $k$ th shock and the $k-1$ th shock. Replacement repair is required after component failure, and the initial failure rate of the component is $\lambda$.

In conclusion, the modeling of equipment spare parts requirements can be divided into the following two situations:

1. For the multi-component system with a single equipment, the probability of failure of type $i$ equipment due to use degradation within $t$ time is calculated as follows:
\[ P_1(i) = 1 - \prod_{j=1}^{M} \Pr\{R(t,j) \mid N(t) = 0\} \]
\[ = 1 - \prod_{j=1}^{M} P(N(t) = 0) \cdot P(t \leq \theta_j) \]
\[ = 1 - \prod_{j=1}^{M} e^{-\lambda_i j} \exp\left( -\int_{0}^{t} \lambda_y(u,0) du \right) \quad (i=1,2,...N) \quad (1) \]

(2) For the multi-component system with a single equipment, the probability of failure due to extreme shock of type \( i \) equipment within \( t \) time is calculated as follows:

\[ P_2(i) = 1 - \prod_{j=1}^{M} \left( 1 - \Pr\{N_j(t) = 1 \mid R(t)\} \right) \]
\[ = 1 - \prod_{j=1}^{M} (1 - P(N_j(t) = 1) \cdot P(t < \theta)) \]
\[ = 1 - \prod_{j=1}^{M} (1 - (\lambda_i j) e^{-\lambda_i j} \cdot \exp(-\int_{0}^{t} \lambda(u,0) du)) \quad (i=1,2,...N) \quad (2) \]

Formula 1 and 2 can be used to calculate the spare parts requirement of \( i \) th equipment multi-component system within time \( t \), as shown in Formula 3.

\[ d_i(t) = P_1(i) \cdot 1 \cdot (1 - p_y^i) + P_2(i) \cdot 1 \quad (3) \]

Similarly, the Monte Carlo simulation method can be used to calculate the total spare parts demand \( D_i(t) \) for the multi-party system of equipment type \( i \) th within \( t \) task time. The modeling and simulation process of specific spare parts requirements is shown in Fig. 4.
4. Case study and Analysis
Take the tunnel construction of a certain unit as an example. The unit shall carry out the tunnel construction task within T according to the established construction plan. In order to guarantee the availability of the construction equipment and improve the guarantee efficiency of the equipment, it is necessary to predict the demand for spare parts. The three types of equipment and their key components...
known to be involved in the operation are shown in Fig. 5. A series system is formed between the key parts of a single equipment.

![Diagram of equipment composition](image1)

**Figure 5.** The composition of the multi-component equipment

And the relevant parameters are shown in table 1. When the equipment is in construction, it is affected by external random impact, and its random common cause failure event obeys exponential distribution. Based on the relevant fault and maintenance strategy described in section 1, the quantity of spare parts required for this unit is calculated.

| Table 1. The equipment failure related parameters |
|---------------------------------------------------|
| Equipment types | A | B | C |
| Quantity of equipment | 3 | 4 | 3 |
| The serial number of the parts | 1 | 2 | 3 |
| | 4 | 5 | 6 |
| | 7 | 8 | 9 |
| | 10 | |
| Parameters of Life Distribution\( (\lambda_i) \) | 0.26 | 0.17 | 0.09 |
| | 0.15 | 0.36 | 0.06 |
| | 0.35 | 0.16 | 0.06 |
| | 0.38 | 0.23 | 0.19 |
| Probability of failure under RCCF\( (p_i) \) | 0.28 | 0.25 | 0.24 |
| | 0.32 | 0.34 | 0.42 |
| | 0.38 | 0.23 | 0.30 |
| Probability Distribution Parameters of RCCF Events\( (\lambda_j) \) | 2 |
| Failure rate growth factor\( (\alpha) \) | 1.01 |
| Mission time(T/h) | 240 |

According to the parameters in Table 1, the simulation calculation is carried out, and the spare parts requirement under the condition of equipment failure correlation is compared with that under the condition of traditional equipment failure independence. The specific data are detailed in Table 2.

| Table 2. Comparison of spare parts requirements under different conditions |
|---------------------------------------------------------------|
| Equipment types | A | B | C |
| The serial number of the parts | 1 | 2 | 3 |
| | 4 | 5 | 6 |
| | 7 | 8 | 9 |
| | 10 | |
| Failure independent | 181 | 133 | 100 |
| | 75 | 125 | 63 |
| | 131 | 129 | 97 |
| | 223 | |
| Fault related\( (\alpha = 1.01) \) | 185 | 153 | 113 |
| | 79 | 127 | 65 |
| | 133 | 139 | 107 |
| | 234 | |
| Fault related\( (\alpha = 1.51) \) | 223 | 181 | 129 |
| | 91 | 148 | 74 |
| | 148 | 172 | 122 |
| | 275 | |

As can be seen from Table 2, spare parts demand is small when considering fault independence. The greater the growth factor \( \alpha \) of equipment failure rate, the greater the impact of equipment impact on degradation, the greater the demand for spare parts. This is due to the neglect of the impact of equipment impact on the use of degradation, which overestimates the reliability of equipment, resulting in a small demand forecast of equipment spare parts, which may lead to the risk of wartime spare parts shortage.
5. Conclusion
During the operation of the equipment, it may cause traumatic failure when it is subjected to external shocks. The correlation between two failure modes of equipment is analyzed. The spare parts demand model under common cause failure is established. Taking tunnel construction equipment as an example, this paper validates the research on spare parts requirement of equipment, which provides theoretical support for the research on spare parts requirement of construction units. In addition, on the basis of this study, we can further study from the following aspects: (1) spare parts demand calculation under various maintenance strategies can be considered; (2) spare parts supply support under maintenance time constraints can be considered.

Acknowledgments
This work was financially supported by National natural science foundation of China (No.71871219) and National social science foundation of China (No.16gj003-069).

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