Optimization of three-echelon inventory project for equipment spare parts based on system support degree

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Abstract: Management of three-echelon maintenance and supply is a common support mode, in which the spare parts inventory project is one of the critical factors for system availability. Focus on the actual problem of the equipment support engineering, the system spare parts are divided into two levels, and based on the METRIC theory, the three-echelon support evaluation model for system spare parts is established. The three-echelon system support degree is used as the optimization target while the cost is taken as the restriction, and the margin analysis method is applied to inventory project optimization. In a given example, the optimal inventory project and the distribution rule for spare parts is got, and the influencing factors for spare parts inventory is analyzed. The optimization result is consistent with the basic principle under the three-echelon support pattern, which can supply decision assistance for equipment support personal to design a reasonable project.

1 Introduction
Spare parts are not only the supportable resources for equipment maintenance and emergency settlement, but also the important factors to ensure equipment to be in good shape in peacetime. Under the background of information warfare, the complexity of the equipment system structure and the high-price of the spare parts’ cost issue the challenge to logistics support engineering. For the fewer consumed and higher priced spare parts, the three-echelon inventory distribution management is a reasonable support mode, which can make equipment get higher availability while saving large money. Therefore, three-echelon supply mode is beneficial to enhance support service level and reduce maintenance expenditure, and now it has been wide applied in military support units. However, the method of how to get reasonable inventory of every station need to be researched, which is not only the difficult but also the core problem in support engineering.

The analysis of multi-echelon inventory systems has a long history, studies on inventory theory are mainly in two aspects, one is establishing inventory model under the different conditions and assumptions, and another is using reasonable method to solve the problem of inventory optimization. In the aspect of inventory model, Mitra analyzed a two-echelon inventory system with returns[1], 2009. Axsater, Anderson & Marklund considered the structure level of spare parts and studied the two-level spare parts inventory distribution model[2,3]. In reference [4] and [5], the three-echelon inventory model of equipment spare parts was established based on classical METRIC theory. In the aspect of optimization, margin analysis is the most common method, as the development of simulation technology and the comprehensive application of evolutionary algorithm (heuristic optimization algorithm, genetic algorithm and particle swarm optimization et al.) in recent years, these methods are also applied to the inventory distribution. For example, Tee & Rossetti studied the multi-echelon inventory model via simulation[6]; Mohammad & Manuel put forward an efficient heuristic optimization algorithm for (R, Q) inventory system[7]; Loo, Ek & Suyan used the simulation-based evolutionary algorithm to solve the multi-objective inventory allocation problem[8]. According to
these researchers’ studies, most of them are focus on the two-echelon inventory allocation problem. However, the three-echelon inventory model is seldom to be studied, despite the three-echelon model for weapon equipment was mentioned in reference [5], the spare parts structure level was not taken into account.

In this paper, considering the system spare parts’ structure, which is divided into two levels, the three-echelon support evaluation model for system spare parts is established. The three-echelon system support degree is used as the optimization target while the cost as the restriction, margin analysis method is applied to inventory project optimization. In a given example, the optimal inventory project is got and the result is reasonable.

2 Description Of Support Process
According to the different structure level in equipment system, spare parts can be divided into the line replaceable unit and the shop replaceable unit, the structure of which is shown in figure 1. Supposing that a three-echelon support institution is composed of one base station, several relay stations and grass roots stations, the supporting cycle is T, all equipments are deployed in grass roots stations. Then, the every support stations’ inventory level need to be reasonably determined in order to assuring the equipment availability to satisfy the demands. During the supporting cycle, if there is something wrong with the equipment in grass roots stations, which is caused by some line replaceable unit (LRU) is failure, then, the failed LRU is need to be immediately disassembled to repair. If the grass roots station have this LRU spare part, which can be fetched to replace the failed one, or a shortage of LRU happened once in grass roots. Restricted by the equipment trouble diagnosis device and the capability of repair technology, the grass roots station has certain repair probability for the failed LRU. If the failed LRU can not be repaired in grass roots station, the failed one will be sent to relay station to repair, at the same time, applying for one of the LRU spare parts from relay station. The relay station also has certain repair probability for the failed LRU, if the relay station can not repair it, it will be sent to base station to repair, at the same time, applying for one of the LRU spare parts from base station. Because the base station is usually disposed with complete trouble diagnosis device and repair technicians, suppose that the base station can repair all failed LRU.

The reason of the failed LRU is that some one of the shop replaceable unit (SRU) is failed, if the SRU spare part is on hand, it can be installed on the LRU, then, the repair for LRU is complete. There is some certain repair probability for the failed SRU in grass roots stations and relay stations, if the current station can not repair the failed SRU, it will be sent to the upper echelon to repair, at the same time, fetching one of the SRU spare parts from the upper echelon. The process of sending and repair for SRU is the same as LRU.

When the repair and supply of the LRU is complete, the problem of spare parts’ shortage is solved.

3 Modeling for Three-Echelon Support Evaluation
3.1 Definition of parameters
Definition of the parameters in this paper is that the subscripting notation i denotes the serial number of SRU (i=1, 2, ..., I), and the subscripting notation 0 denotes LRU; j(j=1, 2, ..., J) denotes the serial number of grass roots stations, k( k=1, 2, ..., K ) denotes the serial number of relay stations and 0 denotes base support station. The list of notation used in three-echelon inventory model is given below.

\(m_{ij}\): the average annual demand rate for LRU in grass roots station j;
\(T_{ij}\): mean time to repair for SRU in grass roots station j;
\(T_{0j}\): mean time to repair for LRU in grass roots station j;
\(T_{ik}\): mean time to repair for SRU in relay station k;
\(T_{0k}\): mean time to repair for LRU in relay station k;
\(T_{0i}\): mean time to repair for SRU in the base station;
\(T_{00}\): mean time to repair for LRU in the base station;
\(r_{ij}\): repair probability for the failed SRU in grass roots station j;
\( r_{0j} \): repair probability for the failed LRU in grass roots station \( j \);
\( r_{ak} \): repair probability for the failed LRU in relay station \( k \);
\( q_{ij} \): when repairing in grass roots station \( j \), the conditional probability for the failed LRU that caused by the SRU \( i \);
\( q_{jk} \): when repairing in relay station \( k \), the conditional probability for the failed LRU that caused by the SRU \( j \);
\( q_{0k} \): when repairing in base station, the conditional probability for the failed LRU that caused by the SRU \( k \);
\( t_{0j} \): mean time of delay that the grass roots station \( j \) applies for LRU from relay station \( k \);
\( t_{ij} \): mean time of delay that the grass roots station \( j \) applies for SRU from relay station \( k \);
\( t_{0k} \): mean time of delay that relay station \( k \) applies for LRU from base station;
\( t_{ik} \): mean time of delay that relay station \( k \) applies for SRU from base station;
\( s_{ij} \): inventory of SRU in grass roots station \( j \);
\( s_{0j} \): inventory of LRU in grass roots station \( j \);
\( s_{jk} \): inventory of LRU in relay station \( k \);
\( s_{0k} \): inventory of LRU in relay station \( k \);
\( s_{jk} \): inventory of SRU in base station;
\( s_{0k} \): inventory of SRU in base station;

The computation formula for Expected Back-order \( EBO(s) \) is given below

\[
EBO(s) = \sum_{x=1}^{\infty} (x - s) \cdot p_x(x) \tag{1}
\]

VBO(s) is the Variance of Back-order, the expressions for VBO(s) is given as below

\[
VBO(s) = E[B^2(s | x)] - [EBO(s)]^2 \tag{2}
\]

\[
E[B^2(s | x)] = \sum_{x=1}^{\infty} (x - s)^2 \cdot p_x(x) \tag{3}
\]

Here \( s \) is the inventory of spare parts, \( p(x) \) is the steady probability distribution for the amount of spare parts waited for supply. Suppose that the demand rate of spare parts obey the Poisson process with the mean values \( m \) during the support cycle \( T \). According to palm theory, if the repair time for failed items is irrelevance and obey the Poisson process with the mean values \( t \), the number of repairing items obey Poisson process with the mean values \( m t \). So \( p(x) \) obey Poisson distribution.

During the short observing time, the amount of demand for spares parts approximately obey stable Poisson process, however, as the increase of the observing time, the ratio of expected demand value to variance will gradually go upward. So the amount of demand takes on the characteristics of unstable Poisson process, then, the Poisson distribution can be replaced by negative binomial distribution\(^9\), and the expressions are shown below.

\[
p(x) = \binom{a + x - 1}{x} b^x (1 - b)^a \quad x = 0, 1, 2 \ldots \tag{4}
\]

E[X] is the mean value and Var[X] is the variance of negative binomial distribution.

\[
E[X] = ab/(1 - b) \quad Var[X] = ab/(1 - b)^2 \tag{5}
\]

EBO(s | E[X], Var[X]) and VBO(s | E[X], Var[X]) respectively denote the negative binomial approximate evaluation for Expected Back-order EBO(s) and the Variance of Back-order VBO(s), if E[X] and Var[X] are given, the parameters \( a \) and \( b \) can be calculated, then, the value of negative binomial distribution can be calculated through formula \( (4) \).

3.2 Determination of spare parts’ demand rate

According to the average annual demand rate of LRU in grass roots stations, the average annual demand rate of LRU and SRU in each support station can be calculated.

For grass roots station \( j \), the annual demand rate of SRU \( i \) is related to its demand rate of LRU \( m_{0j} \), repairing probability \( r_i \) and the conditional probability \( q_{ij} \) that the failed LRU is caused by the SRU \( i \),
the computation formula is given below.
\[ \bar{m}_i = m_{0i} \cdot r_{0i} \cdot q_{0i} \] (6)

For relay station \( k \), the annual demand rate of LRU is equal to the sum of LRU applied from the relay station \( k \) by all grass roots stations.
\[ \bar{m}_n = \sum_{j=k} m_{0j} (1 - r_{0j}) \] (7)

The annual demand rate of SRU \( l \) for relay station \( k \) is equal to the sum of SRU \( l \) applied from the relay station \( k \) by all grass roots stations, in addition, add the amount of SRU \( l \) demand when repairing the failed LRU in relay station \( k \). The equation is given below.
\[ \bar{m}_l = \sum_{j=k} m_{0j} (1 - r_{0j}) + m_{00} q_{0l} \] (8)

Same as the relay station, the annual demand rate of LRU and SRU in base station can be calculated through formula (9) and (10).
\[ \bar{m}_n = \sum_{i=1}^{k} m_{0i} (1 - r_{0i}) \] (9)
\[ \bar{m}_l = \sum_{i=1}^{k} m_{0i} (1 - r_{0i}) + m_{00} q_{0l} \] (10)

3.3 Determination of the Expected value and Variance of spare parts supply channel
Supply channel of spare parts is composed of two aspects, the one is the number of spare parts that are being repaired, the other is the number of spare parts that are being supplying\(^{10}\).

In base station, the proportion of demand rate of SRU \( l \) that caused by the repair for LRU is given below.
\[ f_{lo} = m_{lo} q_{0l} / m_{0l} \] (11)

The supply channel of LRU for base station is composed of two parts: (1) the amount of LRU that are being repaired when base station has the spare parts of SRU \( l \); (2) the amount of LRU that are being delayed to repair because of the shortage of SRU \( l \). Among the sum back-order of SRU \( l \) in base station, the probability of which that lead to LRU supply delay for relay station obey binomial distribution\(^{11}\).

So the Expected value and Variance of LRU supply channel in base station can be got through formula (12) and (13).
\[ E[X_{0l}] = m_{0l} T_{00} + \sum_{i=1}^{l} f_{lo} EBO(s_{0l} | m_{0l} T_{0i}) \] (12)
\[ Var[X_{0l}] = m_{0l} T_{00} + \sum_{i=1}^{l} f_{lo} (1 - f_{lo}) \cdot EBO(s_{0l} | m_{0l} T_{0i}) + \sum_{i=1}^{l} f_{lo}^2 VBO(s_{0l} | m_{0l} T_{0i}) \] (13)

\( f_{ki} \) is the proportion of the amount of SRU \( l \) applied by relay station to the sum demand rate of base station, and the calculation formula is given below.
\[ f_{ki} = m_{ki} (1 - r_{0i}) / m_{0i} \] (14)

The supply channel of SRU \( l \) is equal to the sum of the amount of being repaired and sent to repair by relay station, in addition, add the amount of SRU \( l \) that are delayed to supply because the base station has not SRU \( l \) spare parts. The expectation and variance of SRU \( l \) for relay station’s supply channel can be calculated through formula (15) and (16).
\[ E[X_{lk}] = m_{lk} [1 - r_{0l}] t_{lk} + r_{l} T_{lk} + f_{lk} \cdot EBO(s_{0l} | m_{0l} T_{0i}) \] (15)
\[ Var[X_{lk}] = m_{lk} [(1 - r_{0l}) t_{lk} + r_{l} T_{lk}] + f_{lk} \cdot (1 - f_{lk}) \cdot EBO(s_{0l} | m_{0l} T_{0i}) + f_{lk}^2 \cdot VBO(s_{0l} | m_{0l} T_{0i}) \] (16)

The supply channel of LRU for relay station is composed of three parts: (1) the amount of LRU
received from base station; (2) the amount of LRU that are delayed to supply because the shortage of LRU occurred in base station; (3) the amount of LRU that are being delayed to repair because of the shortage of SRU, in relay station. So, the expectation and variance of LRU for relay station’s supply channel can be calculated through formula (17) and (18).

\[
E[X_{i0}] = m_{i0}[(1 - r_{i0})t_{i0} + r_{i0}T_{i0}] + f_{i0} \cdot EBO(s_{i0} | E[X_{i0}], Var[X_{i0}]) + \sum_{j=1}^{l} EBO(s_{i0} | E[X_{i0}], Var[X_{i0}])
\]

(17)

\[
Var[X_{i0}] = m_{i0}[(1 - r_{i0})t_{i0} + r_{i0}T_{i0}] + f_{i0}(1 - f_{i0})EBO(s_{i0} | E[X_{i0}], Var[X_{i0}]) + f_{i0}^2 \cdot VBO(s_{i0} | E[X_{i0}], Var[X_{i0}]) + \sum_{j=1}^{l} VBO(s_{i0} | E[X_{i0}], Var[X_{i0}])
\]

(18)

The calculation method of expectation and variance for grass roots station’s supply channel is same as that of relay station. The expectation and variance of SRU, for grass roots station’s supply channel are shown below.

\[
E[X_{j}] = m_{j}[(1 - r_{j})t_{j} + r_{j}T_{j}] + f_{j} \cdot EBO(s_{j} | m_{j}T_{j})
\]

\[
Var[X_{j}] = m_{j}[(1 - r_{j})t_{j} + r_{j}T_{j}] + f_{j}(1 - f_{j}) \cdot EBO(s_{j} | m_{j}T_{j}) + f_{j}^2 \cdot VBO(s_{j} | m_{j}T_{j})
\]

(19)

(20)

The expectation and variance of LRU for grass roots station’s supply channel can be calculated through formula (21) and (22).

\[
E[X_{j}] = m_{j}[(1 - r_{j})t_{j} + r_{j}T_{j}] + f_{j} \cdot EBO(s_{j} | E[X_{j}], Var[X_{j}]) + \sum_{j=1}^{l} EBO(s_{j} | E[X_{j}], Var[X_{j}])
\]

(21)

\[
Var[X_{j}] = m_{j}[(1 - r_{j})t_{j} + r_{j}T_{j}] + f_{j}(1 - f_{j})EBO(s_{j} | E[X_{j}], Var[X_{j}]) + f_{j}^2 \cdot VBO(s_{j} | E[X_{j}], Var[X_{j}]) + \sum_{j=1}^{l} VBO(s_{j} | E[X_{j}], Var[X_{j}])
\]

(22)

The calculation method of \(f_{ij}\) and \(f_{0j}\) is same as that of relay station. \(j \in k\) means that all grass roots stations supported by the relay station \(k\), which is determined by support relation between stations of different echelon.

3.4 Project evaluation target

Availability of equipment system is an important evaluation target for integrated logistics support, which means the probability of equipment is in good condition at any given time. The premise of availability for system is that all compositive parts could be in good condition, the availability of LRU for the grass roots station \(j\) is shown below.

\[
A_{j}(i) = (1 - EBO(s_{j} | E[X_{j}], Var[X_{j}])(N_{j}Z_{0}))^{r_{j}}
\]

(23)

In the formula above, \(N_{j}\) is the amount of equipment deployed in grass roots unit \(j\), \(Z_{0}\) is the number of LRU equipped in equipment system.

We suppose that the system is composed of \(N\) different LRU, and any of them failed will lead to unavailability for the system. So we can obtain the availability of equipment system from the formula
below.

\[ A_j = \prod_{i=1}^{N} A_j(i) \]  

(24)

Then we can define support degree \( A_x \) to evaluate the effectiveness of the three-echelon support system. \( A_x \) reflects the proportion of the amount of available equipments to the sum.

\[ A_x = \sum_{j=1}^{N} \left( \frac{N_j}{A_j} \right) / \sum_{j=1}^{N} N_j \]  

(25)

4 Inventory Optimization Model And The Optimization Design

4.1 spare parts inventory optimization model

The inventory optimization model can be described that when three-echelon support effectiveness \( A_x \) reach the required target, minimized the cost of spare parts. Define \( s_{ij} \) is the inventory of the \( i \)th spare part in the \( j \)th station, \( C_i \) is the cost of the \( i \)th spare part. The optimization model is given below.

\[
\min \sum_{i,j} C_i s_{ij} \\
\text{s.t.} \quad A_x = \sum_{j=1}^{N} \left( \frac{N_j}{A_j} \right) / \sum_{j=1}^{N} N_j \geq A_u
\]

(26)

4.2 Optimization method

In this paper, we use the margin analysis method to optimize the three-echelon inventory model, during the process of optimization, this algorithm will repeatedly calculate the target value until it reach the required target. During the cycle process of every time, the control variable need to be adjusted is determined through the analysis of the optimization target value.

First, determine the control variables in the model, add 1 to the number of every control variable during the cycle process of every time, calculate and record the corresponding margin increments of support effectiveness and cost. Then, add 1 to the control variable that has the most contribution to margin effectiveness, and other control variables keep unchanged. At last, the calculation cycle will stop when optimization target value reach the required one, then, the control variables’ value is the optimization result. The optimization steps are given below

Step1: initialize the inventory of different spare parts, set the variable \( s_{ij} = 0 \).

Step2: execute calculation cycle, during the cycle process of every time, calculate the margin value \( \delta_{ij}(s_{ij}) \), which can be got from the computation formula (27).

\[ \delta_{ij}(s_{ij}) = [A_x(s_{ij} + 1) - A_x(s_{ij})] / C_i \]  

(27)

Step3: when the margin value \( \delta_{ij}(s_{ij}) \) is calculated, determine the maximum \( \delta_{ij}(s_{ij}) \) and add 1 to the corresponding spare part inventory.

Step4: according to the inventory \( s_{ij} \), compute the three-echelon support degree \( A_x \) and judge it whether reach the required target. if \( A_x \geq A_u \), calculation cycle is end, or enter the step 2.

5 Analysis of the Given Example

Suppose there is a three-echelon supply and repair system, which is composed of a base station (H_0), two relay stations (R_1, R_2) and three grass roots stations (J_1, J_2, J_3), to supply spare parts and repair for equipment deployed in grass roots field. The amount \( (N_j) \) of this equipment deployed in the three grass roots units are 30, 25 and 20 respectively. The framework and relation of three-echelon support system is shown in figure 1.

The parameters of equipment system’s LRU are shown in table 1. The subscripting notation \( j \) denotes the grass roots supply and repair stations, \( k \) denotes the relay stations and 0 denotes the base station. All of the time parameters are measured by year, and the cost of spare parts are measure by ten thousand dollars. The number \( (Z) \) of LRU equipped in equipment system is 2, 2 and 3 respectively.
Table 1 The spare parts’ parameter of line replaceable unit (LRU)

| Spare part | annual demand rate $m_{01}$ | $m_{02}$ | $m_{03}$ | mean time to repair(year) $T_{0j}$ | $T_{0k}$ | repair probability $r_0$ | $r_{0k}$ | Cost $C_0$ |
|------------|-----------------|----------|----------|-------------------|--------|-----------------|--------|----------|
| LRU1       | 46.4            | 41.4     | 39.7     | 0.0164            | 0.0247 | 0.0329          | 0.24   | 0.53     | $53,400$ |
| LRU2       | 46.4            | 39.8     | 30.4     | 0.0192            | 0.0219 | 0.0301          | 0.28   | 0.49     | $78,800$ |
| LRU3       | 47.7            | 43.4     | 41.7     | 0.0192            | 0.0219 | 0.0356          | 0.22   | 0.61     | $92,300$ |

Suppose the period of support is one year, the superior require the three-echelon support degree value Ax is higher than 0.98. Through margin analysis method, after the computer program experienced 59 times of calculation, the optimal inventory of different supply stations is got, which shown in the table 2. We can get some conclusions from the optimal inventory result.

- For the first-level support station (base station), its inventory for LRU is very low, in some circumstance, the inventory of LRU is zero. However, the inventory of the second-level spare parts SRU is higher than that of LRU.
- For the second-level support station (relay station), its inventory of LRU is higher than that of base station, and lower than that of grass roots station, however, the inventory of SRU is lower than that of base station, and higher than that of grass roots station.
- The grass roots station need to deploy more LRU than that of relay station and base station, however, its inventory of SRU is the lowest, in addition to several kinds of high-demand SRU, the inventory of other SRU is zero.
- The spare parts’ inventory is mainly determined by the amount of equipment deployed in grass roots stations and the organizational relation of three-echelon support system, in addition, it is also related to stations’ repair level, repair time and the supply delay et al.

Table 2 The optimal inventory project of system spare parts

| support station | LRU1 | LRU2 | LRU3 | SRU11 | SRU12 | SRU21 | SRU22 | SRU31 | SRU32 |
|-----------------|------|------|------|-------|-------|-------|-------|-------|-------|
| H₀              | 1    | 1    | 1    | 2     | 3     | 2     | 3     | 2     | 3     |
| R₁              | 0    | 0    | 0    | 1     | 1     | 1     | 1     | 1     | 1     |
| R₂              | 2    | 2    | 2    | 2     | 1     | 2     | 2     | 1     | 1     |
| J₁              | 3    | 2    | 2    | 0     | 0     | 1     | 0     | 0     | 0     |
| J₂              | 3    | 2    | 1    | 0     | 0     | 1     | 0     | 0     | 0     |
| J₃              | 2    | 1    | 1    | 0     | 0     | 1     | 0     | 0     | 0     |

According to analysis of the optimal inventory project shown in table 2, we can know that the optimization result gained from the inventory model established in this paper is consistent with spare parts’ disposition principle under the three-echelon support pattern.
If execute the inventory project shown in table 2, we can get that the availability of equipments deployed in grass roots units during support period, which are $A_{j1}=0.9823$, $A_{j2}=0.9858$, $A_{j3}=0.9718$ respectively, the three-echelon system support degree $A_x=0.9807$, and the support cost is $22,564$ thousand dollars.

Fig.2 The variability curve of system support degree

Fig.3 The curve of system support degree vs. cost

The solution for inventory optimization model need to give large amount of basic parameters, it requires high-accurate input data. Some input data such as demand rate of spare parts, repair probability of support stations and mean time to repair, which are unknown in practice but processed as the known parameters. If we can not accurately evaluate these unknown input parameters, it will lead to error to the result, no matter how advanced the inventory model is, it will not take benefit for us. So we should build complete support analysis record database system, from which we can accurately get the basic support parameters.

6 Conclusion

In this paper, we focus on the actual problem of the equipment support engineering. Considering the structure level of system spare parts, and based on the METRIC theory, the three-echelon inventory optimization model for system spare parts is established. The three-echelon system support degree is used as the optimization target while the cost is taken as the restriction, and the margin analysis method is applied to inventory project optimization. In a given example, the optimal inventory project is got. According to the optimization result, we get the general principle of spare parts disposition and analyze the influencing factors for spare parts inventory. The result is consistent with the disposition principle under the three-echelon support pattern, compared to empiricism, this optimization method can save large amount of support cost under the condition of reaching the required target, which can supply decision assistance for equipment support personal to design a reasonable project. For irreparable or partial-reparable spare parts, we must consider the problem of discard. In this case, the base station needs to order a certain amount $R$ of spare parts from plant or external supplier when its inventory fall to a certain extent $Q$, that is, we should determine the optimal ordering policy $(R, Q)$. In addition, as the increasing of demand rate and types for spare parts, the amount of calculating time become the problem we must consider when using margin analysis method. For large-amount and high-consumed spare parts, we can use evolitional algorithm (such as genetic algorithm, heuristic
optimization algorithm and particle swarm optimization algorithm et al) to get the optimal inventory project in a short time. Aiming at these problems present above, we should do more and further research.

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